

Link-State Routing Optimization for Compound Autonomous Systems in the Internet

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#### ARPANET, 1969

(from <a href="http://som.csudh.edu/cis/lpress/history/arpamaps/">http://som.csudh.edu/cis/lpress/history/arpamaps/</a>)



#### Internet connections in the US, 2009

(map by Z. Deretsky, NSF, adapted from maps by C. Harrison, Human-Computer Interaction Institute of CMU, <u>www.chrisharrison.net</u>)



#### □ Size : connections, hosts, users...



~ 850 Mhosts (Internet Domain Survey Count, July 2011)

#### □ Routing architecture : ARPANET → Internet



Complexity : types of interconnected networks





#### Autonomous Systems



- Routing autonomy
- Inside / outside







□ Wireless ad hoc networks

- Topology unknown a priori
- May change unpredictably during network operation





#### □ Applicability of wireless and ad hoc networks



Rescue and recovery scenarios



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Rescue and recovery scenarios



Vehicular networks (VANETs)



#### □ Applicability of wireless and ad hoc networks



Wireless sensor networks (WSNs)



Rescue and recovery scenarios



Vehicular networks (VANETs)



#### □ Applicability of wireless and ad hoc networks



Wireless sensor networks (WSNs)



Vehicular networks (VANETs)



#### Rescue and recovery scenarios



Spontaneous / community mesh networking



- □ Issues of wireless ad hoc networking
  - Wireless "links", partly shared medium

Unreliability in wireless communication

Topology dynamism and router mobility



Degradation of communication vs wireless links











#### □ Key questions

- Why addressing routing in compound Autonomous Systems ?
- One or several routing solutions for a compound AS ?



#### □ Key questions

- Why addressing routing in compound Autonomous Systems ?
  - Currently deployed IGPs do not work in wireless ad hoc networks

One or several routing solutions for a compound AS ?



#### □ Key questions

- Why addressing routing in compound Autonomous Systems ?
- One or several routing solutions for a compound AS ?







#### □ How ?

Extension of an already used IGP for wireless ad hoc operation

 Open Shortest Path First (OSPF) : one of the main link-state IGPs



# **Link-State Routing**











# Link-State Routing LSA Acquisition

□ Routers advertise all their neighbors in their own LSA

□ Routers retransmit every LSA they receive immediately



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□ Routers retransmit every LSA they receive immediately



□ Every pair of routers have the same information in their LSDBs

□ All routers receive LSAs from every other router in the network



# Link-State Routing Link State Operations

□ Routers advertise *all* their neighbors in their own LSA

□ Routers retransmit *every* LSA they receive *immediately* 





□ Every pair of routers have *the same* information in their LSDBs

LSDB Synchronization

□ All routers receive LSAs from *every other* router in the network



### Link-State Routing Link State Routing over Wireless Ad hoc Networks

	<u>Objective</u>	<u>Open issues</u>	Reduction goals
<ul> <li>Topology view</li> </ul>	Routes towards destinations	Shortest paths	Adv. links, updates
Flooding	Dominating set of forwarders	Wireless collisions	Txs, latency
<ul> <li>Synchronization</li> </ul>	Synchronized paths	LSDB exchange	Synchronizations

 J. A. Cordero, E. Baccelli, P. Jacquet, T. Clausen: Wired/Wireless Compound Networking. In: Xin Wang (ed.): Mobile Ad-Hoc Networks – Applications, InTech Publisher, ISBN 978-953-307-416-0, Jan. 2011.
 J. A. Cordero, P. Jacquet, E. Baccelli: Impact of Jitter-based Techniques on Flooding over Wireless Ad hoc Networks: A Theoretical Approach. (under review for INFOCOM'31)

T. Clausen, E. Baccelli, P. Jacquet: **OSPF-style Database Exchange and Reliable Synchronization in OLSR**. Proc. IEEE Intl. Conf. on Sensor and Ad hoc Networks (SECON'04). Oct. 2004.



