

# Wireless Link Quality Modelling and Mobility Management Optimisation for Cellular Networks

PhD Thesis Defence

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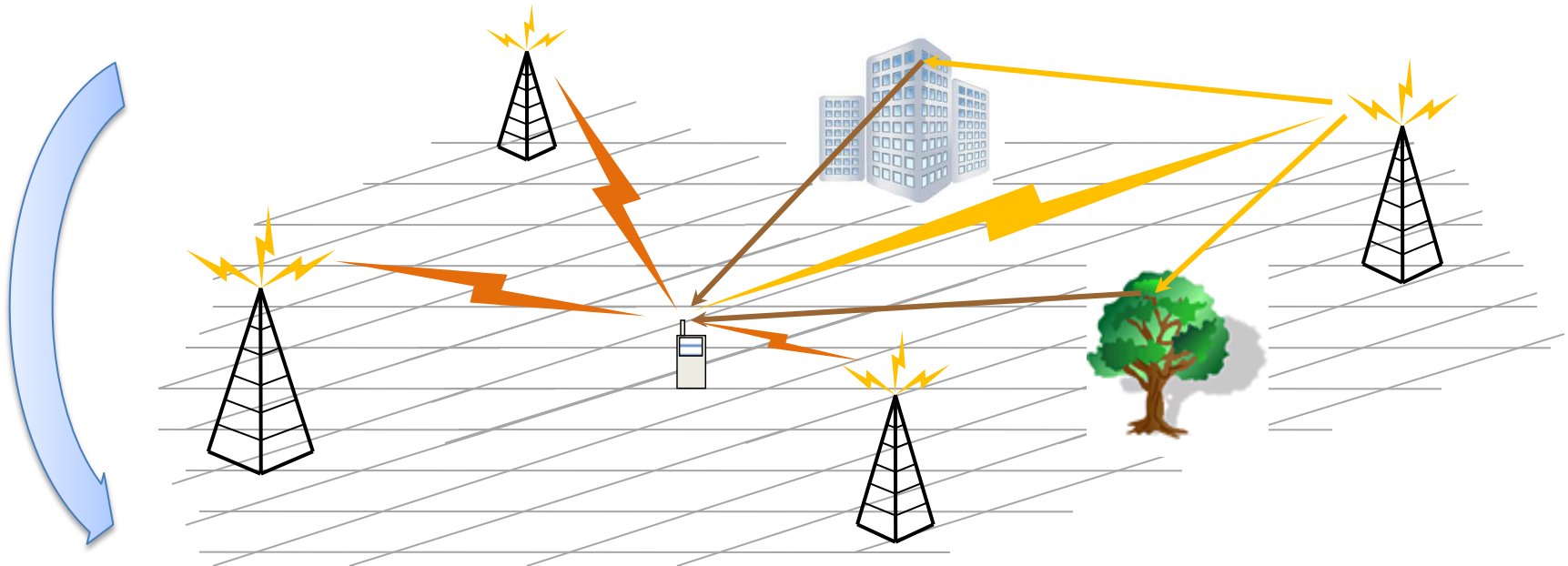
Paris, June 20<sup>th</sup> 2011

Interference  
→ Link quality  
expressed in SINR

Resource  
sharing

Wireless links

Propagation → Path loss  
Obstacles → Shadowing  
Multipath and Motions  
→ Fading, Time-varying



**Best SINR**  
node association  
is fundamental

Wireless  
Networking

Mobile  
cellular  
network

**Mobility Management**  
is a fundamental  
network defining factor

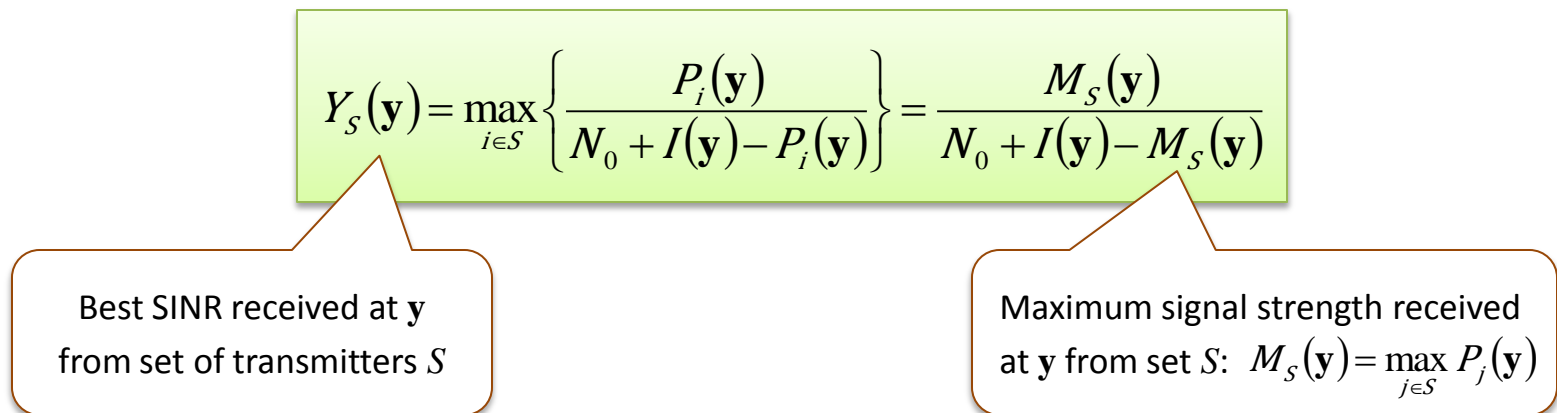
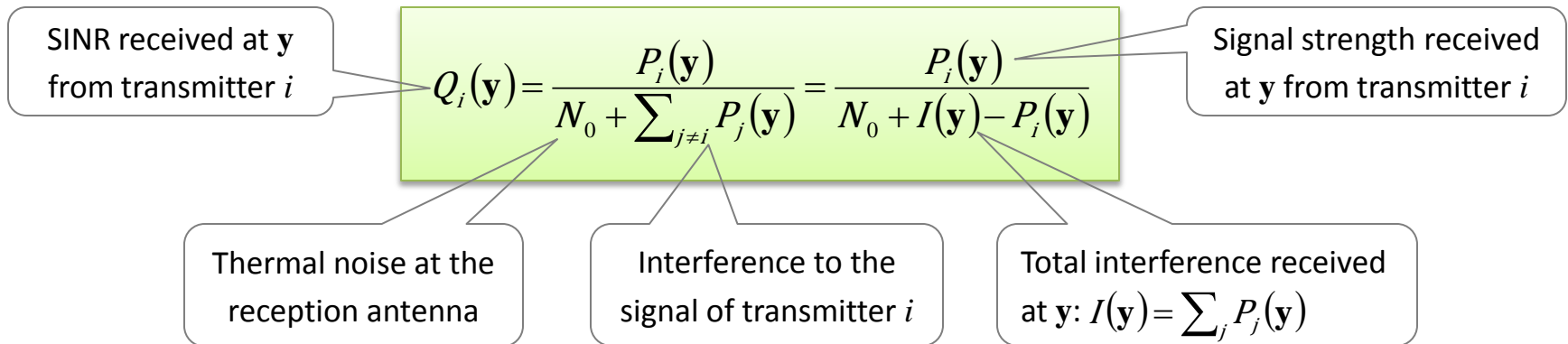
# Outline of Contributions

1. Wireless Link and Best Signal Quality Modelling
  1. Stochastic Geometry Modelling of Wireless Links ([IEEE WiOPT 2010](#))
  2. Heavy-Tail Asymptotics of Wireless Links ([EURASIP JWCN 2010](#))
2. Level Crossing Analysis of Time-varying Wireless Links
  1. Asymptotic Excursions above a Small Level ([To be published](#))
  2. Crossings of Successive High Levels ([To be published](#))
3. Applications to Mobility Management in Cellular Networks
  1. Analytical Model of Handover Measurement with Application to LTE ([IEEE ICC 2011](#))
  2. Autonomous Cell Scanning for Small Cell Networks ([EURASIP JWCN 2010](#))
  3. Self-optimisation of Neighbour Cell Lists in Macrocellular Networks ([IEEE PIMRC'10](#))

- ❖ Presentation of Approach
- ❖ Network Assumptions
- ❖ Stochastic Geometry Modelling
- ❖ Heavy-Tail Asymptotics Modelling

# 1 BEST SIGNAL QUALITY MODELLING

# Approach



Joint distribution of the total interference  $I$  and the maximum signal strength  $M_S$

Derive the distribution of the best signal quality  $Y_S$

# Assumptions

## Basic wireless link

$$P_i(\mathbf{y}) = \frac{P_{\text{tx}} \cdot Z_i}{l(|\mathbf{y} - \mathbf{x}_i|)} \triangleq \frac{m_i}{l(|\mathbf{y} - \mathbf{x}_i|)}$$

