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Thèse

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Télécom ParisTech

Spécialité : Informatique et Réseaux

Modèles de décision pour la sélection
d'interface et l'association flux/interface
pour les terminaux mobiles multi-
interfaces

Présentée par
Phuoc Nguyen TRAN

Soutenue le 17/09/2010 devant le jury composé de :

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Interface selection and flow/interface association decision schemes for multi- interface mobile terminals

Dissertation

submitted in partial fulfillment of the requirements
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Télécom ParisTech

Department of Computer Science and Networking

By

Phuoc Nguyen Tran

September 17th 2010

To my wife, for her true love and continuous encouragements in my life.

To my father and mother who have been constant sources of love, concern, support and strength all these years and for sacrificing whole life to my happiness.

And to my grandparents, my uncles, my aunts, my father and mother-in-law, and my sisters and brothers-in-law for the peaceable environments they have offered to me.

To the memory of my grandfather and grandmother -
Ông Bà Nội.

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This dissertation would not have been possible without the guidance and the help of several individuals who gave me their aids and extended their valuable assistance in the preparation and completion of this study.

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Abstract

The diversity of radio access technologies (e.g., GPRS, UMTS, HSDPA, Wi-Fi, WiMAX, LTE...), their complementary in terms of coverage area, technical characteristics (e.g., bandwidth, QoS) and commercial opportunities for the operators lead to the development of mobile terminals integrating multiple radio interfaces. The ability of mobile terminals to support various interfaces provides many interesting benefits, such as permanent and ubiquitous access, reliability, load sharing/load balancing, bandwidth aggregation, and multi-criteria interface selection.

Mobile terminals with several radio interfaces have the possibility to choose the “best” interface according to several parameters such as application characteristics, user preferences, network characteristics, operator policies, tariff constraints, etc. It becomes also possible to associate the applications to the available network interfaces basing mainly on application requirements.

In the thesis, we tackle the interface selection issue where a mobile terminal equipped with several interfaces has to select at any time the best interface or the best access technology according to multiple criteria. We particularly focus on the decision schemes and investigate the MADM methods

The fundamental objective of the MADM methods is to determine among a finite set of alternatives the optimal one. MADM includes many methods such as Simple Additive Weighting (SAW), Weighting Product (WP), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

The first aim of the thesis is to study and analyze the Multiple Attribute Decision Making (MADM) methods for interface selection issue. A first contribution is to propose a simulation based study which highlights limitations of the methods in this context. TOPSIS suffers from the “ranking abnormality” problem. The ranking abnormality problem occurs when a low ranking alternative is removed from the candidate’s list (e.g., one network is disconnected), the order of higher ranking alternatives will change abnormally.

As a second contribution, we propose Distance to the ideal Alternative (DiA) algorithm which helps terminal to select dynamically the best interface by providing a ranking order between the interfaces. We show that DiA does not suffer from the ranking abnormality which is the shortcoming of the TOPSIS method. Simulation results validate the DiA algorithm.

The third contribution tackles the flow/interface association issue (per-flow interface selection) where a mobile terminal equipped with several interfaces has to associate a specific application to the suitable interface.

We first propose an interface utility function. This utility function allows identifying the interface which considers the satisfaction of the application requirements and economizes the energy consumption of the mobile terminal. We then propose an utility-based flow/interface association scheme that allows to associate the application to the appropriate interface. Network side attributes such as access delay and cost of using the network are also considered in the scheme. The Distance to the ideal Alternative (DiA) algorithm is used to rank the interfaces based on the interface utility values and the network side attributes.

Simulation results are presented to validate the interface utility based scheme.

Additionally, we propose a multiple flow/interface association scheme. In this case, a terminal running several applications tries to associate simultaneously each application flow to the suitable network interface while maximizing global utility. The multiple flow/interface association is an optimization problem. Particularly, it is related to stochastic heuristic optimization problems which are mainly based on search techniques of which solutions and search order depend on random variables.

As the first step, we studies and realizes a simulation comparison of stochastic heuristic optimization methods such as local search, Tabu search, and simulation annealing algorithms.

We then propose an oriented diversification technique of the Tabu search as an improvement. This allows the Tabu search to avoid being re-entrapped in the local optimization several times and to increase the performance of Tabu search in our context. Simulation results demonstrate that the modified Tabu search outperforms other stochastic heuristic algorithms in our context.

We then head to a network centric approach while taking into account the flow/interface association.

We consider a system of multi-interface mobile terminals with the ability of application/interface associations. As multiple terminals compete for common network resources, the system is modeled as a strategic game. Our objective is to find Nash equilibrium strategies of the game.

We let the game evolve according to the so-called Replicator dynamic and then observe whether the system converges and whether the stationary points are Nash equilibria.

We show that the Replicator dynamic is Positively Correlated and the system is a potential game. Our system converges to stationary points which include all Nash equilibria. Furthermore, the stationary points are proven to be efficient as they are solutions of the optimization problem of the total utility. An interesting edge is that our analytical results are valid for a general utility function which depends on the whole system state of connections.

To validate our model and to demonstrate that the system converges to Nash equilibria, we implement two simulation scenarios using Nash learning algorithm with a specific bandwidth allocation scheme as well as a utility function that takes into account the application satisfaction level and the energy consumption.

Résumé

La diversité des technologies d'accès radio (e.g., GPRS, UMTS, HSDPA, Wi-Fi, WiMAX, LTE ...), leur complémentarité en termes de couverture, des caractéristiques (e.g., la bande passante, QoS) et des possibilités commerciales pour les opérateurs conduisent au développement des terminaux mobiles intégrant simultanément plusieurs interfaces radio. La capacité des terminaux mobiles utilisant simultanément différentes interfaces offre de nombreux avantages intéressants, tels que l'accès permanent et omniprésent, la fiabilité, le partage de charge, l'agrégation de bande passante disponible et la sélection d'interface basée sur plusieurs critères, etc.

Les terminaux mobiles avec plusieurs interfaces radio ont la possibilité de choisir la «meilleure» interface en fonction de plusieurs paramètres tels que les caractéristiques des applications, les préférences des utilisateurs, les caractéristiques du réseau, les politiques d'opérateur et les contraintes tarifaires, etc. Il devient également possible d'associer les applications aux différentes interfaces de réseau basant sur les exigences d'application.

Dans cette thèse, nous abordons le problème de sélection d'interface où un terminal mobile équipé de plusieurs interfaces peut sélectionner à tout moment la meilleure interface ou la meilleure technologie d'accès selon plusieurs critères. Nous considérons le problème de décision pour la sélection d'interface. Le problème de décision est un problème très complexe. On peut avoir les différentes approches pour la sélection d'interface (e.g., fonction de coût, fonction d'utilité, ou la politique). Chaque approche est considérée comme un angle d'attaque. Nous nous intéressons à l'approche MADM qui est une approche prometteuse pour la décision avec plusieurs attributs. Nous investiguons ces méthodes dans le contexte de la sélection d'interface.

L'objectif fondamental des méthodes MADM est de déterminer la solution optimale parmi plusieurs solutions. MADM comprend de nombreuses méthodes, comme SAW (Simple Additive Weighting), WP (Weighting Product) et TOPSIS (Technique for Order Preference by Similarity to Ideal Solution).

Le premier objectif de ma thèse est d'étudier et d'analyser les méthodes de MADM pour le problème de sélection d'interface. La première contribution est de proposer une étude de simulation qui met en évidence des limites des méthodes de MADM dans le contexte de la sélection d'interface. Par exemple, TOPSIS a le problème «d'anomalie de classement». Ce problème se produit lorsqu'une interface à faible classement est retirée de la liste du candidat (e.g., un réseau est déconnecté), l'ordre de classement des interfaces changera anormalement.

La deuxième contribution propose l'algorithme de DiA (Distance to the ideal Alternative) qui permet au terminal mobile de sélectionner dynamiquement la meilleure interface. Nous montrons que DiA n'a pas le problème «d'anomalie de classement» qui est le défaut de la méthode TOPSIS. Les résultats de simulation valident l'algorithme de DiA.

La troisième contribution s'attaque au problème d'association flux/interface où un terminal mobile équipé de plusieurs interfaces doit associer une application à l'interface spécifique appropriée.

Nous proposons tout d'abord une fonction d'utilité interface. Cette fonction d'utilité permet d'identifier l'interface qui satisfait des besoins d'application et économise la consommation d'énergie du terminal mobile. Nous proposons ensuite un premier

modèle d'association flux/interface qui permet d'associer séquentiellement des applications aux interfaces. Les attributs de réseau tels que le délai d'accès et le coût monétaire sont également pris en compte dans le régime. L'algorithme de DiA est utilisé pour classer les interfaces basées sur les valeurs d'utilité interface et les attributs de réseau. Les résultats de simulation sont présentés pour valider le schéma proposé.

De plus, nous proposons un deuxième modèle d'association flux/interface. Dans ce modèle, un terminal peut associer simultanément plusieurs applications aux interfaces de réseau. Le modèle vise à maximiser l'utilité globale du terminal. Ce problème est un problème d'optimisation. En particulier, il est lié aux problèmes d'optimisation heuristique stochastique (i.e., méta-heuristique) qui sont principalement basées sur les techniques de recherche dont les solutions et l'ordre de recherche basent sur les procédures aléatoires.

En première étape, nous étudions et réalisons une étude de simulation des méthodes d'optimisation heuristique stochastique, e.g., la recherche locale, la recherche de Tabou, la méthode de recuit simulée.

Nous proposons ensuite une technique de diversification orientée pour la recherche Tabou comme une amélioration. Cela permet à la recherche Tabou d'éviter de se retrouver piégée plusieurs fois dans l'optimum local et d'augmenter les performances de la recherche Tabou dans notre contexte. Les résultats de simulation montrent que la méthode modifiée a meilleure performance comparée avec les autres algorithmes méta-heuristique dans notre contexte.

Nous nous dirigeons ensuite vers une approche au niveau de réseau pour le problème d'association flux/interface.

Nous considérons un système des terminaux mobiles multi-interface. Chaque terminal peut associer des applications aux interfaces. Comme plusieurs terminaux en concurrence pour les ressources de réseau commun, le système est modélisé comme un jeu stratégique. Notre objectif est de trouver des stratégies d'équilibre de Nash pour le jeu.

Nous avons laissé le jeu évoluer en fonction de la dynamique de Replicateur et observons si le système converge et si les points stationnaires sont des équilibres de Nash.

Nous montrons que la dynamique de Replicateur est positivement corrélée et le système est un jeu potentiel. Notre système converge vers des points stationnaires qui comprennent tous les équilibres de Nash. En outre, les points stationnaires sont efficaces car ils optimisent l'utilité du système. Un point intéressant est que nos résultats sont validés pour une fonction d'utilité générale qui dépend de l'état du système.

Pour valider notre modèle et démontrer que le système converge vers des équilibres de Nash, nous mettons en œuvre les scénarios de simulation en utilisant un algorithme d'apprentissage Nash avec un schéma d'allocation de bande passante spécifique ainsi que d'une fonction d'utilité qui prend en compte le niveau de satisfaction d'application et la consommation d'énergie.

Résumé étendu

1 Contexte

Les évolutions qui se dessinent pour les nouvelles générations de réseaux de mobiles sont fondées sur une continuité avec les normes UMTS et CDMA2000, et par une influence très forte d'une cohorte de réseaux sans fil fondés sur les normes IEEE 802.11, .15, .16, .20, .21, .22 ou dans les vocabulaires produits les plus classiques Wi-Fi, WiMedia, WiMAX, Wi-MAX Mobile, Wi-RAN [3Ming].

La complémentarité de ces technologies en termes de couverture, de caractéristiques (débits, QoS, etc.) et d'opportunités commerciales pour les opérateurs a conduit à l'apparition sur le marché des terminaux intégrant à la fois plusieurs technologies d'accès radio.

Il semble que ces différentes technologies peuvent coexister et des solutions d'intégration et d'interopérabilité seront nécessaires pour faire face à la diversité technologique [3Ming].

De plus, les nouveaux usages des terminaux mobiles ont considérablement changé non seulement le type (i.e., vidéo, audio, data) mais aussi le volume du trafic supporté par les réseaux mobiles, les accès mobiles. Les estimations des experts s'attendent à un doublement de ce trafic pour les cinq ans à venir avec une augmentation du trafic de vidéo. Aujourd'hui, le manque de technologies radio pour étendre la capacité de la liaison radio et répondre à ces nouveaux besoins montre les avantages potentiels de la multi-homing pour les opérateurs de réseau en augmentant la bande passante offrant aux clients et l'agrégation des capacités des interfaces disponibles [Alcatel].

2 Motivations

Une fois qu'un terminal est équipé de plusieurs interfaces, il peut utiliser simultanément les différentes interfaces - non simplement basculer de l'un à l'autre.

Dans ce document, nous concentrons sur la capacité qu'un terminal mobile peut communiquer simultanément sur plusieurs interfaces de réseau qui peuvent être les différentes technologies d'accès radio (i.e., à la fois sans fil et cellulaires). Cela ouvre des nouvelles perspectives. Nombreux d'avantages seront fournis [Thierry], e.g., et l'accès permanent et universel, la fiabilité, la sélection d'interface, l'association flow/interface, la partage de charge, et l'agrégation de bande passante.

Dans ce travail, nous attaquons le problème de décision pour la sélection d'interface et l'association flux/interface.

Le problème de décision pour la sélection d'interface

La première motivation de ce travail est de prendre en compte la question de sélection d'interface où le terminal mobile équipé de plusieurs interfaces peut sélectionner la meilleure interface ou la meilleure technologie d'accès selon plusieurs critères, comme indiqué ci-dessus.

La procédure de handover a été bien étudiée et déployée dans les systèmes cellulaires. Elle est aussi une grande importance dans les systèmes sans fil. Traditionnellement, la décision de handover, notamment en cas de handover horizontal, est purement en fonction de la puissance du signal (RSS) et les valeurs de seuils hystérésis comme les paramètres d'entrée. L'handover vertical considère plusieurs critères à prendre une

décision. Toutefois, la décision est principalement basée sur le RSS, dans la région frontalière de deux cellules, et le RSS est supposé d'être le critère le plus prioritaire par rapport aux autres.

Dans le contexte multi-homing, le terminal mobile est dans différentes zones de couverture de réseau. Le paramètre de puissance du signal radio (RSS) est supposé d'être plus élevé que les seuils nécessaires pour la connectivité. Le terminal mobile multi-interface est capable d'accéder à plusieurs réseaux en même temps et sélectionner le meilleur réseau parmi les réseaux disponibles en s'appuyant sur plusieurs attributs. Le défi de la sélection d'interface est de déterminer le plus favorable aux compromis parmi tous les attributs. Les poids associés aux attributs dépendent l'objectif spécifique du décideur.

Le problème de décision pour l'association flux/interface

Notre seconde motivation considère la question d'association flux/interface où chaque application est associée à une interface spécifique basant sur les exigences des applications. D'autres paramètres pourraient être envisagés.

Il existe trois types d'applications principales telles que temps réel, adaptive et élastique. Chaque type d'application a sa caractéristique spécifique. Les applications en temps réel ont besoin de données d'arriver dans un délai lié. Par exemple, des applications de téléphonie traditionnelle. Les applications adaptives, comme la vidéo, la voix, la transmission est plus tolérante aux taux de retard occasionnel et aux paquets perdus (e.g., application de streaming). Les applications élastiques sont les applications traditionnelles, telles que le courrier électronique, FTP, etc. qui peuvent s'adapter aux changements à l'échelle de retard et/ou le débit.

Le défi du problème d'association flux/interface est de déterminer quelle interface réseau étant apte à quelle application.

De nombreux cas d'utilisation intéressante mettent en évidence les motivations de l'association flux/interface. Considérons, par exemple, un terminal intègre trois interfaces radio: Wi-Fi, WiMAX et 3G et gère simultanément trois applications : une application FTP, une application de streaming (vidéo MPEG avec un taux moyen de 2 Mbit/s) et un appel vocal. En outre, considérons que la bande passante disponible est d'environ 1 Mbps sur l'interface Wi-Fi et environ 5 Mbit/s sur l'interface WiMAX, par exemple. Dans ce scénario, il serait intéressant pour le terminal d'associer: l'appel vocal à l'interface 3G, l'application de streaming à l'interface WiMAX car ce réseau fournira une haute qualité, et l'application FTP à l'interface Wi-Fi à économiser la consommation d'énergie terminal (en considérant que la consommation d'énergie de la technologie WiMAX est plus élevé que Wi-Fi).

3 Contributions

La sélection d'interface est un problème de "décision" avec plusieurs alternatives (i.e., interfaces) et les attributs (i.e., caractéristiques de l'interface, les préférences des utilisateurs, etc.)

Le problème de décision est un problème très complexe. On peut avoir les différent approches pour la section d'interface (e.g., fonction de coût, fonction d'utilité, ou la politique, etc.). Chaque approche est considérée comme un angle d'attaque. Nous nous intéressons l'approche MADM qui est une approche prometteuse pour la sélection d'interface.

L'objectif des méthodes MADM est de déterminer la solution optimale parmi plusieurs solutions. MADM comprend de nombreuses méthodes, comme SAW (Simple Additive Weighting), WP (Weighting Product), et TOPSIS (Technique for Order Preference by Similarity to Ideal Solution).

Le premier objectif de ma thèse est d'étudier et d'analyser les méthodes de MADM pour le problème de sélection d'interface. La première contribution est de proposer une étude de simulation qui met en évidence des limites des méthodes de MADM dans le contexte de la sélection d'interface. Par exemple, SAW, WP offrent moins de précision dans l'identification des classements (problème «d'identification de classement»). TOPSIS a le problème «d'anomalie de classement". Ce problème se produit lorsqu'une interface à faible classement est retirée de la liste du candidat (e.g., un réseau est déconnecté), l'ordre de classement des interfaces restants changera anormalement. Par conséquent, la suppression d'une interface de la liste du candidat peut provoquer la prise de décision peu fiable.

Comme la deuxième contribution, nous proposons l'algorithme de DiA (Distance to the ideal Alternative) qui améliore les limitations de MADM. Nous montrons que DiA n'a pas le problème «d'anomalie de classement». Les résultats de simulation valident l'algorithme de DiA.

La troisième contribution s'attaque au problème d'association flux/interface où un terminal mobile équipé de plusieurs interfaces peut associer une application à l'interface spécifique appropriée.

Nous proposons tout d'abord une fonction d'utilité interface. Cette fonction d'utilité décrit le niveau de satisfaction d'application et de consommation d'énergie du terminal mobile. Un premier modèle d'association flux/interface ensuite est proposé qui permet d'associer séquentiellement des applications aux interfaces. Les attributs de réseau tels que le délai d'accès et le coût monétaire sont également pris en compte dans le modèle. L'algorithme de DiA est utilisé pour classer les interfaces basées sur les valeurs d'utilité d'interface et les attributs de réseau. Les résultats de simulation sont présentés pour valider le schéma proposé.

Nous proposons ensuite un deuxième modèle d'association flux/interface. Dans ce modèle, un terminal mobile peut associer simultanément plusieurs applications aux interfaces de réseau. Le modèle vise à maximiser l'utilité globale du terminal. Ce problème est un problème d'optimisation. En particulier, il est lié aux problèmes d'optimisation heuristique stochastique (i.e., méta-heuristique) qui sont principalement basées sur les techniques de recherche dont les solutions et l'ordre de recherche basent sur les procédures aléatoires.

En première étape, nous réalisons une étude de simulation des méthodes de méta-heuristique, e.g., la recherche locale, la recherche de Tabou, la méthode de recuit simulé. Les résultats illustrent les limitations de ces méthodes dans le contexte d'association flux/interface.

Nous proposons une orientation de diversification pour la recherche de Tabou comme une amélioration. Cela permet à la recherche de Tabou d'éviter de se retrouver piégée plusieurs fois dans l'optimum local et d'augmenter les performances de la recherche Tabou dans notre contexte. Les résultats de simulation montrent que la méthode modifiée a meilleure performance comparée avec les autres algorithmes méta-heuristiques dans notre contexte.

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Nous considérons le jeu d'évolution en fonction de la dynamique de Replicateur et observons si le système se converge et si les points stationnaires sont des équilibres de Nash.

Nous montrons que la dynamique de Replicateur est positivement corrélée et le système est un jeu potentiel. Notre système converge vers des points stationnaires qui comprennent tous les équilibres de Nash. En outre, les points stationnaires sont efficaces car ils optimisent l'utilité du système. Un point intéressant est que nos résultats sont valides pour une fonction d'utilité générale qui dépend de l'état du système.

Pour valider notre modèle et démontrer que le système converge vers des équilibres de Nash, nous mettons en œuvre deux scénarios de simulation en utilisant un algorithme d'apprentissage Nash avec un schéma d'allocation de bande passante spécifique ainsi que d'une fonction d'utilité qui prend en compte le niveau de satisfaction d'application et la consommation d'énergie.

4 Organisation

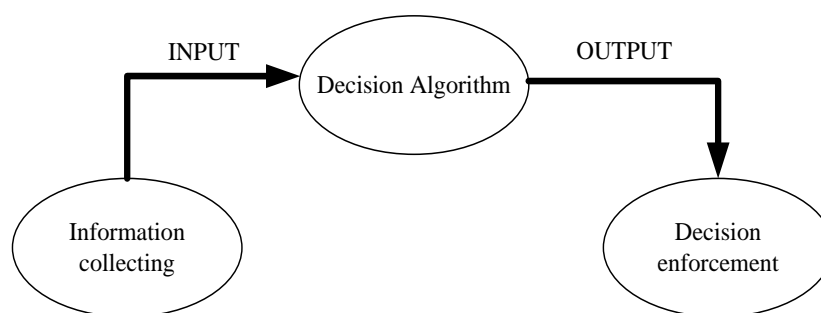
La thèse comprend en six chapitres et une annexe. Dans le chapitre 1, nous introduisons le contexte, les objectifs ainsi que les contributions effectuées dans la thèse. Le chapitre 2 donne un aperçu de l'évolution des technologies sans fil et des terminaux mobiles. Ce chapitre présente également un état de l'art lié à la sélection d'interface et à l'association flux/interface. Dans le chapitre 3, nous présentons une étude comparative de simulation des méthodes MADM et leurs limites. L'algorithme de DiA est également présenté. DiA élimine le problème d'anomalie de classement. Les résultats de simulation valident l'algorithme de DiA. Le chapitre 4 présente les modèles d'association flux/interface. Dans ce chapitre, une fonction d'utilité interface qui reflète le niveau de satisfaction d'application et de consommation d'énergie du terminal mobile est présenté. En outre, nous parlons d'un premier modèle d'association flux/interface. Nous considérons les attributs de réseaux tels que le délai d'accès et le coût monétaire pour ce modèle. L'algorithme DiA est utilisé pour classer les interfaces basées sur les valeurs d'utilité interface et les attributs côté réseau. Enfin, nous abordons un deuxième modèle d'association flux/interface qui permet au terminal mobile d'associer simultanément plusieurs applications aux interfaces appropriées réseaux en maximisant l'utilité de terminaux. Nous faisons une étude comparative de simulation des méthodes méta-heuristiques. L'étude met en évidence leurs limites dans notre contexte. Nous proposons ensuite une orientation de diversification pour la recherche Tabou. Les résultats de simulation montrent que la méthode de Tabou modifié surpasse d'autres algorithmes méta-heuristiques dans notre contexte. Dans le chapitre 5, nous examinons un système des terminaux mobiles multi-interface. Nous modélisons le système comme un jeu stratégique où plusieurs terminaux en concurrence pour les ressources de réseau commun. En utilisant le jeu évolutionnaire, nous montrons que le système converge vers les équilibres de Nash qui permettent d'optimiser l'utilité totale du système. En outre, la mise en œuvre de l'algorithme d'apprentissage de Nash est mise au point pour valider les résultats théoriques. Le chapitre 6 conclut la thèse avec

des perspectives et des travaux futurs. L'annexe présente la spécification des algorithmes méta-heuristiques.

5 Problème de sélection d'interface

Dans les réseaux cellulaires, quand un terminal mobile s'éloigne d'une station de base, le niveau du signal se dégrade et il y a un besoin de changer de connexion à une autre station de base. Le mécanisme pour maintenir une connexion entre le terminal mobile et son correspondant qui est transféré d'un point d'accès de réseau fixe à un autre est appelé l'handover ou la sélection de réseau ou d'interface. Les techniques de handover ont été bien étudiées et déployé dans des systèmes cellulaires et aussi dans les systèmes sans fil.

Le problème de sélection d'interface est habituellement effectué en trois étapes: la collecte d'informations, la prise de décision, et la réalisation de décisions.



Procédure de la sélection d'interface

Collecte d'information

La collecte d'information est un facteur important pour la prise de décision. L'information comprend des paramètres statiques qui sont constantes ou changent de temps en temps, et les paramètres dynamiques qui peuvent être obtenues par des techniques de surveillance et qui présentent des variations rapides.

Algorithme décision

La décision de sélection d'interface peut être faite en s'appuyant sur les informations de la phase précédente. La décision peut être prise au niveau de terminal ou de réseau.

Réalisation de décision

Après avoir toutes les informations nécessaires, la décision donne la meilleure solution. Les décisions sont appliquées par la suite. Plusieurs mécanismes peuvent être utilisés à cette phase. Par exemple, le contrôle d'admission, le routage, etc.

Dans notre travail, nous nous concentrons sur la phase de décision.

Le problème de décision est un problème très complexe. Différentes approches pour la sélection d'interface sont proposées comme les angles d'attaques.

MADM

L'objectif fondamental de MADM consiste à déterminer la solution optimale parmi un ensemble de solutions. Chaque alternative est définie par un ensemble d'attributs. Dans notre contexte spécifique, les alternatives représentent les interfaces possibles du terminal mobile et les attributs représentent les caractéristiques de l'interface. MADM

comprend de nombreuses méthodes, par exemple, SAW, WP, TOPSIS, AHP et GRA. Plusieurs schémas de sélection d'interface [Puttonen][Bari][Tran01][Chen][Qingyang] ont été proposées pour la prise de décision et de sélection de l'interface en utilisant des méthodes MADM.

Fonction de coût

La fonction de coût est une mesure du coût consommé en sélectionnant une interface particulière parmi plusieurs interfaces. L'interface qui a le coût le plus minimal est la meilleure interface.

La fonction de coût est la somme d'une forme normalisée de chaque attribut. La normalisation $N(x_{ij})$ est nécessaire pour normaliser les attributs sur différentes unités. Les décideurs peuvent préciser les poids de chaque attribut. La forme générale de la F_i fonction de coût de l'interface i est:

$$f_i = \sum_j^m w_j N(x_{ij})$$

avec $\sum_j w_j = 1$

où, w_j est le poids de l'attribut j , et $N(x_{ij})$ représente la valeur normalisé de l'alternative i de l'attribut j .

Les schémas [Wang] [Sowmia] utilisent les fonctions de coût pour sélectionner le meilleur réseau disponible dans le contexte de handover.

Fonction d'utilité

L'utilité est une mesure subjective de la valeur ou la satisfaction. Il mesure la valeur relative d'un individu de préférence pour un résultat ou un événement particulier par rapport à l'autre. Par exemple, dans la finance, il est habituellement utilisé pour mesurer les préférences des décideurs en ce qui concerne les attributs influençant directement à un gain pécuniaire ou une perte.

Une fonction d'utilité générale, pourrait être décrite par une expression mathématique qui décrit le niveau de satisfaction d'un décideur ou d'un objectif spécifique en fonction de plusieurs variables.

Une fonction d'utilité est généralement rédigée comme suit:

$$U = f(x_1, x_2, \dots, x_n)$$

où x_1, x_2, \dots, x_n sont les critères nécessaires qui aident les décideurs à calculer la valeur d'utilité ou le niveau de satisfaction. Ces attributs, par exemple, peuvent être le bénéfice ou les coûts en fonction des circonstances et des objectifs des décideurs.

Plusieurs schémas [Ormond] [Suciu01] et [Suciu02] ont été proposés pour la sélection de l'interface et l'association flux/interface en utilisant des fonctions d'utilités.

Politique

Une politique est généralement décrite comme un plan d'action pour guider les décisions et à atteindre un objectif prévu. Cette approche est différente de l'approche mathématique basée sur les fonctions, il n'existe aucune procédure pour classer les solutions.

Une politique comprend généralement un ensemble de règles contenant de nombreuses conditions. Si une alternative répond à un ou plusieurs des conditions, la politique décide de prendre une action appropriée.

Dans [Ylitalo], les auteurs proposent une politique qui permet l'association des applications aux interfaces. Les politiques permettent de choisir dynamiquement l'interface la plus appropriée pour un flux particulier. Différents flux peuvent être transférés entre les différentes interfaces, transparente et indépendante les uns des autres.

Théories des jeux

La théorie des jeux est l'étude formelle des conflits et de la coopération entre les joueurs où leurs actions sont interdépendantes. Ces joueurs peuvent être des individus, des groupes, des entreprises, etc. La théorie des jeux fournit des approches pour structurer, analyser et comprendre les scénarios stratégiques.

La théorie des jeux depuis son apparition a reçu une grande attention sans précédent. Elle a été largement appliquée à divers domaines tels que la guerre, la politique, l'économie, la sociologie, la psychologie et la biologie, etc. Particulièrement, dans le domaine des réseaux et des télécommunications, nous avons rencontré une riche littérature dans le réseau de sécurité [Lakshman] et [Michiardi], le contrôle de puissance [Alpcan] [Alpcan] [Altman01] [Falomari] [Heikkinen] [Ji] [Saraydar01] [Saraydar02] [Sung], le « pricing » [Battiti] [Crowcroft] [Michiardi] [Urpi], le contrôle d'accès [Altman02] [Jin] [MacKenzie], la réservation de ressources [Dramitinos], et le multi-homing [Shakko01] [Shakko02] [Touati], etc.

6 Etude comparative de simulation de méthode MADM

Multiple Attribute Decision Making (MADM) est une approche prometteuse pour réaliser la sélection d'interface avec de multiples alternatives (interfaces) et les attributs (les caractéristiques de l'interface/réseaux, les préférences des utilisateurs, etc.). Dans ce travail, nous présentons une étude comparative de simulation des méthodes MADM. Nous montrons leurs limites. TOPSIS souffre de problème d'anomalie de classement. SAW et WP offrent moins de précision dans l'identification de classement par rapport à TOPSIS.

6.1 Introduction

Dans cette section, nous faisons l'étude comparative et l'évaluation des performances des trois algorithmes MADM (e.g., SAW, WP et TOPSIS). Les simulations sont effectuées en utilisant MATLAB.

La méthode SAW permet de déterminer la meilleure solution en calculant la somme pondérée de toutes les valeurs d'attribut:

$$SAW^* = \max_i \sum_{j=1}^m r_{ij} w_j$$

La méthode WP propose un produit pondéré de tous les attributs normalisés (puissance les poids associées):

$$WP^* = \max_i \prod_{j=1}^m r_{ij}^{w_j}$$

L'objectif fondamental du TOPSIS est de déterminer l'alternative qui a la plus courte distance à la solution idéale. TOPSIS détermine, en premier, les solutions idéales et négatives. Elles sont des meilleures valeurs et des pires valeurs de chaque type d'attribut. TOPSIS calcule, en suite, la distance Euclidien dans m-dimensions entre les alternatives aux solutions idéales et négatives où m est le nombre d'attributs. Il calcule la proximité par rapport la solution idéale pour déterminer la meilleure alternative.

6.2 Scenarios de simulation

Dans la simulation, nous calculons le score global de SAW, de WP et de TOPSIS. La simulation permet de déterminer l'ordre de classement des algorithmes liés à de nombreux critères.

Ensuite, nous abordons le problème d'anomalie classement. Comme indiqué ci-dessus, l'anomalie de classement se produit lorsque l'interface à faible classement est retirée de la liste des candidats. L'ordre de classement des interfaces sera changé. Un algorithme robuste MADM, dans le contexte de la sélection d'interface, assure que la meilleure solution ne change pas quand une alternative qui n'est pas la meilleure est retirée ou remplacée par une autre interface. Par conséquent, si un algorithme a le problème d'anomalie de classement, l'ordre de classement n'est pas stable.

De plus, nous mesurons la précision dans l'indentification de classement. La précision est définie par la différence entre des valeurs de classement. Si cette différence est grande, elle permet d'identifier facilement l'ordre de classement et sélectionner facilement la meilleure interface.

Dans la simulation, nous considérons cinq attributs associés à cinq interfaces réseau (UMTS, 802.11b, 802.11a, 802.11n, 802.16a et). Les attributs sont: jitter, délai, l'utilisation, la perte de paquets, et le coût monétaire. Nous utilisons aussi un vecteur de poids dont le coût est nettement important par rapport à tous les paramètres de QoS.

6.3 Résultats de simulation

Nous avons effectué plusieurs simulations. Nous avons mis en évidence le problème d'anomalie de classement de TOPSIS.

Pour illustrer ce problème, nous allons prendre un exemple. Le tableau présente l'ordre de classement de 5 interfaces déterminé par SAW, WP et TOPSIS.

	SAW	WP	TOPSIS
Network #1	0,154 <i>Rank #5</i>	0,923 <i>Rank #5</i>	0,052 <i>Rank #5</i>
Network #2	0,745 <i>Rank #3</i>	0,994 <i>Rank #4</i>	0,833 <i>Rank #3</i>
Network #3	0,851 <i>Rank #1</i>	0,998 <i>Rank #1</i>	0,947 <i>Rank #1</i>
Network #4	0,799 <i>Rank #2</i>	0,997 <i>Rank #2</i>	0,904 <i>Rank #2</i>
Network #5	0,734 <i>Rank #4</i>	0,995 <i>Rank #3</i>	0,748 <i>Rank #4</i>

On peut trouver que SAW, WP et TOPSIS déterminent l'interface 3 d'être la meilleure interface.

Supposant que l'interface 1 est déconnectée. Cela est l'interface à faible classement. Le tableau suivant présente l'ordre de classement déterminé par SAW, WP et TOPSIS après l'élimination d'interface 1.

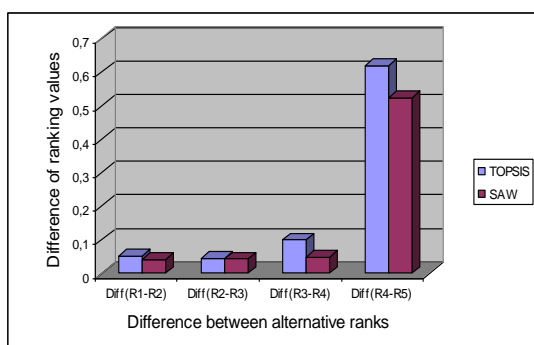
	SAW	WP	TOPSIS
Network #1	-----	-----	-----
Network #2	0,455 <i>Rank#3</i>	0,968 <i>Rank#4</i>	0,397 Rank#3
Network #3	0,693 <i>Rank#1</i>	0,986 <i>Rank#1</i>	0,805 Rank#2
Network #4	0,651 <i>Rank#2</i>	0,984 Rank#2	0,856 Rank#1
Network #5	0,380 Rank#4	0,973 Rank#3	0,142 Rank#4

Nous avons trouvé que le retrait d'une interface provoque un changement dans l'ordre de classement de TOPSIS. Le classement des SAW, WP reste le même. En particulier, la meilleure de classement dans TOPSIS a changé (du réseau # 3 au #4).

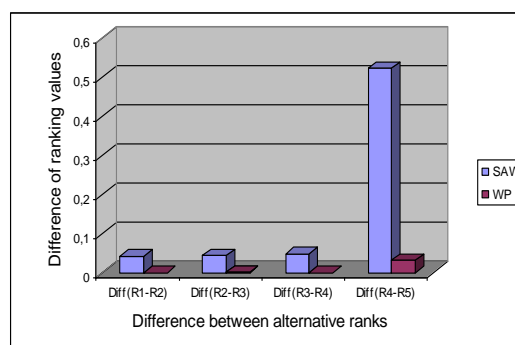
TOPSIS a le problème d'anomalie de classement.

Après avoir bien étudié le TOPSIS, nous avons déterminé d'où vient le problème d'anomalie de classement. Premièrement, la distance Euclidienne à m dimension de TOPSIS a changé avec un écart non-constant. Deuxièmement, la proximité par rapport la solution idéale a aussi changé avec un écart non-constant. L'ordre de classement a été changé qui est dû le calcul de distance Euclidienne et la proximité par rapport la solution idéale.

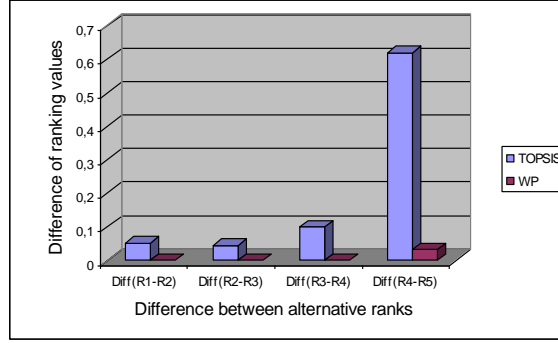
Ensuite, nous considérons la précision dans l'identification de classement. Les résultats de simulations (e.g., la figure suivante) montrent TOPSIS a une grande précision dans l'identification de classement comparé avec SAW et WP.



(a)



(b)



(c)

Les différences de valeur de classement de SAW, WP et TOPSIS

7 Algorithme de DiA

Avec la motivation pour améliorer MADM, nous présentons l'algorithme DiA qui vise à sélectionner la meilleure interface, à ne pose aucun problème d'anomalie de classement et à fournir une meilleure précision dans l'identification de classement.

L'algorithme DiA est basé sur les principes suivants.

Comme TOPSIS, DiA détermine les valeurs d'attribut positives idéales et négatives. Ces sont les valeurs maximales et minimales de chaque type d'attribut.

Si TOPSIS utilise la distance euclidienne à m dimensions, DiA utilise la distance de Manhattan pour calculer la distance entre les valeurs d'attribut et les valeurs positives idéales et négatives de chaque attribut.

$$D_j^+ = \sum_{i=1}^m |v_{ji} - a_i^+|$$

$$D_j^- = \sum_{i=1}^m |v_{ji} - a_i^-|$$

v_{ij} : valeur de l'attribut i de l'interface j

a_i^+ : la meilleure valeur de l'attribut i

a_i^- : la pire valeur de l'attribut i

m : nombre d'attributs

D_j^+ : la distance entre l'interface j et les valeurs positives idéales

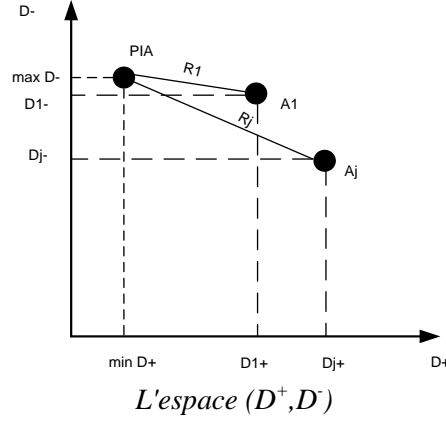
D_j^- : la distance entre l'interface j et les valeurs négatives

Puis, DiA estime la valeur minimale de D^+ et la valeur maximale de D^- .

$$\min D^+ = \min_j D_j^+ = \min_j \sum_{i=1}^m |v_{ji} - a_i^+|$$

$$\max D^- = \max_j D_j^- = \max_j \sum_{i=1}^m |v_{ji} - a_i^-|$$

Si l'on considère l'espace (D^+, D^-) , le point $(\min D_i^+, \max D_i^-)$ est défini comme «l'alternative positive idéale» (PiA) (voir figure ci-dessous).



La meilleure alternative est la plus courte distance de la PIA. Cette distance absolue est calculée :

$$R_j = \sqrt{(D_j^+ - \min(D^+))^2 + (D_j^- - \max(D^-))^2}$$

L'alternative ayant la plus petite valeur R_j a également la plus courte distance de la PiA.

Ensuite, nous allons montrer que la DIA n'a aucun problème d'anomalie de classement par rapport aux TOPSIS.

Considérons qu'un ordre de classement des solutions (par exemple, la meilleure solution est A_1 et la pire solution est A_n)

$$A_1 > A_2 > \dots > A_j > \dots > A_n$$

Nous avons les distances aux PiA

$$R_1 < R_2 < \dots < R_j < \dots < R_n$$

Supposons qu'une solution (par exemple, A_j) qui a une meilleure valeur d'attribut (par exemple, $a_k^{+(old)}$) dans le type d'attribut k est supprimée. Les distances aux attributs négatives D_j^- ne sont pas modifiées.