### Link-State Routing Link State Routing over Wireless Ad hoc Networks

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Separate optimization of each link-state operation over MANETs

 J. A. Cordero, E. Baccelli, P. Jacquet, T. Clausen: Wired/Wireless Compound Networking. In: Xin Wang (ed.): Mobile Ad-Hoc Networks – Applications, InTech Publisher, ISBN 978-953-307-416-0, Jan. 2011.
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Contributions

Optimization techniques for link-state routing over MANETs

□ Synchronized Link Overlay – Triangular (SLOT)

□ Multi-Point Relays (MPR)

□ Smart Peering (SP)

Application to OSPF

□ Implementation/Simulation of Extensions for MANETs

**D** Experiments in a Compound Internetwork



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# Optimization techniques Synchronized Link Overlay

□ Based on the Relative Neighborhood Graph (RNG)

Given a set of points  $S \subset \mathbb{R}^n$ ,  $x, y \in S$ ,  $(x, y) \in RNG(S) \Leftrightarrow \forall z \in S, d(x, z), d(z, y) > d(x, y)$ 



G. Toussaint: **The Relative Neighborhood Graph of Finite Planar Set**. In: Pattern Recognition, Vol. 12, Number 4, 1980.

J. Cartigny, F. Ingelrest, D. Simplot, I. Stojmenovic: **RNG Relay Subset Flooding Protocols in Mobile Ad-Hoc Networks**. In: Intl. Journal of Foundations of Computer Science, Vol. 14, Number 2. April 2003.



# Optimization techniques Synchronized Link Overlay

Two variants considered, depending on the metric in use:

SLOT-D (IR<sup>n</sup> distance)



SLOT-U (hop count)



[3] E. Baccelli, J. A. Cordero, P. Jacquet: Using Relative Neighborhood Graphs for Reliable Database
 Synchronization in MANETs. Proc. 5<sup>th</sup> IEEE SECON Workshop on Wireless Mesh Networks (WiMesh 2010), Jun. 2010.
 [4] E. Baccelli, J. A. Cordero, P. Jacquet: Optimization of Critical Data Synchronization via Link Overlay RNG in
 Mobile Ad Hoc Networks, Proc. 7<sup>th</sup> IEEE Intl. Conf. of Mobile Ad-hoc and Sensor Systems (MASS), Nov. 2010.





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## **Optimization techniques Synchronized Link Overlay**

Average number of links per node



 $M_{SLOT-U}(v) \le 3.6039$  $M_{SLOT-D}(v) \le 2.5575$ 

- Connected overlays
- Bounded overlay size

3,60 2,56



# Optimization techniques Synchronized Link Overlay

Average link creation rate for a node speed s



$$V_{SLOT-U}(s, v) \approx O(s)$$
$$V_{SLOT-D}(s, v) \approx O\left(s\sqrt{v}\right)$$

Improves overlay stability



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Optimization techniques Multi-Point Relays

#### Definition



- 2-hop neighborhood
- Designed for flooding
- Adaptation for topology selection

A. Qayyum, L. Viennot, A. Laouiti: **Multipoint Relaying for Flooding Broadcast Messages in Mobile Wireless Networks**. Proc. 35<sup>th</sup> IEEE Hawaii Intl. Conf. on Social Sciences (HICSS'35), Jan. 2002.

[5] J. A. Cordero: **MPR-based Pruning Techniques for Shortest Path Tree Computation**. Proc. 18<sup>th</sup> IEEE Intl. Conf. on Software Telecommunications and Computer Networks (SoftCOM2010), Sept. 2010.

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(Enhanced) Path MPR

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### Optimization techniques Multi-Point Relays



(GTNetS simulations, mobile network)

 Not adapted for LSDB synchronization

• High link change rate



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 Not adapted for LSDB synchronization

• High link change rate



[6] J. A. Cordero: Adjacency Persistency in OSPF MANET. Proc. 4<sup>th</sup> IET China-Ireland Intl. Conf. on ICTs (CIICT'10). Oct. 2010.