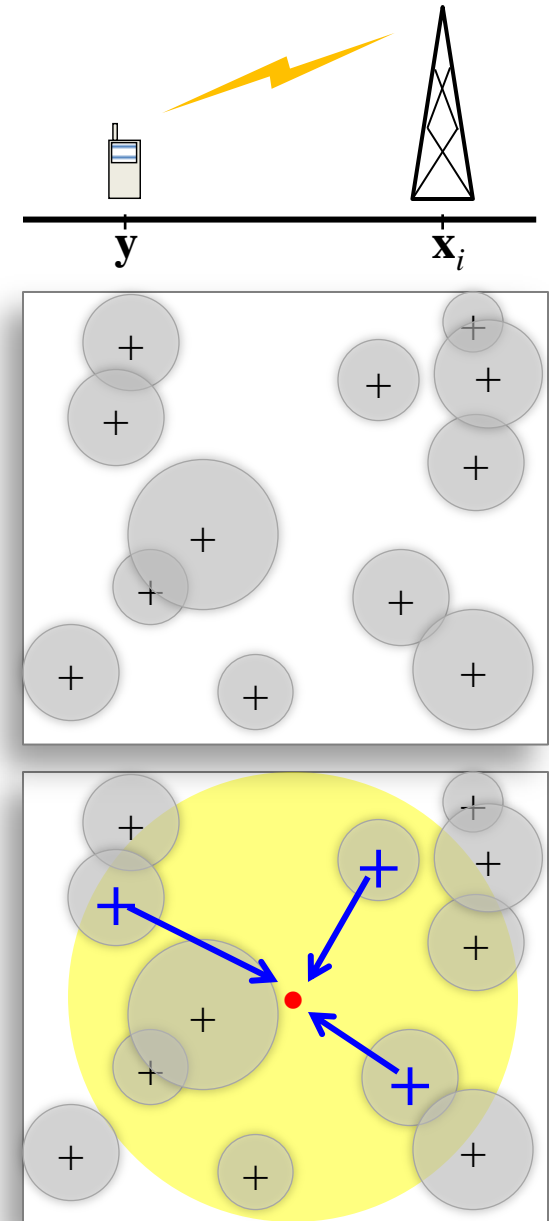
- $\mathbf{y} \in \mathbf{R}^2$  –location of receiver,  $\mathbf{x}_i \in \mathbf{R}^2$  –location of transmitter  $i$ ,
- $P_{\text{tx}}$  –node's transmission power,  $\{Z_i\}$  –fading,
- $\{m_i\}$  –virtual Tx power assumed i.i.d. of df  $F_m$ ,  $m := m_1$
- $1/l(r) = r^{-\beta}$  for  $r \in \mathbf{R}_+$  and  $\beta > 2$  –pathloss function

## Interference field as a shot noise

- $\{\mathbf{x}_i\}$ : Poisson point process with intensity  $\lambda$  on  $\mathbf{R}^2$
- $\tilde{\Phi} = \{(\mathbf{x}_i, m_i)\}$ : independently marked Poisson p.p.
- $L(\mathbf{x}, \mathbf{y}, m) = m/l(|\mathbf{y} - \mathbf{x}|)$ : non-negative real resp. function
- $I(\mathbf{y}) = \sum_{\mathbf{x}_i \in \mathbf{R}^2} P_i(\mathbf{y}) = \sum_{(\mathbf{x}_i, m_i) \in \tilde{\Phi}} L(\mathbf{y}, \mathbf{x}_i, m_i)$ : SN interference

## Set of observed nodes

- $B \subset \mathbf{R}^2$ : disk of radius  $R_B$  centred at the receiver,  $\mathbf{y} \equiv \mathbf{0}$
- $S$  = set of nodes uniformly selected from  $B$  with prob  $\rho \in [0, 1]$



# Stochastic Geometry Modelling

# Primary Result

## Joint distribution of $I$ and $M_S$

For  $u \geq 0$  and  $z \in \mathbb{C}$  with a non-negative real part, define:

$$\mathcal{L}_{(I, M_S \leq u)}(z) \triangleq \mathbf{E}\{\mathbf{1}(M_S \leq u) \exp(-zI)\}.$$

Then

$$\mathcal{L}_{(I, M_S \leq u)}(z) = \exp \left( -\lambda \int_{\mathbb{R}^2} \left( 1 - \mathcal{L}_m\left(\frac{z}{l(|\mathbf{y} - \mathbf{x}|)}\right) \right) d\mathbf{x} - \rho\lambda \int_B \mathbf{E}\left\{ \mathbf{1}\left(\frac{m}{l(|\mathbf{y} - \mathbf{x}|)} > u\right) \exp\left(\frac{-zm}{l(|\mathbf{y} - \mathbf{x}|)}\right) \right\} d\mathbf{x} \right).$$

where  $\mathcal{L}_m(z) \triangleq \mathbf{E}\{\exp(-zm)\}$  which is the Laplace transform of  $m = m_1$ .



# Observations

$$F_{M_S}(u) = \mathcal{L}_{(I, M_S \leq u)}(0)$$

## Distribution of the Maximum Signal Strength $M_S$

$$F_{M_S}(u) = \exp \left( -\pi \rho \lambda R_B^2 \left( 1 - F_p(u R_B^\beta) \right) - \pi \rho \lambda \mathbf{E} \{ \mathbf{1}(p \leq u R_B^\beta) p^\alpha \} u^{-\alpha} \right)$$

where  $\alpha = 2/\beta$ . In particular, if  $B = \mathbb{R}^2$  then:

$$F_{M_S}(u) = \exp \left( -\pi \rho \lambda \mathbf{E} \{ p^\alpha \} u^{-\alpha} \right)$$

which is a Fréchet dist. with shape  $\alpha$  and scale  $(\pi \rho \lambda \mathbf{E} \{ p^\alpha \})^{1/\alpha}$ .

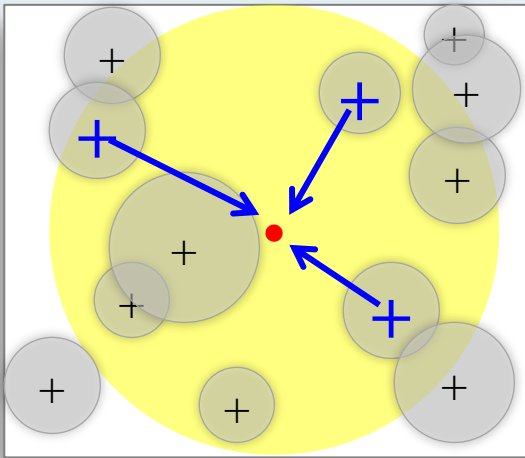
$$\phi_I(w) = \mathcal{L}_{(I, M_S \leq +\infty)}(-jw)$$

## Characteristic Function of the Total Interference $I$

Denote  $\phi_I(w) = \mathbf{E} \{ \exp(jwI) \}$  for  $w \in \mathbb{R}$ . Then

$$\phi_I(w) = \exp \left( -\delta |w|^\alpha \left( 1 - j \operatorname{sign}(w) \tan\left(\frac{\pi\alpha}{2}\right) \right) \right)$$

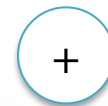
which is the cf of a skewed  $\alpha$ -stable random variable.

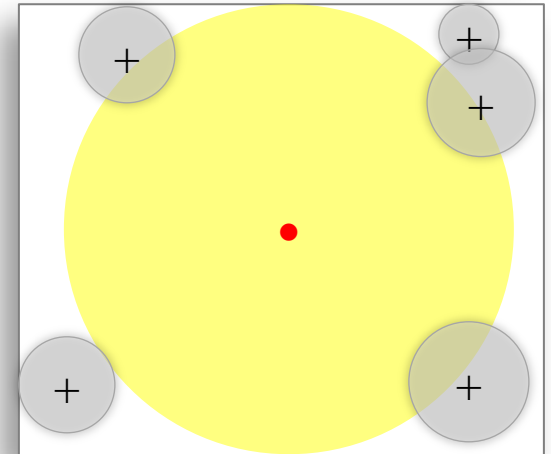
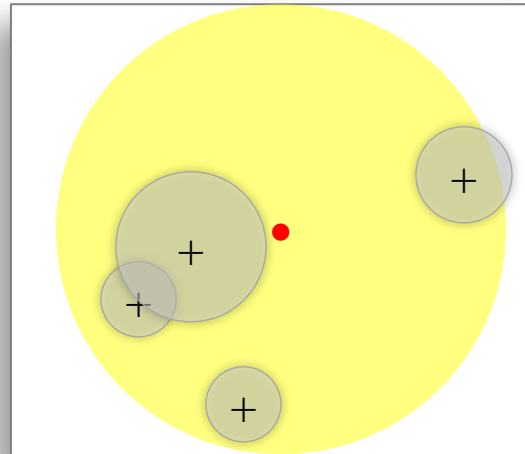
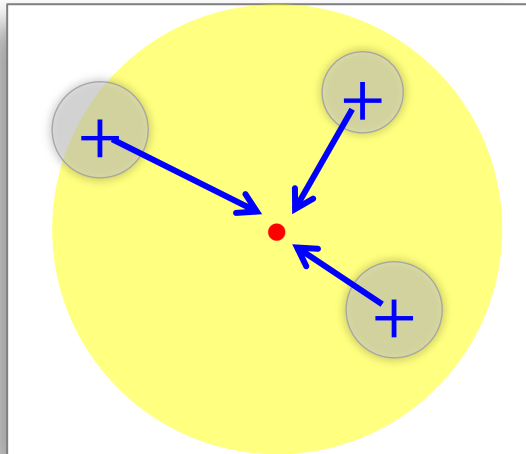


$$\tilde{\Phi}$$

$$=$$

$$\tilde{\Phi}_1$$


$$\tilde{\Phi}_2$$


$$\tilde{\Phi}_3$$


## Skeleton of solution finding

for  $\mathcal{L}_{(I, M_S \leq u)}(z) \triangleq \mathbf{E}\{\mathbf{1}(M_S \leq u) \exp(-zI)\}$

- Step 1: decompose  $\tilde{\Phi}$  into three independent independently marked Poisson p.p.
- Step 2: apply the Laplace transform of each shot noise by Prop 2.2.4 in [Baccelli2009]

F. Baccelli and B. Blaszczyzyn. "Stochastic Geometry and Wireless Networks, Volume I – Theory". *Foundations and Trends in Networking*, vol. 3(3-4), pp.249-449, 2009.