Nous pouvons trouver une nouvelle valeur attribut positive idéal dans le type d'attribut k (par exemple, $a_k^{+(new)}$). La nouvelle valeur de l'attribut positive idéale est plus petite que le précédent.

$$a_k^{+(old)} > a_k^{+(new)}$$

La distance entre les nouveaux attributs et les précédentes est d (où d est constant).

$$|a_k^{+(new)} - a_k^{+(old)}| = d$$

Les distances de Manhattan de toutes les valeurs d'attribut à la valeur de l'attribut positive idéale dans le type d'attribut k avant et après avoir enlevé une solution sont respectivement:

$$D_{ik}^{+old} = |v_{ik} - a_k^{+(old)}|$$

$$D_{ik}^{+new} = |v_{ik} - a_k^{+(new)}|$$

Ensuite,

$$|D_{ik}^{+new} - D_{ik}^{+old}| = |a_k^{+(new)} - a_k^{+(old)}| = d$$

Par conséquent, la distance entre toutes les valeurs d'attribut à l'attribut positive diminue avec une distance constante d.

$$|D_i^{+new} - D_i^{+old}| = \left| \sum_{j=1}^m D_{ij}^{+new} - \sum_{j=1}^m D_{ij}^{+old} \right| = |D_{ik}^{+new} - D_{ik}^{+old}| = d$$

On peut conclure également que la nouvelle valeur minimum de D^{+new} diminue avec un écart constant d comparant avec la ancienne valeur minimale de D^{+old}

$$|\min(D^{+new}) - \min(D^{+old})| = d$$

Ainsi, l'ancienne distance entre l'alternative i et l'ancienne PiA (e.g., R_i^{old}) est égale à nouvelle distance entre l'alternative i et la nouvelle PiA (e.g., R_i^{new}).

$$\begin{aligned} R_i^{new} &= \sqrt{(D_i^{+new} - \min(D^{+new}))^2 + (D_i^- - \max(D^-))^2} \\ &= \sqrt{((D_i^{+old} - d) - \min(D^{+old}))^2 + (D_i^- - \max(D^-))^2} = R_i^{old} \end{aligned}$$

Cela montre que les distances entre toutes les alternatives aux PiA sont inchangées

$$R_1 < R_2 < \dots < R_j < \dots < R_n$$

et donc, l'ordre de classement des alternatives est inchangé

$$A_1 > A_2 > \dots > A_j > \dots > A_n$$

Si l'alternative retirée comprend l'un des attributs négatifs, toutes les distances D_j^- augmentent avec la même distance. Selon l'analyse ci-dessus, la distance à la PIA est également inchangée. Par conséquent, l'ordre de classement des solutions est également inchangé

L'algorithme DiA ne pose aucun problème d'anomalie de classement comparé avec TOPSIS.

Nous avons aussi effectué plusieurs simulations. Les résultats montrent que DiA n'a pas de problème d'anomalie de classement comparé avec TOPSIS et a la meilleure précision dans l'identification de classement comparé avec SAW et WP.

8 Modèles d'association flux/interface

Dans ce travail, nous abordons le problème d'association flux/interface. Les terminaux mobiles peuvent associer chaque application à l'interface réseau appropriée basant principalement sur les exigences des applications.

8.1 Fonction d'utilité d'interface

Aujourd'hui, les terminaux mobiles sont des appareils de plus en plus petits. Ils peuvent non seulement avoir plusieurs interfaces de réseau, mais aussi exécuter plusieurs applications. Pendant ce temps, la taille de la batterie est également réduite en fonction de la taille du terminal et sa durée de vie est limitée. Les terminaux doivent utiliser efficacement leur énergie pour maintenir leurs activités. La consommation d'énergie est un attribut intéressant à considérer pour l'association flux/interface.

L'approche MADM permet de classer les interfaces de réseau basant sur plusieurs attributs. Ces attributs sont présentés dans une matrice MADM. Les attributs sont généralement des valeurs numériques directement liées aux caractéristiques

d'interface/réseau. Si l'on considère d'autres attributs qui ne sont pas directement liés à l'interface (par exemple, les exigences des applications), nous devons définir un moyen pour exprimer ces caractéristiques dans la matrice MADM.

Lors de la première étape de ce travail, nous proposons une fonction d'utilité interface qui considère le niveau de satisfaction d'applications et la consommation d'énergie du terminal mobile.

Par exemple, la fonction d'utilité d'interface est calculée:

$$\begin{bmatrix} I_{1j} \\ \vdots \\ I_{nj} \end{bmatrix} = \alpha_j \begin{bmatrix} U_{1j} \\ \vdots \\ U_{nj} \end{bmatrix} + \beta_j \begin{bmatrix} Q_{1j} \\ \vdots \\ Q_{nj} \end{bmatrix}$$

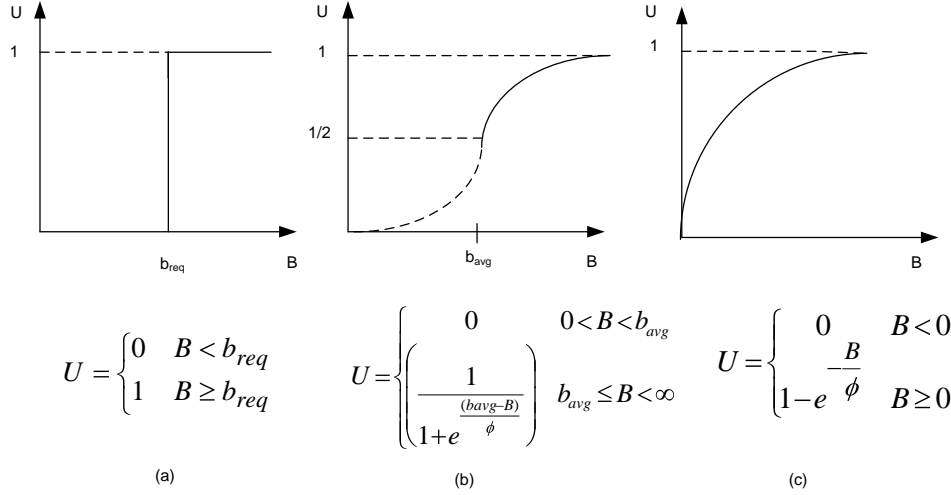
U_{ij} représente le niveau de satisfaction d'application j associé à l'interface i . Q_{ij} représente la consommation d'énergie lorsque l'application j utilise l'interface i .

8.1.1 Fonction d'utilité d'application (U_{ij}) :

Nous décrivons la fonction d'utilité qui détermine la façon dont la satisfaction de l'application change avec la quantité de bande passante qu'il reçoit.

Sur la base de l'analyse de [Baghaei][Fitzek][Eskeda][Shenker][Suciu01][Breslau][Rakocevic] et [Suciu02], chaque type d'application a des exigences spécifiques en terme de bande passante (breq) (voir le tableau ci-dessous). Pour chaque type d'application, une fonction d'utilité spécifique est définie. Nous concentrons sur trois applications basées sur l'analyse [Shenker] [Breslau] [Rakocevic] (voir le figure ci-dessous, temps réel (a), adaptive (b) et élastique (c)).

Application type	Example	Service class	Necessary bandwidth (b_{req} or b_{avg})
Hard-Real time	PCM VoIP	Conversation	64 kbps
Hard-Real time	H.323 VoIP	Conversation	20 kbps
Adaptive	CD-like Audio	Streaming	150 kbps
Adaptive	MPEG4 Video	Streaming	2000 kbps
Elastic	SSH, Instant Messenger, HTTP	Interactive	limitless
Elastic	FTP, Email	Background	limitless



Fonction d'utilité d'application

8.1.2 Fonction d' consommation d'énergie (Q_{ij}) :

Chaque interface possède des caractéristiques spécifiques en termes de consommation d'énergie en fonction des caractéristiques du matériel.

La consommation d'énergie de chaque interface pour la transmission de N bits est la fonction de consommation d'énergie pour la transmission d'un bit sur l'interface et le volume de données (N bits) transférés par l'interface. Dans notre expérience, le volume de données est évalué selon le type d'application. Cela dépend de la bande passante disponible pour l'application élastique et adaptative et de la bande passante requise pour les applications temps réel.

8.2 Modèle 1 :

Nous proposons ensuite un modèle d'association flux/interface qui permet au terminal mobile d'associer séquentiellement l'application à l'interface. Le modèle considère la fonction d'utilité interface ainsi que des attributs de réseau (le délai d'accès, et le coût du réseau). Ces attributs sont ajoutés à la matrice MADM. DiA est utilisé pour classer les interfaces.

Dans un premier temps, quand le terminal lance une application, l'algorithme calcule l'utilité d'application (U_{ij}), la consommation d'énergie (Q_{ij}) et l'utilité d'interface (I_{ij}).

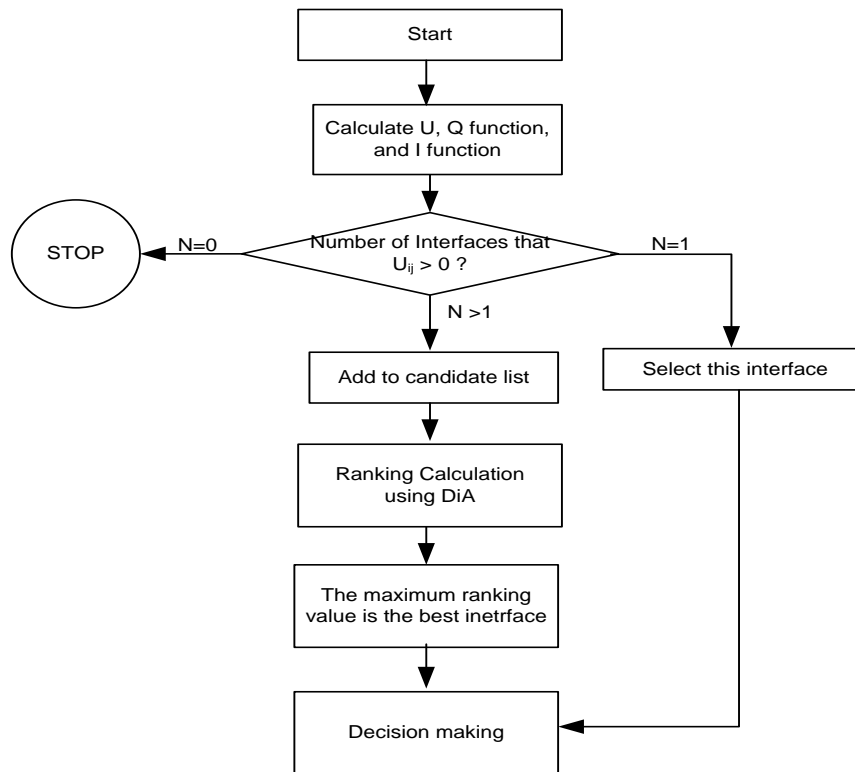
Deuxièmement, l'algorithme vérifie le nombre des interfaces (N) dont l'utilité application est positif ($U_{ij} > 0$)

- Si $N = 0$: STOP. Aucune d'interface n'est sélectionnée.
- Si $N = 1$: Choisir cette interface.
- Si $N > 1$: Ajouter des interfaces dans la liste du candidat.

Ajouter l'utilité d'interface I_{ij} dans la matrice MADM.

Ajouter les attributs de réseau considérés de la matrice MADM.

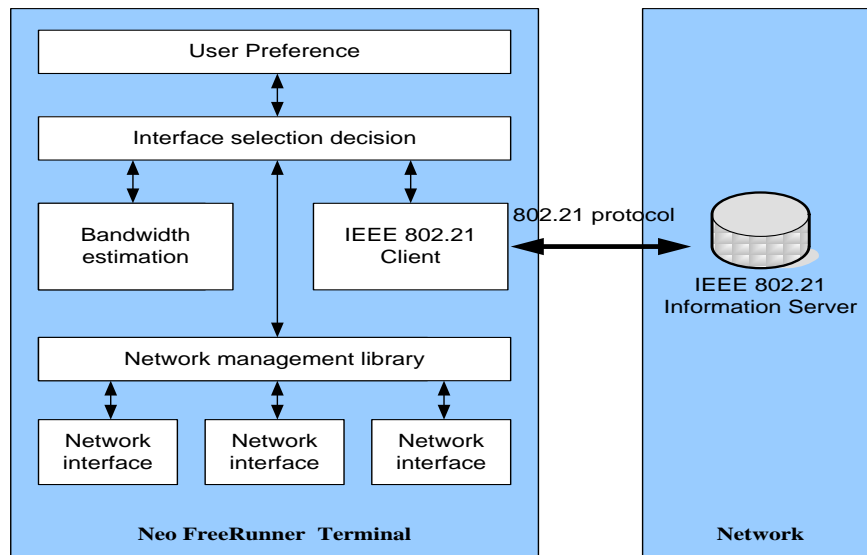
Finalement, DiA est utilisé pour classer les interfaces en fonction des valeurs d'utilité d'interface et les attributs de réseau. DIA décide la meilleure interface pour l'application.



Modèle d'association flux/interface

Plusieurs scenarios de simulation sont été réalisés pour valider ce modèle.

Nous avons aussi mise en œuvre ce modèle sur une plate-forme réelle. La mise en œuvre permet de présenter la faisabilité de ce modèle sur un environnement de réseau réel. Les considérations relatives au système de mise en œuvre sont présentées en soulignant les exigences, les défis à mettre en œuvre le système.



Architecture d'implémentation

La figure ci-dessus présente l'architecture d'implémentation. L'architecture comprend les éléments suivants:

Terminal mobile

Nous choisissons le terminal Neo FreeRunner pour la mise en œuvre du système. Le Neo FreeRunner est conçu pour exécuter des logiciels Openmoko qui est capable d'exécuter des applications développées sous Linux. Utilisation de Debian, Neo FreeRunner a immédiatement un choix de plusieurs logiciels disponibles (plus de 16000 paquets).

Préférence d'utilisateur

Ce module permet aux utilisateurs de définir leurs objectifs de décision. Une interface GUI est développée afin de permettre aux utilisateurs de définir vecteur de poids qui influencent la décision sélection de l'interface.

IEEE 802.21

Nous adoptons la mise en œuvre IEEE 802.21 développé par Alcatel-Lucent [3MING]. La mise en œuvre 802.21 client est intégrée dans l'architecture pour récupérer des informations à partir des serveurs MIH 802.21.

Bibliothèque de gestion de réseaux

Nous considérons également la bibliothèque de gestion de réseau avec IEEE 802.21 pour rassembler des informations concernant les caractéristiques d'interface.

Le paquet Network Manager est l'une des bibliothèques de constructions utilisées dans les systèmes d'exploitation open-source (par exemple, Ubuntu, Fedora, etc).

Estimation de bande passante

IEEE 802.21 et la bibliothèque de gestion de réseau permettent d'obtenir des informations relatives aux caractéristiques de réseau et d'interface. Toutefois, il existe certains paramètres qui ne peuvent pas être obtenus directement comme la bande passante disponible. Le module d'estimation de bande passante permet d'obtenir cet objectif.

Le problème d'estimation de bande passante est un grand sujet. En raison de la multitude d'applications potentielles, un grand nombre de solutions ont été proposées et évaluées. Nous pouvons trouver une riche littérature de ces techniques [Akella] [Cabellos] [Croce] [Dovrolis] [Ekelin] [HU] [Neginhal] [Ribeiro] [Strauss] [WangQ] pour mesurer la bande passante disponible.

L'estimation de bande passante disponible est un gros problème et vraiment un grand défi pour la mise en œuvre de l'association flux/interface. Une étude approfondie doit être effectuée pour sélectionner un outil approprié pour l'association flux/ interface ou des outils doivent être modifiés pour s'adapter à ce contexte.

Décision de sélection d'interface

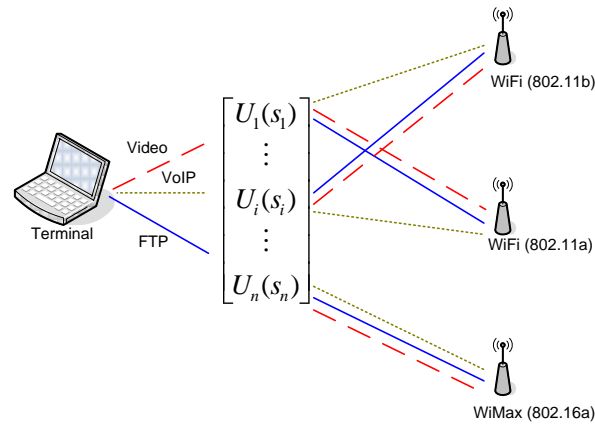
Nous utilisons DiA pour classer les interfaces.

8.1 Modèle 2 :

Enfin, nous abordons un autre modèle d'association flux/interface. Un terminal mobile exécutant plusieurs applications peuvent associer simultanément ses flux aux interfaces réseaux en maximisant l'utilité globale de terminaux.

Considérons un terminal multi-interface est en N zones de couverture de réseau, Le terminal dans ce cas peut utiliser simultanément N interface de réseau.

De plus, Le terminal lance simultanément plusieurs applications (i.e., $A = (a_0, a_1, \dots, a_{K-1})$ applications) à ce moment, le terminal peut avoir un ensemble d'options d'association $S = (s_0, s_1, \dots, s_{(N^K-1)})$. Pour chaque option d'association s_i , le terminal obtient une valeur d'utilité notée $U_i(s_i)$ (voir le figure ci-dessous).



Exemple de modèle d'association flux/interface

Le terminal vise à trouver l'option d'association i pour maximiser l'utilité U

$$\max_i U_i(s_i)$$

Le terminal mobile vise à obtenir une option association maximisant l'utilité globale du terminal. La solution triviale aurait été recherchée dans l'espace global des options d'association S pour trouver la solution optimale. Cependant, cela pose un problème de complexité.

Nous considérons la probabilité d'identification d'optimum global avec un espace de recherche limité. En d'autres termes, nous considérons la probabilité pour trouver une option d'association qui maximise l'utilité de terminaux globaux. Notre problème est lié à des problèmes d'optimisation stochastique heuristique (i.e., méta-heuristique).

Les méthodes méta-heuristiques sont principalement basées sur les techniques de recherche où leur ordre de recherche dépend principalement de procédures aléatoires. Les techniques de recherche peuvent être locales. Ils trouvent le plus proche optimale qui ne peut être l'optimum réel. Sinon, les techniques de recherche peuvent être globale, c'est à dire qu'elles trouvent le vrai optimale, même si elle implique un déménagement dans un optimum local pendant la recherche.

Dans ce travail, nous présentons une étude comparative de simulation des méthodes stochastiques heuristiques, en particulier, la recherche de Tabou, le recuit simulé. Nous analysons et mettre en évidence leur performance dans notre contexte.

Les résultats de simulation montrent que la performance de recherche de Tabou est meilleure que le recuit simulé en termes de la probabilité d'identification de l'optimisation globale et le temps de calcul.

Nous considérons la méthode de Tabou pour l'association flux/interface.

La recherche de Tabou est une démarche d'amélioration itérative de recherche qui commence à partir de toute solution initiale et tente de déterminer une meilleure solution. En général, la recherche de Tabou se caractérise par sa capacité à éviter d'être

piégé dans un optimum local en utilisant la technique de diversification qui est une procédure aléatoire.

Nous visons à modifier la recherche de Tabou pour l'association flux/interface. Nous considérons la technique de diversification de Tabou.

La diversification de la recherche Tabou décide de passer à une autre solution en étant piégée dans l'optimisation locale à l'aide de diversification aléatoire. Cependant, la nouvelle solution aurait pu être examinée plus tôt et l'algorithme est répété plusieurs fois pour rien. Cela conduit à diminuer la probabilité de trouver l'optimisation globale.

Nous avons proposé une orientation de diversification pour la recherche de Tabou. La diversification orientée vise à aider l'algorithme à augmenter la probabilité de l'identification d'optimisation globale. La technique de diversification est largement utilisée pour étendre la recherche Tabou [James] [Osman]. Sa conception dépend fortement du contexte spécifique.

Dans notre contexte spécifique de l'association flux/interface, la diversification orientée sélectionne le prochain mouvement (c.-à-d. l'option d'association suivante) lorsqu'ils sont piégés dans l'optimisation locale. La diversification orientée évite de répéter l'option association enregistrée à la liste Tabou.

Nous avons effectué plusieurs simulations. Les résultats de simulation montrent que la recherche de Tabou modifiée est meilleure que les autres méthodes méta-heuristiques dans notre contexte.

9 Un jeu pour l'association des flux aux interfaces

Dans ce travail, nous abordons le problème d'association flux/interface au niveau de réseau. Nous considérons un système où les terminaux mobiles peuvent associer leurs applications aux interfaces appropriées. Nous modélisons le système comme un jeu stratégique. Les terminaux sont en concurrence pour les ressources de réseau commun. En utilisant la théorie des jeux évolutionnaires, nous montrons que le système converge vers équilibres efficaces de Nash qui permettent d'optimiser l'utilité totale du système. En outre, des scénarios de simulation, la mise en œuvre de l'algorithme que l'on appelle l'apprentissage Nash, est mise au point pour valider les résultats théoriques.

Considérons N terminaux mobiles dans m zones de couverture de réseau. Les réseaux peuvent être différentes technologies et chaque terminal i peut-être dans la zone de plusieurs réseaux C_i . En utilisant des interfaces de réseau approprié, le terminal mobile peut bénéficier pleinement ensemble de réseau disponible C_i . De plus, en lançant plusieurs applications, $a_1, a_2, a_3, \dots, a_k$, le terminal peut décider d'utiliser une stratégie s_i pour associer chaque application a_i à un réseau spécifique $s_i(a_i)$ dans l'ensemble C_i .

Notez que différentes applications appartenant à un ou plusieurs terminaux peuvent être associés au même réseau.

Par conséquent, il existe des compétitions entre les applications et entre les terminaux pour les ressources de réseau commun. Ainsi, nous modélisons notre système comme un jeu stratégique: Chaque terminal est un joueur et l'option d'association s_i est sa stratégie de connexions. Par convention, on désigne par 0, la stratégie inactive lorsque le joueur est déconnecté et désignons par s_{-i} , les stratégies de tous les autres joueurs sauf le joueur i . L'état du système s est de l'ensemble (s_1, s_2, \dots, s_n) .

Dans l'état du système s , le joueur (c.-à-d. le terminal) i obtient une valeur d'utilité notée $U_i(s)$ qui est une fonction de l'état. Cela peut être fonction de la consommation d'énergie

et le niveau de satisfaction application comme illustré dans la section 8. Toutefois, la présence d'un terminal induit une compétition avec les autres joueurs pour les ressources de réseau commun. En effet, en comparaison avec le cas où le joueur i est inactif, les autres reçoivent une perte:

$$\sum_{j \neq i} (U_j(0, s_{-i}) - U_j(s_i, s_{-i}))$$

où $U_j(0, s_{-i})$ désigne le gain de joueur j lorsque le joueur i est inactif .

Basé sur [Cole] et [Touati], nous introduisons cette perte comme le coût marginal de l'accès aux ressources du réseau, afin d'accroître l'efficacité de l'équilibre de Nash.

Choisir la stratégie s_i , le joueur i reçoit la fonction de « reward » proposée par la différence entre le gain et le coût marginal

$$r_i(s) = U_i(s) - \sum_{j \neq i} (U_j(0, s_{-i}) - U_j(s_i, s_{-i}))$$

Nous utilisons les stratégies mixtes dans notre modèle qui détermine la probabilité qu'un terminal choisie une stratégie.

p_{i,s_i} ($p_{i,s_i} | s_i \in \mathcal{S}_i$) est la probabilité quand le terminal i choisit la stratégie s_i

Ou, \mathcal{S}_i est l'ensemble de toutes les stratégies possibles

$p_{i,0} = 1 - \sum p_{i,s_i}$ est la probabilité quand le terminal i est inactif

L'état du système est alors décrit par le vecteur de probabilité

$$p = (p_{i,s_i} | 1 \leq i \leq N, s_i \in \mathcal{S}_i)$$

et le reward moyen offerte au terminal i en choisissant la stratégie s_i

$$f_{i,s_i}(p) = \sum_{s_{-i}} \left(r_i(s_i, s_{-i}) \prod_{j \neq i} p_{j,s_j} \right), \quad p \in \mathcal{P}$$

où \mathcal{P} désigne l'espace globale de probabilité

Dans notre jeu de stratégies mixtes, le joueur i choisit une stratégie aléatoire suivant la loi de probabilité ($p_{i,s_i} | s_i \in \mathcal{S}_i$). Par conséquent, l'espérance de reward est

$$E_p[r_i(s)] = \bar{f}_i = \sum_{s_i \in \mathcal{S}_i} p_{i,s_i} f_{i,s_i}(p)$$

Une stratégie mixte p est un équilibre de Nash si aucun joueur n'a intérêt à changer sa stratégie pour avoir une interaction comme stable.

$$\forall i, \forall p_i \neq \hat{p}_i: E_{\hat{p}_i, \hat{p}_{-i}}(r_i(s)) \geq E_{p_i, \hat{p}_{-i}}(r_i(s))$$

Dans son ouvrage [Nash], Nash a prouvé qu'il existe des équilibres de Nash pour n'importe quel jeu fini de stratégies mixtes. Par conséquent, les équilibres de Nash existent dans notre jeu. Il reste à identifier ces équilibres. Une alternative est de laisser chaque joueur d'évoluer suivant certaines dynamiques, puis observer si les points stationnaires de cette dynamique sont des équilibres de Nash.

Dans ce travail, nous utilisons le dynamique Replicateur. Cette dynamique encourage le joueur à choisir la stratégie qui est meilleure que le payoff moyen du system en

augmentant la probabilité de choisir cette stratégie. Contrairement, la dynamique Replicateur diminue la probabilité de choisir cette stratégie.

Le dynamique Replicateur $\dot{p} = V(p)$, ou $V(p)$, est définie par les équations différentielles suivantes

$$\forall i, \forall s_i: \dot{p}_{i,s_i} = p_{i,s_i}(f_{i,s_i} - \bar{f}_i)$$

où \bar{f}_i est le reward moyen et p est la dérivée de p rapport au temps.

Mathématiquement, nous avons démontré que notre jeu est une fonction potentielle et la dynamique Replicateur est la corrélation positive (PC). Nous avons suivantes un corollaire

Corollaire : Comme le dynamique $V(p)$ est PC et il existe la fonction de potentiel $F(p)$, la dynamique $V(p)$ converge. En outre, tous les équilibres de Nash du jeu sont des points stationnaires de $\dot{p} = V(p)$.

Ensuite, nous considérons l'efficacité des équilibres de Nash.

La vecteur de probabilité \hat{p} est un point d'équilibre si et seulement si pour tous les joueurs i et pour toutes les stratégies s_i ,

$$ou \begin{cases} \dot{\hat{p}}_{i,s_i} = 0 \\ f_{i,s_i}(\hat{p}) = \bar{f}_i(\hat{p}) \end{cases}$$

Il s'agit de conditions de premier ordre de Kuhn-Tucker conditions [Karush], [Kuhn], et [Alibert] du problème de l'optimisation Lagrange dual

$$\max_p F(p)$$

Nous avons déjà noté que toutes les révisions à la stratégie rentable conduire à une augmentation du potentiel. Ceci suggère que les équilibres de Nash du jeu sont liés à l'optimum local de potentiel.

Nous avons implémenté le système en utilisant l'algorithme d'apprentissage de Nash.

Dans la section précédente, nous avons montré que les résultats théoriques sont valables pour toutes les fonctions d'utilité. Toutefois, dans les scénarios de simulation, la fonction de reward, puis toutes les mises à jour dans l'algorithme d'apprentissage Nash, dépend fortement de la fonction d'utilité et le coût marginal est fortement lié au mécanisme d'allocation des ressources. Ainsi, dans cette section, nous proposons une fonction d'utilité spécifique, ainsi qu'un schéma d'allocation de bande passante.

Nous utilisons la fonction d'utilité proposée précédemment. Le réseau vise à influencer sur la décision des joueurs en appliquant un coût marginal pour l'accès aux ressources du réseau. Nous avons proposé un mécanisme d'allocation de bande passante. Ce mécanisme permet d'offrir la bande passante disponible pour les applications. Si les stratégies augmentent l'utilité du système, le système offre beaucoup de bande passante disponible pour les applications. Sinon, il offre peu de bande passante disponible.

Ensuite, nous présentons les résultats de la simulation de l'algorithme d'apprentissage Nash.

Dans ce scénario, nous considérons trois terminaux mobiles intégrant trois interfaces d'accès au réseau: Wi-Fi 802.11b, Wi-Fi 802.11a et WiMAX 802.16a. Leur consommation moyenne d'énergie est $1\mu\text{J/bit}$, $5\mu\text{J/bit}$ et $20\mu\text{J/bit}$, respectivement. Au début de la simulation, la bande passante disponible de réseau est 1Mbps, 2Mbps et

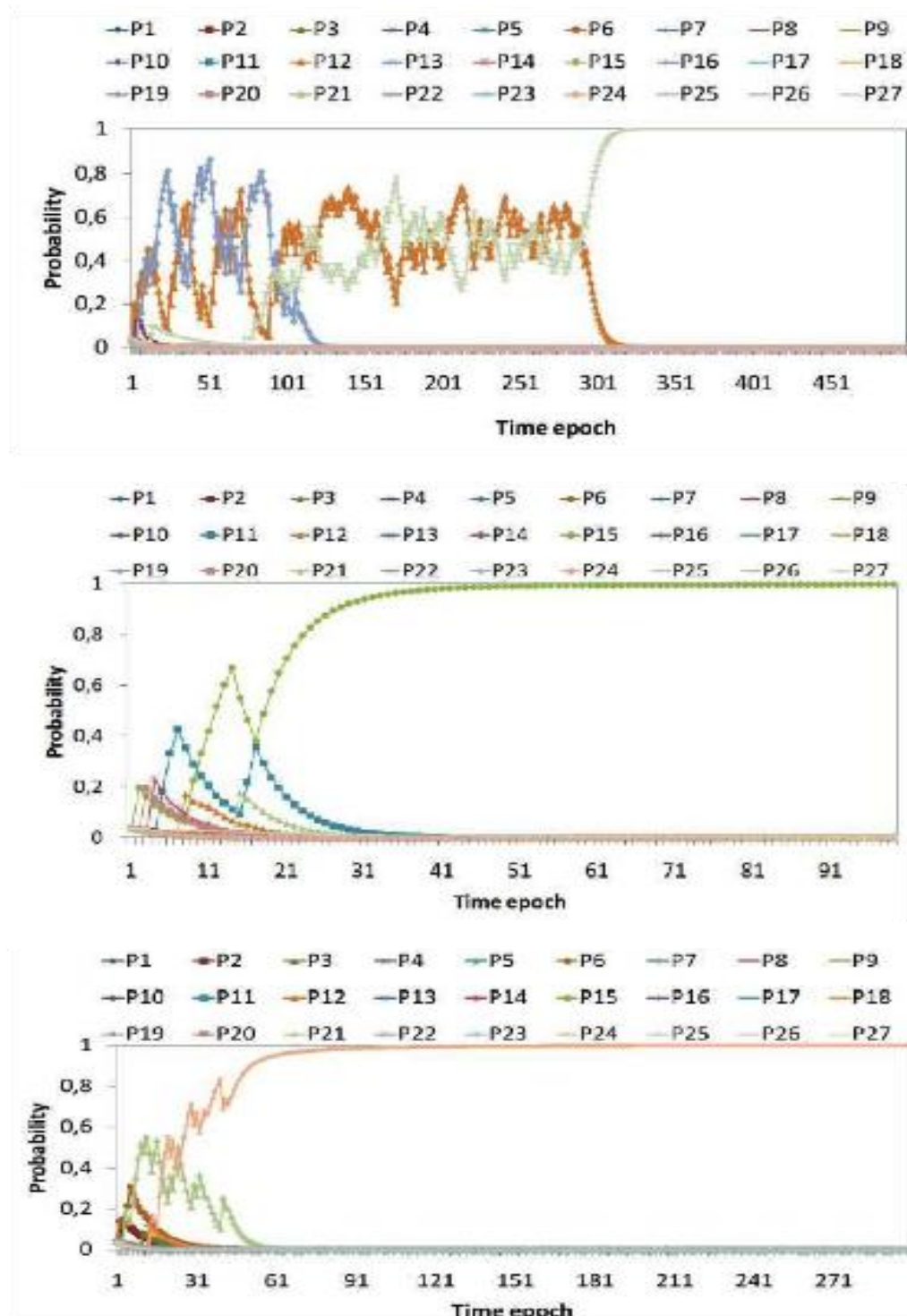
2.5Mbps, respectivement. Tous les terminaux sont dans les zones de couverture de ces réseaux.

En outre, nous considérons trois applications. Chaque terminal génère simultanément une application FTP, un audio CD-débit comme le streaming nécessitant 150kbps et un flux PCM VoIP qui nécessitent 64Kbps.

Pour étudier plusieurs équilibres de Nash, nous avons effectué plusieurs simulations sur le même scénario.

Le résultat de la figure ci-dessous représente l'évolution du vecteur de probabilité de chaque terminal et il montre que les vecteurs de probabilités de les terminaux 1, 2 et 3 converger vers l'équilibre de Nash à la 325e, 51e et 88e temps époque, respectivement. Les stratégies 27e, 15e et 24e sont choisies par le terminal 1, 2 et 3, respectivement.

Ces stratégies dire que les applications du terminal 1 doivent être associés à l'interface 3 (WiMAX). Pendant ce temps, le terminal 2 associe ses application VoIP, l'application de streaming et le FTP pour les interfaces Wi-Fi 802.11b, Wi-Fi 802.11a et WiMAX, respectivement, le terminal 3 associe l'application FTP à l'interface WiMAX et les autres applications sont associé à l'interface Wi-Fi 802.11a.



Résultats de simulation

10 Conclusions

La thèse identifie les problèmes liés celui de décision pour la sélection d'interface et l'association flux/interface. Il propose et évalue les solutions au niveau de terminal et de réseau.

La première contribution de la thèse est d'étudier et d'analyser les méthodes MADM pour la sélection de l'interface. Le travail met en évidence les limites des méthodes. L'algorithme de DiA est proposé comme une amélioration des méthodes MADM.

Ensuite, nous attaquons au problème d'association flux/interface. La décision d'association prend principalement en compte les exigences des applications. En outre, la consommation d'énergie du terminal est également envisagée. C'est une contrainte importante pour le terminal mobile multi-interface. L'énergie doit être utilisée efficacement pour maintenir les activités du terminal.

La deuxième contribution propose une fonction d'utilité d'interface qui prend en compte le niveau de satisfaction de l'application et de la consommation d'énergie du terminal.

Nous proposons ensuite un premier modèle flux/interface qui permet d'associer chaque application à l'interface appropriée tenant compte non seulement l'utilité d'interface, mais aussi les attributs de réseau tels que le délai d'accès, le coût du réseau. Le modèle utilise l'algorithme de DiA pour classer les interfaces basées sur la valeur d'utilité d'interface, le délai d'accès et le coût du réseau.

La troisième contribution propose un deuxième modèle d'association flux/interface qui permet au terminal mobile d'associer simultanément ses applications aux interfaces de réseau visant à maximiser l'utilité de terminaux. Une étude comparative de simulation des méthodes d'optimisation stochastiques heuristique est présentée. Elle identifie leurs limites dans notre contexte. Nous proposons ensuite une diversification orientée vers la recherche de Tabou comme une amélioration. Les résultats de simulation montrent que la recherche modification de Tabou est meilleure que les autres méthodes dans le contexte spécifique de l'association flux/interface.

Pour valider et étudier la faisabilité du modèle d'association flux/interface, un travail qui vise à mettre en œuvre a été initié.

Nous considérons en suite une approche de réseau pour l'association flux/interface. En particulier, la théorie des jeux est adoptée comme un outil de modélisation. Dans ce contexte, chaque terminal peut distribuer ses applications sur les différentes interfaces disponibles en fonction de diverses fonctions utilitaires. Le modèle permet au système de converger vers les points d'équilibre qui permettent d'optimiser l'utilité globale du système. Une mise en œuvre est proposée de valider le modèle et montre que ce jeu converge toujours vers l'équilibre de Nash.

Perspectives.

Dans l'association flux/interface, nous considérons la bande passante disponible, la consommation d'énergie, le délai d'accès, et le coût d'utilisation de réseau en tant que principaux attributs. L'importance relative entre les attributs est indiquée par des valeurs de poids. Dans le schéma, l'attribut de la bande passante disponible a le poids le plus élevé. Cela est dû au fait que le niveau de satisfaction de l'application est un aspect important dans l'association flux/interface. Par ailleurs, l'objectif de consommation d'énergie du terminal est pondéré comme le niveau de priorité suivant. Cette considération est due au problème de l'efficacité énergétique du terminal mobile multi-interface. Le coût monétaire et les objectifs de connexion rapide sont considérés comme un niveau inférieur.

Toutefois, nous utilisons MADM (c.-à-d., l'algorithme DIA) qui permet d'ajouter d'autres attributs et de définir une autre importance relative des attributs. Autres attributs de réseau peuvent être ajoutés à tenir compte des autres objectifs de sélection. Par exemple, la sécurité de l'interface réseau est considérée comme un objectif important en associant l'application à l'interface, etc.

En outre, une issue avec le réglage du poids. Comment pouvons-nous définir exactement l'importance relative des attributs? Dans notre contexte, les pondérations sont estimées par le jugement humain. Par exemple, l'échelle de l'importance relative entre les attributs peuvent être jugés que même importance, un peu plus important, plus important, fortement plus important, ou absolument plus important, etc. La question de pondération devrait être étudiée pour augmenter la précision de l'objectif de sélection.

Le deuxième modèle d'association flux/interface permet d'associer simultanément les applications aux interfaces en maximisant l'utilité de terminaux. Le modèle pourrait envisager l'optimal sociale et les questions d'équité. En d'autres termes, le modèle associe simultanément les applications aux interfaces qui non seulement optimise l'utilité de terminaux globaux, mais aussi considère également le niveau de satisfaction équitable de chaque application.

Considérant le modèle d'association flux/interface au niveau de réseau basé sur le jeu théorique, le réseau influe sur le choix des terminaux en appliquant un coût marginal de l'accès aux ressources réseau et par cette intervention, atteint son but d'optimiser l'utilité totale du système. Il serait intéressant d'envisager un modèle variante où le réseau charge un coût différent pour autres objectifs, ou ne pas influencer les décisions des terminaux et laisse les terminaux évolue égoïstement.

Dans la deuxième partie de ce travail, les résultats d'analyse ont été validés par les simulations mise en œuvre de l'algorithme d'apprentissage Nash et d'un modèle spécifique d'allocation de bande passante ainsi que d'une fonction d'utilité. Les résultats de simulation ont montré que l'algorithme d'apprentissage Nash converge en effet à des équilibres de Nash. Nos travaux en cours se concentrent sur la complexité des algorithmes et la vitesse de convergence. Par ailleurs, les performances du réseau en termes de paramètres de débit et de qualité de service sont mesurées compte tenu des scénarios de simulation sur une grande échelle.

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List of Publications

International Journal

- P.N. Tran and Nadia Boukhatem, "*Design and Implementation of IP-based RFID Location Systems*", on Journal of Communications Software and Systems (JCOMSS), 2010.

Chapter of Book:

- P.N. Tran, and N. Boukhatem, "*IP-based RFID location system*" in the book of "*Radio Frequency Identification Fundamentals and Applications*", pp. 131-144, ISBN: 978-953-7619-73-2, Publisher: INTECH, February 2010.

International conference:

- M.A. Tran, P.N. Tran, and N. Boukhatem, "*Strategy game for flow/interface association in multi-interface mobile terminals*", in Proceeding of the IEEE International Communications Conference (ICC'10), Cape Town, South Africa, May, 2010.
- P.N. Tran and N. Boukhatem, "*An Utility-based Interface Selection Scheme for Multi-interface Mobile Terminals*", in Proceeding of the 20th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications Conference(PIMRC'09), Tokyo, Japan, September, 2009.
- P.N. Tran and N. Boukhatem, "*The distance to the ideal alternative (DiA) algorithm for Interface Selection in Heterogeneous Wireless Networks*", in Proceeding of the 6th ACM International Workshop on Mobility Management and Wireless Access (MobiWac'08), conjunction with MSWiM 2008 (the 11th ACM/IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems), Vancouver (BC), Canada, October, 2008.
- P.N. Tran and N. Boukhatem, "*Extension of multiple care-of-address registration to support host Multihoming*", in Proceeding of the IEEE International Conference on Information Networking (ICOIN'08), Busan, Korea, January 2008.
- P.N. Tran and N. Boukhatem, "*Comparison of MADM Decision Algorithms for Interface Selection in Heterogeneous Wireless Networks*", in Proceeding of the IEEE International Conference on Software, Telecommunications and Computer Networks (SoftCOM'08), Split, Croatia, September 2008.
- P.N. Tran and N. Boukhatem, "*IP-based RFID architecture and location management*", in Proceeding of the IEEE International Conference on Software, Telecommunications and Computer Networks (SoftCOM'08), Split, Croatia, September 2008.
- N. Boukhatem, P.N. Tran and T.T. Luu, "*On Performance Evaluation of a Generic IP Signaling*", in Proceeding of The 6th IEEE Consumer

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- P.N. Tran and N. Boukhatem, "*SiPiA: The Shortest Distance to Positive Ideal Attribute for Interface Selection*", in Proceeding of the IEEE Australasian Telecom Networks and application conference (ATNAC'08), Adelaide, Australia, December 2008.

Deliverables of The French National Research Agency (ANR) projects

- **Mobility Multi-technology Multi-homing (3MING) Project:**
 - Deliverable 1.1: *State of the art*
 - Deliverable 1.2: *Service Scenarios*
 - Deliverable 1.3: *Functional Specification*
 - Deliverable 2.1: *Session Control*
 - Deliverable 2.2: *Multi-homing management and impacts on the terminal*
- **Situated Ubiquitous Network (SUN) Project:**
 - Deliverable 1.1 : *Réseau IoTcR et Handover Diagonal IoTcR Network and Diagonal Handover*
 - Deliverable 2.1 : *Analyse des besoins de continuité de service*
 - Deliverable 3.1 : *Architecture de SUN*

Terminologies

In this document, we define some terminologies within our specific context. This definition allows clarifying and distinguishing these terminologies from others similar existent terminologies.