Contributions

Optimization techniques for link-state routing over MANETs

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**D** Experiments in a Compound Internetwork



Optimization techniques
Smart Peering

#### Definition



 Depends on the network dynamics

 Priority to synchronization with routers maintaining stable links

A. Roy: Adjacency Reduction in OSPF Using SPT Reachability. IETF Internet Draft, draft-roy-ospf-smart-peering-01, Nov. 2005.

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### **Optimization techniques**

#### □ Summary

	SLOT	MPR	SP
Requirements	1-hop neighbors	2-hop neighbors	Global topology knowledge
Topology Selection		Enhanced Path MPR	
Flooding		Full coverage in 2 hops	
LSDB Synchronization	Density bounded Reduced change rate (not dependent on density for SLOT-U)	High link change rate (⇒ persistency)	Sensitive to mobility Priority to stable links



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Application to OSPF
Open Shortest Path First

□ Two routing principles

- User data is forwarded over shortest paths
- User data & control traffic is sent over synchronized links





□ IETF OSPF MANET extensions

- Multipoint Relays (MPR-OSPF)
- MPRs, Smart Peering (OR / SP)



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Additional extensions

- MPR + SP
- SLOT-OSPF
- Persistent Variants of MPR-OSPF

[7] E. Baccelli, J. A. Cordero, P. Jacquet: Multi-Hop Relaying Techniques with OSPF on Ad Hoc Networks. Proc. 4<sup>th</sup> IEEE Intl. Conf. on Sensor Networks and Communications (ICSNC'2010), Sept. 2009.
[8] J. A. Cordero, E. Baccelli, P. Jacquet: OSPF over Multi-Hop Ad Hoc Wireless Communications. In: Intl. Journal of Computer Networks and Communications (IJCNC), Vol. 2, Number 5, Sept. 2010.



#### □ Extensions Overview

	MPR-OSPF RFC5449	OR/SP RFC5820	MPR+SP	SLOT-OSPF
Topology Selection	Path MPR	SP	Path MPR (+ SP)	Path MPR
Flooding	Flooding MPR	MPR o SP	Flooding MPR	Flooding MPR
LSDB Synchr.	MPR	SP	SP	SLOT





□ It is beneficial to preserve shortest paths for user data in MANETs



□ Synchronizing (all) shortest paths is costly in MANETs...



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[9] J. A. Cordero, T. Clausen, E. Baccelli: **MPR+SP – Towards a Unified MPR-based MANET Extension for OSPF**. Proc. 44<sup>th</sup> IEEE Hawaii Intl. Conf. on System Sciences (HICSS'44), Jan. 2011.

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□ Advertise synchronized links ?

MPR+SP vs. SLOT-OSPF



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**Experiments in a Compound Internetwork** 



□ Testbed : compound internetwork, 6 computers

{3 with wired interfaces
3 with wireless interfaces
2 with wired and wless interfaces

- Routing based on OSPF
  - OSPF for IPv6 (RFC 5340)
  - MPR-OSPF (RFC 5449)









Distribution of computers at LIX





Logical topologies considered in the internetwork





Logical topologies considered in the internetwork



Packet Delivery Ratio (/1)

□ Quality of communication degrades linearly as packets traverse more







Synchronization traffic is present during the whole lifetime of a wireless link

wless1:wlan0



### **Main contributions**

□ Enable the Internet to exploit wireless ad hoc networking capabilities

**Framework** for analysis of link-state routing in compound ASes

Optimization of link-state operations over MANETs

- Proposal of new techniques
- Theoretical analysis of existing techniques
- Improvement / generalization of techniques
- □ Implementation and evaluation in OSPF
  - Development and simulations of OSPF MANET extensions
  - Experiments over OSPF in compound internetworks



Perspectives

□ Towards a wireless, more mobile Internet

Optimizations in other link-state routing protocols

Metrics in ad hoc and compound networks

- Beyond hop count: link reliability, distance, available bandwidth, maximum throughput (ETX)...
- Fixed / ad hoc coexistence requires a clear distinction between wired and wireless links
- □ ... beyond the principle of deterministic shortest path ?