## Tail Distribution of the Best Signal Quality

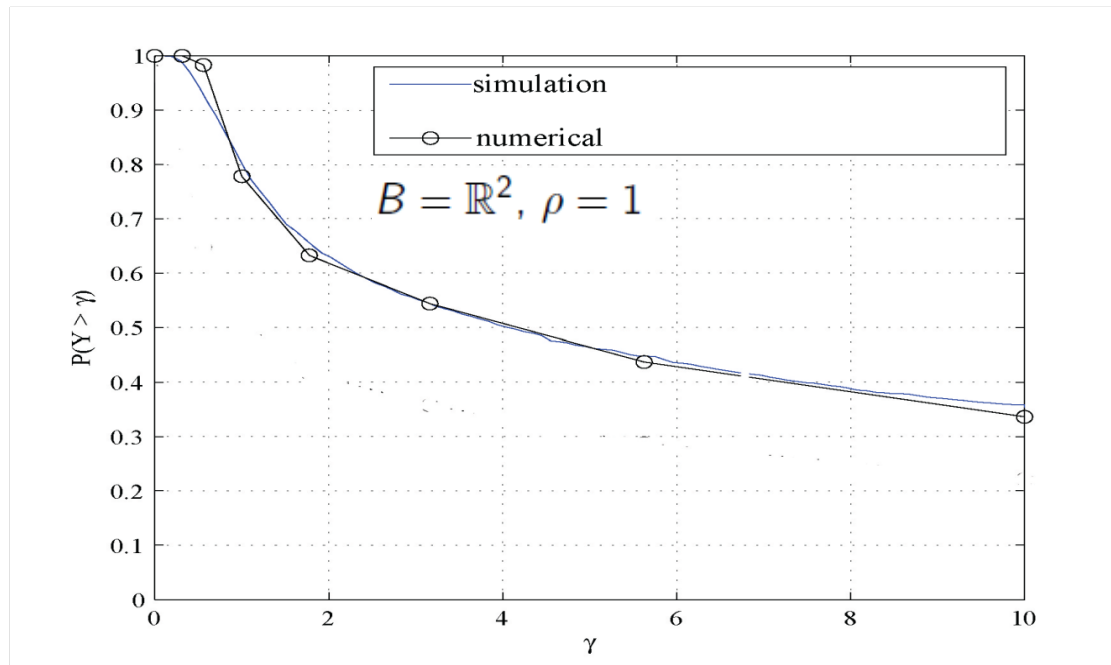
For  $w \in \mathbb{R}$  let  $\phi_{(I, M_S \leq u)}(w) = \mathcal{L}_{(I, M_S \leq u)}(-jw)$ .

If  $0 < \mathbf{E}\{m^\alpha\} < \infty$ , and if  $F_m$  admits a continuous density  $f_m$ :

$$\bar{F}_{Y_S}(\gamma) = \frac{1}{2\pi} \int_{u=\gamma}^{+\infty} \int_{-\infty}^{+\infty} \phi_{(I, M_S \leq u)}(w) g(w, u) dw du, \quad \forall \gamma > 0,$$

where  $g(w, u) = \exp(-jwu) - (1 + \gamma^{-1}) \exp(jw(1 - \frac{1+\gamma}{\gamma}u))$ . And

$$\bar{F}_{Y_S}(0) = 1 - \exp(-\rho\lambda(1 - F_m(0))|B|).$$



## ■ Network Assumptions

- Nodes are spatially distributed according to a Poisson point process
- Virtual transmission powers  $\{m_i\}$  are i.i.d. with general distribution  $F_m$
- Unbounded power-law pathloss model,  $1/l(r) = r^{-\beta}$  for  $r \in \mathbf{R}_+$  and  $\beta > 2$

## ■ Main Results

- Joint distribution of  $I$  and  $M_S$
- Necessary conditions for the integrability & existence of the joint density
- Tail distribution of the best signal quality

## ■ Important Observations

- Total interference is a skewed alpha-stable distribution
- Global maximum signal strength is a Fréchet distribution
- Unbounded power-law pathloss introduces *very heavy-tailed* behaviours of  $I$  and  $M_S$

**independently** of the type of fading

# Heavy-Tail Asymptotics

# Overview

## ■ Motivation

- Impacts of the pathloss singularity on the tail behaviour of wireless links

## ■ Focus

- Unbounded pathloss:  $1/l(r) = (\max\{r, R_{\min}\})^{-\beta}$  for  $r \in \mathbf{R}_+$ ,  $\beta > 2$ , and  $R_{\min} = 0$
- Bounded pathloss:  $1/l(r) = (\max\{r, R_{\min}\})^{-\beta}$  for  $r \in \mathbf{R}_+$ ,  $\beta > 2$ , and  $R_{\min} > 0$
- Fading  $\{Z_i\}$  are i.i.d. lognormal with parameters  $(0, \sigma_Z)$  with  $0 < \sigma_Z < \infty$
- Network area  $B$  is bounded with radius  $R_B < \infty$ .
- (note: with Poisson p.p. assumption of nodes spatial distribution)

## ■ Roadmap

- Study the tail equivalent distribution of the signal strength  $P_i$
- Asymptotic joint dist of the total interference & max signal strength
- Tail distribution of the best signal quality

# Tail Behaviour of Signal Strength

## Theorem

Denote by  $\overline{F}_P$  the tail distribution of the signal strength  $P_i$ .

(a) Under **unbounded** pathloss,  $\overline{F}_P$  is **regularly** varying:

$$\overline{F}_P(x) \sim a^\alpha e^\nu x^{-\alpha}, \quad \text{as } x \rightarrow \infty, \text{ with } \alpha = 2/\beta.$$

(b) Under **bounded** pathloss,  $\overline{F}_P$  is **rapidly** varying:

$$\overline{F}_P(x) \sim \text{const} \cdot \frac{\overline{K}_2(x)}{\log x - \mu_2}, \quad \text{as } x \rightarrow \infty,$$

with  $\overline{K}_2(x)$  the tail of a lognormal distribution.

## Interpretation

- The choice of pathloss model has decisive influence on the tail of wireless links
- Decaying power-law path loss is the dominant component
- Under bounded pathloss, the tail of  $P_i$  is determined by the lognormal fading

# Asymptotic Distribution of Max Signal Strength

## Theorem

Let  $M_n = \max_{i=1, \mathbf{x}_i \in B}^n P_i$  be the maximum signal strength.

(a) Under **unbounded** pathloss,  $\exists c_n > 0, d_n \in \mathbb{R}$  such that

$$c_n^{-1}(M_n - d_n) \xrightarrow{d} \Upsilon_\alpha(x), \quad \text{as } n \rightarrow \infty,$$

where  $\Upsilon_\alpha$  is the std. Fréchet dist. of parameter  $\alpha = 2/\beta$ .

(b) Under **bounded** pathloss,  $\exists c_n > 0, d_n \in \mathbb{R}$  such that

$$c_n^{-1}(M_n - d_n) \xrightarrow{d} \Lambda, \quad \text{as } n \rightarrow \infty,$$

where  $\Lambda$  is the standard Gumbel distribution.