Multi-homing: we define this term to indicate the capacity of a mobile terminal to communicate simultaneously on various network interfaces.

Multi-interface mobile terminal: is a mobile terminal equipping with several network interfaces, which may be of different radio access technologies, both wireless and cellular.

Interface selection: we use this term to refer the capacity that the terminal is able to make the decision of which network can be the best network interface for user's current communications needs. The decision is based on several attributes. This terminology is similar to "vertical handover". However, in handover context, the SNR parameter is considered as the most priority among several parameters. We define the term of "interface selection" in the multi-homing context. The "best" network interface is selected based on the most favorable trade-off among several attributes.

Flow/interface association: We define the flow/interface association to indicate the capacity of a mobile terminal to associate applications to interfaces in the multi-homing context. This approach aims mainly to satisfy the application requirements. This term is known today as "per-flow interface selection".

Chapter 1: Introduction

This chapter outlines the context and motivations of our work. Solutions and contributions arising from this work are also presented.

1 Context

The foreseen evolutions of the next generation of mobile networks are expected to be an evolution of the UMTS and CDMA2000 standards, and to capitalize on a large number of wireless networks based on IEEE standards (802.11, 802.16, ...)

Each access technology has specific characteristics in terms of coverage area and technical characteristics (e.g., bandwidth, QoS, and bit-rate, etc.) and provides diverse commercial opportunities for the operators. It seems likely that these various technologies have to co-exist and, from then, solutions of integration and interoperability will be necessary to deal with the technological diversity [3Ming].

Solutions of integration allow a network operator to reduce the risks of introducing a new technology and to provide users an ubiquitous access to a large range of services.

The new usages of the mobile devices have dramatically changed not only the type but also the amount of traffic supported by the mobile networks. Experts' estimations expect a doubling of this traffic for the next five years with an increase of the video traffic. Nowadays, the lack of radio technologies to extend the capacity of the radio link and to meet these new needs shows the potential benefits of the multi-homing for the network operators in increasing the bandwidth providing to customers and aggregating capacity of the available interfaces.

Furthermore, the number of mobile terminals with two radio interfaces is increasing. The release of Apple iPhone in early 2007 illustrates that such terminals interest more and more the different telecommunication actors. Nowadays dual mobile terminals include a cellular interface (2G, 2.5G, 3G, 4G) and a Wi-Fi interface. The evolution of the wireless technologies including WiMAX and LTE which are the next representatives, and the increased performance of mobile devices batteries, is considered as the realistic massive appearance of terminals incorporating more than two interfaces for the next 5 years. This will lead to an explosion in the possibilities provided by the multi-homing.

2 Motivations

Once a terminal is equipped with several interfaces, it becomes possible to use simultaneously the various interfaces - and not simply to switch from one to another.

In this document, the term "multi-homing" refers to the capacity of a mobile terminal to communicate simultaneously on various network interfaces which may be of different radio access technologies, both wireless and cellular. This opens new perspectives and many benefits will be provided [Thierry]:

Permanent and Ubiquitous Access

This benefit targets to provide an extended coverage area via distinct access technologies. Multiple interfaces bound to distinct technologies can be used to ensure a permanent connectivity, anywhere, anytime, with anyone.

Reliability

Multi-homing provides a potential means to act upon failure. Indeed, a secondary (or backup) interface or path can be used when the primary becomes unavailable. Interface or path duplication can be useful in many situations: in case of preparing a handover to reduce the packet loss, for example.

Multi-criteria Interface Selection

When having multiple paths or activated interfaces, terminal may establish a strategy to select the best interface basing on multiple attributes such as the application requirements, the user preferences, the network/interface characteristics, or network operator policy, ...

Flow/Interface Association

When having multiple available active interfaces, the mobile terminal may associate each application flow to a specific interface considering mainly the requirements of the application. Other parameters could be considered such as the terminal capacity, policy or user preferences, etc.

Aggregated Bandwidth/ Load Sharing

When a terminal is simultaneously connected to multiple paths, it can exploit those paths to aggregate the available bandwidths on the individual path, or out-going traffic can be split over those paths to achieve better resource aggregation, allowing better transfer rates.

In this work, we tackle the interface selection and the flow/interface association decision issues

- **Multi-criteria interface selection decision issue**

The first motivation of this work is to take into account the interface selection issue where the mobile terminal equipped with several interfaces has to select at any time the best interface or the best access technology according to multiple criteria, as stated above.

Handoff techniques have been well studied and deployed in cellular systems and are of a great deal of importance in the wireless systems. Traditionally, the handover decision, especially in case of horizontal handovers, is made purely according to radio signal strength (RSS) thresholds and hysteresis values as input parameters. The vertical handover considers multiple criteria to make decision. However, the decision is mainly based on RSS, in the border region of two cells, and RSS is assumed to be the most priority criterion compared to the others.

In the multi-homing context, the mobile terminal is under different network coverage areas. The radio signal strength (RSS) attribute of the wireless networks is assumed to be higher than the necessary thresholds to make connectivity. The multi-interface mobile terminal is able to access several networks at the same time and to select the best network among the available networks basing on multiple attributes. The interface selection challenge is to determine the most favorable trade-off among all the attributes. The attribute weights depend on specific objective of the decision maker.

- **Flow/Interface association decision issue**

Our second motivation is to tackle the flow/interface association issue where each application is associated to a specific interface basing mainly on the application requirements. Other parameters could be considered.

There exist three main application types such as hard-real-time, adaptive and elastic applications. Each type of application has specific characteristic. Hard real-time applications need data to arrive within a given delay bound. Examples of such applications are traditional telephony applications. Rate-adaptive or delay-adaptive applications such as video, voice, streaming are more tolerant to occasional rate, delay bound violations and dropped packets. Elastic applications are the traditional data

applications such as electronic mail, remote terminal access, and file transfer, etc. which can adjust to wide changes in delay and/or throughput.

The flow/interface association challenge is to determine which network interface being suitable for which application.

Many interesting usage cases highlight the motivations of application/interface association. Consider, for example, a terminal integrates three radio interfaces: Wi-Fi, WiMAX and 3G and runs simultaneously three applications, for example, an FTP application, a streaming application (e.g. MPEG video with an average rate of 2Mbps) and a voice call. Moreover, consider that the available bandwidth is about 1Mbps on the Wi-Fi interface and about 5Mbps on the WiMAX interface, for instance. In this scenario, it would be interesting for the terminal to associate: the voice call to the 3G interface, the streaming application to the WiMAX interface since this network will provide a high streaming quality, and the FTP application to the Wi-Fi interface to economize the terminal energy consumption (considering that the energy consumption of WiMAX is higher than Wi-Fi).

3 Contributions

The interface selection is a “decision making” problem with multiple alternatives (interfaces) and attributes (interface characteristics, user preferences, etc.).

Multiple Attribute Decision Making (MADM) is one of the most promising decision methods [Puttonen][Qingyang][Bari]. The MADM methods aim at determining among a finite set of alternatives the optimal one. MADM includes many methods such as Simple Additive Weighting (SAW), Weighting Product (WP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

The first step of this work studies and analyzes the Multiple Attribute Decision Making (MADM) methods for interface selection. A simulation study highlights and identifies their limitations in this context. The main limitations of TOPSIS lie to the “ranking abnormality” problem. SAW, WP provide less accuracy in identifying the alternative ranks (the “ranking identification” problem). The ranking abnormality problem occurs when a low ranking alternative is removed from the candidate’s list (e.g., one network is disconnected), the order of higher ranking alternatives will change abnormally. Therefore, the removal of an alternative out of the candidate’s list can cause unreliable decision making.

The Distance to the ideal Alternative (DiA) algorithm, a new MADM method, is proposed to help mobile terminal to select dynamically the best interface and ensures no ranking abnormalities contrary to TOPSIS method. Simulation results validate the DiA algorithm.

The second step consists in addressing the flow/interface association issue. The flow/interface association is mainly based on the satisfaction of application (e.g., defined by the satisfaction level of the application requirements). Besides, mobile terminals are nowadays very small devices having multiple functionalities. They strongly depend on battery power to maintain their activities. The battery size of the terminals is reduced according to the size of the terminals. This leads to a limited battery life. It is hence important to minimize their energy consumption.

With the motivation to consider the application requirements and the terminal energy consumption, we define an interface utility function.

When initiating an application, a terminal associates automatically the application to an interface satisfying the application requirements and economizing the terminal energy consumption. Meanwhile, network side attributes such as access delay and cost of using the network are also considered in the scheme. The Distance to the ideal Alternative (DiA) algorithm is used to rank the interfaces based on the interface utility values and the network side attributes. Simulation results are presented to validate the interface utility based scheme.

Moreover, we propose a multiple flow/interface association scheme where a terminal running several applications tries to associate simultaneously each application to a suitable network interface while maximizing the global utility of terminal. The terminal utility in our context is defined by the satisfaction level of the applications and the consideration of the mobile terminal energy consumption. The multiple flow/interface association issue is an optimization problem.

Firstly, we carry out a simulation based combative study of the stochastic heuristic optimization methods such as local search, Tabu search, and simulation annealing algorithms. The stochastic heuristic methods are mainly based on search techniques of which the solutions and their search order depend on random variables.

The simulation based comparative study highlights the performance of each algorithm and their adaptation in the multiple flow/interface association context.

As an improvement, we propose an oriented diversification technique that allows the Tabu search to avoid being re-entrapped in the local optima and to increase the performance of Tabu search in our context. Simulation results demonstrate that the modified Tabu search outperforms other methods in our context.

We then head to a network centric approach while tackling the flow/interface association issue.

We consider a system of multi-interface mobile terminals that allows mobile terminals to associate their applications to the available network interfaces. The mobile terminals compete with each other to deploy common network resources. The system could be modeled as a strategic game. We let the game evolve according to the so-called Replicator dynamic and then to observe whether the system converges and whether the stationary points (i.e., Nash equilibria). Our objective is to find Nash equilibria of the game.

As the first step of this work, a framework is defined and modeled as a strategy game considering the above described application-based model. The game evolves according to the Replicator dynamic. We show that the Replicator dynamic is Positively Correlated and the system is a potential game. Our system converges to Nash equilibria.

Additionally, the Nash equilibria are proven to be efficient as they are solutions of the optimization problem of the total utility. An interesting edge is that our analytical results are valid for a general utility function which depends on the whole system state of connections.

To validate our model and to demonstrate that the system converges to Nash equilibria, we implement two simulation scenarios using Nash learning algorithm with a specific bandwidth allocation scheme as well as a utility function that takes into account the application satisfaction level and the energy consumption.

4 Organization

The dissertation is organized in six chapters

Chapter 1. Introduction

This chapter outlines the context and motivations of our work. Solutions and contributions arising from this work are also presented.

Chapter 2. Background on interface selection and flow/interface association issues for multi-interface mobile terminals

In this chapter, an overview of the evolution of wireless technologies and mobile terminals is introduced. This chapter also presents a state of the art related to interface selection and flow/interface association issues in heterogeneous wireless networks.

Chapter 3. The Distance to the Ideal Alternative (DiA) Algorithm

Multiple Attribute Decision Making (MADM) is a suitable decision approach to realize a dynamic interface selection with multiple alternatives (interfaces) and attributes (network, interface characteristics, user preferences, etc.). In this chapter, we present a simulation based comparative study of MADM methods and their limitations. The Distance to ideal Alternative (DiA) algorithm is also presented. DiA eliminates the ranking abnormalities problem. Simulation results validate the DiA algorithm.

Chapter 4. Flow/Interface Association Schemes

In this chapter, an interface utility function which reflects the satisfaction of the application requirements and economizes the energy consumption of the mobile terminal is presented.

In addition, we present a single flow/interface association scheme. Network side attributes such as access delay and cost of using the network are also considered in the scheme. The Distance to the ideal Alternative (DiA) algorithm is used to rank the interfaces based on the interface utility values and the network side attributes.

Finally, we aim to address a multiple flow/interface association scheme that allows mobile terminal running several applications to be able to associate the applications to the suitable networks interfaces while maximizing the global terminal utility. We present a simulation based comparative study of the stochastic heuristic methods such as local search, Tabu search, and simulate annealing algorithm. The simulation based comparative study highlights their limitations on adaptation in our context. We then propose an oriented diversification of the Tabu search for the multiple flow/interface association as an improvement. Simulation results show that the modified Tabu search outperforms other stochastic heuristic algorithm in our context.

Chapter 5. Strategy game for flow/interface association in multi-interface mobile terminals

In this chapter, we present a system of multi-interface mobile terminals with the ability of flow/interface associations. We model the system as a strategic game where multiple terminals compete for common network resources. By using evolutionary game theory, we show that the system converges to efficient Nash equilibria which optimize the total utility of the system. Moreover, simulation scenarios, implementing the so-called Nash learning algorithm are developed to validate the theoretical results.

Chapter 6. Conclusions and Future works.

This chapter presents conclusion of archived works, perspectives, open issues and future works.

Chapter 2: Background on interface selection and flow/interface association issues for multi-interface mobile terminals

The wireless networks evolve technically and economically. New access technologies (e.g., HSDPA, WiMAX, LTE...) with new features have emerged. Besides, mobile terminals are also evolving into affordable high powered computing terminals (e.g., smart phones, PDA ...). They have more and more options for accessing their desired services via different available radio access networks. It is expected that they are able to select the “best” suitable network interface or associate application flow to the suitable network interface basing on many attributes such as interface, network characteristics, application requirements, terminal capacities, user’s preferences, ...

In this chapter, an overview of the evolution of wireless technologies and mobile terminals is introduced. This chapter also presents a state of the art related to interface selection and flow/interface association issues in heterogeneous wireless networks.

1 Evolution of wireless networks and mobile terminals

Wireless technologies in the last decade have attracted attention from wireless network operators, service providers, developers, vendors, and users. The breathtaking evolution of wireless technologies, services and business applications has resulted in a wide-scale deployment and usage of wireless and mobile networks.

In the first generation of mobile networks, mobile users are tied to a single national operator. The analogue and circuit-switched such as Advanced Mobile Phone System (AMPS) in USA, and Total Access Communication System (TACS), Nordic Mobile Telephony (NMT), and/or Radio Telephone Network C (C-NETZ) in different parts of European countries are considered as the first version of the mobile networks.

The Second Generation of mobile networks (2G) was digitalized, such as Global System for Mobile communications (GSM) in Europe, Personal Digital Cellular (PDC) in Japan, Digital AMPS (D-AMPS) and Code Division Multiple Access (CDMA) in the United States [Walke].

The exclusive monopoly of the operators in most countries was broken down to encourage the competition of the mobile telecommunications. The cellular network evolved to 2.5G which includes High Speed Circuit- Switched Data (HSCSD), General Packet Radio Service (GPRS), and Enhanced Data Rates for GSM Evolution (EDGE).

The 3G services are considered as the advance of the 2.5G by proposing high quality services including wide-area wireless voice telephone, video calls, and wireless data, all in a mobile environment.

3G is a family of standards for mobile telecommunications which includes GSM, EDGE, UMTS, and CDMA2000 as well as DECT and WiMAX defined by the International Telecommunication Union [itu]. Compared to 2G and 2.5G services, 3G allows simultaneous use of speech, data services. The 3G network enables network operators to offer users a wider range of advanced services while achieving greater network capacity through improved spectral efficiency. However, the wide deployment of 3G on the market introduces their shortcomings of the bandwidth capabilities. Particularly, the main drawbacks of the 3G are the low throughput rates on offer and high charges for many of advanced services that lead to a lack of attractive applications.

3.5G was born to resolve the problems of 3G with the addition of High Speed Downstream Packet Access (HSDPA) to enhance the throughput rates offered in the 3G networks. Current HSDPA deployments support downlink speeds of 1.8, 3.6, 7.2 and 14 Mbps. Further speed increases are available with Evolved High-Speed Packet Access (HSPA+), which provides speeds of up to 42 Mbps downlink and 84 Mbps with new release of the 3GPP standards [3GPP_9]. In addition, 3GPP is defining Long Term Evolution (LTE) of UMTS with objectives of increasing capacity, lowering latency and reducing costs for operators [Ekstrom][3GPPc]. The 3GPP is standardizing a Long Term Evolution Advanced as future 4G standard. At the present rates of 15-30 Mbps, 4G is capable of providing users with high-definition television streaming. At rates of 100 Mbps, 4G supports the content of a DVD-5 (e.g., a movie) [4G].

Wireless Local Area Network (WLAN) technologies (such as the Wireless Fidelity (Wi-Fi) IEEE 802.11 a/b/g family) have been widely increasing in recent years [802.11]. These wireless broadband networks are rapidly deployed in home and office for several advantages such as high speed, simplicity, and low installation cost, with very little needed wiring. The IEEE 802.11 is actually the original standard offering data rates of 1 or 2 Mbps. Revisions have been made to the standard to maximize the

throughput (the case of 802.11a, 802.11b and 802.11g standards called 802.11 physical) or specify elements to ensure better security or better inter-operability.

Wireless Metropolitan Area Network (WMAN) which is also known as a Wireless Local Loop (WLL) is based on the IEEE 802.16 standard or WiMAX [802.16]. Wireless local loop can reach effective transfer speeds of 1 to 10 Mbps within a range of 4 to 10 kilometers [802.16], which makes it useful mainly for telecommunications companies. WMAN which is often cheaper and less restrictive than current wire-line options is currently widely used for small businesses.

Mobile terminals are evolving into affordable high powered computing terminals (e.g., smart phones, PDAs and iPhone, ...)

Beside the traditional applications such as Voice call and Short Message Service (SMS), a large number of application types are increasing, for example, the real-time services like video streaming and conferencing, interactive data services like web browsing, and non real-time background services such as video, picture, and MP3 downloads, etc. Mobile terminals are expected to have several radio interfaces (e.g., GPRS, UMTS, Wi-Fi, 3G, 4G, and WiMAX, etc.).

With many technical advantages, mobile terminals are able to run simultaneously several applications. The mobile terminals have opportunities to take advantage of the providers' competition when accessing a diverse range of services.

However, each technology has specific characteristics in terms of coverage area and technical characteristics (e.g., bandwidth, QoS, and bit-rate, etc.) including advantages and limitations. No radio wireless technology could always be the best choice for all applications. In each context, mobile terminals may choose specific access technologies for each application considering the user's preference, the interface/network characteristics, the application requirements and/or the terminal capacities, etc.

Always Best Connected (ABC) concept [Gazis][Fodor] states that a mobile terminal (user) can have the best service connection regardless of place and time. Moreover, a user, who wants to connect to a service, is able to choose the access in a way that suits his or her needs the best, and change the access when other better access networks become available. The users have their right to select the interface for their own applications.

The challenge of mobile terminals is how to make use of the multi-technology, and multi-network to offer high quality services according to several decision metrics.

2 Network/Interface Selection

In cellular networks, when a mobile terminal moves away from a base station, the signal level degrades and there is a need to switch connection to another base station. The mechanism by which an ongoing connection between the mobile terminal and its correspondent is transferred from one point of access to the fixed network to another is called handover or handoff. Handoff techniques have been well studied and deployed in cellular systems and are of a great deal in the wireless systems.

Traditionally, the handover decision, especially in case of horizontal handovers, is made purely according to radio signal strength (RSS) thresholds and hysteresis values as input parameters.

A decision for vertical handoff which consists in choosing the "best" interface may depend on several parameters such as network conditions, application types, power

requirements, terminal conditions, user preferences, security, cost and quality of service parameters.

In traditional cellular network, each mobile terminal is attached to a single cellular radio technology. The handover procedure is used when there is a need for a cell change during a call. The handover aims at maintaining or improving the connectivity to allow the mobile terminal using efficiently the radio resources. When the mobile terminal moves within the same network technologies, the handover scheme is known as horizontal handover

Handover mechanism in Global System for Mobile communications (GSM) [Brunner][Siegmond] is considered as an example of horizontal handover. Handover transfers an ongoing call from one channel to another. The voice call connection is totally controlled by the subscribers' operator.

The handover decision is based on main attributes such as the Received Signal Strength (RSS), the Bit Error Ratio (BER). These attributes are measured by the Mobile Station (MS) and sent frequently to the Base Station Controller (BSC) via the Base Transceiver Station (BTS).

The GSM handover characteristics are summarized in Table 1. The handover procedure is controlled by the network and needs assisted information provided by the mobile station.

Table 1-The GSM handover

Control	Network (may be mobile assisted)
Applications	Voice , SMS
Objective	Quality connectivity maintenance or load balancing
Metric decision	RSS, BER of current uplink and downlink, RSS of alternative cells

Along with the evolution of mobile standards and the migration of GSM to other technologies, there are needs to handoff from one technology to another. When handovers of this nature are required, it is considerably more complicated than a straightforward horizontal handover. These handovers may be called inter-system handovers, inter-radio access technology handovers or vertical handovers.

The most common type of vertical handover is between GSM and UMTS [3GPP_6] [Romero] [3GPP_R7][3GPP_7].

Since UMTS and GSM are different technologies, it is difficult to compare the measurement results from these technologies. To overcome this challenge, the measured results are compared with a technology specific threshold. The minimum threshold for signal strength ensures the handover decision.

In this type of handover, the mobile terminal selects the cell to which it will connect. However, the network can broadcast various parameters to influence this process. Beside radio link quality attribute, the network might also consider other aspects when selecting the cell, for example, the current load of the established service.

The handover between UMTS and Wi-Fi or WiMAX is also considered as an example of a vertical handover [Lugara][Lanpro].

With the availability of the multi-function mobile terminals and the grown of wireless network technologies, it is possible that the traditional cellular network supplements the existing 3G networks by offering in certain areas of their network coverage with radio access technologies.

The 3G mobile communication systems have been designed to offer significant higher data rates more than 2Mbps and wide coverage with high mobility more than 2G mobile systems. The operations in the licensed spectrum and the system configurations for supporting wide area coverage cause serious high costs for deploying the networks. On the other hand, as the IEEE 802.11 WLAN (Wireless Local Area Network) has been designed to provide high data rates more than 10Mbps in the unlicensed spectrum, it is easily deployed with relative low costs. However, the coverage zone is limited. Due to these different reasons, the two systems can inter-work to provide mutual complementary.

Moreover, there is an added complication that the decision should deal not only with network selection for voice connection alone. It may instead involve a data session or combination of data and voice sessions.

Many parameters or decision metrics are involved in the decision such as QoS parameters (e.g., jitter, delay, bit rate, etc.), and other parameters (e.g., coverage area, access cost, power consumption, security, power control scheme, etc.)

Table 2 summarizes the influencing factors for the network selection decision in (UMTS/WLAN).

Table 2 - The handover between UMTS/WLAN.

Control	Network (may be mobile assisted)
Applications	Voice, SMS, MMS and limited selection of new data applications including music, video clip downloads, etc.
Objective	Quality connectivity maintenance or load balancing between cells and between RATs
Metric Decision	RSS, BER of current uplink and downlink, RSS of alternative cells, application type and requirements, terminal characteristics, QoS metrics.

3 Flow/Interface association

The flow/interface association is considered as a particular case of the interface selection. It allows a mobile terminal running several applications to be able to select its suitable network interface for each application considering mainly the satisfaction of the application.

The difference between flow/interface association and the network selection is that flow/interface association, we assume that, is possible to use simultaneously many available networks rather than simply switching between the networks (e.g., horizontal or vertical handover). Moreover, each application is associated to the suitable network interface.

The flow/interface association decision aims to satisfy mainly the application requirements. However, other attributes could be considered for the association decision.

The flow/interface association problems are likely categorized into two classes: single and multiple flow/interface association.

- **Single flow/interface association issue**

The single flow/interface association allows mobile terminal to associate sequentially each application to suitable network interface. The association decision tends to maximize the satisfaction level of the application.

- **Multiple flow/interface association issue**

The multiple flow/interface association issue tends to associate simultaneously several applications to the suitable interfaces considering the global satisfaction. For example, when running several applications, the mobile terminal has several options to associate the applications to the interfaces. However, it could select an association option to maximize the global satisfaction of the terminal.

4 State of the art

As presented in the previous section, a horizontal handoff is made between two networks that use a same technology. Vertical handoff occurs when the mobile terminal moves between two different networks of different technologies. In the simplest context, a vertical handover involves at least two different network interfaces.

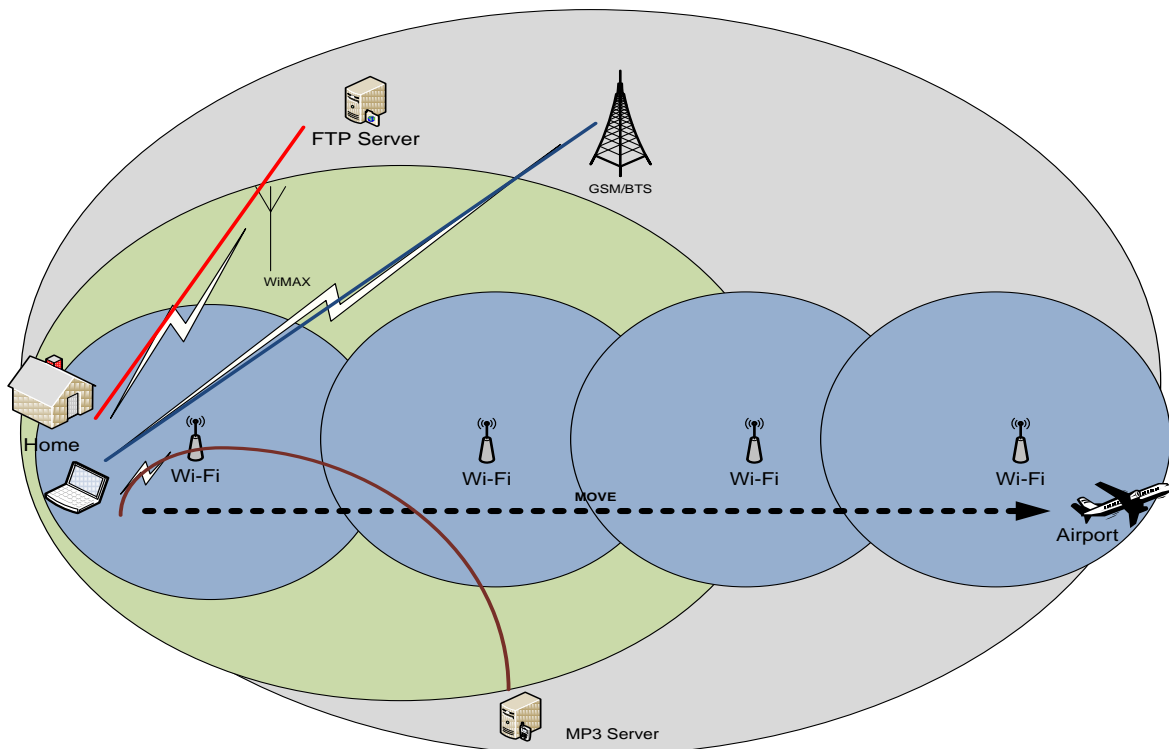


Figure 1– The interface selection in heterogeneous wireless network.

The horizontal handover decision is made purely according to radio signal strength (RSS) thresholds and hysteresis values as input parameters. A decision for vertical handoff may consider different parameters, as stated above.

Handover related criteria can be classified into static or dynamic parameters depending on reasons of the changes and the frequency. The user preferences and the cost of the different access networks constitute an example of static criteria, whereas the mobile terminal's velocity and RSS are typically dynamic criteria [Kassar].

In heterogeneous wireless networks, the mobile terminal is assumed to be in the overlapping zone of several networks. The radio signal strength (RSS) attributes are assumed to be higher than the necessary thresholds to make connectivity. The interface selection challenge is to determine the most favorable trade-off among all these metrics to select the "best" network interface.

Being a particular case of interface selection, the flow/interface association challenge is to select suitable interface and to associate it to the suitable application. The flow/interface decision is based mainly on the application requirements. Other parameters could however be considered (e.g., energy consumption, monetary cost, etc).

Network/interface selection problem is usually carried out in three steps: *information collecting*, *decision making*, and *decision enforcement*.

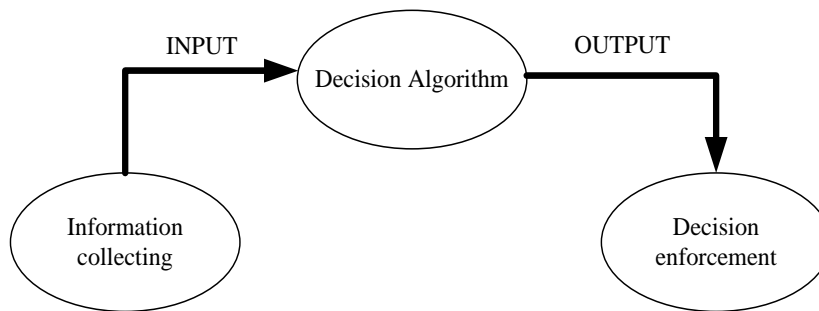


Figure 2– Decision algorithm steps

Information collecting

Information collecting is an important factor for decision making. The information (i.e., decision metric) includes static parameters which are constant or change occasionally, and dynamic parameters which can be obtained by monitoring techniques and which exhibit rapid variations. In section 3.1, we describe the different decision metrics.

Profiling is one of the mechanisms used to represent and to structure the information [Niedermeicer][Mohyeldin].

Usually many profiles are defined to represent the capacities of the terminals, the application requirements, the service requirements, the network conditions and the user preferences.

Decision algorithms

The interface selection decision can be made basing on the information collected from previous phase. In terminal-centric approaches, the decision is made by the terminal. In network-centric approach, it is the network that makes the decision. Many approaches are used for making decision. These approaches are presented in section 4.2.

Decision enforcement

After having all necessary information, the interface selection decision deploys various decision making techniques that give best solutions. Decisions are enforced afterward. Several mechanisms can be used for this purpose. For example, admission control is one of the enforcement mechanisms. It can be used to filter access according to the decision. Routing can also be used as an enforcement mechanism, it can modify local routing table to route the packet through the selected interfaces.

4.1 Decision metrics

Network/Interface related metrics are the information related to the current available networks characteristics. There are various possible metrics used to compare different networks, for example, *the signal quality (RSS, CIR (Carrier to-Interferences Ratio), and, coverage area), the quality of service (available bandwidth, jitter, bit-error rate, packet loss ratio, etc.), interface characteristics (power consumption, security level) and monetary cost of using network, etc.*

User related metrics involve the users' behavior and requirement, *e.g., user preferences (preferred network, preferred technology, the application priority order, and limited monetary cost of using network, etc.).*

Application related metrics concern the information related to the applications, requiring connectivity. The information may include: *application flow type, application's current status and application requirements, etc.*

Terminal related metrics are the information related to terminal. The information may be *the terminal capacity, the energy consumption (e.g., battery power level status).*

The more metrics are considered in the decision, the more complex the resulting decision will be and thus more processor and time consuming should be needed. There is a trade-off between the amount of information processed and decision speed and accuracy.

4.2 Decision approaches

This section examines the approaches related to the multi-attribute decision problems, in particularly, the Multiple Attribute Decision Making (MADM). Besides, utility function, profit function, cost function, policy based, game theory approaches are also presented.

4.2.1 MADM approach

The fundamental objective of the Multiple Attribute Decision Making (MADM) approach is to determine the optimal alternative among a finite set of alternatives. Each alternative is defined by a finite set of attributes. In our specific context, the alternatives represent the possible interfaces of the mobile terminal and the attributes represent the interface characteristics.

MADM approach has been widely used for a variety of decision-making problems: technical or economical decision problems, such as project or investment evaluation, portfolio management, strategic planning, personnel management, etc.

As stated above, each alternative may have one or several attributes (or criteria). Each attribute has an associated weight. The attributes represent the characteristics of the

alternative and the weights are the relative importance of the attributes [Yoon01][Yoon02].

A MADM problem is formulated as follows:

Table 3- MADM matrix

	C_1 (w_1)	C_2 (w_2)	\cdot	\cdot	C_m (w_m)
A_1	x_{11}	x_{12}	\cdot	\cdot	x_{1m}
A_2	x_{21}	x_{22}	\cdot	\cdot	x_{2m}
\cdot	\cdot	\cdot	\cdot	\cdot	\cdot
\cdot	\cdot	\cdot	\cdot	\cdot	\cdot
A_n	x_{n1}	x_{n2}	\cdot	\cdot	x_{nm}

$$A = \{A_i, i = 1, 2, \dots, n\}$$

is a set of a finite number of alternatives which represents the possible interfaces the mobile terminal supports.

$$C = \{C_j, j = 1, 2, \dots, m\}$$

is a set of attributes against which the alternatives have to be judged.

The weight vector $w = \{w_1, w_2, \dots, w_m\}$ represents the relative importance of these attributes.

To transform the attribute values to a compatible unit scale, normalization procedure is used. Many normalization methods exist.

4.2.1.1 Normalization methods

The four well known normalization procedures used in MADM are briefly described below:

Euclidean normalization method

In this method, each attribute value of the decision matrix is divided by its norm. The normalized value r_{ij} is then obtained by

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^n x_{ij}^2}}$$

This method has the advantage of converting all attributes into dimensionless measurement unit, thus making inter-attribute comparison easier [Yoon01][Yoon02].

Max-Min Method

This method considers both the maximum and minimum performance ratings of the attributes during calculation. For benefit attributes, the normalized value r_{ij} is obtained by

$$r_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}}$$

For cost attributes, r_{ij} is computed as

$$r_{ij} = \frac{x_j^{max} - x_{ij}}{x_j^{max} - x_j^{min}}$$

where x_j^{max} is the maximum attribute value among the alternatives and x_j^{min} is the minimum attribute value among the alternatives.

This method has the advantage that the scale measurement is precisely between 0 and 1 for each attribute [Yoon01][Yoon02] .

Max Method

This method divides the attribute value of each alternative by the maximum attribute value among alternatives. For benefit attributes, the normalized value r_{ij} is obtained by

$$r_{ij} = \frac{x_{ij}}{x_j^{max}}$$

For cost attributes, the normalized value r_{ij} is computed as

$$r_{ij} = 1 - \frac{x_{ij}}{x_j^{max}}$$

where x_j^{max} is the maximum attribute value among alternatives.

Sum Method

This method divides the attribute value of each alternative by the sum of the attribute values of all alternatives:

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^n x_{ij}}$$

where x_j is the attribute value for each alternative.

4.2.1.2 MADM methods

MADM includes many methods, for example, Simple Additive Weighting (SAW), Weighting Product (WP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Analytical Hierarchy Process (AHP), and Grey Relational Analysis (GRA).

Simple Additive Weighting (SAW) method

The SAW approach is probably the well-known method of MADM because it is simple and widely used. The overall score of an alternative is determined by the weighted sum of all attribute values. The score of alternative is obtained by adding the normalized contributions from each metric r_{ij} multiplied by the assigned importance weight w_j of metric j . The selected alternative is then:

$$SAW^* = \max_i \sum_{j=1}^m r_{ij} \times w_j$$

where

$i = \{i = 1, 2, \dots, n\}$ is a set of a finite number of alternatives.

$j = \{j = 1, 2, \dots, m\}$ is a set of attributes.

Weighting Product (WP) method

This approach is similar to SAW but it is the weighted product of all normalized attributes. The selected alternative is then:

$$WP^* = \max_i \prod_{j=1}^m r_{ij}^{w_j}$$

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method

TOPSIS is an algorithm widely used for interface selection [Bari][Tran01]. The approach is based upon the concept that the chosen alternative should have the relative shortest distance to the ideal solution. The TOPSIS alternative calculation includes several steps:

Step 1: Construct the normalized decision matrix. Each element r_{ij} of the Euclidean normalized decision matrix R can be calculated as follows:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^n x_{ij}^2}}$$

Step 2: Construct the weighted normalized decision matrix. This matrix V is calculated by multiplying each column of the matrix R with its associated weight w_i .

$$V = \begin{bmatrix} v_{11} & \cdots & v_{1m} \\ \vdots & \ddots & \vdots \\ v_{1n} & \cdots & v_{nm} \end{bmatrix} = \begin{bmatrix} r_{11}w_1 & \cdots & r_{1m}w_m \\ \vdots & \ddots & \vdots \\ r_{n1}w_1 & \cdots & r_{nm}w_m \end{bmatrix}$$

Step 3: Determine ideal and negative-ideal solutions:

$$A^+ = \max_j v_{ij} = [v_1^+, v_2^+, \dots, v_i^+, \dots, v_m^+]$$

$$A^- = \min_j v_{ij} = [v_1^-, v_2^-, \dots, v_i^-, \dots, v_m^-]$$

Step 4: The distance between alternatives are measured using the m-dimensional Euclidean distance.

The distance between each alternative and the positive ideal solution is:

$$S_j^+ = \sqrt{\sum_{i=1}^m (v_{ij} - v_i^+)^2}$$

The distance between each alternative and the negative ideal solution is:

$$S_j^- = \sqrt{\sum_{i=1}^m (v_{ij} - v_i^-)^2}$$

Step 5: Calculate the relative closeness to the ideal solution:

$$C_j = \frac{S_j^-}{S_j^- + S_j^+}$$

Step 6: Rank the preference order. A set of alternatives can now be ranked according to the decreasing order of C_j

Analytic Hierarchy Process (AHP) method

AHP is one of MADM method that was originally developed by Thomas L. Saaty [Saaty01] [Saaty02] dealing with complex decision making.

Before tackling the AHP problem, we consider an example related to a complex decision problem.

John's goal is to buy a car. His decision depends on three main criteria: color, price and space. Three cars: A, B and C are considered as the alternatives which have different colors, prices, space and different trademarks. The hierarchy on "choosing a car" is established as shown in Figure 3.

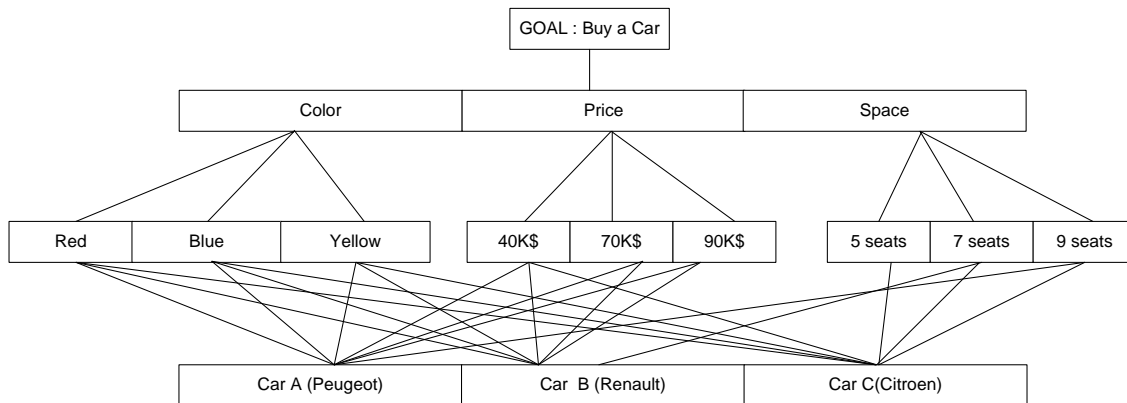


Figure 3– An example of hierarchy establishment

To buy a suitable car, John firstly considers the weighted priority between the criteria (e.g., color, price, and space). Moreover, in each criterion, John needs to determine his favorable degree of each sub-criterion. For example, considering color criterion, he prefers the red color among red, blue, yellow. Additionally, he does not want to spend much money, hopes to have a spacious car and a favorable trademark between Peugeot, Renault, and Citroen.

Finally, after considering the criteria, sub-criteria and alternatives and making complex judgments, John will know which car is a suitable one to buy.

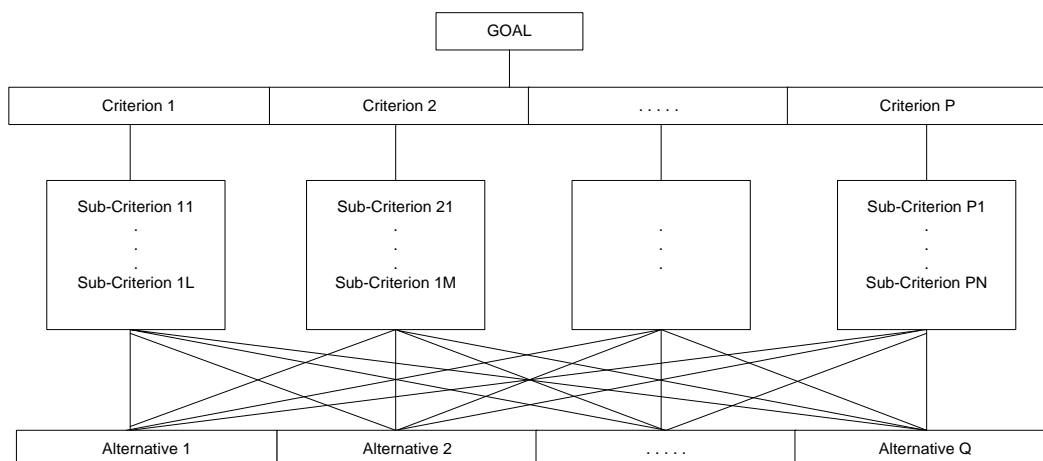


Figure 4– The hierarchic problem of AHP.