Link-State Routing Optimization for Compound Autonomous Systems in the Internet

## Questions ?



Link-State Routing Optimization for Compound Autonomous Systems in the Internet

## Backup slides



### Autonomous Systems

 RFC 975 (1986): "...a set of gateways, each of which can reach any other gateway in the same system using paths via gateways only in that system. The gateways of a system cooperatively maintain a routing data base using an <u>interior gateway protocol</u>..."

• RFC 1930 (1996): "...a connected group of one or more IP prefixes [internetworks] (..) which has a SINGLE and CLEARLY DEFINED routing policy."

RFC 1812 (1995): "...routers [inside an AS] may use one or more interior routing protocols..."



## Link Characterization

Definition (def. 1.5)

Let *a*, *b* be network interfaces.

There is a **link** *l* **between** *a* **and** *b*, denoted by  $l: a \rightarrow b$ , iff *a* is able to transmit data to *b* and *b* is able to receive such data, without the intervention of any other network interface.

Equivalence (def. A.1)

Let  $l_1: s_1 \rightarrow d_1, l_2: s_2 \rightarrow d_2$  be links.

 $l_1$  and  $l_2$  are **equivalent**, and denoted as  $l_1 \equiv l_2$  iff any of the following conditions is satisfied:

- (i)  $s_1 = s_2, d_1 = d_2$
- (ii)  $s_1 = s_2$ ,  $d_1 \neq d_2$  and any pkt sent from  $s_1$  to  $d_1$  (via  $l_1$ ) is also received by  $d_2$  (via  $l_2$ ), and viceversa
- (iii)  $s_1 \neq s_2$  and  $\exists l_{12}^*: s_1 \rightarrow s_2, l_{21}^*: s_2 \rightarrow s_1 \mid \text{any pkt sent from } s_1 \text{ to } d_1 \text{ (via } l_1 \text{) is also received by } s_2 \text{ (via } l_{12}^*) \text{ and } d_2 \text{ (via } l_2 \text{).}$
- (Prop. A.1) Relation  $\equiv$  is an equivalence relation.



#### **General Simulation Parameters**

- · 20 samples/experiment
- . Data traffic pattern
  - Constant Bit Rate UDP flow
  - Packet size: 1472 bytes
  - Packet rate: 85 pkts/sec
- Scenario
  - . Square grid
  - Grid size: 400x400 m
- . Node configuration
  - Radio range: 150 m
  - Propagation: Two-ray
  - Wireless α: 0,5
  - MAC protocol: IEEE 802.11b
- . Node mobility
  - Random waypoint model
  - Pause: 0 sec
  - Speed: 0, 5 m/s (ct.)

### **Simulation Parameters**

#### **Performed Experiments**

. Fixed size grid

#### **OSPF** Configuration

 Standard Parameters - HelloInterval: 2 sec DeadInterval: 6 sec • RxmtInterval: 5 sec • MinLSInterval: 5 sec MinLSArrival: 1 sec LSRefreshInterval: 20 sec RFC 5449-like AckInterval: 1.8 sec RFC 5820 AckInterval: 1.8 sec PushbackInterval: 2 sec



## **Testbed Configuration Parameters**

#### **Networking Interfaces**

- Wired : Digital Equipment Corp. DECchip 21140
- Wireless : Broadcom BCM4306 WLAN

#### Software

- OS : Ubuntu v.10.04, kernel 2.6.32
- Routing implementation : ospf6d daemon of Quagga/Zebra suite, v.0.99.15
- OSPF interface types
  - Wired : Point-to-point
  - Wireless : MANET, RFC 5449