## Interpretation

- Network densification scenario:  $n \rightarrow \infty$  within a bounded network area  $B$
- Unbounded pathloss:  $M_n$  is asymptotically Fréchet distribution under both network extension and network densification
- Bounded pathloss:  $M_n$  is asymp. Gumbel dist. under network densification



# Asymptotic Joint Distribution

## Asymptotic Independence

*Let  $I_n = \sum_{i=1, \mathbf{x}_i \in B}^n P_i$  be the interference received from  $n$  nodes in  $B$ . Under the bounded pathloss model, there exists constants  $a_n > 0$  and  $b_n \in \mathbb{R}$ ,  $c_n > 0$  and  $d_n \in \mathbb{R}$  such that*

$$\left( \frac{I_n - b_n}{a_n}, \frac{M_n - d_n}{c_n} \right) \xrightarrow{d} (\Phi, \Lambda), \quad \text{as } n \rightarrow \infty,$$

*and where the coordinates  $\Phi$ , std. Gaussian dist., and  $\Lambda$  are ind.*

## Joint Density

*Under bounded pathloss, for moderate or large  $n$ ,  $(M_n, I_n)$ , and  $(M_n, I)$  admit the following approximations*

$$f_{(M_n, I_n)}(u, v) \approx f_{M_n}(u) \times f_{I_n}(v),$$

$$f_{(M_n, I)}(u, v) \approx f_{M_n}(u) \times f_I(v),$$

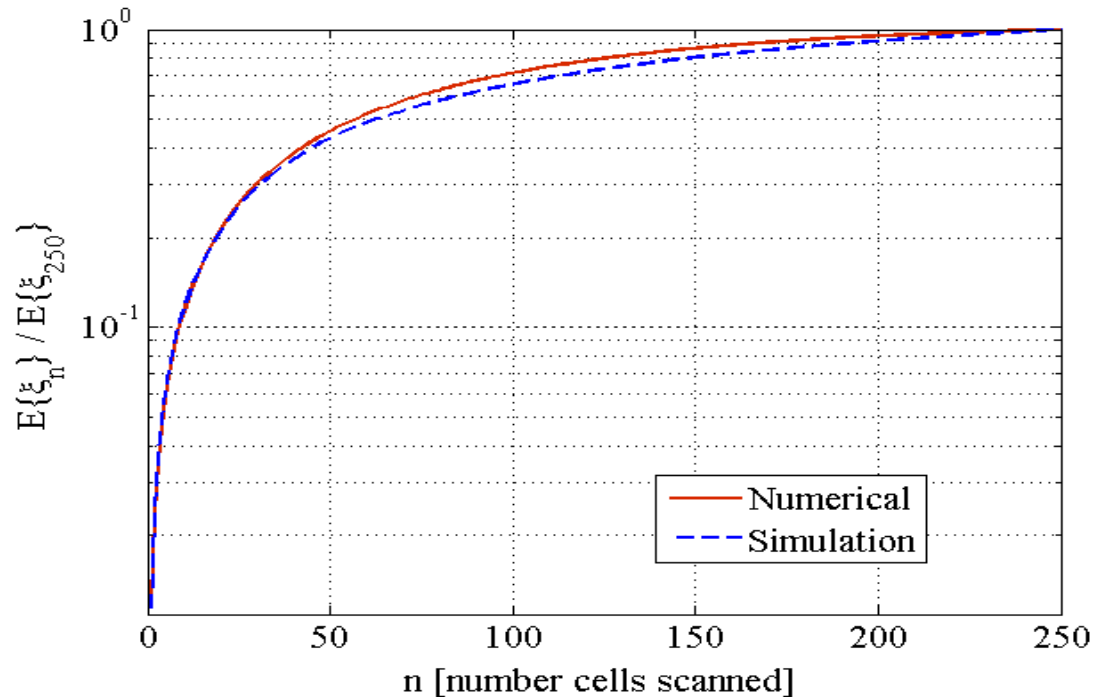
*where  $f_{M_n}$ ,  $f_{I_n}$ , and  $f_I$  are respectively the pdf of  $M_n$ ,  $I_n$ , and  $I$ .*

## Tail Distribution of the Best Signal Quality

Let  $Y_n = \max_{i=1, \dots, n} Q_i$  be the best signal quality received from  $n$  nodes uniformly selected from  $B$ . Assume the bounded pathloss model and that  $P_{tx} R_{\min}^{-\beta}$  is large. Then the tail dist of  $Y_n$  admits the following approx:

$$\bar{F}_{Y_n}(\gamma) \approx \int_{\gamma}^{\infty} \left\{ f_{M_n}(u) \int_0^{\infty} \frac{2}{\pi w} e^{-\delta w^{\alpha}} \sin\left(w \frac{u - \gamma}{2\gamma}\right) \times \cos\left(wu + w \frac{u - \gamma}{2\gamma} - \delta w^{\alpha} \tan \frac{\pi\alpha}{2}\right) dw \right\} du.$$

Evaluation of  
Shannon  
capacity using  
tail distribution  
of the best  
signal quality



# Heavy Tail Asymptotics Modelling

## ■ Focus

- Impacts of the singularity of power-law pathloss on wireless links
- Network densification scenario:  $n \rightarrow \infty$  within a bounded network area  $B$
- Fading  $\{Z_i\}$  are i.i.d. lognormal with parameters  $(0, \sigma_Z)$  with  $0 < \sigma_Z < \infty$

## ■ Unbounded pathloss

- *Very heavy-tailed* behaviours of interference and maximum signal strength
- Interference and maximum signal strength behave *dependently* due the common dominant component corresponding to the pathloss singularity

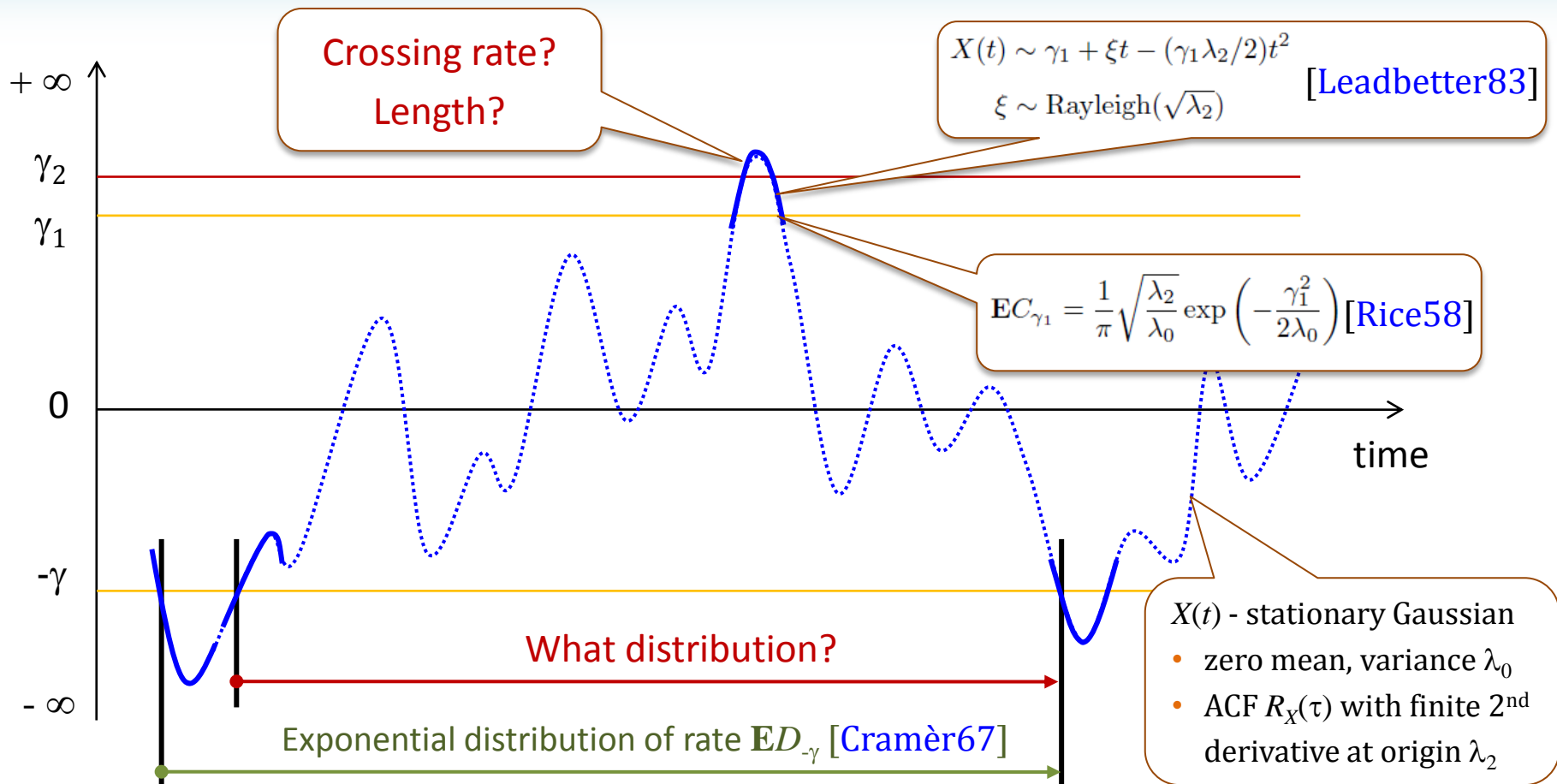
## ■ Bounded pathloss

- Asymptotic ind. between the interference and the max signal strength
- Approximation of the tail distribution of the best signal quality

- ❖ Excursions Above a Low Level
- ❖ Crossings of Successive High Levels

# 2

## LEVEL CROSSING PROPERTIES OF A STATIONARY GAUSSIAN PROCESS



[Rice58] S. O. Rice. "Distribution of the duration of fades in radio transmission: Gaussian noise model". *Bell Syst. Tech. J.*, 37(3):581-635, 1958

[Leadbetter83] M. R. Leadbetter, G. Lindgren, and H. Rootzen. *Extremes and Related Properties of Random Sequences and Processes*. Springer Verlag. 1983

[Cramèr67] H. Cramèr and M. R. Leadbetter. *Stationary and related stochastic processes: Sample function properties and their applications*, volume 7. John Wiley and Sons, Inc, 1967.