AHP provides a proven, effective means to deal with such complex decision making and can assist with identifying and weighting selection criteria, and realizing the

decision-making process. AHP helps capture both subjective and objective evaluation measures, providing a useful mechanism for checking the consistency of the evaluation measures. The AHP approach includes several steps.

Firstly, the AHP problem is decomposed into a hierarchy of goals, criteria, sub-criteria and alternatives (see Figure 4).

Decision maker carries out pair-wise comparisons of elements such as criteria, sub-criteria, and alternatives at each level. The pair-wise comparison generally refers to process of comparing elements in pairs to judge which of each element in pair is preferred, or has a greater amount of quantitative property. Decision-makers can rate, for example, the comparison as equal, marginally strong, strong, very strong, and extremely strong.

The pair-wise comparisons of various criteria generated are organized into a square matrix. The diagonal elements of the matrix are 1. The criterion in the i^{th} row is better than criterion in the j^{th} column if the value of element (i, j) is more than 1; otherwise the criterion in the j^{th} column is better than that in the i^{th} row. The (j, i) element of the matrix is the reciprocal of the (i, j) element.

The consistency is evaluated. If this consistency index fails to reach a required level then the answers to comparisons may be re-examined. The consistency index (CI) is calculated as follow:

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)}$$

where λ_{max} is the maximum eigenvalue of the judgment matrix, n is the number of comparing elements in each level.

The consistence ratio (CR) is finally calculated as the ratio of consistency index (CI) and random consistency index (RI). The RI is the random index representing the consistency of a randomly generated pair-wise comparison matrix [Saaty02]. It is derived as average random consistency index (see Table 4) calculated from a sample of 500 of randomly generated matrices based on the AHP scale (see Table 5).

Table 4 presents the random consistency index (RI), derived from Saaty's work [Saaty02], in which the upper row is the number of elements to be compared and the lower is the corresponding index of consistency for random judgments. Practically, the Consistency Ratio value (CR) should be less than 0.1.

Table 4 - The random consistency index (RI)

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

For example, we have 4 elements to be compared ($n=4$) and the CI is 0.060. CR is calculated as $0.060/0.90=0.0677$.

Saaty argues that a $CR > 0.1$ indicates that the judgments are at the limit of consistency (but not too much more) to be accepted. A CR as high as, for example, 0.9 would mean that the pair-wise judgments are just about random and are completely untrustworthy.

Finally, the rating of each alternative is multiplied by the weights of the sub-criteria and aggregated to get local ratings with respect to each criterion. The local ratings are then multiplied by the weights of the criteria to get global ratings.

Table 5- Scale of relative importance for pair-wise comparison.

Scale of relative importance	Definition
1	same importance
2	slightly more important
3	weekly more important
4	weekly to moderately more important
5	moderately more important
6	moderately to strongly more important
7	strongly more important
8	greatly more important
9	absolutely more important

Grey Relational Analysis (GRA) method

GRA builds grey relationships between alternatives. GRA is usually implemented following several steps. It classifies the attributes by three situations: *larger-the-better*, *smaller-the better*, and *nominal-the-best*. Then, it defines the lower, moderate, or upper bounds of attributes. Normalizing individual entities and defining the ideal attributes is in next step. Finally, the grey relational coefficients (GRCs) are calculated to select the best alternative with the largest GRC.

Consider a decision problem includes n alternatives (A_1, A_2, \dots, A_n), m attributes for each alternative and x_{ij} represent attribute j of the alternative i . The problem is formulated as in Table 3.

A procedure for the grey relational analysis consists of the following steps.

1. Generate reference alternative A_0 which consists of the most ideal attributes.

$$A_0 = \max_i x_{ij} = (x_1^+, x_2^+, \dots, x_m^+)$$

where m is the number of attributes, x_j^+ is the most favorable attribute in each column of attribute j (see Table 2.3).

2. Consider alternative A_i .

$$A_i = (x_{i1}, x_{i2}, \dots, x_{im})$$

3. Compute the difference between alternative A_i and alternative reference A_0 (Δ)

$$\begin{aligned} \Delta_{ij} &= (\Delta_{i1}, \Delta_{i2}, \dots, \Delta_{im}) \\ &= (|x_1^+ - x_{i1}|, |x_2^+ - x_{i2}|, \dots, |x_m^+ - x_{im}|) \end{aligned}$$

4. Find the global maximum value (Δ_{\max}) and minimum value (Δ_{\min}) in the Δ .

$$\Delta_{\max} = \max_{\forall ij} \Delta_{ij}$$

$$\Delta_{\min} = \min_{\forall ij} \Delta_{ij}$$

5. Calculate grey relational coefficient. Let γ_{ij} represents the grey relational coefficient of the j^{th} attribute in the i^{th} alternative difference, then

$$\gamma_{ij} = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{ij} + \zeta \Delta_{\max}}$$

ς is a value between 0 and 1. The coefficient ς is used to compensate the effect of Δ_{max} . In general the value of ς can be set to 0.5.

6. Compute grey relational grade Γ_i (GRC) for each difference data series.

$$\Gamma_i = \frac{1}{m} \sum_{j=1}^m \gamma_{ij}$$

7. The comparative series with the largest Γ (GRC) has the highest priority

4.2.2 Cost function approach

The cost function is a measurement of the cost consumed by selecting a particular alternative among several alternatives. The alternative which has the most minimum cost is the best alternative.

The cost function is the sum of some normalized form of each attribute. Normalization $N(x_{ij})$ is needed to ensure that the sum of the values in different units is meaningful as stated previously. Decision makers may specify the importance or weights of each attribute. The general form of the cost function f_i of alternative (interface) i is:

$$f_i = \sum_j^m w_j N(x_{ij})$$

with $\sum_j w_j = 1$

where, w_j stands for the weight of attribute j , and $N(x_{ij})$ represents the normalized score of alternative i of attribute j .

4.2.3 Utility function approach

Utility is a subjective measure of value or satisfaction. It measures an individual's relative value of preference for a particular outcome or event in relation to another. For example, in finance, it is usually used to measure decision makers' preferences regarding attributes directly influencing to monetary gain or loss.

A utility function generally could be described by a mathematical expression that describes the satisfaction level of a decision maker or a specific objective based on several variables. The utility function is shaped or formulated depending on specific goal of decision maker.

A utility function is generally written as follows:

$$U = f(x_1, x_2, \dots, x_n)$$

where x_1, x_2, \dots, x_n are necessary criteria that helps decision makers to calculate the utility value or the satisfaction level. These attributes, for example, may be the benefit or cost attributes depending on circumstances and decision makers' objectives.

4.2.4 Profit function approach

The profit function proposes a measurement of benefit that decision maker obtains when making decision. The one providing maximum profit is the best alternative.

The profit function (P) is usually calculated by the difference between benefit (B) and cost (C)

$$P = f(B, C)$$

The cost depends on many factors and is classified into two main types: fixed cost and variable cost. For example, some costs always exist and do not change during the decision procedure. These are the fixed costs. The variable costs change during the decision procedure. For example, in economic, they are directly proportional to sales or production volumes. The total cost (C) is the sum of the fixed cost and variable cost.

The total benefit (B) is the total income, for example, from the sale of a good.

4.2.5 Policy approach

A policy is typically described as a deliberate plan of action to guide the decisions and achieve an expected objective. This approach is different from the mathematical function-based approaches in the sense that, in this approach, there is no procedure to rank the alternatives.

A policy usually includes a set of rules containing many conditions (see Figure 5). If an alternative satisfies one or several conditions of the rules, the policy decides to take a suitable action for the alternative. For example, if the alternative matches the condition A, the action 2 is applied.

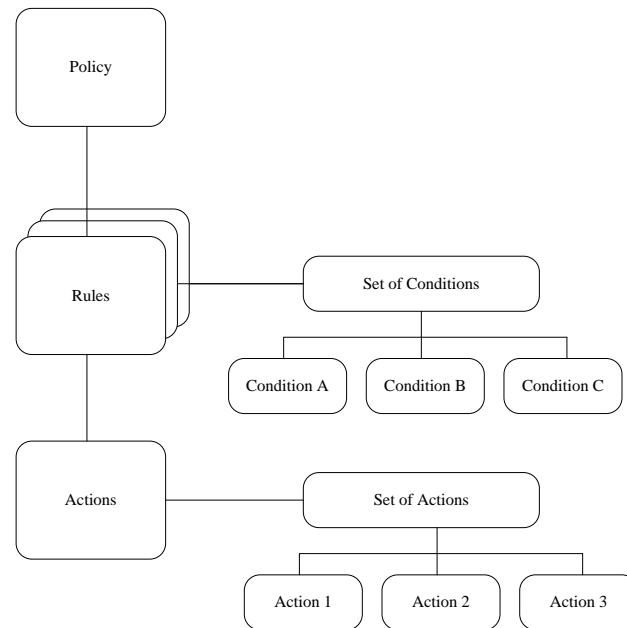


Figure 5—An example of the policy

4.2.6 Game theory approach

Game theory is the formal study of conflict and cooperation between players where their actions are interdependent. These players may be individuals, groups, firms, etc. Game theory provides approaches to structure, analyze, and understand strategic scenarios.

Game theory since its appearance has received an unprecedented attention. It has been widely applied to various fields such as war, politics, economic, sociology, psychology, and biology, etc. Particularly, in the network and telecommunications area, we have encountered a rich literature in network security [Lakshman] and [Michiardi], power control [Alpcan] [Alpcan] [Altman01] [Falomari] [Heikkinen] [Ji] [Saraydar01] [Saraydar02] [Sung], pricing and incentive for cooperation between mobile terminals

[Battiti] [Crowcroft] [Michiardi] [Urpi], the access control to a common shared radio channel [Altman02] [Jin][MacKenzie], auctions for resource reservation [Dramitinos], and multi-homing [Shakko01][Shakko02][Touati], etc.

The descriptions of the game theory, related work on the interface selection are presented in Chapter 5.

4.3 Related work

In this section, we present the current works related to the network/interface selection and flow/interface association issues.

4.3.1 Network/Interface selection

4.3.1.1 MADM based approach

Several interface selection schemes [Puttonen][Bari][Tran01] have been proposed for decision making and interface selection using MADM methods. In [Puttonen], the interface selection scheme considers several attributes: the signal strength, available bandwidth, power consumption, monetary cost of using the link, coverage radius and security level. The goal of this work is to select the optimal interface among network interfaces (e.g., IEEE 802.3 Ethernet, IEEE 802.11b/g WLAN, Bluetooth and GPRS/EDGE/UMTS). This work carries out several simulation scenarios and compares the MADM methods to the traditional signal strength scheme. With the objective to maximize the throughput of applications, most algorithms are usually effective. However, in mobility environment, the attributes are often changed. The MADM methods are flexible to adapt to this circumstance. Particularly, TOPSIS outperforms the other methods in this situation.

In [Chen][Qingyang], the authors propose a network selection algorithm which combines analytical hierarchy process (AHP) and grey relational analysis (GRA).

Figure 6 presents the network selection scheme which considers the quality of service of the network as the objective in the process of network selection. UMTS and WLAN are considered as available network alternatives. In this scheme, AHP is used to weight the attributes of alternatives and GRA determines the best network based on a weight vector calculated by AHP.

The main considered network QoS attributes are *throughput*, *timeliness*, *reliability*, *security*, and *cost*. In these parameters, the *timeless* attribute has sub-attributes such as *delay*, *response time*, and *jitter*. The *reliability* attribute has also sub-attributes such as *Bit error rate (BER)*, *burst error*, and *average number of retransmissions per packet*. Once all the information on the QoS parameters is collected, pair-wise comparisons are performed at each level using AHP. Three AHP matrices are constructed. One of them is used to compare *QoS attributes*, and the other two are used to compare *timeliness* and *reliability* sub-attributes, respectively. The global priorities of sub-attributes are achieved through multiplying priorities of sub-attributes by the global priorities of the corresponding parent.

Next, GRA is used to rank the UMTS and WLAN network. The network condition information is first normalized using the method introduced earlier. Then, the previously computed weights by AHP are used for the calculation of GRC. The detail calculation steps are presented in section 4.2.1.2. Finally, the network with the largest GRC is the most desirable.

The whole network selection model is shown in Figure 6. When a network is detected as available, the scheme estimates and collects the network performance, service class, and user preference. UMTS is assumed that it could be always available. When the RSS of WLAN is larger than the RSS threshold (e.g., -80 dBm), which allows communication service for a period of time, and the user is estimated to be in the coverage of WLAN for more than a time limit (e.g., 1 minute), the network selector begins to collect other QoS information from the network and user to determine whether to hand off to WLAN. Otherwise, the GRCs of WLAN and UMTS are assigned 0 and 1, respectively, allowing the decision maker to keep UMTS connected.

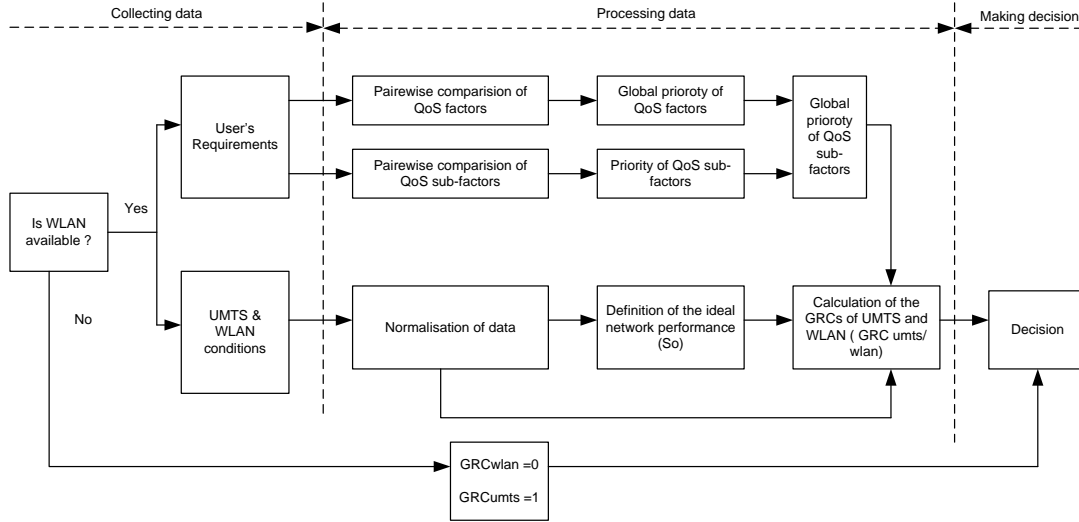


Figure 6– The network selection model using GRA and AHP [Qingyang]

4.3.1.2 Cost function based approach

In [Wang][Sowmia], the authors introduce a cost function to select the best available network for the handover process. They design a handoff mechanism which separates the decision making (e.g., select the “best” interface when to handoff) from the handoff execution.

In this scheme, the handover decisions are controlled by the mobile terminal. Periodically, the mobile terminal collects the current network conditions and then consults a policy module to determine which network is the best reachable network. The policy module uses a cost function to calculate the interface cost. The used parameters are the bandwidth B_n that network n can offer, the power consumption P_n of using the network device for n and the monetary cost C_n of n . The cost of using a network n is defined as:

$$f_n = w_b N\left(\frac{1}{B_n}\right) + w_p N(P_n) + w_c N(C_n)$$

where $N(i)$ as the normalization function of parameter i

The interface that has the lowest cost is chosen as the target interface. Therefore, this cost function-based model estimates dynamic network conditions and includes a stability period (a waiting period before handovers) to ensure that a handover is worthwhile for each terminal.

4.3.1.3 Profit function based approach

In [Xiaoshan], the interface selection is achieved by associating each interface with a profitability function. This function is evaluated as the difference between a gain and a cost due to the handover. In particular, the algorithm input data comes from two different sources: the bandwidth gain and the handoff cost. The handoff cost is the data volume lost due to handoff delay and the bandwidth gain is the data volume gained due to handoff.

At each handoff epoch, the mobile node compares the profit from different networks and chooses the one that gives maximum profit.

In [Xiaoshan], for example, the profitability function is described as follows:

$$P = f(G, C)$$

(P) depends on the bandwidth Gain (G) and the handoff Cost (C).

The authors define the bandwidth gain G of a handoff decision for network i at handover epoch t_k as follows:

$$G_i(t_k) = \begin{cases} m(i, t_k) - m(j, t_{k-1}) & k \geq 1 \\ m(i, t_k) & k = 0 \end{cases}$$

$G_i(t_k)$ is the difference in bandwidth between the next period and the current period and $m(i, t_k)$ is the bandwidth of the network i used by the mobile node at handoff decision epochs t_k .

The handoff cost which is the data volume lost due to handoff delay corresponds to:

$$m(i, t_{k-1})d(x, y)$$

where $d(x, y)$ is the handoff delay when a mobile makes a handoff from base station x to y .

The profit function for interface i is then:

$$P_t = (t_{k+1} - t_k)G_t(t_k) - m(i, t_{k-1})d(x, y)$$

4.3.1.4 Utility function based approach

In [Ormond], the authors propose a user-centric solution designed for non real-time traffic and use the notion of consumer surplus which is largely used in microeconomics. In the paper, the consumer surplus is the difference between the monetary value of the data to the user and the actual price charged for transferring the data. In other terms, it expresses the difference between what the user has to pay for a data transfer and what he is willing to pay. The strategy aims at maximizing the consumer surplus while meeting user's defined constraints in term of transfer completion time.

The mechanism predicts the transfer rates T_c of each interface and then derives transfer completion times.

$$T_c = \frac{F_i}{r}$$

F_i is size of file i and r is the average rate for total transfer.

It then calculates the predicted utility U_i which reflects the user's willingness to pay for a data transfer regarding the transfer completion time. Finally, the mechanism calculates the consumer surplus (CS), and the selected network has the best consumer surplus.

$$CS_i = U_i(T_c) - C_i$$

Where CS is consumer surplus (in cent), $U_i(T_c)$ is the monetary value (in cent) that the user places on the transfer of file i in the given transfer completion time (T_c) and C_i is the cost charged by the network (in cent), for the competed file transfer.

A number of utility functions have been examined to explore different user attitudes to risk for money and delay preferences related to the data transfer. These utility functions are described below and are graphically represented in Figure 7.

The use attitudes in terms of utility functions, for example, are:

- **Risk neutral:** user equally prefers paying less to experiencing less delay
- **Risk seeking:** user prefers alternative of less delay to assured money saving
- **Risk adverse:** user prefers to be certain of paying less

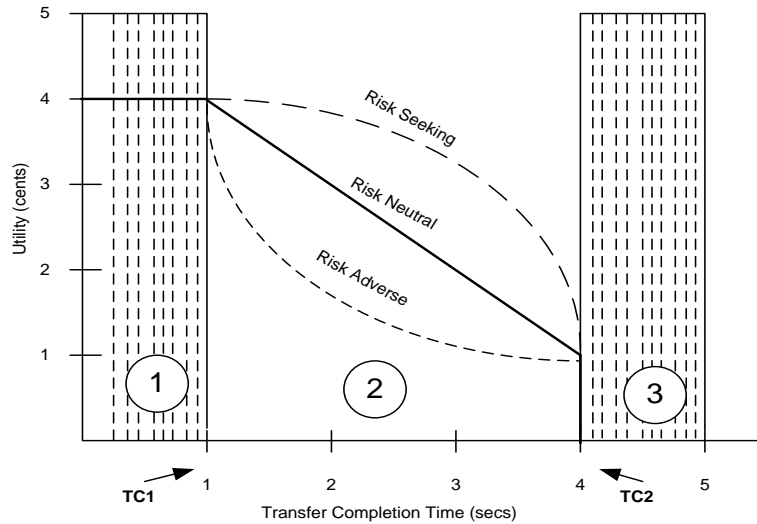


Figure 7- Different user attitude risks [Ormond].

4.3.1.5 Game theory based approach

In [Touati], a work on the vertical handover issue using game theory is presented. In the work, mobile terminals integrating multiple radio interfaces are able to switch (vertical handover) between networks of different technologies.

In the paper, the authors consider the system as an evolutionary game with a finite number of users.

Each terminal is assumed to have an utility function. The authors propose an iterative distributed algorithm which guarantees the game converges to the Nash equilibrium. The iterative algorithm allows each mobile terminal gradually updating the probability of choosing one among available networks at each epoch. On the other hand, the network sends a reward to each terminal that represents the impact each terminal has on the network throughput.

Basing on potential games and Replicator dynamic, the authors showed that the solutions are efficient and fair in terms of throughput. In addition, the equilibrium is

pure, in the sense that, after convergence, each user is associated to a single network cell.

4.3.2 Flow/interface association

4.3.2.1 Utility function based approach

In [Suciu01] and [Suciu02], a utility based method is also defined considering the application requirements. The authors design an utility function that considers the following parameters of the application requirements and the network interface capacity: bandwidth, delay, and security level. The objective of this function is to maximize the utility of the applications. The utility function of interface i and application j is described as follow:

$$U_{ij} = [\ln(B_i - b_j) + \ln(e_j - E_i) + \ln(d_j - D_i) + \ln(S_i - s_j)] \cdot [(B_i \Delta b_j) \cdot (e_j \Delta E_i) \cdot (d_j \Delta D_i) \cdot (S_i \Delta s_j)]$$

$$\text{where } x \Delta y = \begin{cases} 1 & \text{if } x \geq y \\ 0 & \text{otherwise} \end{cases}$$

Considering the interface i :

- B_i : is the mean available bit rate of the interface i .
- E_i : is the monitored packet error rate.
- D_i : is the average delay in millisecond (ms).
- S_i : is the security level of the access network i .

For the application j :

- b_j : is the minimum necessary bit rate.
- e_j : is the supported packet error rate.
- d_j : is the maximum tolerated delay in millisecond (ms).
- s_j : is the required security level for the application j .

The utility function scores each interface by comparing the application requirements parameters to the network resources. This determines the satisfaction level of the application for each interface.

4.3.2.2 Policy based approach

In [Ylitalo], the authors propose policy based mechanism that allows associating the applications to the interfaces.

The policies allow selecting dynamically the most appropriate interface for a particular flow. Different traffic flows can be transferred between different interfaces, transparently and independently of each other.

In this scheme, the policy is described by a set of actions. There are conditional clauses in each action.

The actions in a policy must have some priority defining the order in which the actions are searched and matched. Figure 8 shows an example of a policy of which the priority is implicitly included in the structure. The first action in the list has the highest priority. The default action must always have the lowest priority.

When an application is accepted by an action, the policy verifies the preference of a network interface. Basing on the policy, the local routing mechanism routes the outgoing IP packets towards the available interfaces. The most preferred available interface is always used. If it becomes unavailable (e.g., when a user moves out of a wireless network coverage area), the connections is switched to the lower preferred interface.

If an action is forced, all traffic that is matching to the action may not use any other interfaces than specified in that specific action. Likewise, if an action is not forced and all the interfaces listed in that action are unavailable, the next preferred action can be followed.

A typical conditional clause within an action consists of the information related to connection association (e.g., HTTP, SMTP...). If this condition is verified, then the candidates are searched in the preferred order of available interface.

An example of a pseudo statement is:

if (address=A and port=B) then use the interface WLAN with the condition (price < P). Otherwise, use the GPRS interface.

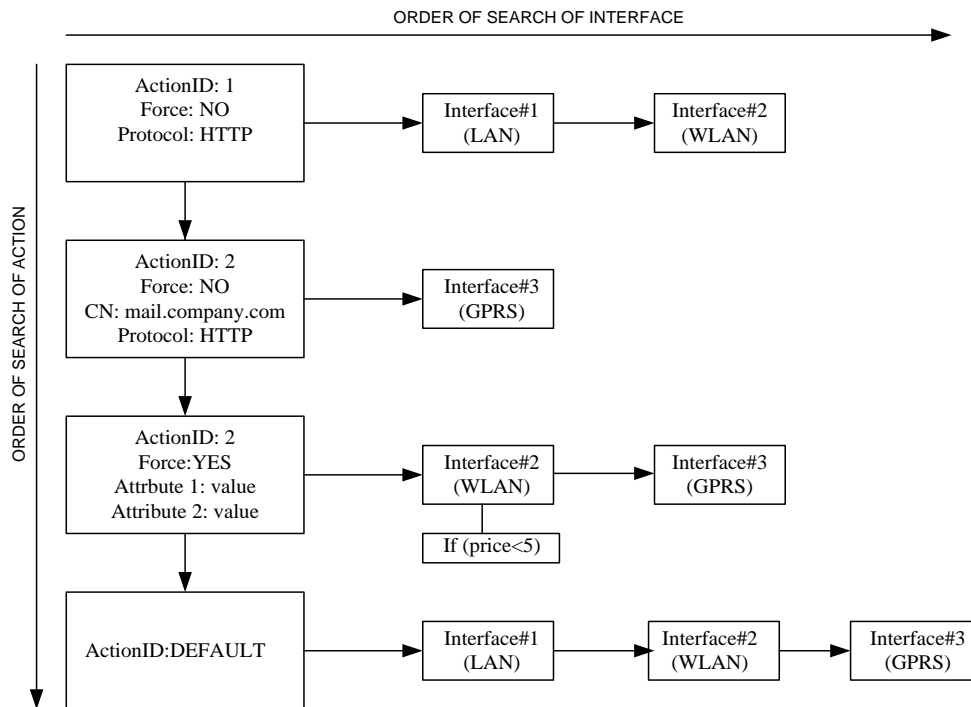


Figure 8– The example of the interface selection policy [Sowmia].

4.3.2.3 Game theory based approach

This work proposes the possibility of using simultaneously several network interfaces rather switching between the available networks.

In [Shakko01] and [Shakko02], Shakkottai et al., study the case of non-cooperative multi-homing of users to access IEEE 802.11 APs using a non-cooperative game. The work considers the scenario where mobile terminals could be multi-interface. Mobile terminals could connect simultaneously to all the available access points. They could then divide their traffic among the different access points in order to maximize their

individual throughput. The term multi-homing refers here to the ability of the users to split their traffic amongst all the available access points.

Basing on observations made on the characteristics of IEEE 802.11x physical rate selection schemes and channel occupancy, the work aimed at showing that, if the mobile terminals are allowed to split their traffic while maximizing their payoff (expressed as a function of the obtained throughput and the price charged), then the global system throughput is maximized.

In this work, an infinite number of users are considered and the system is modeled as a population game. The authors prove that the system evolution converges to Wardrop equilibrium and interestingly, the convergence limits are effective in the sense that they optimize some global function of the system despite terminals' selfish strategies.

5 Summary

This chapter introduces a panorama of the evolution of wireless networks and mobile terminals. We figure out the challenge of the mobile terminals to make use of the multi-technology, and multi-network in order to offer high quality services according to several decision metrics.

We then present the network/interface selection and the flow/interface association issues. A common point of the issues is that they are a decision making problem basing on several attributes.

A state of the art of the decision approaches is presented. We also investigate the related works surrounding the interface selection and the flow/interface association in the multi-interface context.

Chapter 3: The Distance to the Ideal Alternative (DiA) Algorithm

Multiple Attribute Decision Making (MADM) is a suitable decision approach to realize a dynamic interface selection with multiple alternatives (interfaces) and attributes (network, interface characteristics, user preferences, etc.). In this chapter, we present a simulation based comparative study of MADM methods. We show their limitations. TOPSIS suffers from “ranking abnormalities”. SAW and WP provide less precision in identifying the alternative rank compared to TOPSIS.

To improve MADM for interface selection, we propose the Distance to ideal Alternative (DiA) algorithm. We show that DiA does not suffer from the ranking abnormalities problem. Simulation results validate the DiA algorithm.

1 Introduction

As presented in Chapter 2, MADM includes many methods such as SAW, WP and TOPSIS.

We are motivated to study the MADM approach for network/interface selection. A simulation based comparative study will allow identifying advantages and drawbacks of each method in making decision. Revisions, from then, will be necessary to improve MADM to support the interface selection.

In this chapter, we carry out simulation based comparative study of the MADM methods. The simulations are set up based on the interface selection scenarios in the multi-homing context. The simulation results illustrate that the performance evaluation of each MADM method. Moreover, in each simulation scenario, the simulation based comparative study outlines an evidence of advantages and drawbacks for the interface selection.

With the motivation to improve MADM for the interface selection decision, we propose Distance to ideal Alternative (DiA) algorithm. DiA aims to select the best interface while avoiding the MADM limitations. We demonstrate that DiA outperforms MADM methods.

2 Comparative study of SAW, WP and TOPSIS

2.1 Introduction

In this section, we present the simulation based comparative study and performance evaluation of the three MADM decision algorithms such as SAW, WP, and TOPSIS. The simulations are carried out using MATLAB.

As presented previously, the SAW approach allows determining the best alternative by calculating the weighted sum of all attribute values:

$$SAW^* = \max_i \sum_{j=1}^m r_{ij} w_j$$

The WP approach proposes the weighted product of all normalized attributes:

$$WP^* = \max_i \prod_{j=1}^m r_{ij}^{w_j}$$

The TOPSIS approach aims at determining the best alternative which has always the relative shortest distance to the ideal solution.

The TOPSIS algorithm is realized by several steps such as construction of the normalized decision matrix using Euclidean normalization method, construction of the weighted normalized decision matrix, identification of ideal and negative-ideal solutions, calculation of the distance between alternatives using the m-dimensional Euclidean distance, and calculation of the relative closeness to the ideal solution. The selected alternative should have the relative shortest distance to the ideal solution.

The detail description of MADM methods is presented in Chapter 2.

2.2 Simulation Scenarios

In the first simulation, we calculate the overall score of SAW and WP and the relative closeness distance to the ideal solution of TOPSIS. The simulation allows determining the ranking order of the algorithms related to many criteria.

In the second simulation, we tackle the ranking abnormality issue. As stated above, the ranking abnormality happens when the low ranking alternative is removed from the candidate list. The ranking order of the alternatives then changes. A robust MADM algorithm, in the interface selection context, ensures that the best alternative does not change when an alternative which is not the best is removed or replaced by another alternative. Therefore, if an algorithm suffers from the ranking abnormality problem, the ranking order is not stable.

In the third simulation, we measure the difference of the ranking values of each algorithm. In SAW and WP, the ranking values are the overall score values of the alternatives. In TOPSIS, the ranking values are the relative closeness values to the ideal solution of alternatives.

The difference of ranking values between alternatives allows determining the accuracy of the algorithm in identifying the alternative ranks.

In the simulation, we consider five attributes associated to five network interfaces (UMTS, 802.11b, 802.11a, 802.11n, and 802.16a). The attributes are: packet jitter, packet delay, utilization, packet loss, and cost per byte for each network as presented in Table 6. These attributes represent two main criteria: QoS parameters and user's preferences.

Table 6- The attribute parameters

	J (ms)	D (ms)	U (%)	L (per 10⁶)	CB (cent/ byte)
Net #1 UMTS	50	400	10	100	100
Net #2 802.11b	25	200	20	20	20
Net #3 802.1a	15	100	20	15	10
Net #4 802.11n	30	150	40	20	5
Net #5 802.16a	20	100	20	15	30

The Packet Jitter (J): a measure of the average delay variation within the access system. It can be measured in milliseconds.

The Packet delay (D): measures the average delay variation within the access system. It can be measured in milliseconds.

Utilization (U): a measure of the current utilization of the access network or the wireless link. It can be expressed in percentage.

The Packet Loss (L): a measure of the average packet loss rate within the access system over a considerable duration of time. It can be expressed in packet losses per million packets.

The Cost (CB): the cost of the access network. (cent/byte).

The attribute values of all algorithms are normalized by the Euclidean normalization method. We choose this method since it provides the highest ranking consistency [Chakra].

In the simulation, we use a weight vector for which the cost is significantly important compared to any QoS parameters for the candidate interface to be selected.

$$W = [0.2 \ 0.1 \ 0.05 \ 0.1 \ 0.55]$$

3 Simulation results

3.1 Simulation 1

In this simulation, we calculate the ranking order of the alternatives by using the SAW, WP and TOPSIS algorithms. Table 7 presents the relative closeness to the ideal solution of TOPSIS and the overall score of SAW and WP.

The results show that the ranking order of the alternatives is the same for both TOPSIS and SAW algorithms. The ranking order of SAW and TOPSIS is **Network_{#3}**, **Network_{#4}**, **Network_{#2}**, **Network_{#5}** and **Network_{#1}**.

The ranking order of WP is **Network_{#3}**, **Network_{#4}**, **Network_{#5}**, **Network_{#2}** and **Network_{#1}**.

Table 7-The ranking order of SAW, WP, and TOPSIS

	SAW	WP	TOPSIS
Network #1	0,154 <i>Rank #5</i>	0,923 <i>Rank #5</i>	0,052 <i>Rank #5</i>
Network #2	0,745 <i>Rank #3</i>	0,994 <i>Rank #4</i>	0,833 <i>Rank #3</i>
Network #3	0,851 <i>Rank #1</i>	0,998 <i>Rank #1</i>	0,947 <i>Rank #1</i>
Network #4	0,799 <i>Rank #2</i>	0,997 <i>Rank #2</i>	0,904 <i>Rank #2</i>
Network #5	0,734 <i>Rank #4</i>	0,995 <i>Rank #3</i>	0,748 <i>Rank #4</i>

The ranking order of WP is different from the ranking order of SAW and TOPSIS related to **Network_{#5}** and **Network_{#2}**. The reason is that WP penalizes the alternative having the bad attribute values. In this situation, the ranking order of **Network_{#2}** is lower than **Network_{#5}** since **Network_{#2}** has poor QoS attribute values comparing to **Network_{#5}**.

Although **Network_{#2}** has poor QoS attributes, its cost with the very high weight is better than **Network_{#5}**. WP does not make a good decision in ranking the **Network_{#5}** and **Network_{#2}** when it considers only the poor attributes.

Note that SAW, WP, and TOPSIS algorithms provide the same best alternative (e.g., **Network_{#3}**).

3.2 Simulation 2

In this simulation, we focus on the ranking abnormality problem and the “robustness” of the algorithms regarding the interfaces shut down.

We then remove one alternative (e.g., **Network #1**) from the alternative candidate list. Table 8 presents the relative closeness to the ideal solution of TOPSIS and the overall score of SAW and WP.

Table 8- The ranking order of SAW, WP, and TOPSIS

	SAW	WP	TOPSIS
Network #1	-----	-----	-----
Network #2	0,455 Rank#3	0,968 Rank#4	0,397 Rank#3
Network #3	0,693 Rank#1	0,986 Rank#1	0,805 Rank#2
Network #4	0,651 Rank#2	0,984 Rank#2	0,856 Rank#1
Network #5	0,380 Rank#4	0,973 Rank#3	0,142 Rank#4

In this situation, the results show that a removal of an alternative causes a change in the ranking order of TOPSIS. The ranking order of SAW, WP remains the same. In particular, the top ranked alternative in TOPSIS has changed (from **Network#3** to **Network#4**).

We continue removing one alternative (e.g., **Network#5**) from the alternative candidate list.

The results, in Table 9, show that the ranking order in SAW and WP is always stable, but the top ranked alternative in TOPSIS has changed from **Network#4** to **Network#3**.

In Table 7, all algorithms determine that **Network#3** is the best interface since it has the best QoS attribute values and the cost is not very high. **Network#1** is the worst interface because it has the worst QoS and cost attribute values.

Table 9- The ranking order of SAW, WP, and TOPSIS

	SAW	WP	TOPSIS
Network #1	-----	-----	-----
Network #2	0,456 Rank#3	0,968 Rank#3	0,412 Rank#3
Network #3	0,694 Rank#1	0,986 Rank#1	0,838 Rank#1
Network #4	0,636 Rank#2	0,983 Rank#2	0,851 Rank#2
Network #5	-----	-----	-----

When we remove the worst interface (e.g., **Network#1**) out of the candidates list, this does not influence the ranking order of the other interfaces for SAW and WP. However, the best interface in TOPSIS changes (e.g., from **Network#3** to **Network#4**, see Table 8). When another worst interface (e.g., **Network#5**) is removed, the best interface in TOPSIS also changes (see Table 9).

The simulation results highlight the ranking abnormality problem of TOPSIS and show that SAW and WP provide a more efficient behavior in this situation.

3.3 Simulation 3

In this simulation, we are motivated to measure the precision in identifying the alternative ranks of all algorithms. We measure the difference of ranking values of all algorithms. This difference allows distinguishing the ranking order and selecting easily the best alternative.

We consider the ranking values measured by SAW, WP and TOPSIS as in Table 7 to calculate the difference of ranking values.

Figure 9a, b, and c show the difference of ranking values of all algorithms. We measure the difference of ranking values between $rank_{\#1}$ and $rank_{\#2}$ (e.g., $Diff(R_1 - R_2)$), $rank_{\#2}$ and $rank_{\#3}$ (e.g., $Diff(R_2 - R_3)$), $rank_{\#3}$ and $rank_{\#4}$ (e.g., $Diff(R_3 - R_4)$), and $rank_{\#4}$ and $rank_{\#5}$ (e.g., $Diff(R_4 - R_5)$) of all algorithms. The results show that the difference of ranking values in SAW is larger than WP and the difference of ranking values in TOPSIS is larger than SAW and WP.

TOPSIS has the largest difference of ranking values and allows more accuracy in identifying the ranks between the alternatives compared to SAW and WP.

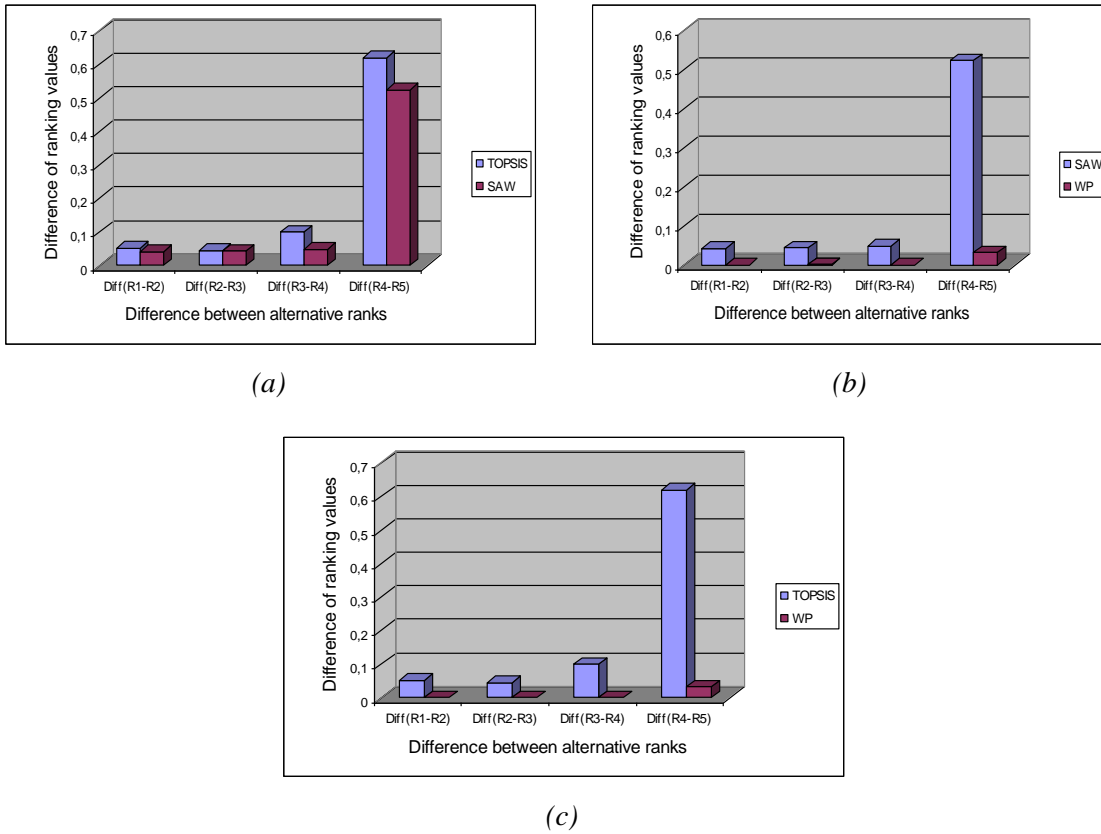


Figure 9– The difference of ranking values of SAW, and TOPSIS (a), SAW and WP(b) and WP and TOPSIS (c)

To provide results applicable to a wide range attribute values, we conduct a simulation considering random attribute values.

The simulation generates random decision matrices with alternatives A_i ($i = 1,2,3,4$) and attributes C_j ($j = 1,2,3,4$). The decision matrix is normalized by using the Euclidean normalization. To obtain an unbiased result, the following settings are used in the simulation.

-10000 decision matrices are generated randomly for each simulation

-For each data range, the process is repeated 10 times and the average is noted in the final result table

Figure 10a, b, and c depict the average difference of ranking values in 10000 times of simulation. The results show that the same conclusion can be made. TOPSIS is more accurate than SAW and WP because it shows a larger difference of ranking values.