#### **OSPF** Configuration

- HelloInterval: 2 sec
- DeadInterval: 10 sec
- RxmtInterval: 5 sec
- AckInterval: 2 sec
- Jitter (max.): 100 msec
- MinLSInterval: 5 sec
- MinLSArrival: 1 sec
- . LSRefreshInterval: 60 sec

#### **Measures**

- Router starting:
- [0, 2] sec 60 samples
- PDR of UDP flows:
   Control traffic:
- 84 samples

- **UDP Flows** 
  - Nom. sender bitrate: 100 pkt/s
  - Packet payload: 1024 B
  - CBR real traffic rate: 300 kbps
  - Flow duration: 5 min/flow



### Wireless a



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## **MPR Heuristics**

- Input: x, N(x),  $N_2(x)$
- MPR = {∅}
- MPR  $\leftarrow \{n \in N(x) : \exists m \in N_2(x), m \text{ only covered by } n\}$
- while (∃ uncovered 2-hop neighbors)
   MPR ← n ∈ N(x) : covers max. # of uncovered 2-hop neighbors
- **Output:** MPR(x, N(x), N<sub>2</sub>(x))



## **Enhanced Path MPR**



$$N'(x) = \{n \in N(x) : m(x, n) = dist_{2}(x, n)\} \subseteq N(x)$$
  

$$N'_{2}(x) = \{n \in N(x) \cup N_{2}(x) \mid n \notin N'(x), \exists m \in N'(x) : m(n, m) + m(m, x) = dist_{2}(n, x)\}$$
  

$$\subseteq N(x) \cup N_{2}(x)$$

$$(E_x^2)' = \{\overline{nm} \in E(G) : n \in N'(x), m \in N'_2(x), m(x,n) + m(n,m) = dist_2(x,m)\} \\ \cup \{\overline{xn} \in E(G) : n \in N'(x)\}$$



## Persistency in MPR-OSPF (1)

	Adjacencies	Flooding	Topology	
PPM	Persistent	Persistent	Path MPRs	
PMP	Persistent	MPR Selectors	Persistent	
PMM	Persistent	MPR Selectors	Path MPRs	(RFC 5449)
MMM	MPRs	MPR Selectors	Path MPRs	(Non-pers.)



## Persistency in MPR-OSPF (2)

• The non-persistent configuration (*MMM*) performs **significantly worse** than the other (partially persistent) configurations

• The delivery achieved by current standard *RFC 5449* can be **improved** by implementing persistency also in flooding (*PPM*) or in topology selection (*PMP*)



**Delivery** ratio

Conf. PPM —+— Conf. PMP ----≯<del>69</del> Conf. PMM (min. RFC 5449) ----\*-Conf. MMM (non-persistent) -----



## Persistency in MPR-OSPF (3)

• Persistent adjacencies are **far more stable**, but persistency **increases the size** of the adjacent links set.





## Persistency in MPR-OSPF (4)



 Overall, the cost (in overhead) of implementing persistency in flooding (*PPM*) is more significant than implementing it for topology selection (*PMP*)

 The benefits of flooding persistency are roughly equivalent as those of topology selection persistency

 Non-persistent configuration (MMM) generates more overhead than other persistent confs. (PMM and PMP) due to adjacency unstability



## Wireless collisions (1)



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### The Jitter mechanism

# Wireless collisions (3)

#### □ Flooding with jitter : RFC 5148





### The Jitter mechanism

# Wireless collisions (4)

#### Objectives

 $\checkmark$  Theoretical analysis of the impact of jitter in flooding

(from the perspective of a wireless interface)



✓ Focusing on:

✓ Delay introduced in forwarding

✓ Changes in (out-)packet transmission rate



Avg fwding delay per interface

## Wireless collisions (5)

- Given a jitter value T, what is the average delay before retransmission ?
- □ Two (extreme) cases :
  - Retx of a packet only depends on further arrivals





Retx of a packet depends (also) on all possible previous arrivals





#### Introduced delay (in average)

## Wireless collisions (6)