# Main Result (1/2)

## Excursion Above a Very Low Level

Assume that  $X(t)$  admits an autocorrelation function  $R_X(\tau)$  satisfying:

$$R_X(\tau) = 1 - \frac{\lambda_2}{2!}\tau^2 + \frac{\lambda_4}{4!}\tau^4 + o(\tau^4)$$

with finite  $\lambda_2$  and  $\lambda_4$ , as  $\tau \rightarrow 0$ , and satisfying

$$R_X(\tau) = O(\tau^{-a}) \text{ for some } a > 0 \text{ as } \tau \rightarrow \infty.$$

[Cramèr67]: for the exponential dist of time between two successive down-crossings

Then the length  $\tau_u$  of an up-excursion of  $X(t)$  above a very small level  $-\gamma \rightarrow -\infty$  is asymptotically an exponential dist of rate  $\mu = \mathbf{E}U_{-\gamma}$ , i.e.

$$\mathbf{P}(\tau_u \leq \tau) = 1 - e^{-\mu\tau}, \quad \text{as } -\gamma \rightarrow -\infty.$$

By the memorylessness of exponential dist

## Observation

- $\mathbf{E}U_{-\gamma} \rightarrow 0$  as  $-\gamma \rightarrow -\infty$ :  $\mathbf{P}(\tau_u \leq \tau) \approx 0 \ \forall \tau < \infty$ , i.e.  $X(t)$  above a low level most of the time
- Thus, for an excursion above a **low level**, we only know the distribution of **length**
- By contrast, an excursion above a **high level** is short: **length** & **trajectory** by [Leadbetter83]

# Main Result (2/2)

[Leadbetter83]: for the asymp. parabola trajectory of up-excursion above a high level

## Crossings of Successive High Levels

Assume that  $R_X(\tau)$  has a finite second derivative at the origin  $\lambda_2$ , and that

$$R_X(\tau) = O(\tau^{-a}) \text{ for some } a > 0 \text{ as } \tau \rightarrow \infty.$$

Given that  $X(t)$  has an up-excursion above level  $\gamma_1$ , then

1. The mean number of up-crossings of  $X(t)$  of level  $\gamma_2 \geq \gamma_1$  is

$$\mathbf{E}U_{\gamma_2|\gamma_1} = \exp(-\gamma_1(\gamma_2 - \gamma_1)),$$

2. The length of an up-excursion of  $X(t)$  of level  $\gamma_2 \geq \gamma_1$  is

$$\mathbf{P}(T_2 > \tau \mid X(t) \text{ above } \gamma_1) = \exp(-V\tau^2) \exp(-\gamma_1(\gamma_2 - \gamma_1))$$

with  $V = \frac{\gamma_1^2 \lambda_2}{8}$  for  $\tau \geq 0$ , and

$$\mathbf{P}(T_2 = 0 \mid X(t) \text{ above } \gamma_1) = 1 - \exp(-\gamma_1(\gamma_2 - \gamma_1))$$

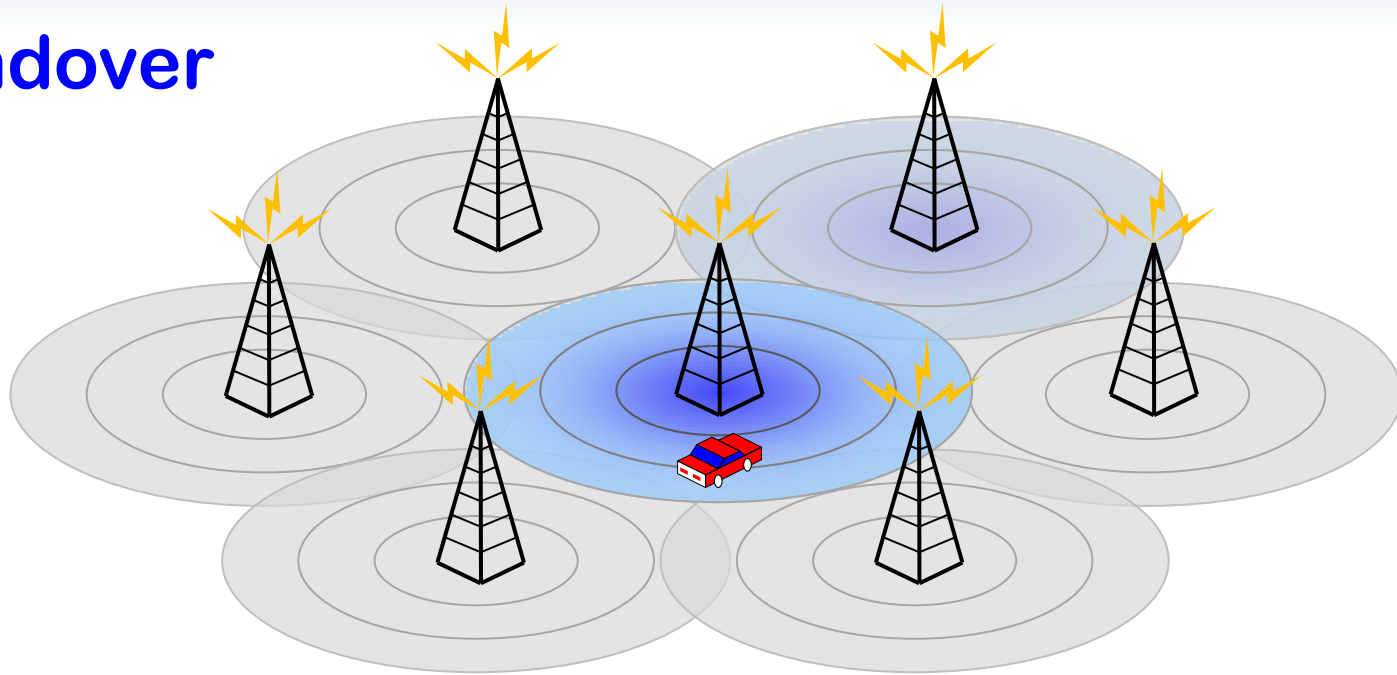
as  $\gamma_1 \rightarrow +\infty$

- ❖ HO Measurement Procedure
- ❖ Skeleton of Analytical Solution
- ❖ Application to Long Term Evolution

## 3 ANALYTICAL MODEL OF HANDOVER MEASUREMENT



# Handover



## Our work

### Handover Measurement

- **Mobile** measures neighbouring cells and reports to the network
- **Purpose:** to find a suitable HO target when the serving cell's signal deteriorates
- **Literature:** simulation and parameter-specific approaches, poor in analytical

### Handover Decision-Execution

- **Network** decides and executes the connection switching
- **Purpose:** to perform optimal and reliable connection switching
- **Literature:** very rich including optimal control, signal prediction, protocol design

# Why is Analytical Model for HO Measurement?

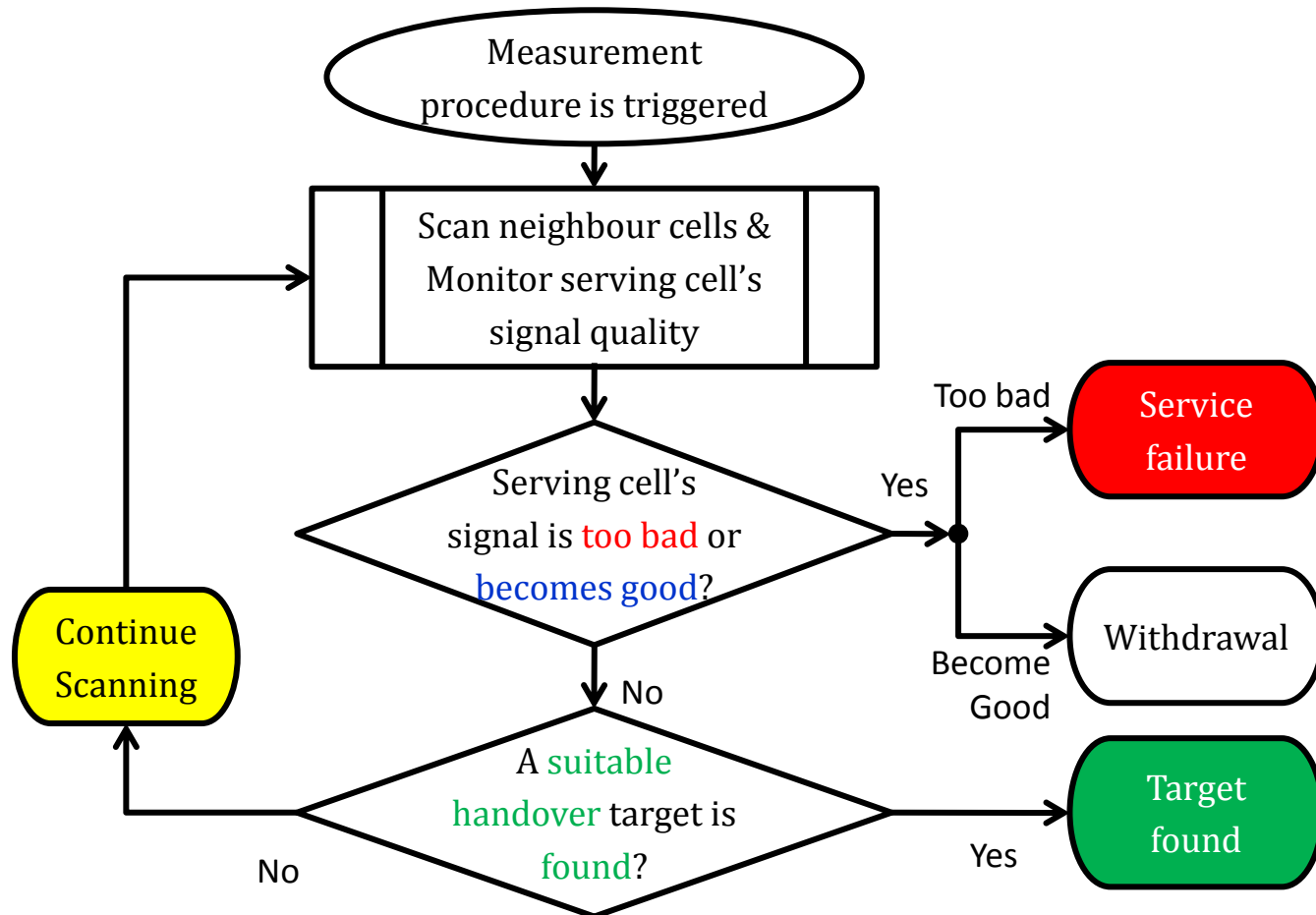
- Strong impacts of HO Measurement on
  - The quality of the handover target
  - The user's experience: service interruptions, throughput degradation
- Complex operation of HO Measurement due to
  - Specific PHY layer procedures: e.g., frame structure, synchronisation,
  - The measurement capability of mobile terminal
  - Combining effect of RRC parameters, e.g. > 10 Triggering Events in WDCMA, 7 in LTE
  - Time-varying and spatial-varying factors, e.g. signal quality, user's mobility
  - The interference nature of a multiple-cell system