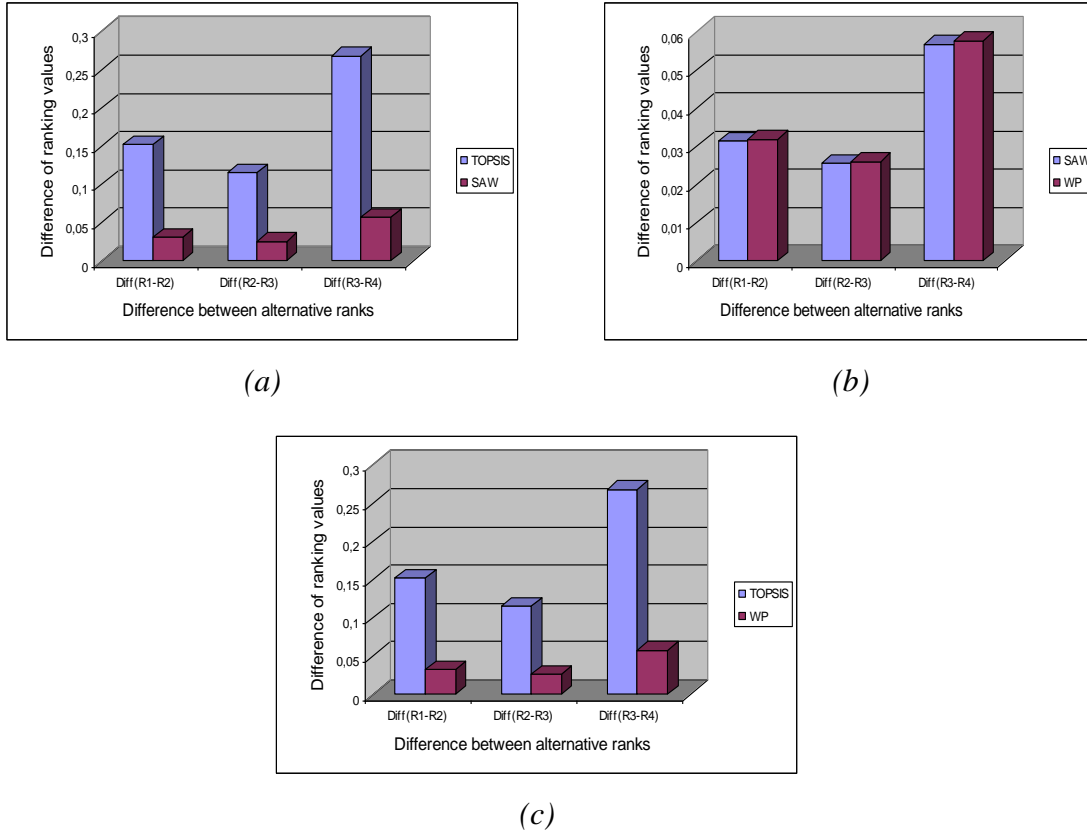


Figure 10 - The difference of ranking values of SAW and TOPSIS (a), SAW and WP(b) and TOPSIS and WP (c)

3.4 Discussion

The simulation results presented above show that each algorithm has its own limitations. TOPSIS suffers from “ranking abnormalities” and SAW, WP provide less precision in identifying the alternative ranks compared to TOPSIS.

The “ranking identification” problem in SAW and WP happens especially when the attribute values of alternatives are extremely close. The overall scores of alternatives are similar leading to confusion in the decision making as stated above.

Additionally, the WP algorithm penalizes the alternatives with bad attribute values. Moreover, there are also some limitations of WP. If some values of the constraint

factor, for example, are equal to zero (e.g., the connection is free of charge), the overall score of alternative is equal to zero. In this case, a decision cannot be made.

There are many factors influencing the ranking abnormality of TOPSIS. When one of the alternatives is removed from the candidates list, the normalized attribute values of all alternatives will change. Subsequently, the calculation of the weighted normalized decision values of TOPSIS will change and the best and worst values for each of the attributes will change also.

TOPSIS calculates the m-dimensional Euclidean distance of attributes from the respective positive ideal and negative ideal values.

When an alternative is removed, the Euclidean distance calculation for each alternative will be based on the new normalized attribute values, the new positive Ideal and new negative Ideal values.

The relative closeness to the ideal solution based on these new values will change and, as a result, the calculation of the preference order C_j can provide a different ranking order than the prior one.

Although TOPSIS suffers from the ranking abnormality problem, it provides better precision in alternative ranking than SAW and WP.

4 The DiA algorithm

With the motivation to improve MADM to allow mobile terminals selecting dynamically the best interface according to many attributes, we present the DiA algorithm which aims at selecting the best interface while ensuring no ranking abnormality problem and providing a good accuracy in identifying the alternative ranks.

The DiA algorithm is based on the following principles.

As like TOPSIS, DiA determines the positive and negative ideal alternative attribute values of each attribute. These are the maximum and minimum values of attribute in each column of the MADM matrix.

$$a_i^+ = \max_j [v_{ij}]$$

$$a_i^- = \min_j [v_{ij}]$$

While TOPSIS uses the positive ideal solution values to calculate in the m-dimensional space the Euclidean distance between the solutions and the ideal solution, DiA uses the Manhattan distance to calculate the distance between the attribute values and the positive and negative ideal values of each attribute.

$$D_j^+ = \sum_i^m |v_{ji} - a_i^+|$$

$$D_j^- = \sum_i^m |v_{ji} - a_i^-|$$

Then, DiA considers the minimum value of D^+ and maximum value of D^- .

$$\min D^+ = \min_j D_j^+ = \min_j \sum_i^m |v_{ji} - a_i^+|$$

$$\max D^- = \max_j D_j^- = \max_j \sum_i^m |v_{ji} - a_i^-|$$

If we consider the (D^+, D^-) plane, the point $(\min D_i^+, \max D_i^-)$ is defined as the “positive ideal alternative” (PIA) (see Figure 11).

The best alternative has the shortest distance to the PIA. This absolute distance is calculated as follow.

$$R_j = \sqrt{(D_j^+ - \min(D^+))^2 + (D_j^- - \max(D^-))^2}$$

The alternative having the smallest R_j value has also the shortest distance to the PIA.

In the following, we will show that DiA has no ranking abnormality compared to TOPSIS.

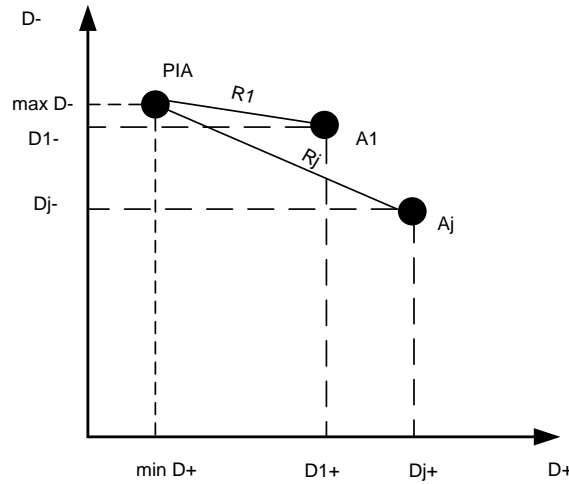


Figure 11 - The D^+, D^- plane

If we consider a ranking order of the alternatives as follows (e.g., the best alternative is A_1 and the worst alternative is A_n)

$$A_1 > A_2 > \dots > A_j > \dots > A_n$$

We have the following distances to the PIA associated to the alternatives.

$$R_1 < R_2 < \dots < R_j < \dots < R_n$$

Now, we suppose that an alternative (e.g., A_j) including one of the positive ideal attribute value (e.g., $a_k^{+(old)}$) in the k^{th} column of the MADM matrix is removed. The distances to the negative ideal attribute of alternatives D_j^- are not changed.

We can find a new positive ideal attribute value in the k^{th} column (e.g., $a_k^{+(new)}$).

The new value of the positive ideal attribute is smaller than the previous one.

$$a_k^{+(old)} > a_k^{+(new)}$$

The distance between the new and previous positive ideal attributes is d (where d is constant).

$$|a_k^{+(new)} - a_k^{+(old)}| = d$$

The Manhattan distances of all attribute values to the positive ideal attribute value in the k^{th} column before and after removing an alternative are respectively:

$$D_{ik}^{+old} = |v_{ik} - a_k^{+(old)}|$$

$$D_{ik}^{+new} = |v_{ik} - a_k^{+(new)}|$$

We have:

$$|D_{ik}^{+new} - D_{ik}^{+old}| = |a_k^{+(new)} - a_k^{+(old)}| = d$$

Therefore, the distance between all attribute values to the new positive ideal attributes will decrease with a constant distance d .

$$|D_i^{+new} - D_i^{+old}| = \left| \sum_{j=1}^m D_{ij}^{+new} - \sum_{j=1}^m D_{ij}^{+old} \right| = |D_{ik}^{+new} - D_{ik}^{+old}| = d$$

We can conclude also that the new minimum value of D^+ decreases uniformly also with a constant distance d comparing to the old minimum value of D^+

$$|\min(D^{+new}) - \min(D^{+old})| = d$$

Thus, the old distance to the old PIA of the alternative i (e.g., R_i^{old}) is equal to the new distance to the new PIA (new R_i^{new}).

$$\begin{aligned} R_i^{new} &= \sqrt{(D_i^{+new} - \min(D^{+new}))^2 + (D_i^- - \max(D^-))^2} \\ &= \sqrt{((D_i^{+old} - d) - \min(D^{+old}))^2 + (D_i^- - \max(D^-))^2} = R_i^{old} \end{aligned}$$

This shows that the distances to the PIA of all alternatives are unchanged ($R_1 < R_2 < \dots < R_j < \dots < R_n$), and thus, the ranking order of alternatives is unchanged ($A_1 > A_2 > \dots > A_j > \dots > A_n$).

If the removed alternative includes one of negative ideal attributes, all distances D_j^- of the alternatives to negative ideal alternative will increase constantly with the same distance. As analyzed above, the distance to the PIA is also unchanged. Therefore, the ranking order of alternatives is also unchanged

The DiA algorithm is not subject to the ranking abnormality problem and outperforms TOPSIS algorithm.

In the following, we tackle the accuracy of the alternative ranking identification and we demonstrate easily that DiA provides better accuracy than SAW.

In SAW, the difference of ranking values between two alternatives (e.g., two alternatives A_k and A_t), is calculated as the subtraction of two overall score SAW_k and SAW_t .

$$SAW_k - SAW_t = \sum_{j=1}^m (r_{kj} - r_{tj}) w_j = \sum_{j=1}^m (v_{kj} - v_{tj})$$

In DiA, the difference between D_k^+ and D_t^+ is

$$D_k^+ - D_t^+ = \sum_{i=1}^m (a_i^+ - v_{ki}) - \sum_{i=1}^m (a_i^+ - v_{ti}) = \sum_{i=1}^m (v_{ti} - v_{ki})$$

The difference between D_k^- and D_t^-

$$D_k^- - D_t^- = \sum_{i=1}^m (v_{ki} - a_i^-) - \sum_{i=1}^m (v_{ti} - a_i^-) = \sum_{i=1}^m (v_{ki} - v_{ti})$$

Then

$$|SAW_k - SAW_t| = |D_k^+ - D_t^+| = |D_k^- - D_t^-|$$

The difference of ranking values in DiA is the distance between two alternatives (e.g., two alternatives A_k and A_t) calculated as follow:

$$\begin{aligned} R_{kt} &= \sqrt{(D_k^+ - D_t^+)^2 + (D_k^- - D_t^-)^2} \\ &= \sqrt{2(SAW_k - SAW_t)^2} \end{aligned}$$

We have:

$$R_{kt} > |SAW_k - SAW_t|$$

Therefore, we can conclude that the difference of ranking values in DiA is larger than in SAW.

Considering WP, it is hard to prove analytically that DiA provides better accuracy than WP. However, the simulation results presented in section 6 demonstrate that DiA outperforms WP as well as SAW.

In the following, we summarize the main steps of DiA algorithm:

- *Step 1:* Construct the normalized decision matrix R . Each element r_{ij} of the Euclidean normalized decision matrix R can be calculated as TOPSIS.
- *Step 2:* Construct the weighted normalized decision matrix. This matrix V is calculated by multiplying each column of the matrix R with its associated weight w_i .
- *Step 3:* Determine positive and negative ideal attribute values of the alternatives.
- *Step 4:* Calculate the Manhattan distance to the positive and negative attribute.

$$\begin{aligned} D_j^+ &= \sum_{i=1}^m |v_{ji} - a_i^+| \\ D_j^- &= \sum_{i=1}^m |v_{ji} - a_i^-| \end{aligned}$$

- *Step 5:* Determine the “positive ideal alternative” (PIA) which has minimum D^+ , and maximum D^- .

$$PIA = \{\min(D_j^+), \max(D_j^-)\}$$

- *Step 6:* The distance of an alternative to the PIA is calculated as follow:

$$R_i = \sqrt{(D_i^+ - \min(D^+))^2 + (D_i^- - \max(D^-))^2}$$

A set of alternatives can now be ranked according to the increasing order of R_i .

5 Performance comparison

The section presents the simulation results and performance comparison of the three MADM decision algorithms: SAW, WP, TOPSIS, and DiA. The simulations are carried out using MATLAB in the same simulation scenarios as presented in Section 2.

5.1 Simulation 1

In this simulation, we calculate the ranking order of alternatives by using the SAW, WP, TOPSIS and DiA algorithms. Table 10 presents the overall score of SAW and WP, the relative closeness to the ideal solution of TOPSIS and the distance to PIA of DiA.

The results show that the ranking order of the alternatives is the same for three algorithms SAW, TOPSIS and DiA. The ranking order is *Network_{#3}*, *Network_{#4}*, *Network_{#2}*, *Network_{#5}* and *Network_{#1}*.

The ranking order of WP is *Network_{#3}*, *Network_{#4}*, *Network_{#5}*, *Network_{#2}* and *Network_{#1}*.

As analyzed in section 3.1, WP penalizes the alternative having worse attributes than the other alternatives. Therefore, the ranking order of WP is different from SAW, TOPSIS and DiA in this case.

Table 10 - The ranking order of SAW, WP, TOPSIS, and DiA

	SAW	WP	TOPSIS	DiA
Network #1	0,154 Rank #5	0,923 Rank #5	0,052 Rank #5	0,987 Rank #5
Network #2	0,745 Rank #3	0,994 Rank #4	0,833 Rank #3	0,149 Rank #3
Network #3	0,851 Rank #1	0,998 Rank #1	0,947 Rank #1	0 Rank #1
Network #4	0,799 Rank #2	0,997 Rank #2	0,904 Rank #2	0,073 Rank #2
Network #5	0,734 Rank #4	0,995 Rank #3	0,748 Rank #4	0,166 Rank #4

5.2 Simulation 2

In this simulation, we focus on the ranking abnormality problem and the “robustness” of the algorithms regarding that the interfaces are disconnected.

We then remove one alternative (e.g., *Network_{#1}*) from the alternatives candidate list. Table 11 presents the overall score of SAW and WP, the relative closeness to the ideal solution of TOPSIS and the distance to PIA of DiA.

As analyzed in section 2, TOPSIS suffers from the abnormality problem when a removal of an alternative causes a change in the ranking order of TOPSIS. The ranking order of SAW, WP and DiA remains the same. The top ranked alternative in TOPSIS has changed (from *Network_{#3}* to *Network_{#4}*).

We continue removing one alternative (e.g., *Network_{#5}*) from the alternatives candidate list.

Table 11- The ranking order of SAW, WP, TOPSIS, and DiA

	SAW	WP	TOPSIS	DiA
Network #1	-----	-----	-----	-----
Network #2	0,455 Rank#3	0,968 Rank#4	0,397 Rank#3	0,335 Rank #3
Network #3	0,693 Rank#1	0,986 Rank#1	0,805 Rank#2	0 Rank #1
Network #4	0,651 Rank#2	0,984 Rank#2	0,856 Rank#1	0,081 Rank #2
Network #5	0,380 Rank#4	0,973 Rank#3	0,142 Rank#4	0,441 Rank #4

The results, in Table 12, show that the ranking order in SAW, WP and DiA is always stable, but the top ranked alternative in TOPSIS has changed from *Network_{#4}* to *Network_{#3}*.

Table 12- The ranking order of SAW, WP, TOPSIS, and DiA

	SAW	WP	TOPSIS	DiA
Network #1	-----	-----	-----	-----
Network #2	0,456 Rank#3	0,968 Rank#3	0,412 Rank#3	0,513 Rank#3
Network #3	0,694 Rank#1	0,986 Rank#1	0,838 Rank#1	0 Rank#1
Network #4	0,636 Rank#2	0,983 Rank#2	0,851 Rank#2	0,111 Rank#2
Network #5	-----	-----	-----	-----

The simulation results outline the ranking abnormality problem of TOPSIS and show that SAW, WP and DiA provide a more efficient behavior in this situation.

5.3 Simulation 3

In this simulation, we are motivated to measure the precision in identifying the alternative ranks of all algorithms. We compare DiA to SAW and WP by measuring the difference of ranking values of three algorithms. This difference allows distinguishing the ranking order and selecting easily the best alternative.

We consider the ranking values measured by SAW, WP and DiA in Table 12 to calculate the difference of ranking values.

Figures 12a, b and c show the difference of ranking values of all algorithms. The results outline that the difference of ranking values in SAW is larger than WP and the difference of ranking values in DiA is larger than SAW and WP.

DiA has the largest difference of ranking values and allows more accuracy in identifying the ranks between the alternatives compared to SAW and WP.

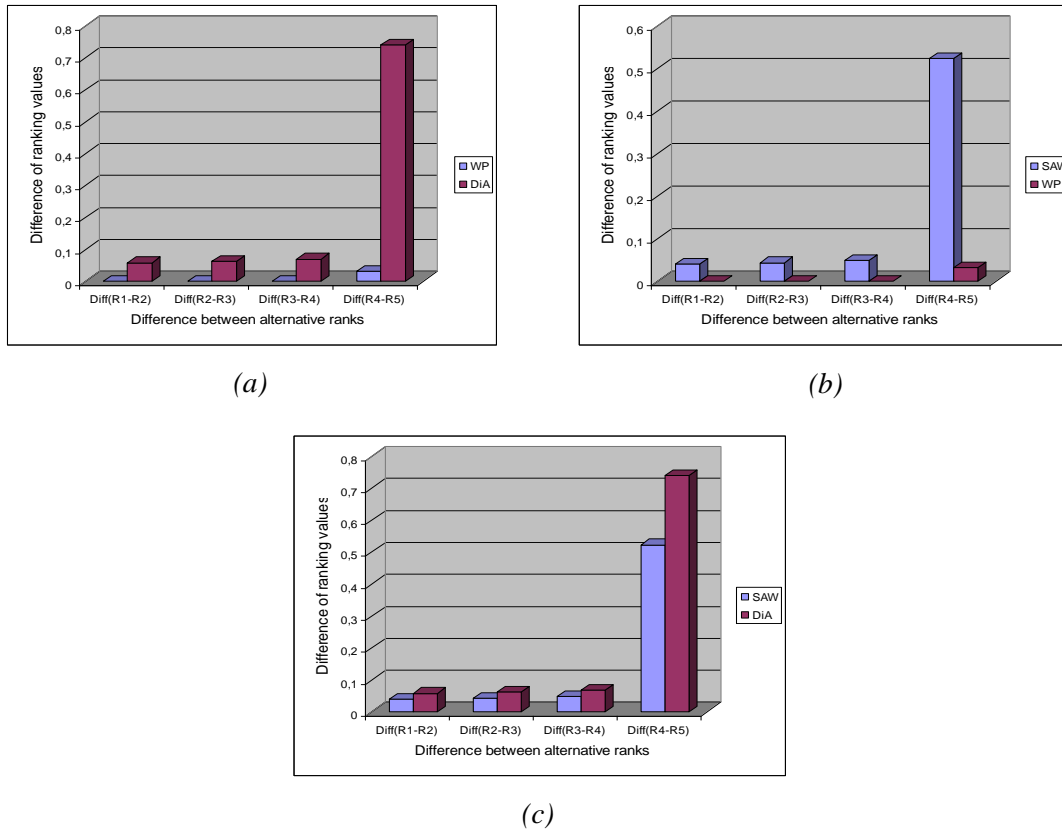
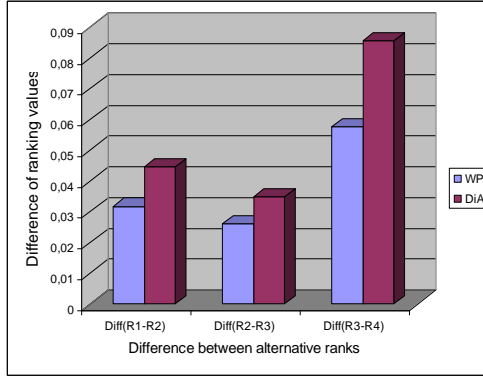


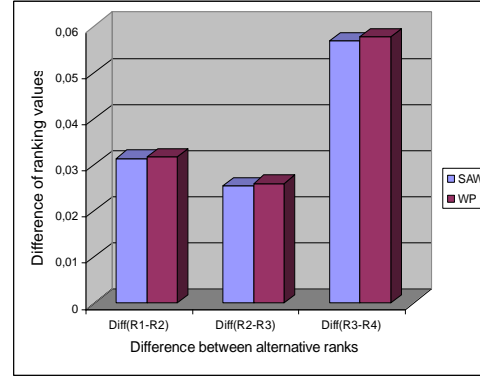
Figure 12 - The difference of ranking values of WP and DiA(a), WP and SAW(b), and SAW and DiA(c)

To provide results applicable to a wide range attribute values, we conduct a simulation considering random attribute values. We carried out a simulation scenario which is similar to section 2.2.3.

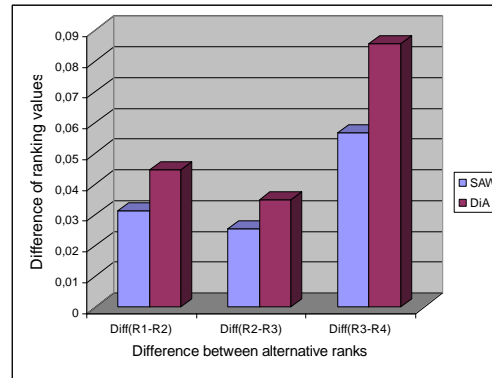
Figures 13a, b and c depict the average difference of ranking values. The results show that the same conclusion can be made. DiA is more accurate than SAW and WP, it shows a larger difference of ranking values.



(a)



(b)



(c)

Figure 13 - The difference of ranking values of WP and DiA(a), SAW and WP(b) and SAW and DiA(c)

6 Summary

In this chapter, we present a performance comparison of SAW, WP and TOPSIS methods through simulation. This study allows us to highlight and identify the limitations of each MADM algorithm influencing the decision making for interface selection.

We propose, from then, the DiA algorithm to select the best alternative (interface) basing on multiple attributes.

To avoid the limitation of TOPSIS, DiA calculates the Manhattan distance¹ (in the m-dimensional space) to the positive and negative ideal attributes instead of the Euclidean distance in TOPSIS. This allows these distances to change with a constant step when an alternative is removed out of the list of candidates. Moreover, the positive ideal alternative (PIA) which has the minimum distance to the positive ideal attribute and maximum distance to the negative ideal attribute is determined. The best “actual” alternative has the shortest distance to the PIA instead of the relative closeness to the ideal solution in TOPSIS.

Our solution improves the limits of the MADM approach, particularly SAW, WP and TOPSIS algorithms. The simulation results validated our proposal.

¹ Manhattan distance is also known as rectilinear distance, L1 distance, or city blocks distance. It is the distance between two points measured along axes at right angles.

Chapter 4: Flow/Interface Association Schemes

In this chapter, we tackle the flow/interface association issue. In this case, the mobile terminal associates each application to the suitable network interface considering mainly the application requirements.

Nowadays, mobile terminals are smaller and smaller devices. They not only integrate several network interfaces, but also run multiple applications. Meanwhile, the battery size is also reduced according to the terminal size and its life is limited. The terminals should use efficiently their energy to maintain their activities. The energy consumption is an interesting attribute to consider for the flow/interface association.

The MADM approach allows ranking network interfaces basing on multiple attributes. These attributes are presented in a MADM matrix. The attributes are usually numerical values directly related to the interface characteristics. If we consider other attributes which are not directly tied to the interface (e.g., the application requirements), we have to define a way to express these characteristics in the MADM matrix.

At the first step of this work, we propose an interface utility function which considers satisfaction level of the application and the energy consumption of the mobile terminal.

We then propose a single flow/interface association scheme which allows the mobile terminal to associate sequentially the application to the interface. The scheme considers the interface utility function as well as network attributes (i.e., access delay and cost of the network). These attributes are added to the MADM matrix. The Distance to the ideal Alternative (DiA) algorithm is used to rank the interfaces collecting the attributers from the MADM matrix.

We then aim to implement the single flow/interface association scheme on a real platform. The implementation allows to present feasibility of the scheme on a real network environment. System implementation considerations are presented highlighting requirements, challenges to implement the system.

Finally, we address the multiple flow/interface association issue. A mobile terminal running several applications can associate its application flows to networks interfaces maximizing the global terminal utility. The multiple flow/interface association is an optimization problem. In particular, it is related to stochastic heuristic optimization methods.

In this chapter, we present a simulation based comparative study of stochastic heuristic methods, in particular, Tabu search and simulate annealing algorithm. We analyze and highlight their advantages and drawbacks in our context.

We then propose an oriented diversification of the Tabu search for the multiple flow/interface association. Simulation results show that the modified Tabu search outperforms the other methods.

1 Introduction

The flow/interface association differs from the interface selection on the capacity of simultaneous use of several network interfaces and the ability of per-application interface selection. In other words, the mobile terminal can use simultaneously several available network interfaces and select the suitable interface among the available interfaces for each application.

As presented in Chapter 2, for the flow/interface association, we consider two main models: single and multiple flow/interface association models.

The single flow/interface association model allows the mobile terminal to associate sequentially an application to an interface while maximizing the satisfaction level of the application.

In the multiple flow/interface association model, the terminal associates simultaneously different applications to the network interfaces at each association epoch. The association decision aims at maximizing the global satisfaction of the terminal rather than the satisfaction level of each application. The association epoch is defined as the moment that the terminal makes decision and then realizes the association. The terminal re-considers its decision at each association epoch.

As presented above, the application requirements are considered as the primary attribute in the flow/interface association. Other attributes however are also taken into account.

Mobile terminals (e.g., smart phones, PDAs ...) nowadays have multiple functionalities. They are able to run simultaneously several applications such as file download (FTP), voice service, video streaming, IP telephony, etc. Each application has different characteristics and requirements.

Additionally, mobile terminals are smaller and smaller devices with limited battery life. With the progress and rapid increase of wireless and mobile technologies, mobile terminals may also integrate many network interfaces using different technologies. Each network interface has different characteristics, particularly, in term of energy consumption. The minimization of the battery according to the terminal size limits the battery life. The energy consumption is therefore considered as an interesting attribute for the flow/interface association.

Moreover, we also consider the characteristics of the network. These attributes are very different depending on specific radio access networks, for example, the signal quality (RSS, CIR (Carrier to-Interferences Ratio), coverage area), the quality of service (available bandwidth, jitter, bit-error rate, packet loss ratio, etc.) and monetary cost of using network, etc. It is difficult to consider all of these attributes for the flow/interface association. We consider the available bandwidth, access delay and monetary cost of using network as the network side attributes for the flow/interface association scheme consider. The available bandwidth is weighted as the most important because the satisfaction level of the application is an important aspect in the flow/association issue. The access delay and the monetary cost of using network are then considered by setting the weight less priority than the available bandwidth.

2 Single flow/interface association scheme

2.1 Motivation usage case

As an illustration, let consider a mobile terminal integrating two network interfaces and a voice service of 64Kbps. We assume that the available bandwidth on the first interface is about 1Mbps (e.g., using Wi-Fi technology) and the second one is about 300 Kbps (e.g., using WiMAX technology). Basically, the two interfaces satisfy the application requirements. However, the energy consumption for data transmission on the WiMAX interface is higher than the Wi-Fi interface.

If the WiMAX interface is selected, the application would satisfy the application requirements but consumes much energy. However, mobile terminals depend strongly on the battery power. It is thus important to minimize the energy consumption. The selection of the Wi-Fi network interface is more suitable in this example.

The second motivation is that the selected interface not only assures the application requirements and the terminal capacity but can also consider the network side attributes such as access delay and cost of using the network. For example, if a number of interfaces satisfy the application requirements, it could be interesting for the user to select the cheapest network interface for his application and the network which allows a rapid connection.

2.2 Related work

In chapter 2, we presented a state of the art related to interface selection and flow/interface association issues.

In this section, we summarize the works that focus on multiple attributes decision making problem and per-application interface selection.

We presented in the previous chapter the drawbacks of the MADM and propose the DiA algorithm as a new MADM method for the interface selection [Tran01] [Tran02]. Additionally, as mentioned above, the MADM attributes are added into a MADM matrix. These attributes are directly related to the interface characteristics and expressed as numerical values. If we want to consider other attributes such as the application characteristics for the MADM problems, we need to express these characteristics by another way (e.g., a mathematical function) and then add the values into the MADM matrix.

In [Suciu01] and [Suciu02], a utility based method is defined considering the application requirements. The utility function considers many parameters such as bandwidth, delay, and security level to represent the application requirements. The utility function scores each interface by comparing the application requirements parameters to the network resources. This determines the satisfaction level of the application for each interface.

For example, the utility function of interface i and application j is described as follow:

$$U_{ij} = [\ln|B_i - b_j| + \ln|e_j - E_i| + \ln|d_j - D_i| + \ln|S_i - s_j|]$$

where,

B_i, E_i, D_i, S_i are respectively the mean available bit rate, the monitored packet error rate, the average delay and the security level of accessing network i .

b_j, e_j, d_j, s_j are respectively the minimum necessary bit rate, the supported packet error rate, the maximum tolerated delay and the required security level for application j .

In this scheme, the utility values (scores) change with the variation of the network resources. This can cause a Ping-Pong effect [Yu] which leads the selection mechanism to switch frequently from one interface to another whenever the network resources change significantly (even if the current selected interface also satisfies the application requirements).

In [Ormond], the authors propose a user-centric network selection solution that allows associating a non real-time application to the suitable interface based on a utility function. In this work, the utility function uses the notion of consumer surplus which is largely used in microeconomics. The consumer surplus is the difference between the monetary value of the data to the user and the actual price charged for transferring the data. The strategy aims at maximizing the consumer surplus while meeting user defined constraints in term of transfer completion time. This scheme is specifically designed for non real-time applications (e.g., FTP application) and is not appropriate for other types of application, e.g., a real-time traffic with more delay constraints.

2.3 Interface Utility Function

With the motivation to consider the application requirements and the terminal energy consumption, we propose an interface utility function. The application utility function depends on the available bandwidth. The energy consumption function expresses the energy consumption by bit transmitted.

2.3.1 The Application Utility Function

We describe the utility function that determines how the satisfaction of the application changes with the amount of bandwidth it receives.

Based on the analysis of [Baghaei][Fitzek][Eskeda][Shenker][Suciu01][Breslau][Rakocevic] and [Suciu02], each type of application has specific requirements in terms of bandwidth (b_{req}) (see Table 13).

For each type of application, a specific utility function is defined. We focus on three types of applications based on the analysis in [Shenker][Breslau][Rakocevic].

Table 13– The application requirements in terms of bandwidth

Application type	Example	Service class	Necessary bandwidth (b_{req} or b_{avg})
Hard-Real time	PCM VoIP	Conversation	64 kbps
Hard-Real time	H.323 VoIP	Conversation	20 kbps
Adaptive	CD-like Audio	Streaming	150 kbps
Adaptive	MPEG4 Video	Streaming	2000 kbps
Elastic	SSH, Instant Messenger, HTTP	Interactive	limitless
Elastic	FTP, Email	Background	limitless

The first type is the hard real-time applications which need its data to arrive within a given delay bound. Examples of such applications are traditional telephony applications. These applications that are designed to be transmitted at a fixed rate (b_{req}) have a mathematical utility function and shape as shown in Figure 14.a.

The second type is the rate-adaptive or delay-adaptive applications such as video, voice, streaming applications which are more tolerant to occasional rate delay bound violations and dropped packets. This type of application may be represented by the mathematical function and unified model as shown in Figure 14.b. Note that ϕ is a constant which expresses the convergence speed of the exponential function.

In Figure 14b, b_{avg} is a point of inflexion of the application utility function. It denotes the average rate of the adaptive application. The utility function is convex in the range $[0, b_{avg}[$ and concave in the range $[b_{avg}, \infty[$. For streaming adaptive applications, for example, at small bandwidth, the marginal utility is very slight. The application is not satisfied with the allocated bandwidth. It, however, changes significantly, when the available bandwidth is around its average rate. The adaptive applications then are almost completely satisfied when the allocated bandwidth up to peak rates of applications (i.e., $U=1$). For simplicity, we do not consider the application utility in the range $[0, b_{avg}[$ by setting $U=0$. Otherwise, the utility changes according to a concave function in the range $[b_{avg}, \infty[$.

The third type is elastic applications which are the traditional data applications such as electronic mail, remote terminal access, and file transfer. The mathematical utility function and shape of elastic application could be as shown in Figure 14.c. The utility function is a concave function in the range $[0, \infty[$.

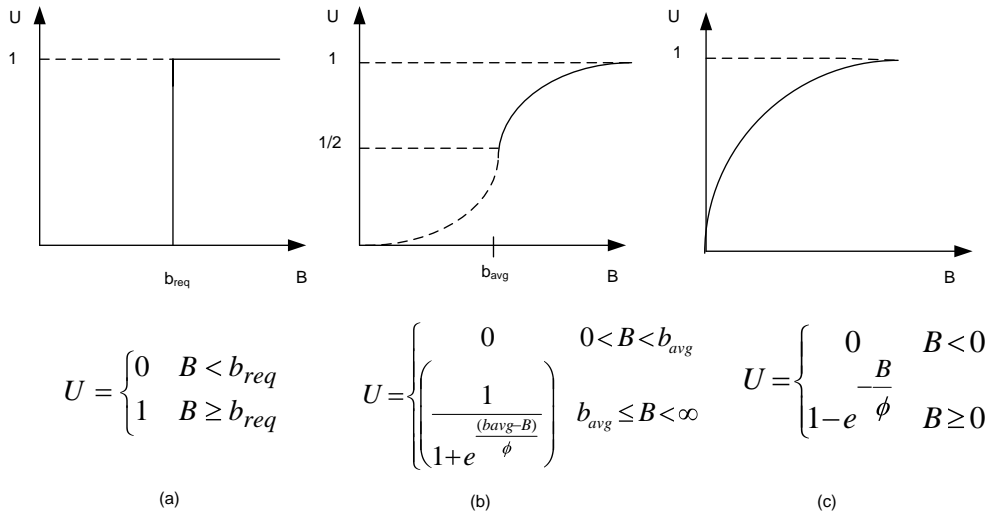


Figure 14– The application utility functions

2.3.2 The Battery Consumption Function

Each interface has specific characteristics in terms of energy consumption depending on the hardware characteristics.

The battery consumption of each interface for transmitting N bits is a function of the energy consumption for transmitting one bit on the interface and the volume of data (N bits) transferred by the interface. In our experiment, the data volume is evaluated according to the application type. It depends on the available bandwidth for the elastic and the rate/delay-adaptive applications and the required bandwidth for hard real-time applications.

2.3.3 The Interface Utility Function

The interface utility function is defined to describe the satisfaction of the application and the energy consumption of the mobile terminal.

U_{ij} represents the satisfaction level of application j when selecting the interface i . Q_{ij} represents the battery consumption when the application j uses the interface i . The interface utility for the application j using the network interface i is described as follows:

$$\begin{bmatrix} I_{1j} \\ \vdots \\ I_{nj} \end{bmatrix} = \alpha_j \begin{bmatrix} U_{1j} \\ \vdots \\ U_{nj} \end{bmatrix} + \beta_j \begin{bmatrix} Q_{1j} \\ \vdots \\ Q_{nj} \end{bmatrix}$$

U_{1j}, \dots, U_{nj} are the normalized application utility values.

Q_{1j}, \dots, Q_{nj} are the normalized battery consumption values.

I_{1j}, \dots, I_{nj} are the utility values of the interface $1^{\text{th}}, \dots, n^{\text{th}}$, respectively.

α, β are the weights which indicate the relative importance between the application utility and the battery consumption. Different decision makers may set different values of α and β depending on their own strategy.

2.4 Utility-based flow/interface association scheme

When initiating an application and having several available network interfaces, the terminal firstly filters and selects the network interfaces satisfying the application requirements. These interfaces are considered as the candidates for the application. The scheme then calculates the interface utility as presented above. The selection decision is based on multiple attributes: the interface utility value, but also access delay and cost of using the network. In the scheme, we use DiA to rank the interfaces according to the attributes above. The scheme associates the application to the interface having the best rank.

The utility-based flow/interface association algorithm is illustrated in Figure 15.

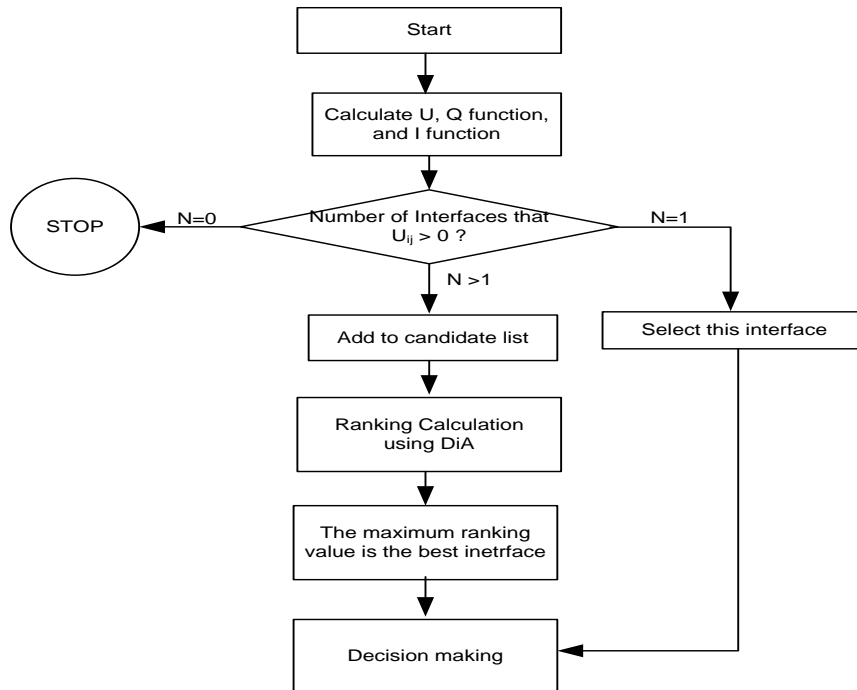


Figure 15– The decision strategy

At first, the algorithm calculates the application utility (U_{ij}), the battery consumption (Q_{ij}) and the interface utility (I_{ij}) of the interface i for the application j .

Second, the algorithm verifies the number of the interfaces (N) for which the application utility is positive (U_{ij})

- If $N=0$: STOP . No interface is selected.
- If $N=1$: Decide to select this interface.
- If $N>1$: Add the interfaces into the candidate's list.
 - Add the interface utility values I_{ij} into the MADM matrix.
 - Add the considered network side attributes to the MADM matrix.

Third, the algorithm uses DiA to rank the interfaces according to the interface utility values and the network attributes in the MADM matrix and decides to select the interface having the maximum ranking value.

In Chapter 3, the distance to the ideal alternative (DiA) algorithm is proposed to rank the network interfaces.

Note that our interface selection scheme uses a user-centric decision approach. The mobile terminal makes the selection basing on the information (network attributes) broadcasted by the network.

2.5 Performance Evaluation

2.5.1 Simulation scenarios

To validate the proposed scheme, a simulation model is developed using a mobile terminal integrating three access network interfaces: Wi-Fi 802.11b, Wi-Fi 802.11a, and WiMAX 802.16a. Their average energy consumption is $1\mu\text{J/bit}$, $3\mu\text{J/bit}$ and $20\mu\text{J/bit}$, respectively.

Table 14- The characteristics of the network at each discrete time t_k

802.11b	t_0	t_1	t_2	t_3	t_4
BW(kbps)	800	100	100	450	100
D(ms)	150	100	180	115	100
CB (cent/byte)	1	1	1	1	1

802.11a	t_0	t_1	t_2	t_3	t_4
BW(kbps)	100	800	300	300	700
D(ms)	150	120	100	80	100
CB (cent/byte)	1	1	1	1	1

802.16a	t_0	t_1	t_2	t_3	t_4
BW(kbps)	1000	1200	1200	400	1000
D(ms)	200	200	180	180	180
CB (cent/byte)	1.5	1.5	1.5	1.5	1.5

The considered network side attributes are: the available bandwidth (BW), access delay (D), and cost (CB) per byte for each network. Furthermore, we assume that the

characteristics of the access network evolve over time as in Table 14. This table presents the characteristics of the access network at each discrete time t_k .

In addition, we consider three application flows: elastic application (FTP flow), rate-adaptive application (CD-like audio streaming flow) with an average rate of 150 Kbps and hard-real-time application (PCM VoIP flow) which requires 64 Kbps.