generalised analytical model of handover measurement

is helpful to understand

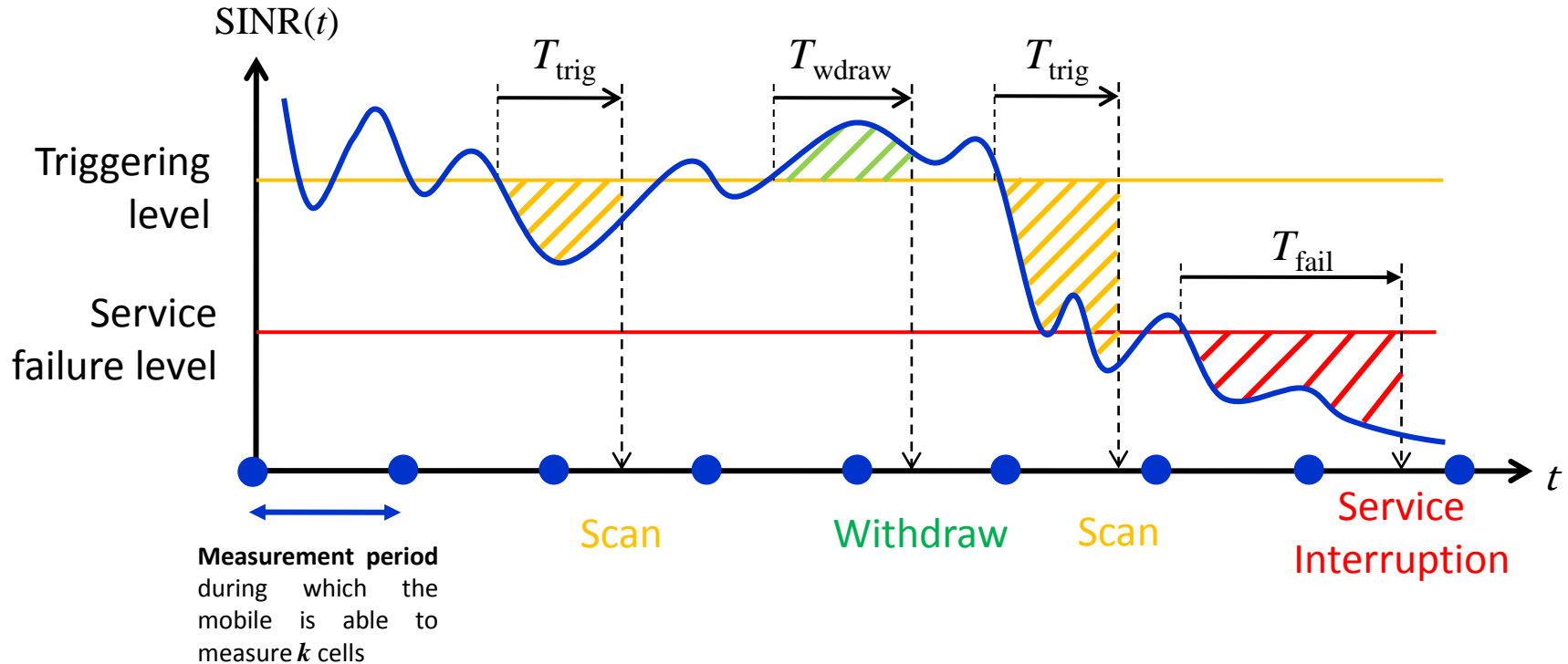
unified impacts of controlling params + user's mobility + system capabilities  
on the system performance

# Generic HO Measurement Procedure



A primary objective of the network configuration is to minimise the probability of service failure due to the handover measurement

# Basic Probabilistic Events



Service Failure  $\equiv SINR(t)$  staying below  $SINR_{fail}$  during at least  $T_{fail}$

Triggering  $\equiv SINR(t)$  staying below  $SINR_{trig}$  during at least  $T_{trig}$  and Not Failure

Withdrawal  $\equiv SINR(t)$  staying below  $SINR_{wdraw}$  during at least  $T_{wdraw}$

Target Found  $\equiv$  Best SINR received from measured cells  $\geq SINR_{req}$

**P(Withdrawal)**

=

**P**(excur. of  $X(t)$  above  $X_{\text{wdraw}}$  with  
length longer than  $T_{\text{wdraw}}$ )

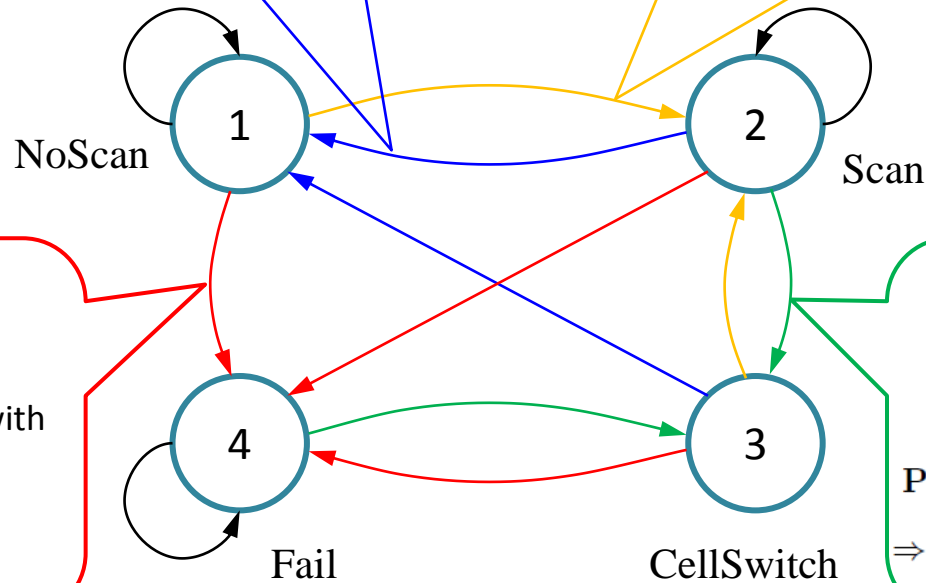
$\Rightarrow$  **Level crossing**

**P(Triggering)**

=

**P** (excur. of  $X(t)$  below  $X_{\text{trig}}$  with  $\geq T_{\text{trig}}$   
and  
NOT excur. of  $X(t)$  below  $X_{\text{fail}}$  with  $\geq T_{\text{fail}}$ )