In the simulation, we calculate the ranking order of the interfaces using the proposed interface selection scheme and compare it to the ranking order proposed by the MADM methods (e.g., the SAW method) and the utility based method described in [Suciu01] and [Suciu02] (that it is called in the following, Suciu-utility based method). As mentioned previously, this method defines the utility function as a logarithm function of the application requirements in terms of bandwidth (e.g., $U = \ln |BW_{req} - BW_{net}|$).

The following weight vector is used to compare the interface utility to the other network side parameters. This weight vector is also used for the MADM-based method.

$$w = [0.5 \ 0.25 \ 0.25]$$

The simulations are carried out using MATLAB.

2.5.2 Simulation cases:

2.5.2.1 Case 1:

At t_0 , the mobile terminal initiates a FTP application. Figure 16 shows simulation results. The MADM-based and the Suciu-utility based methods determine that 802.16a is the best interface. Our interface selection scheme determines that 802.11b is the best interface for this application.

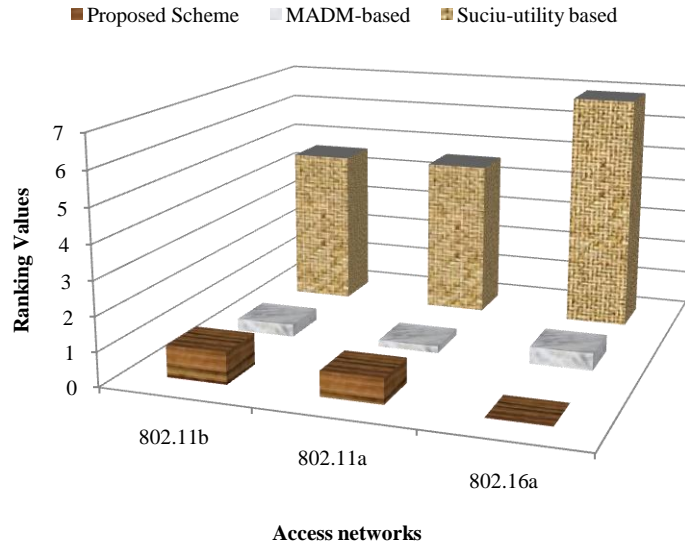


Figure 16– The ranking values for all methods.

By analyzing the weight vector, the decision of the MADM-based and the Suciu-utility based methods aims at maximizing the available bandwidth while the proposed scheme considers the interface utility as the high priority parameter. The 802.16a interface is selected by the MADM-based and the Suciu-utility based methods since this interface offers the highest available bandwidth. The interface utility of the proposed scheme considers not only the satisfaction of the application in terms of the bandwidth but also

the lowest energy consumption. 802.11b satisfies both these conditions. It is thus selected.

2.5.2.2 Case 2:

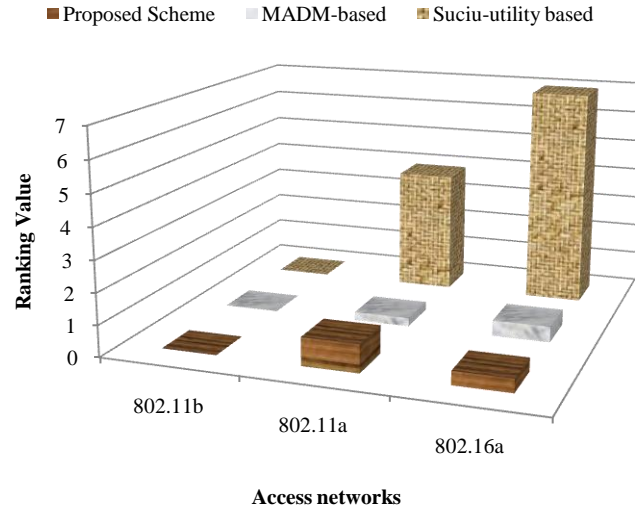


Figure 17– The ranking values for all methods

At t_1 , the terminal initiates CD-like audio streaming application with the average rate of 150 Kbps. The simulation results are presented in Figure 17. The MADM-based and the Suci-utility based methods determine that the 802.16a interface is always the best interface since the available bandwidth of this interface is higher than the other interfaces. The proposed scheme determines that 802.11a is the best interface for this application.

The 802.11b interface which does not satisfy the application requirements is eliminated. The 802.16a and 802.11a interface satisfy the application requirements, the 802.16a interface however consumes much more energy than the 802.11a interface.

2.5.2.3 Case 3:

At t_2 , the terminal initiates a PCM VoIP flow requiring with an average rate of 64 kbps. Figure 18 shows the simulation results.

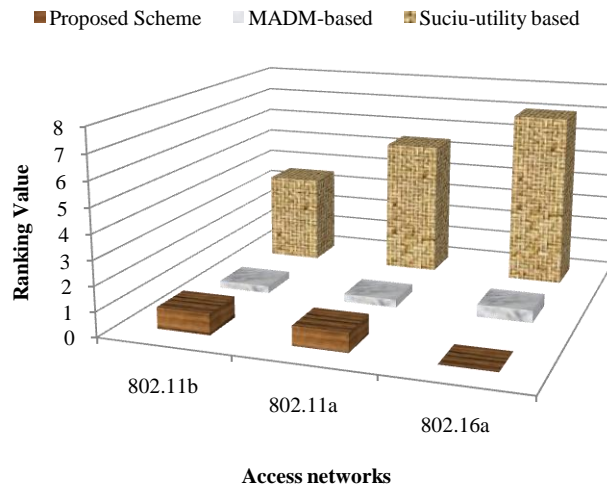


Figure 18– The ranking values for all methods.

The MADM-based and the Suciutility based methods determine that the 802.16a interface is always the best interface. The proposed scheme determines that the 802.11b interface is the best interface for this application.

For the hard-real time application, the three interfaces satisfy the application requirements. They have the same maximum application utility (U_{\max}) in this case. The interface utility of 802.11b is the highest one since it has the lowest energy consumption (see Table 4.2, and 4.3). DiA decides to select the 802.11b interface in this case.

2.5.2.4 Case 4:

At t_3 , we consider the CD-like audio streaming flow and a specific case where the available bandwidth of the 802.11a interface is greater than that of 802.16a. Using MADM and Suciutility methods the application flow is switched to the 802.11a interface. The simulation results in Figure 19 represent the new ranking order of the interfaces for the CD-like audio streaming flow. The MADM-based and the Suciutility based methods determine that the 802.11a interface is the best one. The decision of the proposed scheme is unchanged.

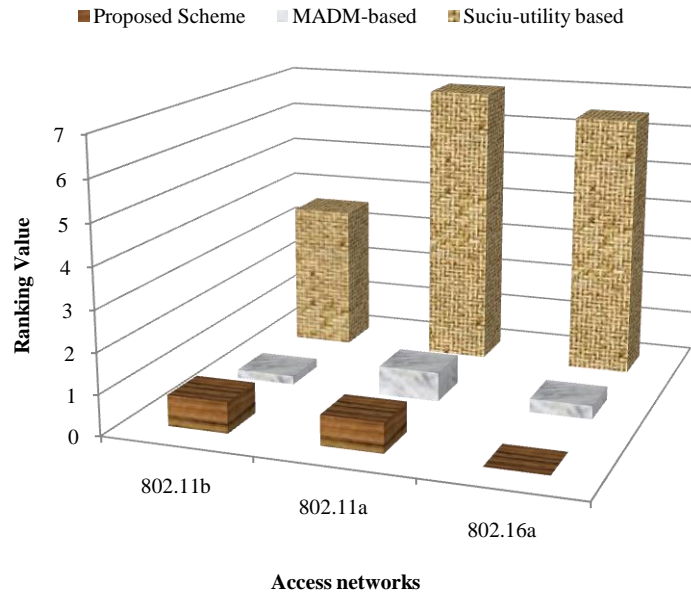


Figure 19– The ranking values for all methods.

2.5.2.5 Case 5:

At t_4 , the available bandwidth of the 802.11a interface is lower than that of 802.16a. The application flow is switched to the 802.16a interface when using the MADM-based and the Suciutility based methods. The decision of the proposed scheme is unchanged.

In the simulations above, with the considered weight vector, the MADM-based and the Suciutility based methods aim at maximizing the available bandwidth. The proposed interface selection scheme aims at maximizing the interface utility which is function of the available bandwidth and the energy consumption of the interface. The goal of this function is to find the interface which satisfies the application requirements and has the lowest energy consumption for this application.

In addition, the MADM-based and the Suciutility based method suffer from the Ping-pong effect. When the network resources (e.g., the available bandwidth) change significantly the application is switched frequently among the interfaces (case 4 and case 5). Contrariwise, the proposed scheme avoids the Ping-pong effect comfortably by

switching the interface only when it cannot satisfy the application requirements and the battery consumption.

3 Implementation considerations

In this section, we aim at showing the feasibility of the proposed scheme on a real network environment.

Several elements have to be considered for the system implementation.

Collection of information about the state of the network is very important. One of the challenges is how to collect the necessary information.

Our scheme considers the available bandwidth, the access delay and the monetary cost of using network as network side attributes. Among these attributes, and the monetary cost attributes are static information. The available bandwidth, the access delay attributes are dynamic information and varies in time. Another challenge is how to measure and update in real-time the available bandwidth of the networks.

3.1 Basic concept of IEEE 802.21

At the first step, we consider the IEEE 802.21 (Media Independent Handover - MIH) as a mean for providing the necessary information of the flow/interface association scheme.

The main purpose of IEEE 802.21 is to enable handovers between heterogeneous technologies (including IEEE 802 and non-IEEE). The requirements for providing session continuity depend on complex interactions that are specific to each particular technology. IEEE 802.21 provides architecture to enable low-latency handover across multiple technology access networks, functions for gathering network characteristics and necessary information to make handover decision. A set of command procedures is proposed for seamless handovers, supporting both terminals initiated and network initiated handovers. IEEE 802.21 provides a framework that allows higher levels to interact with lower layers to provide session continuity without dealing with the specifics of each technology

3.2 System implementation

3.2.1 Architecture

In this section, we present architecture for the flow/interface association.

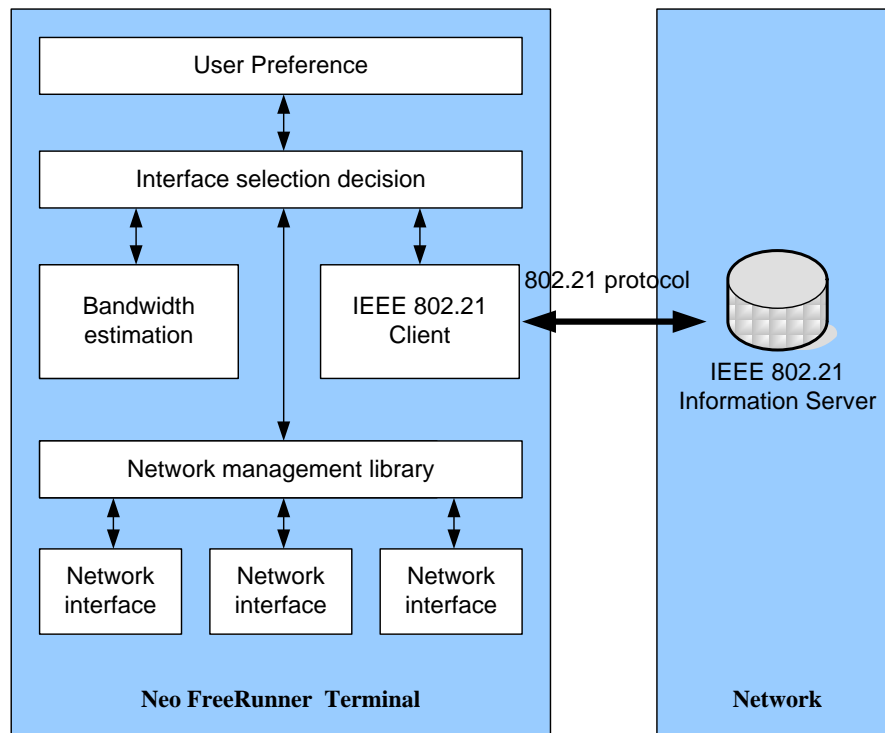


Figure 20- System implement architecture

The architecture includes the following components:

3.2.1.1 Multi-interface mobile terminal

We choose Neo FreeRunner terminal (see Figure 22) for the system implementation according to the orientation of the 3MING project [3MING]. It is a smart phone designed with high resolution touch screen 2.84" (43mm x 58mm) 480x640 pixels, 128MB SDRAM memory, 256 MB integrated flash memory (expandable with microSD or microSDHC card), Bluetooth, 802.11 b/g Wi-Fi, 400Mhz ARM processor, Tri-band GSM and GPRS, USB Host function with 500mA power, allowing to power USB devices for short periods. The Neo FreeRunner is designed to run Openmoko software which is able to run applications developed on Linux. Using Debian Linux as base for the operating system has immediately a choice of several software packages (more than 16000 packages) ready for installation.



Figure 21 – The Neo FreeRunner mobile terminal

3.2.1.2 User preference

This module allows the users defining their own decision objectives. A graphical user interface (GUI) is developed in order to allow users to define weight vector influencing the interface selection decision.

3.2.1.3 IEEE 802.21 client

We adopt the IEEE 802.21 implementation developed by Alcatel-Lucent [3MING]. The 802.21 client retrieves information from the 802.21 MIH servers via MIH messages (commands and information services) defined in the IEEE802.21 MIH protocol [802.21].

3.2.1.4 Network manager library

The Network Manager package is one of in-built libraries used in open-source operating systems (i.e., Ubuntu, Fedora, etc). The network manager controls and inspects the network interfaces in the computers. It becomes a handy tool for application developers as it allows them to utilize the features of Network Manager with the knowledge of DBUS (a message bus that allows applications to talk to each other).

Figure 23 presents diagram of Network Manager where it is located in the operation system. The application user can use it. Network Manager interacts to various network devices (i.e., Hardware Abstraction Layer (HAL)), and provides the ability for applications to learn about existing and new hardware. Network Manager queries HAL at startup to learn what network interfaces are available. Any change in network hardware and link information is detected by HAL, and this information is immediately relayed to Network Manager.

All this information can reach the user via DBUS. Network Manager uses D-BUS to interact with other applications. Using D-BUS allows for the flexibility of a standard interface while also including built-in security.

D-BUS is used internally for communication between:

- Network Manager daemon and Network Manager Info
- Network Manager Info and Network Manager Notification
- Network Manager daemon and HAL

Externally, Network Manager uses D-BUS to broadcast information about various state changes (new access points, signal strength connection details etc...). Thus, as an application developer we used DBUS message bus to retrieve all the useful information needed by our application. The role of DBUS in our project is to deliver the network parameters to the user.

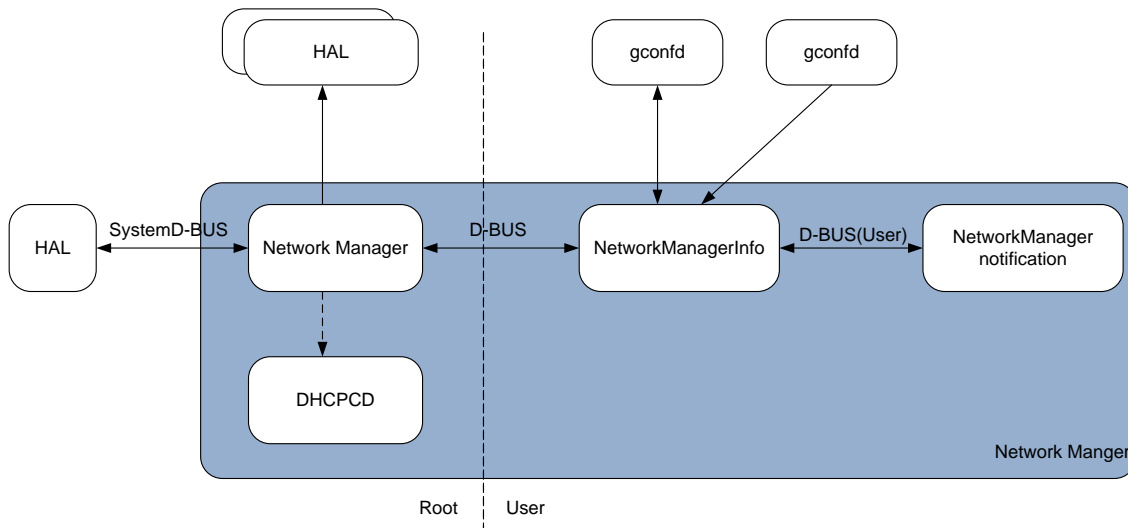


Figure 22 – The network manager

3.2.1.5 Bandwidth estimation module

IEEE 802.21 and the network manager library allow obtaining information related to network and interface characteristics. However, there are some parameters which cannot be directly obtained, that do not have any source. These parameters are delay, available bandwidth. The bandwidth estimation module allows getting this goal.

Bandwidth estimation issue is a grand topic that has been investigated for a long time. Due to the multitude of potential applications, a large number of solutions have been proposed and evaluated. We can find a rich literature of techniques [Akella] [Cabellos] [Croke] [Dovrolis] [Ekelin] [Hu] [Neginhal] [Ribeiro] [Strauss] [WangQ] for measuring the available bandwidth.

Generally, the bandwidth estimation tools consider the cooperation of the two hosts at the end to end path to be measured. One host plays a role as a sender and other as a receiver. The sender sends a number of probing packets through the network path towards the receiver. When the probing packets arrive at the receiver, the probing packets are captured and some predefined metrics are computed. Considering that the characteristics of the packets transmitted by the sender (rate, size, etc.) are predefined, the receiver analyzes such metrics and estimates the available bandwidth of the path.

Typically, existing tools are based on one or more of the following estimation metrics:

- *Latency*, either in terms of One-Way Delay (OWD), i.e. the time needed for the transmitted packets to reach the receiver, or in terms of Round-Trip-Time (RTT), when a received packet is expected to generate an answer from the receiver back to the sender.
- *Rate* is defined as the number of Bytes received per unit of time.

- *Inter-Packet Gap (IPG)*, which is the time interval between the receptions of two consecutive packets.
- *Jitter*, which measures the variability of the latency over time.
- *Loss*, the number of transmitted packets which were never received.

The bandwidth estimation tools could be classified into the following categories:

Variable Packet Size

The Variable Packet Size (VPS) technique aims at measuring the link capacity of the path. It was first described by [Bellovin] and used in tools like pathchar [Jacobson], clink [Downey] and pchar [Mah]. The key element of the technique is to measure the RTT from the source to each hop of the path as a function of the probing packet size. For a generic link of capacity C_i , a probing packet size L , the transmission delay is calculated as L/C_i . VPS uses the Time-To-Live (TTL) field of the IP header to force probing packets to expire at a particular hop. The router at that hop discards the probing packets, returning ICMP “Time-exceeded” error messages back to the source. The source uses the received ICMP packets to measure the RTT to that hop. However, when queuing delays occurs in the buffers of routers or switches, VPS can suffer from error propagation. Therefore, in order to obtain delay samples unaffected by cross-traffic, a large number of probing packets must be sent and only the minimum delay is considered.

Packet Pairs

The Packet Pair (PP) technique measures the bottleneck capacity of a path. When two packets are sent consecutively within an interval of time, i.e., one after the other, they will be received at the end of the path spaced in time. The spacing (or dispersion) between the packets is inversely proportional to the capacity of the bottleneck link. The PP technique is implemented for example in bprobe [Crovella], Nettimer [Lai], SProbe [Saroiu], pathrate [Dovrolis02] and CapProbe [Kapoor] .

Packet trains: Average Dispersion Rate

Packet trains technique injects a number of packet trains into the network. The dispersion mean values of the probe packets at the receiver side are then calculated to estimate the available bandwidth.

For example, a host sends L probing packets of size S to receiver. At the receiver, the Average Dispersion Rate (ADR) is defined in [Dovrolis02] as $R = (L-1)S/\Delta$, where the dispersion Δ is the time between the arrival of the first and the last packet of the train. The ADR will be equal to the capacity. ADR estimations are used in pathrate [Dovrolis02] and pathload [Dovrolis] .

These existing tools have very different characteristics and make use of various probing strategies, inference metrics and algorithms.

However, they pose several problems. Most of these tools need to be installed on all end-hosts of the paths to be measured. This lacks the usability of these tools because the end-hosts usually belong and are controlled by different organizations or domains.

Moreover, existing techniques ignore considerations of characteristics of the different physical and MAC layers of the links traversed. Finally, when these techniques are deployed at large scale, different hosts may interfere with each other. Therefore, it is difficult to know how much the different existing techniques are affected by interference and this may influence to network performance.

Available bandwidth estimation is a big issue and really a grand challenge for the implementation of the flow/interface association system. A deep investigation should be carried out to select a suitable tool for the flow/interface association or some tools need to be modified to adapt to the flow/interface selection context.

3.2.1.6 Interface selection decision

This module implements the DiA algorithm to rank the network interfaces.

3.3 Parameters Fetching

The network selection algorithm needs information regarding bandwidth, power consumption, delay and cost of a particular interface. However, more information could be added in the MADM matrix to provide a more decision objectives.

Table 15 presents a summary of some important parameters to be considered by the interface selector and the possible source of this information.

Table 15 presents important network parameters. There are some parameters which cannot be directly obtained, that do not have any source. These parameters are delay, power consumption and available bandwidth.

The specific cases of bandwidth and delay will be dealt with in the section 3.2.15.

Power consumption is a parameter which is difficult to find directly. However, the a good estimation can be made based on parameters such as transmitting power and bit rate of a wireless NIC along with the manufacturer information.

Linux packages like *iwconfig* and *aircrack-ng* allows the user to collect information regarding the *tx_power* and bit rate. For future work, these tools could be studied in order to see how these parameters are obtained and include them in the interface selector decision making.

Table 15 - Summary of some considered important parameters

Parameter	Source	Type	Primitive	Description
Available networks	Network Manager	Dynamic	NetworkManager.Device.Wired Carrier	Indicates whether the physical carrier is found (e.g. whether a cable is plugged in or not).
		Dynamic	NetworkManager.Device.Wireless GetAccessPoints ()	Get the list of access points visible to this device of the 802.11 family
		Dynamic	NetworkManager.AccessPoints SSID Frequency Mode	A number of physical and security parameters of the access points detected by the Wireless NIC.
	IEEE 802.21	Dynamic	MIH_MN_HO_Candidate_Query	Query of QoS and IP parameters of candidate networks for a possible handover.
		Static	MIH_Get_Information IE_CONTAINER_LIST_OF_NETWORKS IE_NETWORK_TYPE IE_OPERATOR_ID	List of neighboring Access Network Containers, containing information that depicts a list of heterogeneous neighboring access networks for a given geographical location.
Available interfaces	Network Manager	Dynamic	NetworkManager GetDevices()	Lists the interfaces (MAC addresses) that are turned on.
		Dynamic	NetworkManager.Device.Wired HwAddress	Hardware address of the wired device (e.g. Ethernet NIC)
		Dynamic	NetworkManager.Device.Wireless HwAddress	The hardware address of the wireless device (e.g IEEE 802.11 family)
		Dynamic	NetworkManager.Device.Bluetooth HwAddress	The hardware address of the bluetooth family device
QoS parameters	IEEE 802.21	Dynamic	MIH_Link_Get_Parameters	Get the status of a particular link. A list of measurable link parameters and their current values. The parameters given are not specified by the standard.
		Static	MIH_Get_Information IE_CONTAINER_NETWORK IE_NETWORK_QOS	QoS characteristics of the link layer. The specific parameters are not defined in the standard.
Throughput	Network Manager	Static/Dynamic	NetworkManager.AccessPoint.Max Bitrate NetworkManager.Device.Wireless. Bitrate	The maximum bitrate this AP is capable of, in kilobits/second (Kb/s) and The bit rate currently used by the wireless device, according to the type of network and modulations scheme. These are binary values not precise.
	Investigation	Dynamic	Aircrack-ng package of Linux. The tool must be developed.	By listening to the beacon messages of wifi APs, a throughput approximation can be made for all the networks detected by a Wireless NIC without need to authenticate.
	IEEE 802.21	Static	MIH_Get_Information IE_CONTAINER_NETWORK IE_NETWORK_DATA_RATE	Data Rate. The maximum value of the data rate supported by the link layer of the access network.
Power consumption	Investigation	Static/Dynamic	TX power is available through iwconfig	Estimation may be based on TX power, bit rate and type of interface.
Cost	IEEE 802.21	Static	MIH_Get_Information IE_CONTAINER_NETWORK IE_COST	Indication of cost for service or network usage.
Delay	Investigation	Dynamic	Using Aircrack-ng	
BER	Investigation	Dynamic	Using Aircrack-ng	
Jitter	Investigation			

3.4 Conclusions

In this section, we aim to study the IEEE 802.21 to support the information collecting for the flow/interface association. We provide the objective and the considerations of the system implementation.

At the first step, we worked on the Network Interface Selector and the Network Parameter Retriever components. We first implement the DiA algorithm and study the way to integrate it in Neo FreeRunner terminal.

Then, we determined the required network parameters and the way in which we can get each parameter (either from Network Manager or from IEEE 802.21 using Alcatel-Lucent 802.21 implementation). Some parameters can be directly obtained by these two sources. Others should be indirectly obtained by using another ways of estimation, especially for the available bandwidth.

Afterwards, we implemented a program in C linux to retrieve some useful parameters from Network Manager using the DBUS API. Future work will consist in integrating Alcatel's 802.21 client, server and database to our code, choosing and implementing tools for available bandwidth, delay, power consumption and error rate estimation; integrate both codes in Neo FreeRunner terminal and test the whole system on Alcatel's network.

4 Multiple Flow/Interface association scheme

The proposed multiple flow/interface association scheme is presented in this section. This scheme allows associating simultaneously several applications to the network interfaces while maximizing the terminal global utility.

4.1 Model Description

Consider a multi-interface terminal is in coverage zones of N network cells. Using the suitable network interfaces, the terminal is able to fully benefit from the set \mathcal{C}_N of the available network cells. More specifically, running multiple applications $A = (a_0, a_1, \dots, a_{K-1})$, the terminal may have a set of association options $S = (s_0, s_1, \dots, s_{(N^{K-1})})$ to associate its applications to the different interfaces.

Each association option allows a set of applications $A = (a_0, a_1, \dots, a_{K-1})$ connecting to different interfaces. Note that several applications can connect to the same interfaces.

For example, an association option s_i allows application a_0 connecting to interface C_1 , application a_1 connecting to interface C_2 , application a_2 connecting to interface C_2, \dots , and application a_i connecting to interface C_N , etc.

For each association option s_i , the terminal obtains a utility value denoted by $U_i(s_i)$ (e.g. see Figure 20).

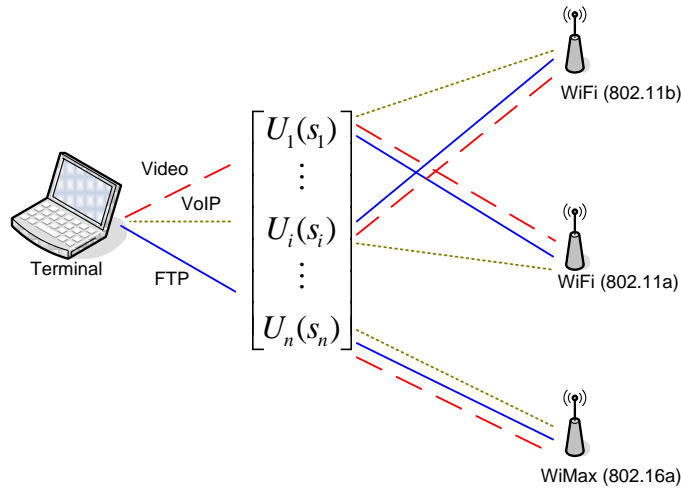


Figure 23- The flow association model example

Consider an association option $s_i \in S$ and an application $a_l \in A$, the association option s_i allows the application a_l connecting to the network C_j . Let L_{j,a_l} be the satisfaction level of application a_l associated to network C_j . Let Q_{j,a_l} be the battery consumption when the application a_l uses the interface C_j . The interface utility for the application a_l using the network interface C_j is described as follows:

$$U_{s_i,a_l} = \alpha_j L_{j,a_l} + \beta_j Q_{j,a_l}$$

where α, β are the weights which indicate the relative importance between the application utility and the battery consumption.

The obtained terminal utility using an association option s_i is calculated as follow:

$$U_i(s_i) = \sum_{l=0}^{K-1} U_{s_i,a_l}$$

The selected option should maximize the global utility of the terminal:

$$\max_i U_i(s_i)$$

The utility function U is the objective function where the association option s is the variable. The multiple flow/interface association decision is an optimization problem.

Optimization theory [Bazaraa][Bertsekas][Minoux] has been widely developing in many fields during the last few decades. We have encountered a rich literature of optimization theory. New theories, algorithms, and computational contributions of optimization have been proposed to solve various types of difficult problems in science and engineering.

In our context, the objective function is a discrete function. The function variation cannot be determined. This problem does not belong to classical optimization problems where the optimal solution is found by derivative calculation.

The mobile terminal aims at seeking an association option maximizing the global utility of the terminal. A trivial way is that the terminal searches in global space of the association options to find out the optimal solution. However, this poses a complexity problem.

We aim to consider probability of global optimum identification with a limited search space. In other words, we consider the probability to find an association option which maximizes the global terminal utility. Our problem is related to stochastic heuristic optimization problems.

4.2 Basic concepts of stochastic heuristic problems

The optimization problems aim to choose of a best configuration of a set of variables to achieve certain goals.

In this section, we focus on the stochastic heuristic problems that generally maximize or minimize a function of discrete and stochastic variables. The stochastic heuristic problems are the mathematical study of finding an optimal arrangement, grouping, ordering, or selection of discrete objects usually finite in numbers.

The stochastic heuristic methods are mainly based on search techniques where their search order depends mainly on random procedures. Search techniques may be *local*, that is, they find the nearest optimum which may not be the real optimum. Otherwise, search techniques may be *global*, that is, they find the true optimum even if it involves moving to *local optima* during search.

The basic elements of the stochastic heuristic problems are stated and defined as follows

- **Search:** is the term used for constructing/improving solutions to obtain the optimum or near-optimum.
- **Constructive:** search techniques work by constructing a solution step by step.
- **Improvement:** search techniques evaluate solution for feasibility and objective function.
- **Neighborhood:** Nearby solutions (i.e., solution space)
- **Diversification:** Drive the search to new unexplored regions in the search space by generating new structures of programs.
- **Move:** jump from current solution to another (usually neighborhood)

- **Evaluation:** The solutions' feasibility and objective function value

4.2.1 Notion of Neighborhood

Almost stochastic heuristic algorithms use a notion of neighborhood which limits the search space. As a definition, a neighborhood of point x is $N(x)$ in global space S satisfying the following conditions:

$$\begin{array}{c} \hline x \in S, \\ N(x) \subseteq S \\ x \notin N(x). \\ \hline \end{array}$$

4.2.2 The stochastic heuristic algorithms

The stochastic heuristic methods include many algorithms such as *local search algorithm*, *Tabu search algorithm*, *simulated annealing* and *genetic algorithms*.

In this section, we present the main concepts of each algorithm. The detail description of the stochastic heuristic algorithms is presented in Appendix.

4.2.2.1 Local Search

The local search algorithm [Aarts][Osman] allows identifying the optimization point (i.e., either maximum or minimum) within a limited search space (i.e., a set of neighbors).

Firstly, the algorithm selects randomly an initial point x in the global space S . Each point x may have several sets of the neighborhood as defined above.

The algorithm then selects a set of the neighbors $N(x)$ of x among many set of neighborhoods. The local optimization (i.e., maximum or minimum) of $N(x)$ will be identified. If we consider that the size of $N(x)$ is equal to the global space S , the algorithm will determine the global optimization of S .

4.2.2.2 Tabu Search

The basic concept of Tabu Search (TS) is described by Glover (1986) [Glo001][Glo02][Glo03]. TS is an iterative improvement search procedure which starts from any initial solution and attempts to determine a better solution. Generally, TS is characterized by its ability to avoid being entrapped in local optima.

The basic elements of TS are stated and defined as follows:

- **Current solution** ($x_{current}$): is a current point $x \in S$ at any iteration. It plays a central role in generating the neighbor solutions.
- **Set of candidate moves** ($N(x_{current})$): is the neighborhoods of $x_{current}$.
- **Search:** the algorithm searches the best solution within the neighborhood of $x_{current}$.
- **Local optimum:** the best solution of the neighborhood is the local optimization solution.
- **Tabu list:** this list contains the local optima identified by the algorithm. It is used to prevent cycling and avoid returning to the local optimum just visited.

- **Diversification:** this step determines the next move when the algorithm is entrapped within local optima. The diversification of Tabu search selects randomly next move to jump out the local optimal solution.
- **Stopping Criteria:** these are the conditions under which the search process will terminate. The search will terminate if one of the following criteria is satisfied: the number of iterations since the last change of the best solution is greater than a pre-specified number or the number of iterations reaches the maximum allowable number.

4.2.2.3 Simulated Annealing Algorithm

The simulated annealing algorithm (SA) is based on the concept of the manner in which liquids freeze or metals re-crystallize in the process of annealing [Johnson][Kirk].

Firstly, we present basic concept of an annealing process of a melt. This process is initiated at high temperature and disordered, is slowly cooled so that the system at any time is approximately in thermodynamic equilibrium. As cooling proceeds, the system becomes a "frozen" ground state at $T=0$. Hence, the process can be thought of as an adiabatic approach to the lowest energy state. If the initial temperature of the system is too low or cooling is done insufficiently slowly, the system may become quenched forming defects or freezing out in metastable states (i.e., trapped in a local minimum energy state).

The original Metropolis scheme [Metropolis] was that an initial state of a thermodynamic system was chosen at energy E and temperature T , holding T constant the initial configuration is perturbed and the change in energy dE is computed. If the change in energy is negative the new configuration is accepted. If the change in energy is positive, it is accepted with a probability given by the Boltzmann factor $e^{-(dE/T)}$. This process is then repeated sufficient times to give good sampling statistics for the current temperature, and then the temperature is decreased and the entire process repeated until a frozen state is achieved at $T=0$.

The basic ideas of an annealing process of a melt is used and applied to the stochastic heuristic problems.

The basic elements of SA are stated and defined as follows:

- **The control parameter T** (for example, temperature): allows controlling the search procedure. T is firstly initiated. For each iteration, the parameter T decreases an amount ΔT . The search procedure stops at $T=0$. The number of the iterations depends on the initial chosen value of T and ΔT .
- **Current solution ($x_{current}$)**: is a current point $x \in S$ at any iteration.
- **Set of candidate moves ($N(x_{current})$)**: is the neighborhoods of $x_{current}$.
- **Select a candidate for next move:** select randomly a solution $z \in N(x_{current})$.
- **Move:** the algorithm performs the so called Metropolis test [Metropolis] in order to accept a move from $x_{current}$ to z if it does not decrease the objective function $F(x)$ (i.e., $F(x_{current}) \leq F(z)$). Otherwise, if $F(x_{current}) > F(z)$, the algorithm checks the acceptance probability condition in order to accept a move from $x_{current}$ to z or not.
- **Acceptance probability:** the move is also accepted with probability $e^{-(dF/T)} < random(0,1)$ even though it results in a decrease of $F(x)$. For fixed T , the

acceptance probability is an exponentially decreasing function of ΔF so the acceptance probability quickly becomes very large with the decrease of ΔF . The condition only accepts the move if the decrease of ΔF is sufficiently small and the process is at the beginning period (i.e., control parameter T is large). Otherwise, the algorithm prefers to stay at the current solution.

- **Stopping Criteria:** This process is repeated several times to give good sampling statistics for the current control parameter and then the control parameter is decremented. The entire process repeated until a frozen state is achieved at $T=0$.

4.2.2.4 Genetic Algorithm

Genetic algorithms (GA) are search methods that take their inspiration from natural selection and survival of the fittest in the biological world [Michalewicz][Goldberg].

The basic elements of GA are stated and defined as follows:

- **Population:** GA differs from traditional optimization techniques in which it involves a "population" search problem.
- **Fitness:** evaluate the fitness $f(x)$ of each individual (i.e., chromosome x) in the population
- **Selection:** select two parent chromosomes from a population according to their fitness (the better fitness, the bigger chance to be selected)
- **Crossover:** is a procedure to cross over the parents to form a new offspring (children). If no crossover was performed, offspring is an exact copy of parents.
- **Recombination and mutation:** solutions are also mutated by making a small change to a single element of the solution. Recombination and mutation are used to generate new solutions that are biased towards regions where good solutions have already been.
- **Accepting** Select new offspring in a new population
- **Evolution:** Each iteration involves a competitive selection that weeds out poor solutions. The solutions with high "fitness" are "recombined" with other solutions by swapping parts of a solution with another.

4.3 Performance evaluation comparison

In this section, we present a simulation based comparative study and a performance evaluation of the stochastic heuristic methods in multiple flow/interface association context. The local search, Tabu search, simulated annealing are considered. The implementation is carried out using MATLAB.

In this work, we do not consider the genetic algorithm. The algorithm aims to create new generations inheriting the characteristics of their ancestry and search the one having the best characteristic. However, in our context, the association options have no genetic relationship. An offspring (i.e., an association option) which is born from the crossover of two individuals (i.e., two other association options) does not inherit genetically the characteristics of its ancestry. Therefore, the genetic algorithm is not suitable for the flow/interface association.

The simulation results illustrate the performance of each method. Moreover, the comparative study outlines the adaptation of the methods, their advantages and drawbacks in our context.

4.3.1 Simulation set up

In the simulation, we consider a mobile terminal integrating four access network interfaces: Wi-Fi 802.11b, Wi-Fi 802.11a, Wi-Fi 802.11n and WiMAX 802.16a. Their average energy consumption is 1μJ/bit, 5μJ/bit, 15μJ/bit and 20μJ/bit, respectively. During the simulation, the available bandwidth of networks is successfully 100Kbps, 200Kbps, 300Kbps and 500Kbps. The terminal is in the overlapping coverage zones of these networks.

In addition, we consider five application flows. The terminal runs an FTP application, two HTTP applications, a CD-like audio streaming flow with an average rate of 150Kbps (rate-adaptive application) and a PCM VoIP flow requiring 64Kbps (hard-real-time application).

We assume that the network allocates fairly the available bandwidth to the applications when they connect to the same network interfaces.

4.3.2 Simulation scenarios

In the simulation, we have totally 1024 possible association options (i.e., association of five applications and four interfaces). The algorithms select randomly the initial option association and aim at determining the association option maximizing the global terminal utility (i.e., *global optimization solution* or *global optimum*).

We then define a number of iterations (N) that allows each algorithm to find out the global optimization solution.

The simulation aims to evaluate the performance of the stochastic heuristic algorithms in terms of the capacity of global optimization identification with N iterations. In other words, with N attempts, what is the probability of identifying the global optimization?

For the *local search*, we set the search space equal to the global space. This allows the algorithm identifying the global optimization solution. However, the algorithm has to examine the global space (i.e., 1024 iterations).

For the *Tabu search algorithm*, we define the *rate* parameter. The number of iterations N is calculated as the ratio of the global search space (i.e., 1024 association options) and the rate. The simulation aims at examining the performance of TS when changing number of the iterations. The *rate* is increased by 0.01 in each simulation.

For the *simulated annealing algorithm*, T is a control parameter to determine when the search terminates. In our context, we set T=1. The search will stop at T=0. For each iteration, we decrease an amount dt. The number of iterations N is calculated as the ratio of the control parameter T and dt. In the simulation, dt is calculated as $\frac{1}{rate_dt}$ where the *rate_dt* increases from 5 to 300.

We carry out 1000 simulations for each algorithm.

4.3.3 Simulation results

4.3.3.1 Local search

In the simulation, we implement the local search. We set the search space equal to the global space. The local search runs a loop in the global search space (e.g., 1024 rounds) to determine the global optimization maximizing the terminal utility.

The algorithm identifies the association option having the terminal utility about 1.311 as the global optimization. The average computing time is approximately 1.212 second.

4.3.3.2 Tabu search

Figure 21 presents the simulation results of TS. It illustrates the terminal utility and the calculation time according to the *rate* parameter.

When the *rate* is small, the number of iterations *N* is large. The algorithm has many chances to find out the global optimization solution. When the rate increases, the number of iterations *N* decreases. The possibility to identify the global optimization solution decreases and the computing time is decreased.

The result shows that the probability to find global optimization is about 63% at the rate from 1 to 4, and the average calculation time is approximately 0.58 second. With the rate from 4 to 8, about 32% of the global optimization is determined, and the average calculation time is approximately 0.23 second. With the rate from 8 to 10, the average probability to find the global optimization is less than 18 %, the average calculation time is approximately 0.086 second.