$\Rightarrow$  **Level crossing of successive levels**



**P(Service Failure)**

=

**P**(excur. of  $X(t)$  below  $X_{\text{fail}}$  with  
length longer than  $T_{\text{fail}}$ )

$\Rightarrow$  **Level crossing**

**P(Target Found)**

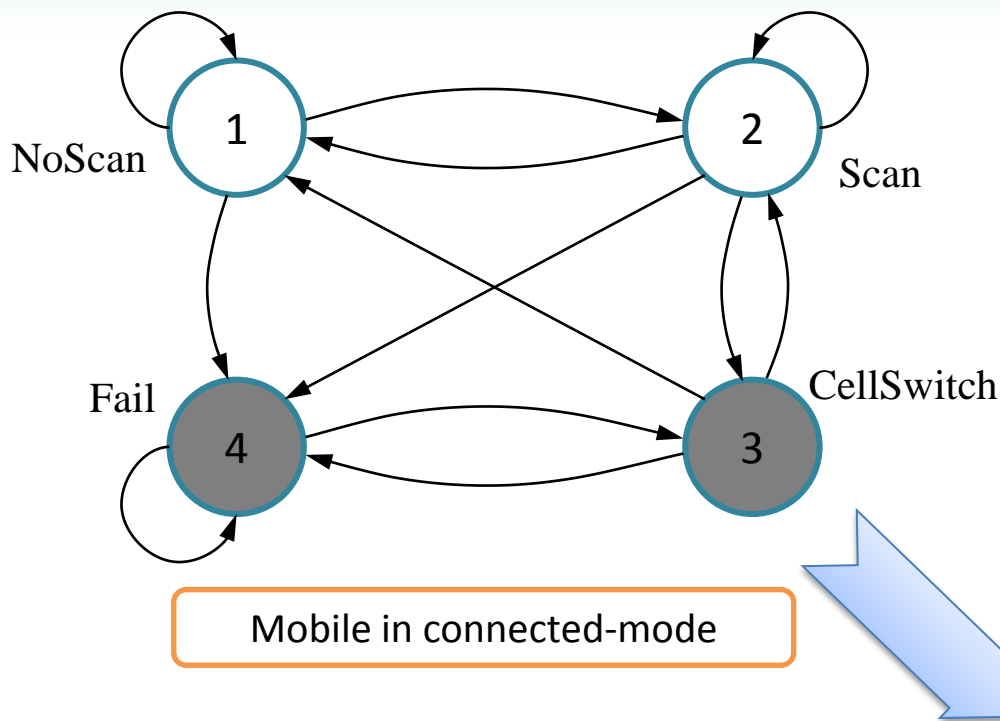
$$Y_k \triangleq \max_{i=1, \dots, k} \text{SINR}_i$$

**P**(Target Found) = **P**( $Y_k \geq \text{SINR}_{\text{req}}$ )

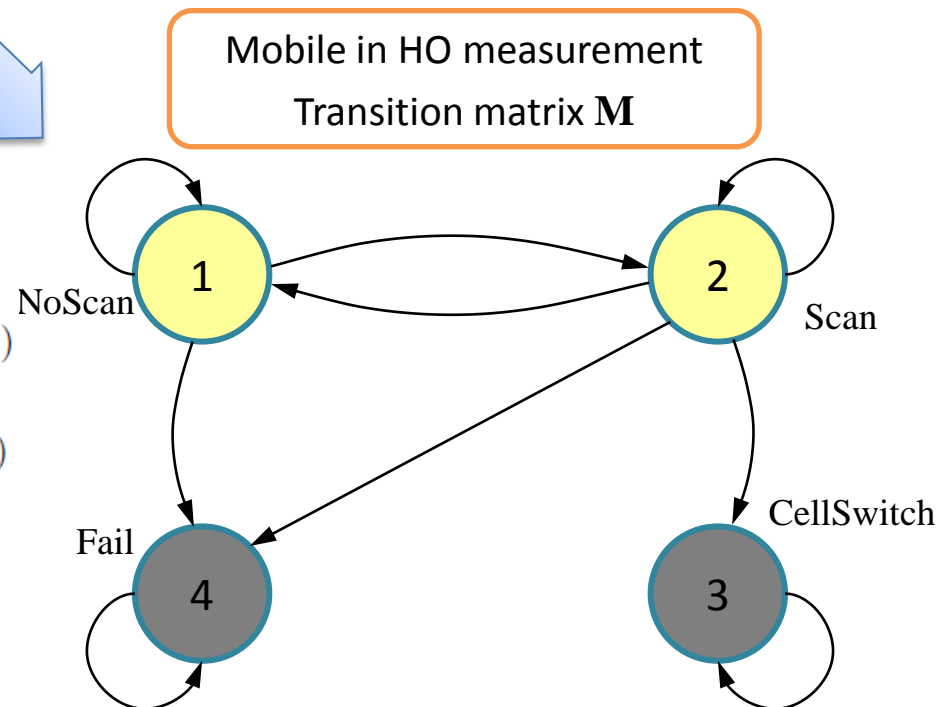
$\Rightarrow$  **Tail dist of Best Signal Quality**

$$\text{In dB scale: } \text{SINR}(t) = X(t) + 10 \log \left( \frac{P_{\text{tx}}}{l(d(t))(N_0 + I(t))} \right)$$

$$\text{SINR}(t) < \text{SINR}_{\text{fail}} \Leftrightarrow X(t) < X_{\text{fail}} \text{ where } X_{\text{fail}} := \text{SINR}_{\text{fail}} - 10 \log \left( \frac{P_{\text{tx}}}{l(d(t))(N_0 + I(t))} \right)$$



- MS is connected to the current serving cell
- MS is NOT connected to the current serving cell



Measurement Failure:  $\mathcal{F} = \int_0^\infty \mathbf{M}^{\lceil t/T_{\text{meas}} \rceil}(2, 4) F_D(dt)$

Measurement Success:  $\mathcal{S} = \int_0^\infty \mathbf{M}^{\lceil t/T_{\text{meas}} \rceil}(2, 3) F_D(dt)$

Quality of Target Cell:  $\mathcal{Q} = \mathcal{S} \times \mathbf{E}\{Y_k | Y_k \geq \gamma_{\text{req}}\}$

$F_D$ : distribution of call duration within one cell

# LTE Handover Measurement

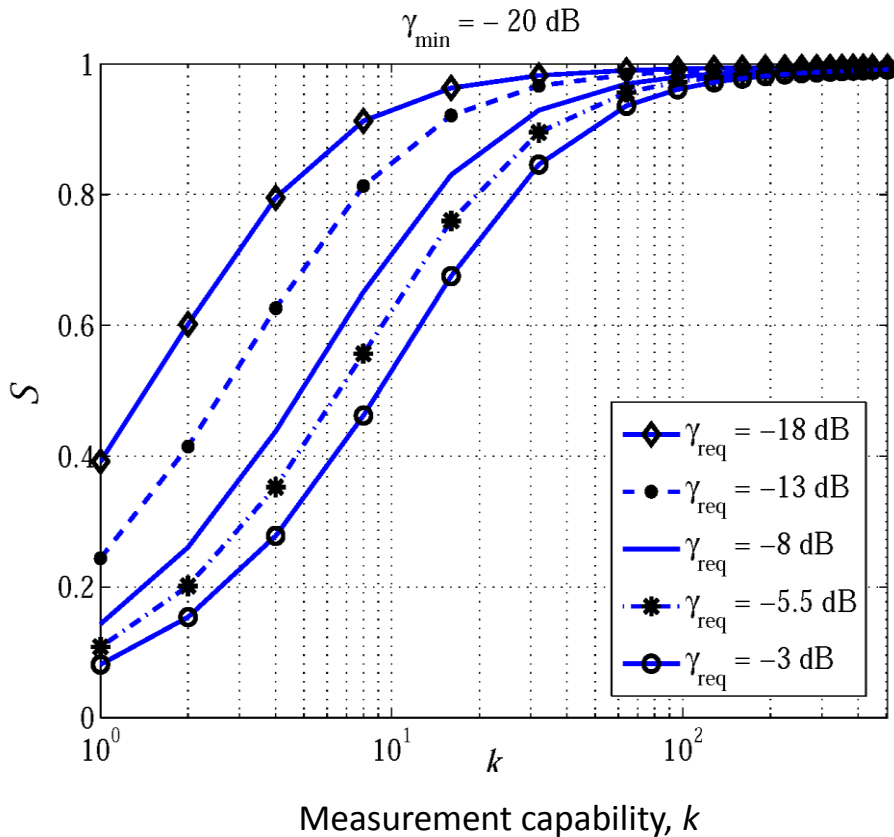
## Intra-freq Measurement

- Intra-frequency measurement is **predominant** due to frequency-reuse 1 of LTE
- UE measures intra-frequency cells **continuously** during RRC\_CONNECTED mode
  - $P(\text{Scanning Triggering}) = 1$
  - $P(\text{Withdrawal}) = 0$
- UE measures intra-frequency cells **autonomously** using all 504 physical cell Ids (PCIs)
  - *Unlimited candidate set* of target cell