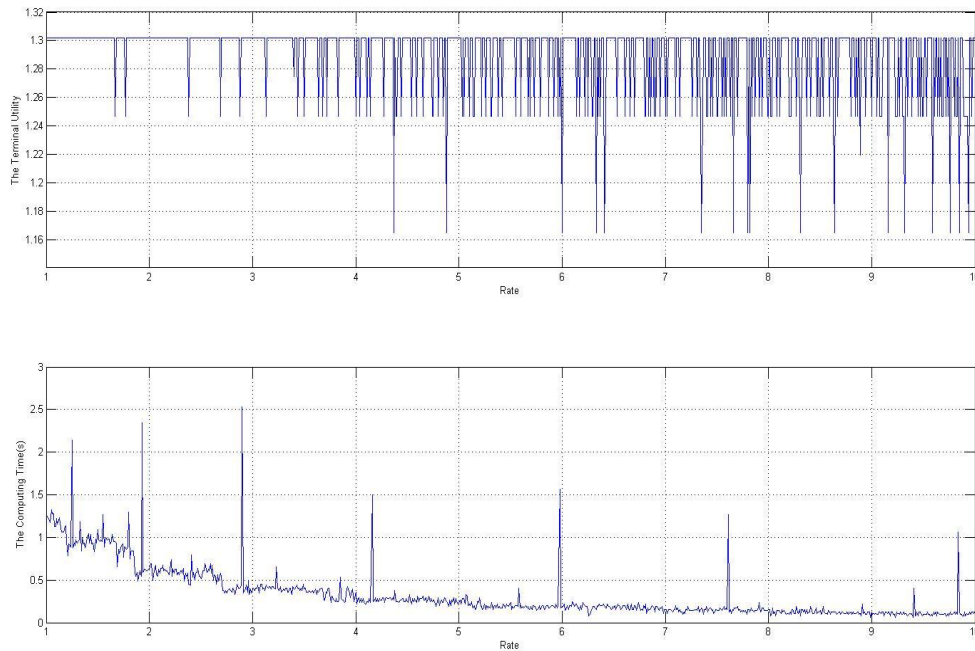


Figure 24- The simulation results of the Tabu search

4.3.3.3 Simulated annealing

Figure 22 presents the simulation results of SA. It illustrates the terminal utility and the calculation time according to *rate_dt*.

When we increase the *rate_dt*, the number of iterations *N* increases. The probability to find out the global optimization increases. However, the computing time is also increased.

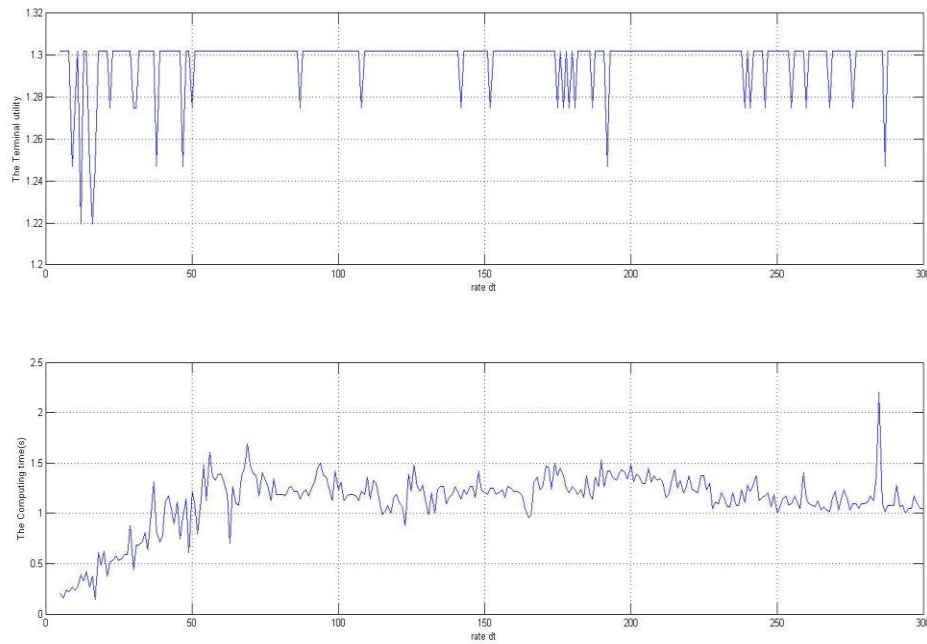


Figure 25 - The simulation results of the simulated annealing

The simulation results depict that the average probability of the global optimization identification is approximately 19% with the *rate_dt* from 5 to 150 while the computing time is about 0.74 second and 27.5% with the *rate_dt* from 150 to 300 while the computing time is approximately 1.27 second.

Table 16- The performance comparison of Tabu search and simulated annealing

N (iterations) per global space (1024 association options)	Tabu search		Simulated Annealing	
	Probability(%)	Computing time(s)	Probability(%)	Computing time(s)
100	18.2%	0.079	17.6%	1.21
150	31%	0.21	23%	1.26
200	34%	0.35	28%	1.28
250	60%	0.47	29%	1.32
300	53%	0.52	31%	1.45
400	66%	0.58	38%	1.6
500	69%	0.62	42%	1.82

We summarize the performance comparison of the Tabu search and the simulated annealing algorithms in Table 15. The results show that with the same N iterations, the Tabu search algorithm outperforms the simulated annealing algorithm in our context.

4.3.4 Discussions

The simulation results shows that the Tabu search is better than the simulated annealing in terms of the identification of the global optimization and computing time.

The difference between the Tabu search and the simulated annealing algorithm is that the Tabu search considers randomly another initiating association option when being

entrapped within the local optimization instead of the acceptance probability of the simulated annealing.

As presented above, when being entrapped in the local optima, the simulated annealing finds that the current solution is better than compared solution (i.e., $dU = U(s_{\text{next}}) - U(s_{\text{current}}) < 0$). The move of the simulated annealing is only accepted with probability $e^{-(dU/T)} < \text{random}(0,1)$. However, when T decreases, it is very difficult to satisfy this condition. The algorithm risks to be entrapped within the local optimization and cannot jump out of the local optimization. This leads to a poor performance of the simulated annealing.

Unlikely, the diversification of Tabu search decides to jump to another solution when being entrapped in the local optimization by using a random way. The algorithm may jump to another solution in this situation.

However, the Tabu diversification is a random procedure. The new solution could have been examined earlier and the algorithm is repeated several times for nothing. This leads to decrease the probability of finding the global optimization.

4.4 Oriented diversification of Tabu search for the multiple flow/interface association

As presented above, the diversification of Tabu is implemented on a random way. In this section, we aim at improving the Tabu search by proposing an oriented diversification of the Tabu search for the multiple flow/interface association issue.

The oriented diversification aims to help the algorithm increasing the probability of global optimization identification. The diversification technique is widely used to extend the Tabu search [James][Osman]. Its design depends strongly on the specific problem context.

In our specific context of the multiple flow/interface association, the diversification orients the algorithm to select the next move (i.e., next association option) when being entrapped in the local optimization. The oriented diversification avoids repeating the association option recorded to the Tabu list.

To illustrate these problems, we present the following example:

Considering a terminal running 4 applications and having 4 available network interfaces, an association option s_i can be presented as follows:

$$s_i = [x_j] = [4 \ 4 \ 1 \ 4]$$

where x_j is the interface and j is the application.

In this example, the association option s_i allows the application 1, 2 and 4 connect to the interface 4. The application 3 connects to the interface 1.

When the algorithm identifies a local optimum, it records this optimum to a list which is called *Tabu list*. We assume that the current Tabu list of this example can be as follows:

$$\text{Tabu_list} = \begin{bmatrix} 1 & 4 & 1 & 3 \\ 4 & 4 & 1 & 2 \\ 1 & 4 & 3 & 3 \end{bmatrix}$$

When a local optimization solution is identified but it already existed in Tabu list, the algorithm is entrapped within the local optimization. It means that the algorithm cannot find a new local optimum and stay always at this local optimum. It risks that the

algorithm wastes time to search without finding out any new local optima. An example of this situation is presented as follows:

$$Tabu_list = \begin{bmatrix} 1 & 4 & 1 & 3 \\ 4 & 4 & 1 & 2 \\ \mathbf{1} & \mathbf{4} & \mathbf{3} & \mathbf{3} \\ \mathbf{1} & \mathbf{4} & \mathbf{3} & \mathbf{3} \end{bmatrix}$$

The association option [1 4 3 3] is re-identified as local optimum. As specified by the Tabu search, if the algorithm continues to search, it will search within the neighborhood of the association option [1 4 3 3] and the association option [1 4 3 3] will be always the local optimum. The algorithm is then entrapped in this situation.

The algorithm must then jump to another association option. In Tabu search, an association option is randomly generated. However, this random process may generate an association option already existing in the Tabu list.

When the number of local optima in the Tabu list increases, the use of random procedure may lead to a re-entrapment of the algorithm in the local optima.

In our context, we want to modify the Tabu search algorithm considering a new diversification procedure which orients the Tabu search and avoids re-selecting a next move existing in the Tabu list.

The oriented diversification includes two steps:

Step 1: The algorithm checks the Tabu list and verifies if an application has never changed the connection yet. If it is in the case, the algorithm will change the connection. A new association option is generated and the search is initiated. If the algorithm identifies that all applications changed the connection, it goes to step 2.

For example, consider the Tabu list below, the application 2 always connects to the interface 2.

$$Tabu_list = \begin{bmatrix} 4 & \mathbf{2} & 1 & 4 \\ 1 & \mathbf{2} & 3 & 3 \\ 1 & \mathbf{2} & 4 & 3 \\ 1 & \mathbf{2} & 4 & 3 \end{bmatrix}$$

To generate a new association option, the algorithm then changes the connection of application 2 which differs from the current connection (e.g., [1 1 2 3]). The algorithm considers [1 1 2 3] as the next association option and continues to search.

Step 2: in this step, we consider the diversification of the Tabu Search. The algorithm generates randomly a new association option. However, the step differs from the diversification of the Tabu Search on verification of new association option after being generated. If the new association option does not exist in the Tabu list, it continues to search. Otherwise, it generates another one, then verifies before searching.

To carry out this step in our context, the algorithm selects randomly an application and then changes its connection differing from the past connection of this application in the Tabu list.

In the case that this application used to connect to all interfaces, the algorithm cannot generate a new connection. It then switches to another application and changes its connection.

If the algorithm finds that all applications used to connect to all interfaces, the diversification generates a new option association that is similar to the diversification of the classical Tabu search.

For example, consider the Tabu list below, the condition of the step 1 is not satisfied. Application 3 is selected, it however used to connect to all interface (i.e., from 1 to 4). The algorithm has to consider another application to generate a new association option. The algorithm selects application 1 and changes the connection from the interface 1 to the interface 2 differing from the past connection of the application 1 (i.e., 1 and 4). A new association option is generated (e.g., [2 2 2 3]).

$$Tabu_list = \begin{bmatrix} 4 & 3 & 1 & 4 \\ 1 & 2 & 3 & 3 \\ 1 & 2 & 4 & 3 \\ 1 & 2 & 1 & 3 \\ 1 & 2 & 2 & 3 \\ 1 & 2 & 2 & 3 \end{bmatrix}$$

In our context, the oriented diversification assures that the algorithm generates a new association option differing from the local optima in the Tabu list

4.5 Performance evaluation

In this section, we carry out the implementation of the Tabu search with the oriented diversification using the same simulation scenarios presented above.

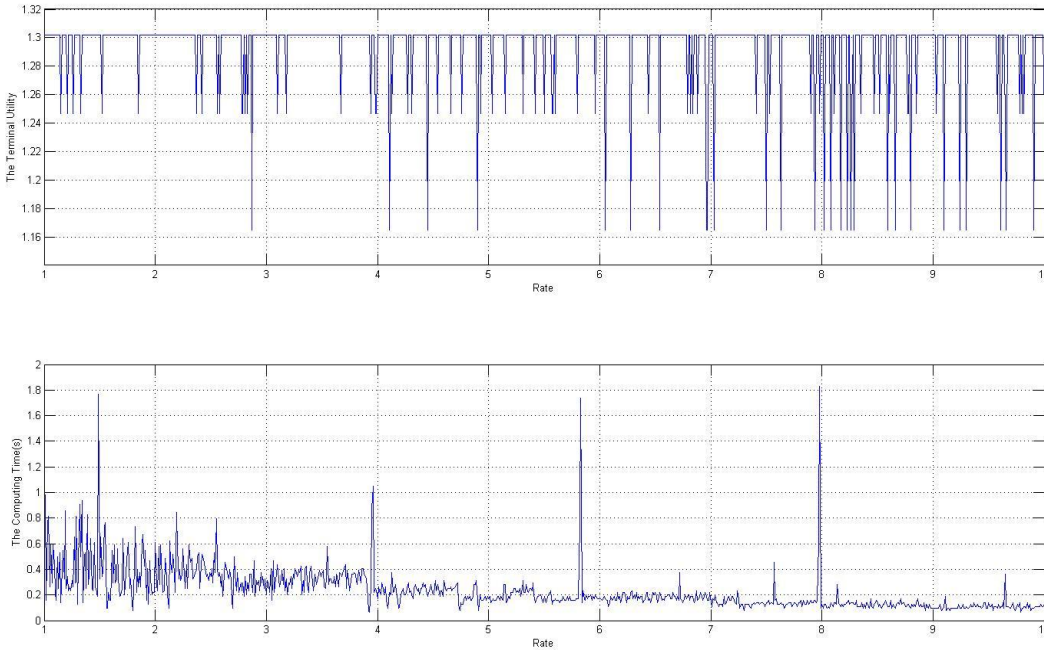


Figure 26- The simulation results of the modified Tabu search

We compare the modified Tabu search to the classical Tabu search, and the simulated annealing algorithm. The simulation results highlight the advantages of the modified Tabu search. Figure 23 presents the simulation results of the modified Tabu search. The result shows that about 82% of global optimization is identified at with the rate from 1 to 4, and the average calculation time is approximately 0.37 second. With the rate from 4 to 8, about 45% of global optimization is determined, and the average calculation time

is approximately 0,16 second. With the rate from 8 to 10, the average probability to find the global optimization is less than 30%, the average calculation time is approximately 0,089 second.

Comparing to the Tabu search and the simulated annealing, the modified Tabu search is better in terms of identification of the global maximal solution (see Table 16). The computing time of the modified Tabu search is quite better than the Tabu search.

Table 17 - The performance comparison of TS, SA and modified TS

N (iterations)	Tabu search		Simulated Annealing		Modified Tabu search	
	Prob.(%)	Computing time(s)	Prob.(%)	Computing time(s)	Prob.(%)	Computing time(s)
100	18.2%	0.079	17.6%	1,21	23%	0.079
150	31%	0.21	23%	1.26	36%	0.21
200	34%	0.35	28%	1.28	42%	0.34
250	60%	0.47	29%	1.32	71%	0.46
300	53%	0.52	31%	1.45	78%	0.49
400	66%	0.58	38%	1.6	82%	0.52
500	75%	0.62	42%	1.82	86%	0.56

5 Summary

In this chapter, we present an interface utility function which takes into account the application requirements and the energy consumption of the terminal. The utility-based flow/interface association has been proposed combining the interface utility function and the DiA algorithm.

DiA is used to rank the interfaces considering the interface utility values and the network side attributes. The simulation results validate our proposal and demonstrate that the interface selection scheme outperforms the MADM-based and Suci-u-utility based methods.

The single flow/interface system implementation in a practical test-bed has been initiated

In addition, we propose the multiple flow/interface association scheme that allows the mobile terminal to associate several application flows to its own network interfaces maximizing the global terminal utility function. A comparative study of stochastic heuristic methods highlights their advantages and drawbacks in our context. Moreover, an oriented diversification of the Tabu search is proposed to improve performance of the stochastic heuristic methods. Simulation results show that the modified Tabu search outperforms the other methods.

In our simulation, the computing time is measured when carrying out the simulations on the same machine (e.g., using dual CPU). This value may vary when implementing the algorithms on a practical mobile terminal.

Chapter 5: Strategy game for flow/interface association in multi-interface mobile terminals

In this chapter, we tackle network centric approach for addressing the flow/interface association issues. We consider a system that mobile terminals are able to associate their applications to the suitable interfaces. We model the system as a strategic game. The multiple terminals compete for common network resources. By using evolutionary game theory, we show that the system converges to efficient Nash equilibria which optimize the total utility of the system. Moreover, simulation scenarios, implementing the so-called Nash learning algorithm, are developed to validate the theoretical results.

1 Introduction

In this Chapter, we adopt a network centric approach for flow/interface association. We consider a system constituted by several multi-interface mobile terminals, the terminals compete with each other to associate their application flows to various network interfaces by using common network resources. Each terminal tends to behave selfishly, and tries to associate its applications to various network interfaces satisfying its own objectives.

The main question is how the terminal decides which action to choose in this competitive situation? The problem seems intractable because what is optimal for one terminal depends on what the other terminals do.

Game theory is considered as a powerful tool to model interactions of players with mutually conflicting objectives, e.g., the interaction among selfish multi-interface terminals and the network resources at the other side.

Game theory can be classified based on several forms (normal, extensive), types (non-cooperative, cooperative), and strategies (pure and mixed strategies) to model various issues.

Especially, there exist equilibrium strategies in game theory. The equilibria are considered as a solution concept of a game involving players. Nash equilibrium conception is one of these, and is the most widely used as "solution concept" in game theory.

Game theory techniques have recently been applied to various design problems. In particular, we have encountered a rich literature of game theory applied to the telecommunications and network area. For example, in heterogeneous networks, wireless services are provided to multiple users in which each one is assumed to be rational enough to achieve the highest performance. The action of the user conflicts with any other users while deploying common network resources. Therefore, game theory can be considered as a stable solution for the users who can be obtained through the concept of equilibrium.

With many advantages of game theory, we are motivated to use this approach as tool for modeling our problem.

Before directing to our framework based on the game theory, we present a brief panorama of the game theory in next section.

2 Introduction to game theory

Game theory is the mathematical analysis of interest conflict of players to find optimal choices that will lead to a desired outcome (payoff) under given conditions. Game theory is actually becoming major interest in fields like economics, sociology, political, military and computer sciences.

Game theory was firstly proposed in 1921 by Emile Borel that was furthered by John von Neumann in 1928 in a "theory of parlor games". The first book of game theory "*Theory of Games and Economic Behavior*" was published in 1944 by Neumann and the economist Oskar Morgenstern. This book provided much of the basic terminology and problem setup that is still in use today.

In 1950, John Forbes Nash demonstrated that finite games always have an equilibrium point, at which all players choose actions which are best for them given their opponents' choices.

Until now, game theory has been applied to various problems such as war, politics, economic, sociology, psychology, and biology, etc.

Especially, game theory has received an unprecedented attention when Nobel Memorial Prize in Economic Sciences was given to John Forbes Nash (American), John Charles Harsanyi (Hungarian), and Reinhard Selten (German) in 1994.

2.1 Definition of games

A game is a formal description of a strategic situation. The objective of game theory is to form a game which is a formal model of interaction scenario involving several players. The game usually defines the players, their preferences, their information, the strategic actions available to them, and how these influence to the outcome.

In game theory, a main assumption is that the players are *rational*. A player is said to be *rational* if he always seeks to play in a manner which optimizes his own payoff. It is often assumed that the rationality of all players is *common knowledge*.

Common knowledge is concerned if all players know the game, other players in the game and how to play it. The structure of the game is often assumed to be common knowledge among the players.

The goal of game theory is to analyze and predict how the game will be played by rational players.

A player's *strategy* in a game is a complete plan of action (i.e., *pure strategies*). This fully determines the player's behavior. The space of pure strategy ξ_p for each player is p ($1 \leq p \leq n$) where n is the players of the game

Besides, game theory defines also notion of mixed strategies. A *mixed strategy* is an assignment of a probability to each pure strategy. This allows a player to randomly select a pure strategy. A strategy profile is a set of strategies for each player which fully specifies all actions in a game. A strategy profile must include one and only one strategy for every player.

The game can be formally branched by two main types such as cooperative and non-cooperative.

Cooperative game is coalitional games with respect to the relative characteristics of various players. This game is widely applied to problems arising in political science or international relations.

Non-cooperative game is focused on the analysis of strategic choices. Players are unable to make enforceable contracts outside of those specifically modeled in the game. In non-cooperative game, the ordering and timing of players' choices are crucial to determine the outcome of a game.

The game can be played under two main forms:

Strategic form game

A game in strategic form, also called normal form, is a natural and adequate description of a simultaneous move game. The payoffs are presented in a table with a cell for each strategy combination.

Extensive form game

An extensive form game describes with a tree how a game is played. It depicts the order in which players make moves, and the information each player has at each decision point.

2.2 Examples of Games

As presented above, all players are assumed to be rational. They always make choices which result from the outcome they prefer most.

For example, a player has two strategies A and B. We assume that the payoff resulting from strategy A is always better than from strategy B with any combination of strategies of the other players. Then strategy A is said to be *dominating* to strategy B. A rational player will never choose to play a dominated strategy (i.e., strategy B).

The following examples illustrate this idea.

Prisoner's Dilemma Game

The Prisoner's Dilemma is a strategic form game of two players. Each player has two strategies, called "cooperate" and "defect," which are labeled C and D for player I and c and d for player II, respectively.

Table 18- An example of the prisoner's Dilemma Game

		II	
		c	d
I	C	2 2	0 3
	D	3 0	1 1

Table 18 shows the payoffs in the game. The payoff is number of years that the players are reduced for prison sentence. Player I chooses a row, either C or D, and simultaneously player II chooses one of the columns c or d. For example, the strategy combination (C; c) has payoff 2 for each player, and the combination (D; d) gives each player payoff 1. The combination (C; d) results in payoff 0 for player I and 3 for player II, and when (D; c) is played, player I gets 3 and player II gets 0.

In the Prisoner's Dilemma game, "defect" is a strategy that dominates "cooperate". Strategy D of player I dominates C since if player II chooses c, then player I's payoff is 3 when choosing D and 2 when choosing C; if player II chooses d, then player I receives 1 for D as opposed to 0 for C.

In this game, player I, and II will not choose a dominated strategy. The rational players tend to select the dominating strategy. Therefore, they will choose (D; d) with payoffs (1; 1). However, paradoxically, the players may have the payoff (2; 2) when the players chose (C; c).

Quality choice game

In some games, certain players cannot identify the dominating strategies. They must know how to eliminate the dominated strategy basing on the analysis of other players' behaviors. This example illustrates the principle of elimination of dominated strategies.

Suppose that player I is an internet service provider and player II a customer. They consider a contract of service provision for a period of time. Two levels of quality of service (i.e., *High or Low*) could be provided. High-quality service is more costly to provider, and some of the cost is independent of whether the contract is signed or not.

The level of service cannot be put verifiably into the contract. High-quality service is more valuable than low-quality service to the customer. The customer would prefer not to buy the service if he knew that the quality is low. His choices are to *buy* or *not to buy* the service.

Table 19- An example of the Quality choice game

		II	
		Buy	Don't buy
I	High	2 2	0 1
	Low	3 0	1 1

Table 17 gives possible payoffs that describe this example. The customer prefers to buy if player I provides high-quality service, otherwise, he does not buy.

Without considering whether the reaction of the customer (buy or not), the provider always prefers to provide the low-quality service. Therefore, the strategy *Low* dominates the strategy *High* for player I.

Being a rational player, player II believes that player I prefers to provide low-quality service (*Low*). Then he prefers *not to buy* (payoff 1) to *buy* (payoff 0). Therefore, rationally, both players conclude that the provider will implement low-quality service and, as a result, the contract will not be signed.

This game is very similar to the Prisoner's Dilemma game. However, the difference is that the preference of player II in this game depends on the action of player I. Therefore, player II does not have a dominating strategy.

In this game, the players rationally select the strategy combination (*Low, don't buy*). However, the rational outcome is the strategy combination (*High, buy*) that high quality service is provided and the customer signs the contract. However, that outcome is not credible, since the provider always prefers to provide only the low quality service.

2.3 Example of Nash equilibria

In the previous examples, we present the consideration of dominating strategies and the advices to the players on how to play the game. However, in many games, there are no dominating strategies. It is difficult to rule out any outcomes or to provide more specific advice on how to play the game.

Nash equilibria (i.e., equilibrium strategies) are a list of strategies, one for each player, which has the property that no player can unilaterally change his strategy and get a better payoff.

Table 20- An example of the Nash equilibria

		II	
		Buy	Don't buy
I	High	2 2	0 1
	Low	1 0	1 1

To illustrate Nash equilibrium, we revisit the quality choice game as presented above. In the example, the behavior of player II is changed (see Table 18).

Here, provider receives payoff 1 when providing low-quality service even when the customer decides to buy or not. This encourages the Internet provider to increase the quality service.

The game is played as presented above. This game has no dominating strategy for either player. The players thus cannot determine the rational strategies.

In this situation, Nash proposes the concept of Nash equilibrium to help the player identify the rational strategies.

According to Nash, the game has two Nash equilibria in which each player chooses his strategy deterministically.

One of them is the strategy combination (*Low, don't buy*). This is an equilibrium since *Low* is the *best response* (payoff-maximizing strategy) to *don't buy* and vice versa. The second Nash equilibrium is the strategy combination (*High, buy*). It is an equilibrium since player I prefers to provide high-quality service when the customer buys, and conversely, player II prefers to buy when the quality is high. This equilibrium has a higher payoff to both players than the former one, and is a more desirable solution.

Both Nash equilibria are legitimate recommendations to the two players of how to play the game. Once the players have settled on strategies that form a Nash equilibrium, neither player has incentive to deviate, so that they will rationally stay with their strategies. This makes the Nash equilibrium a consistent solution concept for games.

2.4 Equilibrium strategies

As presented above, the game solution aims at obtaining equilibrium strategies. The Nash equilibria [Nash] are the most popular solutions. A Nash equilibrium ensures that a player cannot improve its payoff if none of the other players in the game deviates from the solution.

2.4.1 Nash Equilibria for pure strategies

A pure strategy Nash equilibrium of a game is a Nash equilibrium in which each player uses a pure strategy, but not necessarily one determined by the iterated elimination of dominated strategies [Nash].

For example, let $\langle I, (S_i), u_i \rangle$ be a strategic game where I is the number of players, S_i is set of pure strategies of player i , and u_i is the payoff of the player i .

Consider a game including two players, pure strategies of player 1 is $(\alpha_1, \alpha_2, \dots, \alpha_k)$ and pure strategies of player 2 is $(\beta_1, \beta_2, \dots, \beta_k)$.

We call (α^*, β^*) is a Nash equilibrium if

$$u(\alpha^*, \beta^*) \geq u(\alpha_i, \beta^*)$$

or

$$u(\alpha^*, \beta^*) \geq u(\alpha^*, \beta_i)$$

This says that neither player has motivation to change unilaterally from its strategy.

2.4.2 Nash Equilibria for mixed strategies

Let Σ_i represent the set of probability distributions over s_i , the set of actions for player i and $\delta_i \in \Sigma_i$ represent a mixed strategy for player i , which is a probability function over pure strategies, $s_i \in S$.

A mixed strategy profile δ^* is a (mixed strategy) Nash Equilibrium if for each player i and for each $\delta_i \in \Sigma_i$, the following condition holds

$$u_i(\delta_i^*, \delta_{-i}^*) \geq u_i(\delta_i', \delta_{-i}^*)$$

where δ_{-i}^* refers to the set of mixed strategies of all players except i and δ_i' refers to the set of mixed strategies of player i except δ_i^* .

2.5 Introduction to Evolutionary Games

Models from evolutionary game theory consider the behavior of large populations in strategic environments (e.g., population games) [Sandholm][Hofbauer][William][Taylor]. An evolutionary game extends the formulation of a non-cooperative game by including the concept of population. A population is a group of individuals (i.e., players) in which the number of individuals can be finite or infinite. The individuals of one population may choose strategies against individuals of another population. An evolutionary game defines a foundation to obtain the equilibrium solution for the game of the populations.

In the following, the main theoretic concepts of the evolutionary game are presented [Sandholm].

An *evolutionary game* F , with Q non-atomic classes of players is defined by a mass and a *strategy set* for each class and a *payoff function* for each strategy.

The set of classes is denoted by

$$Q = \{1, \dots, Q\}, \quad \text{where } Q \geq 1$$

The class q has mass \hat{d}_q .

The set of strategies for class q is denoted $S_q = \{1, \dots, s_q\}$.

A particular strategy distribution (i.e., probability distribution) is the way the class q partitions itself into the different actions available, i.e., a strategy distribution for q is a vector of the form

$$y_q = \{y_q^1, y_q^2, \dots, y_q^{s_q}\}, \quad \text{where } \sum_{i=1}^{s_q} y_q^i = \hat{d}_q$$

The vector of strategy distributions being used by the entire population is denoted by $\mathcal{Y} = \{y_1, y_2, \dots, y_Q\}$. The vector \mathcal{Y} can be thought of as the state of the system.

The marginal payoff function (per unit mass) obtained from strategy $i \in S_q$ by users of class q , when the state of the system is \mathcal{Y} and \mathbb{R} denotes the set of real numbers, is denoted by $F_q^i(\mathcal{Y}) \in \mathbb{R}$. The total payoff to users of class q is then given by

$$\sum_{i=1}^{s_q} F_q^i(\mathcal{Y}) y_q^i \quad (1)$$

2.5.1 Potential game

Potential games are a subclass of games that have a specific structure on the payoff functions that we study below:

Definition 1: We call F a potential game if exist a C^1 function $f: \mathcal{Y} \rightarrow \mathbb{R}$ such that $\frac{\partial f}{\partial y_q^i}(\mathcal{Y}) = F_q^i(\mathcal{Y})$ for all $i \in \mathcal{S}_q$ and $q \in \mathcal{Q}$.

The definition says that the rate of change of potential with mass of a population using a strategy is the payoff obtained per unit mass by that population for that strategy.

2.5.2 Evolutionary dynamics

Evolutionary dynamics describe the change in populations (number of members of species and behavior distributions). There exist many evolutionary dynamics. For example, *deterministic evolutionary dynamics*, usually taking the form of ordinary differential equations, are used to describe behavior over moderate time spans. *Stochastic evolutionary dynamics*, modeled using Markov processes, employed to study behavior over very long time spans. Additionally, recent works [Hofbauer01] [Hofbauer02] [Brown] have shown that *Replicator Dynamics* and *Brown-von Neumann-Nash (BNN) dynamics* determine how well a population is adapted to its environment, lead to efficient equilibria which is very interesting.

Evolutionary dynamics are usually described by a vector field $V: \mathcal{Y} \in \mathbb{R}$ which implicitly defines an equation of motion $\dot{\mathcal{Y}} = V(\mathcal{Y})$.

2.5.2.1 Replicator dynamics

The first dynamic is called *Replicator Dynamics* [Hofbauer01]. The rate of increase of \dot{y}_q^s/y_q^s of the strategy s is a measure of its evolutionary success. We may express this success as the difference in fitness $F_q^s(\mathcal{Y})$ of the strategy s and the average fitness $\frac{1}{\hat{a}_q} \sum_{i=1}^{\mathcal{S}_q} y_q^i F_q^i(\mathcal{Y})$ of the class q . Then the dynamic used to describe changes in the mass of class q playing strategy s is given by

$$\dot{y}_q^s = V(\mathcal{Y}) = y_q^s \left[F_q^s(\mathcal{Y}) - \frac{1}{\hat{a}_q} \sum_{i=1}^{\mathcal{S}_q} y_q^i F_q^i(\mathcal{Y}) \right] \quad (2)$$

The proportion of individuals using strategy i increases (decreases) if its payoff is bigger (smaller) than the average payoff in the population.

2.5.2.2 Brown-von Neumann-Nash (BNN) dynamics

Another commonly used model is called *Brown-von Neumann-Nash (BNN) dynamic* [Hofbauer02][Brown], which is somewhat more complex.

Let,

$$\gamma_q^s = \max \left\{ \left[F_q^s(\mathcal{Y}) - \frac{1}{\hat{a}_q} \sum_{i=1}^{\mathcal{S}_q} y_q^i F_q^i(\mathcal{Y}) \right], 0 \right\} \quad (3)$$

denote the excess marginal payoff to strategy s relative to the average payoff in its class. Then BNN dynamics are described by

$$\dot{\mathcal{Y}} = V(\mathcal{Y}) = \hat{a}_q \gamma_q^s - y_q^s \sum_{i=1}^{\mathcal{S}_q} \gamma_q^i, \quad (4)$$

where the dynamics take place within the set $\sum_{j=1}^{\mathcal{S}_q} y_q^j = \hat{a}_q, \forall q \in \{1, 2, \dots, Q\}$.

A rough evolutionary interpretation of (BNN) is that suppose there are N player populations. New players joining the game use only strategies that are better than average, and better strategies are more likely to be adopted. On the other hand, randomly chosen players leave the game.

2.5.3 Positive correlation (PC)

The main condition on the dynamics called *positive correlation* is described as follows:

Definition 2: The dynamics $\dot{\mathcal{Y}} = V(\mathcal{Y})$ are said to be positively correlated (PC) if

$$\sum_{q=1}^Q \sum_{i=1}^{S_q} F_q^i(\mathcal{Y}) V_q^i(\mathcal{Y}) > 0 \text{ whenever } V(\mathcal{Y}) \neq 0 \quad (5)$$

The definition says that the trajectory of the dynamics must be such that increases in a particular population coincide with positive payoff or fitness and decreases coincide with negative fitness. In other words, positive correlation requires that whenever the population is moving, it is moving uphill.

2.5.4 Equilibrium

We then consider the characteristic of equilibria for evolutionary games [Sandholm].

Theorem 1: If F is a potential game, and V satisfies PC, then the potential function of F is a global Lyapunov function for $\dot{\mathcal{Y}} = V(\mathcal{Y})$.

Proof: Positive correlation implies that $\frac{\partial f}{\partial y_q^i}(\mathcal{Y}) = F_q^i(\mathcal{Y}) V_q^i(\mathcal{Y}) > 0$ and that $V_q^i(\mathcal{Y}) = 0$ whenever $\frac{\partial f}{\partial y_q^i}(\mathcal{Y}) = 0$.

Lemma 1: If $V(\mathcal{Y})$ satisfies PC, all Nash equilibria of F are the stationary points of $\dot{\mathcal{Y}} = V(\mathcal{Y})$.

Lemma 2: If F is a potential game, and V satisfies PC, $V(\mathcal{Y}) = 0$ implies that \mathcal{Y} is a Nash equilibrium of F .

2.5.5 Nash learning algorithm

Nash learning algorithm [Touati] is an iterative algorithm with guaranteed convergence to the Nash equilibrium of the system. The algorithm allows the players to evaluate and adapt their own strategies. Nash learning algorithm is equivalent to a replicator dynamic.

At each epoch, the Nash learning algorithm updates iteratively the probability of each player for choosing one amongst actions. On the other hand, the system sends a reward to each player that represents the impact of payoff that each player has. The reward function is defined as the way each player in the system should pay a tax balancing the loss caused by his presence.

The Nash learning algorithm can be described as follows:

We consider a game including a set players I .

Let $q_i(0)$ be the initial arbitrarily vectors used by player i and $q_i(t)$ be the probability strategy used by player i at the moment t in the strategy space S_i .

For each player i :

- Select an action l according to the mixed strategy $q_i(t)$
- Obtain a reward $r_{i,l}(t)$
- Update the probability distribution $q_i(t)$

$$q_i(t+1) = q_i(t) + b \times r_{i,l}(t)(\delta - q_i(t))$$

where

b is the algorithm step for user i at each epoch, $b \in]0,1[$

δ is equal to 1 if the current strategy matches to the previous strategy and 0 otherwise. The algorithm increases the probability if a strategy is re-selected. Otherwise, it reduces the probability.

For further illustration, the Nash learning algorithm is shown as follows:

Nash Learning Algorithm

Initialize arbitrarily vectors $q_i(0)$ for all players

At each time epoch σ , for all user i do

Take decision a_i with the probability $q_{i,a_i}(\sigma)$

Receive reward $r_{a_i}(\sigma)$

Update strategy vector

$$q_{i,a_i}(\sigma + 1) = q_{i,a_i}(\sigma) + b \times r_{a_i}(\sigma)(\delta - q_{i,a_i}(\sigma))$$

The equation above determines the update mechanism (i.e., system dynamic). It can be described in the matrix form:

$$Q(\sigma + 1) = Q(\sigma) + b \times H(Q(\sigma))$$

where $Q(\sigma) \stackrel{\text{def}}{=} (q_i(\sigma))_{i \in I} \in S_i$ denotes the state of users at instant σ .

The Nash learning algorithm is a replicator dynamic where the probability update $H(Q(\sigma))$ corresponds to replicator dynamics. This is demonstrated in [Touati].

2.6 Related work

Game theory has been widely applied to various fields. In the network and telecommunications area, game theory receives a big attention. A rich literature is encountered such as network security [Lakshman] and [Michiardi], power control [Alpcan][Alpcan][Altman01][Falomari][Heikkinen][Ji][Saraydar01][Saraydar02][Sun], pricing and incentive for cooperation between mobile terminals [Battiti][Crowcroft][Michiardi][Urpi], the access control to a common shared radio channel [Altman02][Jin][MacKenzie], and auctions for resource reservation [Dramitinos], etc.

Especially, the works [Shakko01][Shakko02][Touati] outline the game theory application in the multi-homing context.

In [Shakko01] and [Shakko02], Shakkottai et al., study the case of non-cooperative multi-homing of users to access IEEE 802.11 APs using a non-cooperative game. The term multi-homing refers here to the ability of the users to split their traffic amongst all the available APs. Based on observations made on the characteristics of IEEE 802.11x physical rate selection schemes and channel occupancy, the work aimed at showing that, if the users are allowed to split their traffic while maximizing their payoff (expressed as a function of the obtained throughput and the price charged), then the global system throughput is maximized. In the work, an infinite number of users were considered and the system was modeled as a population game. The authors prove that the system evolution converges to Wardrop equilibria [Wardrop] and interestingly, the convergence limits are effective in the sense that they optimize some global function of the system despite terminals' selfish strategies.

In [Touati], Coucheney et al., address the vertical handover issue for mobile terminals integrating multiple radio interfaces of various types. Vertical handover means switching between networks of different technologies. The authors study the system as an evolutionary game with a finite number of users. They proposed an iterative distributed algorithm (i.e., Nash learning algorithm) which guarantees the convergence of the game. The Nash learning algorithm is iterative since at each epoch, each mobile terminal gradually updates the probability of choosing one amongst available networks. On the other hand, the network sends a reward to each terminal that represents the impact each terminal has on the network throughput. Based on potential games and replicator dynamic, the authors showed that the solutions are efficient and fair in terms of throughput. In addition, the equilibrium is pure, in the sense that, after convergence, each user is associated to a single network cell.

Our work is in line with [Shakko01], [Shakko02] and [Touati], but aims at studying a multi-homing model where the mobile terminals integrate several different access technologies (rather than the specific IEEE 802.11 case as in [Shakko01] and [Shakko02]). Each terminal can initiate multiple applications and meet the expectation of being able to associate each of them to a specific available interface (rather than addressing the vertical handover issue as in [Touati]). Instead of considering a payoff which is a function of the throughput as in [Touati], each terminal, in our work, considers a utility function which reflects, in particular, the satisfaction of the user.

3 Framework and model

3.1 Application-based model

Consider N mobile terminals in coverage zones of m network cells. The network cells might be of various technologies and each terminal i might be in the overlapping zone of a subset \mathcal{C}_i of several network cells. Using the suitable network interfaces, the terminal is able to fully benefit from the set \mathcal{C}_i of available network cells. More specifically, running multiple applications $a_1, a_2 \dots a_k$, the terminal may decide to use a mapping strategy s_i to associate each application a_l to a specific network cell $s_i(a_l)$ in the set \mathcal{C}_i .

Note that different applications belonging to one or several terminals may be associated to the same network cell. Therefore, there are competitions between applications and between terminals for common network resources. Thus, we model our system as a strategic game: Each terminal i is a player and the mapping s_i is its strategy of connections. By convention, denote by 0 the inactive strategy where the player is disconnected and denote by s_{-i} the strategies of all players other than i . The system state s is the mappings $(s_1 \dots s_N)$. This system state includes which cell being associated to which application of which terminal.

In the system state s , the player (i.e., terminal) i obtains a utility value denoted by $U_i(s)$ which is a function of s . This might be a function of the energy consumption and the application satisfaction level as illustrated in Section 4. However, its presence induces a competition with the other players for common network resources. Indeed, in comparison with the case where the player i is inactive, the others receive less and lose exactly

$$\sum_{j \neq i} (U_j(0, s_{-i}) - U_j(s_i, s_{-i})) \quad (6)$$

where $U_j(0, s_{-i})$ denotes the utility gain of the player j when the player i is inactive.

Based on [Cole] and [Touati], we introduce this loss as the marginal cost of accessing to the network resources, in order to increase the efficiency of the Nash equilibria.

Choosing the strategy s_i , the player i receives the reward function given by the difference between the utility gain and the marginal cost:

$$r_i(s) = U_i(s) - \sum_{j \neq i} (U_j(0, s_{-i}) - U_j(s_i, s_{-i})) \quad (7)$$

3.2 Mixed strategy and equilibrium

In this section, we recall some definitions of game theory and integrate mixed strategies in our model. First, let \mathcal{S}_i be the set of all possible strategies for the player i (all mappings from its applications to the set of available cells \mathcal{C}_i). Mixed strategy allows each player i to pick up a decision randomly following some probability law $(p_{i,s_i} | s_i \in \mathcal{S}_i)$. That is, it picks a strategy s_i with probability p_{i,s_i} . It may stay inactive with probability $p_{i,0} = 1 - \sum p_{i,s_i}$. The system state is then described by the probability vector of selecting strategies $p = (p_{i,s_i} | 1 \leq i \leq N, s_i \in \mathcal{S}_i)$, and the average reward offered to the player i for choosing the strategy s_i is equal to

$$f_{i,s_i}(p) = \sum_{s_{-i}} (r_i(s_i, s_{-i}) \prod_{j \neq i} p_{j,s_j}), \quad p \in \mathcal{P}; \quad (8)$$

where \mathcal{P} denotes the set of all possible probabilities of selecting strategies.

In our game of mixed strategies, the player i chooses a strategy randomly following the probability law $(p_{i,s_i} | s_i \in \mathcal{S}_i)$. Therefore, the expected reward is given by

$$E_p[r_i(s)] = \bar{f}_i = \sum_{s_i \in \mathcal{S}_i} p_{i,s_i} f_{i,s_i}(p) \quad (9)$$

A mixed strategy \hat{p} is a Nash equilibrium if no unilateral deviation in strategy by any single player is profitable for that player, that is

$$\forall i, \forall p_i \neq \hat{p}_i: E_{\hat{p}_i, \hat{p}_{-i}}(r_i(s)) \geq E_{p_i, \hat{p}_{-i}}(r_i(s)) \quad (10)$$

In his work [Nash], Nash proved that there exist Nash equilibria for any finite game of mixed strategies. Hence, Nash equilibria exist in our game. It remains to identify these equilibria. One alternative is to let each player evolve following some dynamic and then observe if the stationary points of this dynamic are Nash equilibria.

3.3 Replicator Dynamic

In this work, we let the system evolve following the Replicator dynamic. This dynamic ensures that only good strategies giving above-averaged reward survive: each player i increases the probability of choosing good strategies and decreases the probability of choosing bad ones, and the evolution rate is given by the equation (2) in the following definition.

The Replicator dynamic $\dot{p} = V(p)$, or $V(p)$ for short, is defined by the following differential equations

$$\forall i, \forall s_i: \dot{p}_{i,s_i} = p_{i,s_i} (f_{i,s_i} - \bar{f}_i) \quad (11)$$

where \bar{f}_i is the expected reward given by equation (10) and \dot{p} is the derivative of p with respect to time.

According to **Definition 2**, the Replicator dynamic $V(p)$ is said to be Positively Correlated (PC) if the scalar product $\langle f(p), V(p) \rangle$ is strictly positive whenever $V(p)$ is non-zero. The scalar product is defined by

$$\langle f(p), V(p) \rangle = \sum_{i,s_i} f_{i,s_i}(p) V_{i,s_i}(p)$$

$$\begin{aligned}
&= \sum_{i,s_i} f_{i,s_i}(p) p_{i,s_i} (f_{i,s_i} - \bar{f}_i) \\
&= \sum_{i,s_i} f_{i,s_i}^2 p_{i,s_i} - (\sum_{i,s_i} f_{i,s_i}(p) p_{i,s_i})^2 \quad (12)
\end{aligned}$$

Using Jensen's inequality, the previous term is indeed strictly positive whenever $V(p)$ non-zero is. Thus, the Replicator dynamic $V(p)$ is Positively Correlated (PC).

This result is interesting in game theory since a positively correlated dynamic converges if there exists a positive function $F(p)$ whose partial derivatives are $f_{i,s_i}(p)$. The function F is then called the Potential Function of the system. Now let us prove that such a function exists in our game and that is the total utility of the system corresponding to the system state p :

$$F(p) = \sum_s [\sum_i U_i(s) \prod_j p_{j,s_j}] \quad (13)$$

According to **Definition 1**, $F(p)$ is a \mathcal{C}^1 -function from \mathcal{P} to \mathbb{R}^+ such that

$$\forall i, \forall s_i: \frac{\partial F}{\partial p_{i,s_i}} = f_{i,s_i}(p) \quad (14)$$

The proof of this theorem is straight by replacing the term $p_{i,0}$ in $F(p)$ by $(1 - \sum_{s_i} p_{i,s_i})$.

Thus, $F(p)$ is the Potential Function which represents the system through the equations (2) and increases strictly as the system evolves following the dynamic $V(p)$. Our game is then called a Potential Game [Monderer]. We have the following corollary:

Corollary 1: As the dynamic $V(p)$ is PC and there exists the Potential Function $F(p)$, the dynamic $V(p)$ converges. Moreover, all Nash equilibria of the game are stationary points of $\dot{p} = V(p)$.

3.4 Efficiency of the equilibrium points

The probability vector \hat{p} is a equilibrium point if and only if for all players i and for all strategies s_i ,

$$or \begin{cases} \hat{p}_{i,s_i} = 0 \\ f_{i,s_i}(\hat{p}) = \bar{f}_i(\hat{p}) \end{cases}$$

These are Kuhn-Tucker first order conditions [Karush], [Kuhn], and [Alibert] of the Lagrange dual problem of the optimization

$$\max_p F(p)$$

We noted earlier that all profitable strategy revisions lead to increases in potential. This suggests that the Nash equilibria of the game are related to the local maximizers of potential. The Lagrangian for this maximization problem is

$$L(p, \mu, \lambda) = f(p) + \mu(1 - \sum_{i \in S} p_{i,s_i}) + \sum_{i \in S} \lambda_i p_{i,s_i}$$

so the Kuhn-Tucker first-order necessary conditions are

$$\frac{\partial f}{\partial p_{i,s_i}}(p) = \mu - \lambda_i \quad (15)$$

$$\lambda_i p_{i,s_i} = 0 \quad (16)$$

$$\lambda_i \geq 0 \quad (17)$$

for all $i \in S$

Theorem 2: The state p is a Nash equilibrium of the potential game F if and only if (p, μ, λ) satisfies equations (15), (16), and (17).

Prof: If p is a Nash equilibrium of F , then since $F(p) = \nabla f(p)$ the Kuhn-Tucker conditions are satisfied by p , $\mu = \max_j F_j(p)$ and $\lambda_i = \mu - F_i(p)$.

Conversely, if (p, μ, λ) satisfies the Kuhn-Tucker conditions, (KT1) and (KT2) imply that $\frac{\partial f}{\partial p_{i,s_i}} = F_i(p) = \mu_n$. Furthermore, (15) and (17) imply that $F_i(p) = \mu - \lambda_i \leq \mu$.

Hence, $p \in \operatorname{argmax}_j F_j(p)$.

As a result, all equilibrium points \hat{p} are solutions of the optimization problem of the total system utility $F(p)$. In conclusion, the Replicator dynamic converges, all Nash equilibrium points are stationary points of this dynamic, and furthermore, these limits maximize the total utility of the system.

On top of that, note that the total utility and the average reward of each player in our strategic game are all functions of probabilities of selecting strategies. Thus, we do not need to specify the terminals' utility functions $U_i(s)$ throughout this section. Given this point, our theoretical results are valid for any general utility function $U_i(s)$ which depends on the whole system state.

3.5 Nash learning algorithm

In the above, we proved that our application-based model converges and the stationary points, including all Nash equilibria, are efficient as they are solutions of the total utility maximization problem. These interesting properties hold if the system evolves following the Replicator dynamic. The question is then, in the real system, how to lead all terminals to evolve at exactly the rate given in equation (11).

In this work, we consider the Nash learning algorithm ([Barth] and [Touati]) that is equivalent to the Replicator dynamic V and converges to the same stationary points. At each time epoch, the algorithm tells each player to how to adapt its own strategy, or more precisely its probabilities of selecting strategies, as we consider mixed strategy, in order to get a better reward.

1. At the beginning, initialize arbitrary vectors $p_i(0)$ for all players.
2. At each time epoch t , for each player i do
 - Take a random decision $s_i(t)$ with probability $p_{i,s_i(t)}(t)$.
 - Update probabilities of selecting strategies:

Receive the rewards $r_i(s(t))$ for all $s_i \in \mathcal{S}_i$.

For all $s_i \in \mathcal{S}_i$, set $p_{i,s_i}(t+1)$ equal to

$$p_{i,s_i}(t) + b(t)r_i(s_i, s_{-i}(t))(\delta_{s_i(t),s_i} - p_{i,s_i}(t)) \quad (18)$$

where $b(t)$ is the step size at time epoch t ; $\delta_{s_i(t),s_i}$ is equal to 1 if $s_i(t) \equiv s_i$ and 0 otherwise.

The affectation of probabilities of selecting strategies given in equation (13) ensures that each player evolves in the same way as in the Replicator dynamic specified by the

rate (11). At each time epoch, the step size $b(t)$ retains all probability values in the interval $(0,1)$ and allows the algorithm to control the convergence speed of the system.

4 Implementation and validation

This section is devoted to the implementation aspects and simulation results.

4.1 Implementation

In the previous section, we showed that the theoretical results are valid for any general utility function. However, in concrete simulation scenarios, the reward function and then all updates in the Nash learning algorithm depends strongly on the utility function, and the marginal cost is closely related to the resource allocation mechanism. Thus, in the following sub-sections, we propose a specific utility function as well as a bandwidth allocation scheme.

4.1.1 Utility function

For the implementation purposes, we adopt the interface utility function as described in Chapter 4. In this utility function are considered two main aspects in associating the applications to the network interfaces: satisfy the applications and economize the energy consumption of the terminal. The satisfaction level of the applications is expressed for each type of application and depends on the available bandwidth provided by the network. The applications are categorized into three types: real-time, adaptive and elastic (see Figure 28a, b and c, respectively)

On the other hand, each network interface has specific characteristics in terms of energy consumption depending on the hardware characteristics. The battery consumption (Q) of each interface for transmitting M bits is a function of the energy consumption for transmitting one bit on the interface and the volume of data (e.g., M bits) transferred by the interface. In our experiment, the data volume is evaluated according to the application type. It depends on the available bandwidth for the elastic applications and the bandwidth requirements for the rate/delay-adaptive and hard-real-time applications.

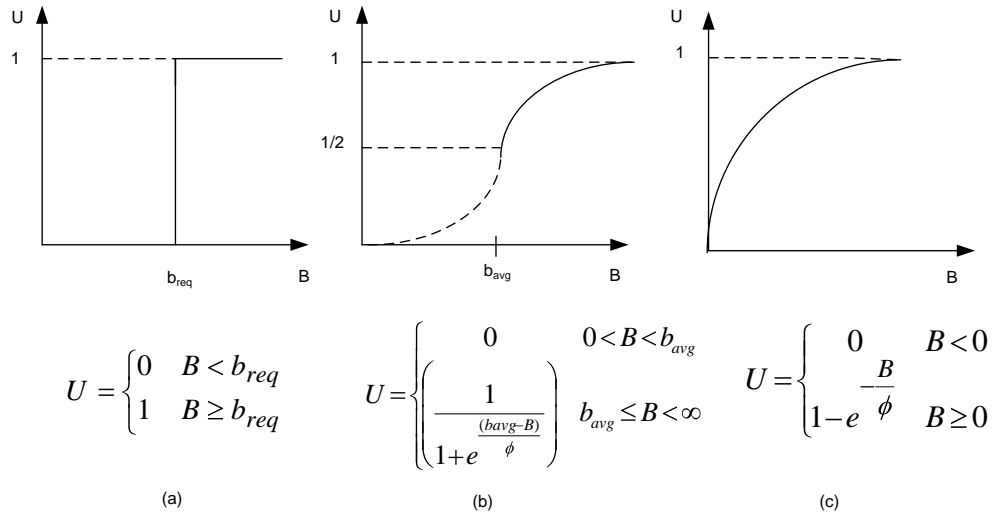


Figure 27- Application satisfaction level in terms of bandwidth

Let $L_{i,a_l}(s)$ be the satisfaction level of application a_l associated the network cell $s_i(a_l)$. Let $Q_{i,a_l}(s)$ be the battery consumption when the application a_l uses the interface $s_i(a_l)$. The interface utility for the application a_l using the network interface $s_i(a_l)$ is described as follows:

$$U_{i,a_l}(s) = \alpha_i L_{i,a_l}(s) + \beta_i Q_{i,a_l}(s)$$

where α, β are the weights which indicate the relative importance between the application utility and the battery consumption.

The utility of the terminal i is given by

$$U_i(s) = \sum_l U_{i,a_l}(s).$$

4.1.2 Bandwidth allocation

As discussed in the previous chapter, many applications can be connected to the same network and each of them seeks for increasing the reward value which depends strongly on the allocated bandwidth (see Figure 29). As it is impossible to maximize the utility functions for all applications at the same time, the network has to implement a specific bandwidth allocation scheme which may respond to the application needs. The simplest idea is to share the available bandwidth fairly for all applications.

However, many other schemes could be envisaged. In our bandwidth allocation strategy, each application type has a priority order. The network available bandwidth is offered consecutively to application types from high to low priorities. Nevertheless, all applications of the same type should be treated fairly, i.e. receive the same amount of bandwidth. This is more flexible than the above mentioned scheme that treats all applications equally, since decreasing (or increasing) the number of types strengthens fairness (or efficiency) of the bandwidth allocation scheme. In fact, considering only one type gives the previous scheme with a perfect fairness.

Now, if the bandwidth provided by the network is insufficient to ensure the applications' satisfaction, a strict policy is applied: these applications receive nothing and all available bandwidth is reserved to applications of lower priorities. This strict policy tells terminals to avoid bottleneck situations where too many applications are associated to the same network; therefore it allows deploying efficiently the network resources.

4.2 Simulations

In this section, we present the simulation results of the Nash learning algorithm through two simulation scenarios.

During the run time of the algorithm, each terminal stays connected to all available networks. Thus, it may transfer to these networks its utility values calculated from the current connection state while receiving the utility values of others from these networks. From this information, each terminal calculates the reward corresponding to each connection strategy. Its probability vector is then updated at each time epoch. Each terminal then chooses a strategy of flow/interface association according to the probability vector. The convergence is reached once the probability vector of terminal i becomes unchanged.

4.2.1 Scenario 1 (Simple scenario)

For this scenario, a simulation model was developed using two mobile terminals integrating two network interfaces: Wi-Fi 802.11b, and WiMAX 802.16a with overlapping coverage zones. Their average energy consumption is $1\mu\text{J/bit}$ and $20\mu\text{J/bit}$,

respectively. We assume that, at the beginning of the simulation, the available bandwidth of the Wi-Fi and WiMAX is 40Kbps and 80Kbps, respectively.

We consider that the terminal 1 initiates a hard-real-time application (PCM VoIP flow) which requires 64Kbps, and the terminal 2 initiates a hard-real-time application (AD PCM VoIP flow) which requires 32Kbps.

Table 21- Rewards for each strategy selection

(Terminal 1, Terminal 2)	Interface 1	Interface 2
Interface 1	(0,0)	(0,0.05)
Interface 2	(0.488,0.012)	(0,0)

Before running the simulation, we calculate manually the utility values since the game is simple and each terminal has only two flow/interface association strategies. For each association strategy, the reward for each terminal is calculated using the utility function and the bandwidth allocation scheme presented in section 3.1. The numerical values are provided in Table 19. When the two terminals select the same interface 1 (or 2), they have no utility since the sum of the bandwidth requirement is larger than the available bandwidth. The calculation results show that Nash equilibria exist uniquely and an effective algorithm should lead the system to situations where the terminal 1 connects to interface 2 and the terminal 2 connects to the interface 1.

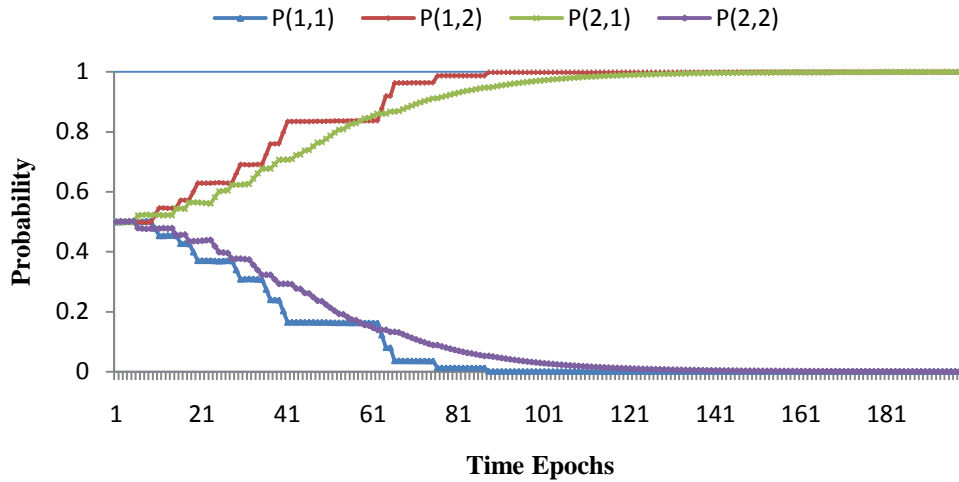


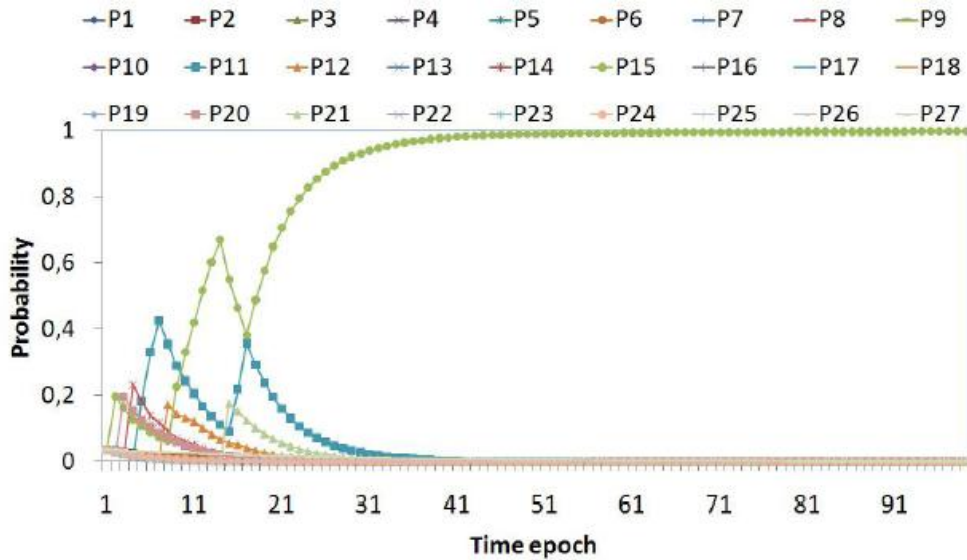
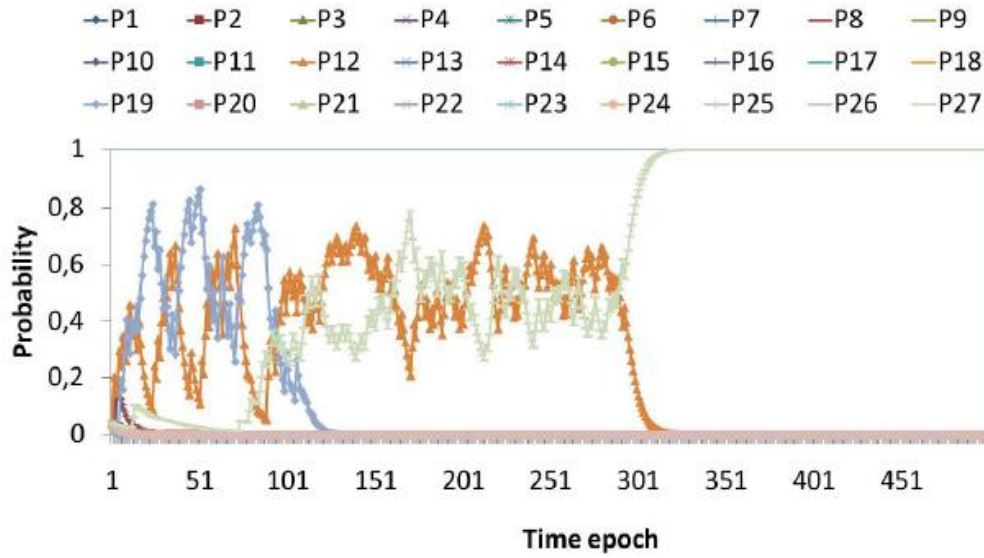
Figure 28- The evolution of the strategy selecting probabilities

In this simulation, the probability vector stays unchanged from the 125th time epoch (Figure 29). The stationary point is one of the optimal Nash equilibria, where the terminals 1 and 2 select respectively the interfaces 2 (WiMAX) and 1 (Wi-Fi). This flow/interface association renders the rewards (0.488, 0.012) calculated manually in Table 17. And this is a pure strategy as the terminals choose the corresponding strategies with probability 1.

4.2.2 Scenario 2

In this scenario, we consider three mobile terminals integrating three access network interfaces: Wi-Fi 802.11b, Wi-Fi 802.11a and WiMAX 802.16a. Their average energy consumption is 1μJ/bit, 5μJ/bit and 20μJ/bit, respectively. At the beginning of the simulation, the network available bandwidths are 1Mbps, 2Mbps and 2.5Mbps, respectively. All terminals are in the overlapping coverage zones of these networks.

In addition, we consider three application flows. Each terminal initiates simultaneously an FTP application (elastic application), a CD-like audio streaming flow requiring 150Kbps (rate-adaptive application) and a PCM VoIP flow requiring 64Kbps (hard-real-time application).



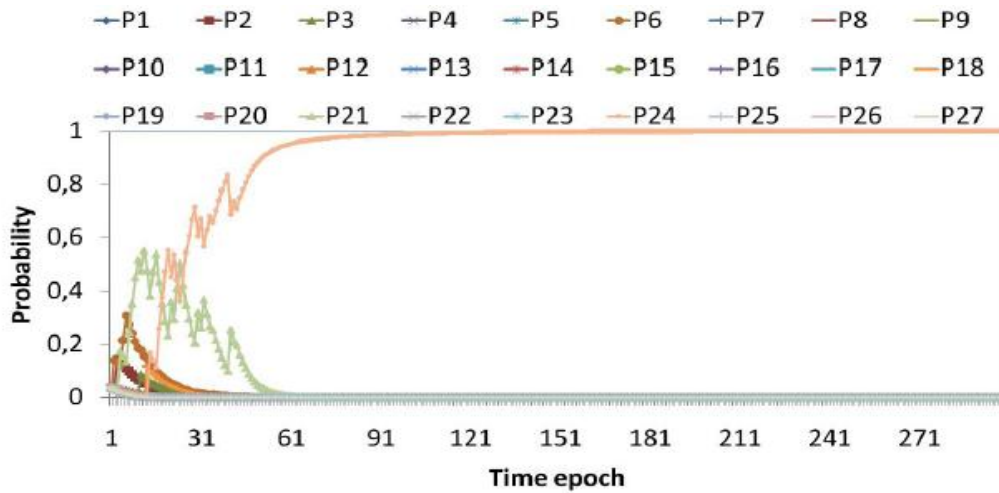


Figure 29- The evolution of the probability vectors of the terminals 1, 2 and 3

Each time slot, the system runs 1000 time epochs. Each terminal has 27 possible strategies to choose. The probability vectors are recalculated at each time epoch and are updated.

To study several Nash equilibria, we have carried out several simulations on the same scenario.

The result in Figure 31 represents the evolution of the probability vector of each terminal and it shows that the probability vectors of the terminals 1, 2 and 3 converge to Nash equilibrium at the 325th, 51th and 88th time epoch, respectively. The 27th, 15th and 24th strategies are selected by the terminal 1, 2 and 3, respectively.

These strategies mean that the applications of the terminal 1 have to be associated to the interface 3 (WiMAX). Meanwhile, the terminal 2 associates their hard-real-time, adaptive and elastic applications to the interfaces Wi-Fi 802.11b, Wi-Fi 802.11a and WiMAX respectively; the terminals 3 associates the elastic application to the WiMAX interface while associating the other applications to the interface Wi-Fi 802.11a.

4.2.3 Discussion

In this chapter, we present a system as a strategic game. The game aims at reaching the Nash equilibria which optimize the total system utility. The network influences the choices of the terminals by charging each terminal the marginal cost of accessing the network resources. To calculate the reward and to update its probabilities of selecting strategies, the system needs to know the utility values of all terminals. It is very interesting if we consider various models that allows the network charging different cost for other objectives or even does not influence the decisions of the terminals and lets the terminals evolve selfishly.

Moreover, we discuss the algorithm complexity issue. The convergence time is the time that the system converges to the Nash equilibria, where the probabilities of selecting strategies are unchanged (e.g., stay at 1 in our simulations). The computational complexity to determine these probabilities has a linear complexity, or $O(n)$ where n is the total number of the strategies (depending on the number of terminals and the applications). Thus, the convergence time of the system is linear with n . Although this algorithm demonstrates the system converges to Nash equilibria, the algorithm complexity issue needs a further improvement for scalability purpose [Auer].

5 Summary

In conclusion, we have used evolutionary game theory to model a system of multi-interface mobile terminals where the terminals associate each of their running applications to a specific network interface according to the application-based utility function and the marginal cost charged by the network. We have proven that our model converges to efficient Nash equilibria giving the optimal system utility. The system implementation is presented to validate the proposed model.

Chapter 6: Conclusion

Thank to the development and the advancement of mobile and wireless technologies, mobile terminals are becoming more and more powerful with many advantages, multiple functionalities and multi-network interface support. In this context, the mobile terminals are able to select the best network interface among available ones or to select the suitable network interface for each application.

Since the candidate radio access networks vary in characteristics (e.g., technology, capability, pricing ...) and capacity of the mobile terminals is dynamically changing depending on several factors (i.e., the load, the battery life ...), the decision is not trivial. Intelligent and dynamic algorithms should be defined so that allowing the mobile terminals to select the best interface or to associate the application flows to various network interfaces satisfying decision objectives basing on multiple attributes (e.g., application characteristics, user preferences, networks characteristics, operator policies, tariff constraints).

The thesis identifies the problems related to multi-attribute network/interface selection and flow/interface association decision algorithms. It proposes and evaluates both terminal and network centric solutions.

The first contribution of the thesis is to study and analyze the Multiple Attribute Decision Making (MADM) methods for the interface selection issue. The work highlights and identifies the limitations of the methods. The Distance to the ideal Alternative (DiA) algorithm is proposed as an improvement of the MADM methods.

As the next step, we tackle and identify the flow/interface association issue. We consider mainly two models: single and multiple flow/interface association models.

The association decision takes mainly into account the application requirements. Besides, the terminal energy consumption is also considered. It is significant constraint for multi-interface terminal. The energy should be efficiently used to maintain the terminal activities.

The second contribution proposes an interface utility that considers the satisfaction level of the application and the terminal energy consumption.

We then propose a single flow/interface association scheme that allows to associate each application to the suitable interface considering not only the interface utility but also network side attributes such as access delay, cost of the network. The scheme is based on the use of the Distance to the ideal Alternative (DiA) algorithm that allows ranking the interfaces based on the interface utility value, access delay, and cost of the network.

The third contribution proposes a multiple flow/interface association scheme that allows mobile terminal associating simultaneously its applications to the network interfaces maximizing the global terminal utility. A simulation based comparative study of stochastic heuristic optimization methods (i.e., Tabu search and simulated annealing algorithms) is presented. It identifies their limitations in our context. We then propose an oriented diversification of the Tabu search as an improvement. Simulation results shows that the modified Tabu search outperforms the other methods in the specific context of the flow/interface association.

To validate and study feasibility of the single flow/interface association scheme, a work which aims at implementing the proposal in a practical test-bed has been initiated.

We then consider a network-centric approach for addressing the flow/interface association issue. In particular, game theory is adopted as a modeling tool. In this context, each terminal can distribute its applications on different interfaces available according to various utility functions. The model allows the system to converge to equilibrium points that optimize the global utility of system. An implementation is

proposed to validate the proposal and shown that this game converges always to the Nash equilibrium.

Open issues remain for future works.

In the single flow/interface association model, we consider the available bandwidth, the energy consumption, the access delay, and the cost of using network as main attributes. The relative importance between the attributes is indicated through weight values. In the scheme, the available bandwidth attribute has the highest priority weight. This is due to the fact that the satisfaction level of the application is an important aspect in the flow/association issue. Besides, the terminal energy consumption objective is weighted as the next priority level. This consideration is due to the multi-interface mobile terminal energy efficiency issue. The monetary cost and the rapid connection objectives are considered at lower level.

However, MADM based solution that we develop (i.e., the DiA algorithm) allows adding other attributes and defining another relative importance of attributes. Other network attributes can be added to consider more selection objectives. For example, the users aim to connect to the cheapest networks rather than considering the rapid connection. The security of the network interface is considered as an important goal while associating the application to the interface, etc.

Moreover, an open issue concerns with the weight setting. How can we define exactly the relative importance of attributes? In our context, the weights are estimated by human judgment. For example, the scale of relative importance between attributes can be judged as same importance, slightly more important, weekly more important, moderately more important, strongly more important, or absolutely more important, etc. The weighting issue should be investigated so that increasing the accuracy of the selection objective.

The multiple flow/interface association allows associating the applications to the interfaces maximizing the global terminal utility. The scheme could consider *social optimal* and *fairness* issues. In other words, the scheme associates simultaneously the applications to the interfaces that not only optimizes the global terminal utility but also considers the fair satisfaction level of each application.

Considering the network centric flow/interface association model based on theoretical game, the network influences the choices of the terminals by applying a marginal cost of accessing the network resources and by this intervention, achieves its goal of optimizing the total system utility. It would be interesting to consider a variant model where the network charges a different cost for other objectives, or even does not influence the decisions of the terminals and lets the terminals evolve selfishly.

In the second part of the work, the analytical results have been validated by two simulation scenarios implementing the Nash learning algorithm and a specific bandwidth allocation scheme as well as a utility function. The simulation evidences have shown that the Nash learning algorithm converges indeed to Nash equilibria. Our ongoing works focus on the algorithm complexity and convergence speed. Besides, the network performance in terms of throughput and QoS parameters are measured considering large scale simulation scenarios.

Appendix : Stochastic Heuristic Algorithms

This appendix presents stochastic heuristic algorithms such as *local search*, *Tabu search*, *simulated annealing* and *genetic algorithm* in a detailed manner.

1 Notion of Neighborhood

A basic concept of stochastic heuristic optimization methods is the neighborhood. A neighborhood of point x is $N(x)$ in global space S satisfying the following conditions:

$$\begin{aligned} x &\in S, \\ N(x) &\subseteq S \\ x &\notin N(x). \end{aligned}$$

2 Local Search

The local search algorithm allows identifying the local optimization (i.e., either maximal or minimum) in its neighborhoods. The searching space is limited within a set of neighborhoods (i.e., $N(x)$).

The local search method for minimizing a given objective function (F), for example, can be formalized as presented bellow.

Local Search Algorithm with Steepest Descent (SDLS)

procedure SDLS

begin

choose_initial_point(x);

choose_neighborhoods_of_x ($N(x)$);

repeat

$z := x$;

for $y \in N(x)$ **do** **if** $F(y) < F(z)$ **then** $z := y$;

until $z = x$

end { *procedure* }

The algorithm firstly selects randomly an initial point x in the global space S . As the definition of neighborhood, each point x may have several a set of the neighborhoods (i.e., $N(x)$). The algorithm then selects a set of the neighborhoods $N(x)$ of x among many sets of neighborhoods. The local minimum of $N(x)$ will be identified. If we consider that $N(x)$ is equal to the global space S , the *SDLS* algorithm will determine the global minimum of S .

3 Tabu Search (TS)

The general TS algorithm can be described in steps as follows:

Tabu Search algorithm (TS) for the minimization problems

procedure TS

begin

choose initial point(x); $F^{best} := F(x)$; $x^{best} := x$;

Randomly select a set of neighbor $N^* := N(x)$;

Tabu_list := \emptyset ;

while *stopping criterion* **not true** **do**

begin

$y := \text{worst_neighbor}(N^*)$;

if $F(y) \leq F^{best}$ **then**

begin $F^{best} := F(y)$; $x^{best} := y$

```

        if  $y \notin T$  ; then
            begin
                add (Tabu_list);
                 $x := y$ ;
            end
        else
            begin
                update (Tabu_list );
                Diversification:
                Randomly select initial point  $x$ 
            end
        else
            update (Tabu_list );
            Diversification:
            Randomly select initial point  $x$ 
        end
    end
end { procedure }

```

Step 1: Set the Tabu list ($T = \emptyset$) and randomly generate an initial solution $x_{initial}$. Set this solution as the current solution $x_{current}$ as well as the best solution x_{best} (i.e., $x_{initial} = x_{current} = x_{best}$).

Step 2: Randomly select a set of neighbors of the current solution, $N(x_{current})$.

Step 3: Sort the neighbors based on their objective function values in ascending order as the problem is a minimization one. Assume that y represents the worst neighbor solution in $N(x_{current})$.

Step 4: If $F(y) \leq F(x_{best})$, set $x_{best} = y$ and go to step 5. Otherwise, go to step 7.

Step 5: Check the Tabu status of y . If it is not in the Tabu list then put it in the Tabu list, set $x_{current} = y$, and go to Step 8. If it is in Tabu list go to Step 6.

Step 6: set $x_{current} = y$, randomly generate an initial point $x \in N(x_{current})$ and go to Step 8.

Step 7: If $F(y) > F(x_{best})$, update Tabu list and randomly generate an initial point x and go to Step 8.

Step 8: Check the stopping criteria. If one of them is satisfied then stop, else go back to Step 2.

4 Simulated Annealing Algorithm (SA)

The SA algorithm can be described in steps as follows:

Simulated Annealing (SAN) for the minimization problems

```

procedure SAN
    begin
        choose_initial_point( $x$ );  $x^{best} := x$ ;  $F^{best} = F(x)$ 
         $T := T^0$ ;
        while stopping_criterion not true
            begin
                 $z := \text{random\_neighbor}(N(x))$ ;
                 $\Delta F := F(z) - F(x)$ ;
                if  $\Delta F \geq 0$  then
                    begin

```

```

        x := z;
        if F(x) ≥ Fbest then begin Fbest := F(x); xbest := x end;
    end
    else if random(0,1) < e-ΔF/T then x := z;
    reduce(T);
end { procedure }

```

Step 1: Set the controlled parameter $T = T^0$ and randomly generate an initial solution $x_{initial}$. Set this solution as the current solution $x_{current}$ as well as the best solution x_{best} (i.e., $x_{initial} = x_{current} = x_{best}$).

Step 2: Randomly select a solution y in the neighborhood of the current solution $N(x_{current})$.

Step 3: Calculate $\Delta F = F(y) - F(x_{current})$.

Step 4: If $\Delta F \leq 0$, set $x_{current} = y$, else the (uphill) move is accepted with probability $e^{-\frac{\Delta F}{T}} > random(0,1)$.

Step 5: The controlled parameter reduction is $T := \tau T$, for some parameter τ from interval $(0,1)$, e.g., $\tau = 0.99$.

Step 6: Check the stopping criteria. If $T = 0$, the algorithm stops.

5 Genetic Algorithm (GA)

The GA can be described in steps as follows:

- **Step 1 [Start]** Generate random population of n chromosomes (suitable solutions for the problem)
- **Step 2 [Fitness]** Evaluate the fitness $f(x)$ of each chromosome x in the population
- **Step 3 [New population]** Create a new population by repeating following steps until the new population is complete
 1. **[Selection]** Select two parent chromosomes from a population according to their fitness (the better fitness, the bigger chance to be selected)
 2. **[Crossover]** With a crossover probability cross over the parents to form a new offspring (children). If no crossover was performed, offspring is an exact copy of parents.
 3. **[Mutation]** With a mutation probability mutate new offspring at each locus (position in chromosome).
 4. **[Accepting]** Place new offspring in a new population
- **Step 4 [Replace]** Use new generated population for a further run of algorithm
- **Step 5 [Test]** If the end condition is satisfied, **stop**, and return the best solution in current population
- **Step 6 [Loop]** Go to step 2

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Acronyms

2G	<i>Second Generation Mobile Phone Technology</i>
3.5G	<i>An intermediate step between 3G and 4G Mobile Phone Technology</i>
3G	<i>Third Generation Mobile Phone Technology</i>
4G	<i>Fourth Generation Mobile Phone Technology</i>
ABC	<i>Always Best Connected</i>
AHP	<i>Analytic Hierarchy Process</i>
AMPS	<i>Advanced Mobile Phone System</i>
AP	<i>Access Point</i>
B3G	<i>Beyond Third Generation Mobile Phone Technology</i>
BER	<i>Bit Error Ratio</i>
BNN	<i>Brown-von Neumann-Nash</i>
BSC	<i>Base Station Controller</i>
BSS	<i>Base Station Subsystem</i>
BTS	<i>Base Transceiver Station</i>
CBR	<i>Constant Bit Rate</i>
CDMA	<i>Code Division Multiple Access</i>
CDMA2000	<i>A registered trademark of the Telecommunications Industry Association (TIA-USA) in the United States. There are several versions such as CDMA2000</i>
C-NETZ C	<i>Network - first-generation analog network in Germany</i>
CS	<i>Consumer Surplus</i>
CSMA/CA	<i>Carrier Sense Multiple Access with Collision Avoidance</i>
D-AMPS	<i>Digital AMPS</i>
DCF	<i>Distributed Coordination Function</i>
DECT	<i>Digital Enhanced Cordless Telecommunications</i>
DVB-H	<i>Digital Video Broadcast - Handheld</i>
DVB-T	<i>Digital Video Broadcast - Terrestrial</i>
DVD	<i>Digital Versatile Disc</i>
D-VH	<i>Downward Vertical Handover</i>
EDGE	<i>Enhanced Data Rates for GSM Evolution</i>

EV-DV	<i>(Code Division Multiple Access (Evolution-Data/Voice)), 2.5G CDMA2000</i>
FTP	<i>File Transfer Protocol</i>
G.711	<i>ITU-T standard for encoding audio</i>
GA	<i>Generic Algorithm</i>
GPRS	<i>General Packet Radio Service</i>
GSM	<i>Global System for Mobile Communication</i>
HIPERLAN	<i>High PERformance Radio LAN</i>
HSCSD	<i>High Speed Circuit-Switched Data</i>
HSDPA	<i>High Speed Downstream Packet Access</i>
HSUPA	<i>High Speed Upstream Packet Access</i>
HTTP	<i>Hypertext Transfer Protocol</i>
ICT	<i>Information and Communication Technology</i>
IEEE	<i>Institute of Electrical and Electronics Engineers</i>
IETF	<i>Internet Engineering Task Force</i>
IP	<i>Internet Protocol</i>
IrDA	<i>Infrared Data Association</i>
ISP	<i>Internet Service Provider</i>
LAN	<i>Local Area Network</i>
MAC	<i>Media Access Control</i>
MADM	<i>Multiple Attribute Decision Making</i>
MIP	<i>Mobile IP</i>
MIPv6	<i>Mobile IPv6</i>
MPEG	<i>Moving Pictures Expert Group</i>
MSC	<i>Mobile Switching Centre</i>
NC	<i>Network Centric</i>
NCHO	<i>Network Controlled Handover</i>
NE	<i>Nash Equilibrium</i>
NMT	<i>Nordic Mobile Telephony</i>
OS	<i>Operating System</i>
OSI	<i>Open Systems Interconnection</i>
PC	<i>Positively correlated</i>
PDA	<i>Personal Digital Assistant</i>
PHY	<i>Physical layer</i>

<i>PLMN</i>	<i>Public Land Mobile Networks</i>
<i>QoS</i>	<i>Quality of Service</i>
<i>RAN</i>	<i>Radio Access Network</i>
<i>RAT</i>	<i>Radio Access Technology</i>
<i>RSS</i>	<i>Received Signal Strength</i>
<i>RTP</i>	<i>Real-Time Transport Protocol</i>
<i>RTT</i>	<i>Round Trip Time</i>
<i>SA</i>	<i>Simulated Annealing Algorithm</i>
<i>SAW</i>	<i>Simple Additive</i>
<i>SINR</i>	<i>Signal to Interference plus Noise Ratio</i>
<i>SMS</i>	<i>Short Message Service</i>
<i>SNR</i>	<i>Signal-to-Noise Ratio</i>
<i>TCP</i>	<i>Transport Control Protocol</i>
<i>TDMA</i>	<i>Time Division Multiple Access</i>
<i>TD-SCDMA</i>	<i>Time Division - Synchronous Code Division Multiple Access</i>
<i>TOPSIS</i>	<i>Technique for Order Preference by Similarity to Ideal Solution</i>
<i>TS</i>	<i>Tabu Search Algorithm</i>
<i>UDP</i>	<i>User Datagram Protocol</i>
<i>UMTS</i>	<i>Universal Mobile Telecommunication System</i>
<i>U-VH</i>	<i>Upward Vertical Handover</i>
<i>UWB</i>	<i>Ultra Wideband</i>
<i>VoIP</i>	<i>Voice over IP</i>
<i>WAN</i>	<i>Wide Area Network</i>
<i>WAP</i>	<i>Wireless Application Protocol</i>
<i>W-CDMA</i>	<i>Wideband Code Division Multiple Access</i>
<i>Wi-Fi</i>	<i>Wireless Fidelity</i>
<i>WiMAX</i>	<i>Worldwide Interoperability for Microwave Access</i>
<i>WLAN</i>	<i>Wireless Local Area Network</i>
<i>WP</i>	<i>Weighting Method</i>