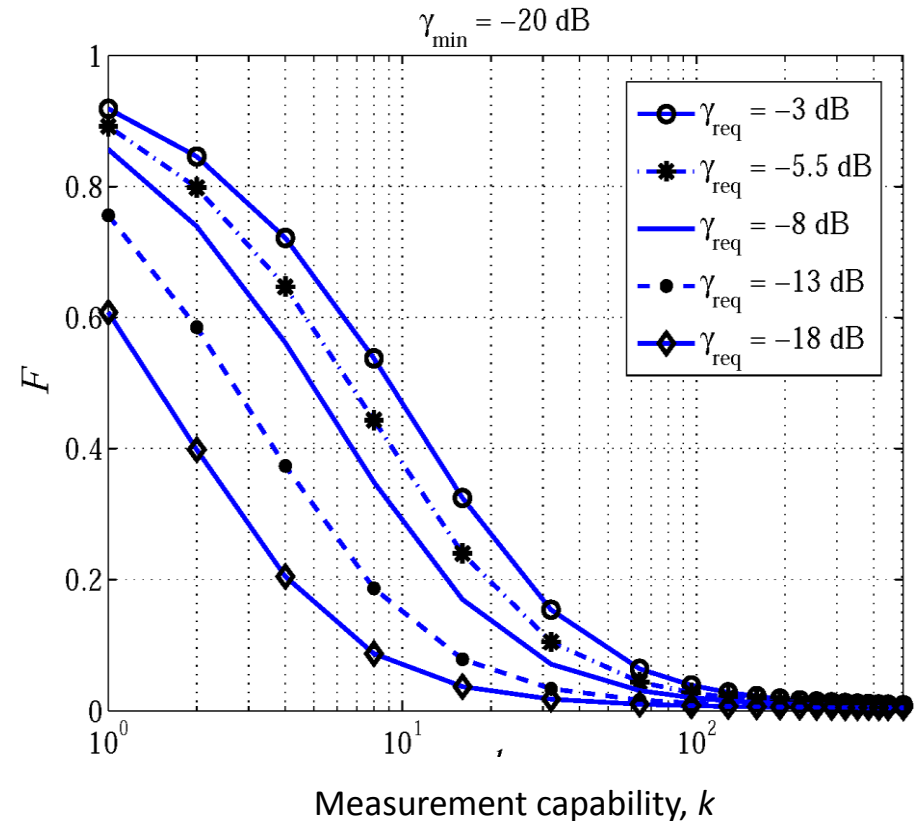
## Evaluation parameters

	Parameter	Assumption
Scenario	Environment	Urban macro cell
	Path loss ( $d$ in m)	$L(d) = 15.3 + 37.6 \log_{10} d$
	User's velocity	$v = 10$ m/s
BS	Transmission power	$P_{BS} = 43$ dBm
	Antenna pattern	Omnidirectional
	Cell radius	$R = 700$ m
Shadowing	Standard deviation	$\sigma_Z = 10$ dB
	Decorr. distance	$d_c = 50$ m
Noise	Noise density	$= -174$ dBm/Hz
	UE noise figure	$N_F = 9$ dB
Service	Min outage duration	$\tau_{min} = 200$ ms
	Min allowable level	$\gamma_{min} = -20$ to $-5$ dB
Measurement	Measurement period	$T_{meas} = 200$ ms
	Handover margin	$\Delta_{HO} = 2$ dB
	Required threshold	$\gamma_{req} = \gamma_{min} + \Delta_{HO}$
	Triggering level	$\gamma_t = +\infty$
	Withdrawal level	$\gamma_w = +\infty$

(a) HO measurement SUCCESS probability



(b) HO measurement FAILURE probability



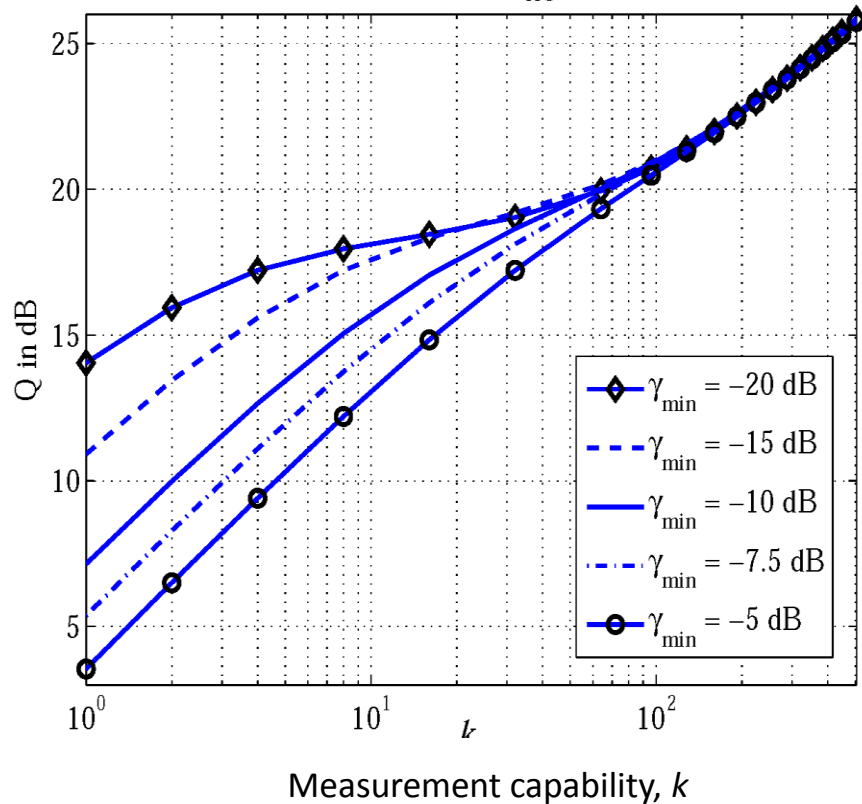
- Increasing *the measurement capability* more than about  $10^2$  improves the performance very marginally
- Regarding FAILURE probability plot: current LTE requirement for measurement capability of  $k = 8$  seems insufficient for reliable HO performance



(a) Quality of target cell  
under Relative threshold, i.e.

$$\text{SINR}_{\text{req}} = \text{SINR}_{\text{fail}} + \Delta_{\text{HO}}$$

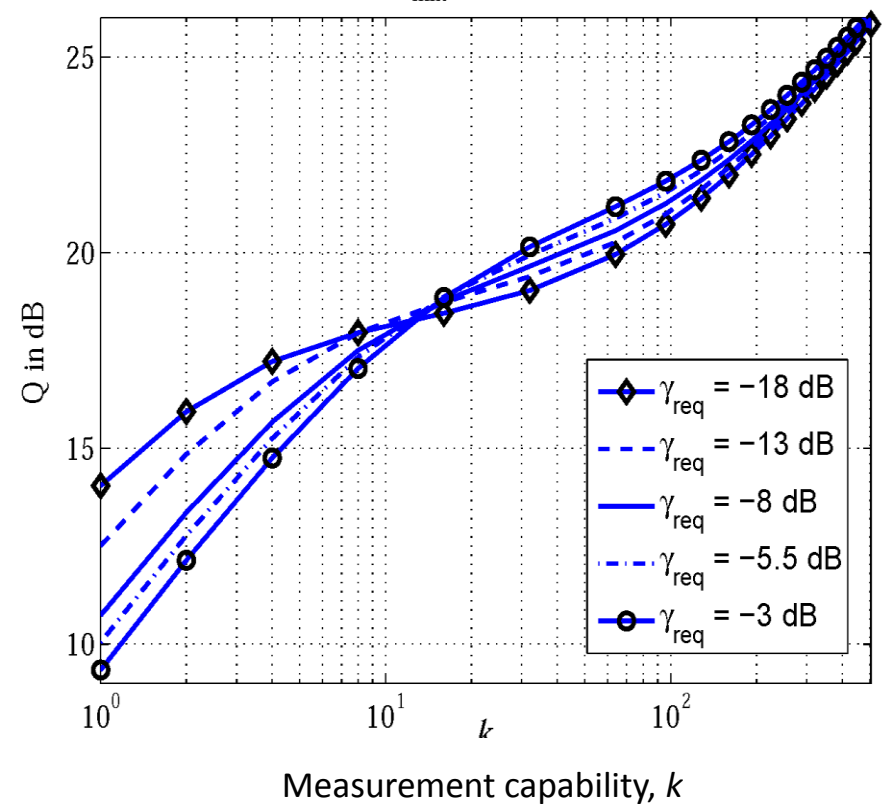
Handover margin  $\Delta_{\text{HO}} = 2 \text{ dB}$



(b) Quality of target cell  
under Absolute threshold, i.e.

$$\text{SINR}_{\text{fail}} = -20 \text{ dB}$$

$\gamma_{\text{min}} = -20 \text{ dB}$



- *Relative* threshold: robust service (i.e. low  $\text{SINR}_{\text{fail}} \equiv \gamma_{\text{min}}$ ), enhances target cell's quality
- *Absolute* threshold: crossing point for  $k$  in-between 10 and 16. Set low  $\text{SINR}_{\text{req}}$  for small  $k$ , and set high  $\text{SINR}_{\text{req}}$  for big  $k$  in order to achieve greater performance

## Analytical model

- Characterise HO measurement procedure as a Markov chain by determining key events associated with a discrete-time model
- Formulate and derive key probabilistic events using the developed results on the best signal quality and on level crossings

## LTE intra-frequency measurement

- High meas. capability enhances the mobility management performance
- Current requirement of 8 intra-freq cells / 200ms seems insufficient
- Measurement capability higher than  $10^2$  cells / 200ms
  - *Marginal* improvement in the HO measurement performance
  - *Significant* enhancement of the quality of target cell
- Future applications to Inter-freq and Inter-RAT measurements

## Other applications

- Autonomous scanning for small cell networks
- Self-optimisation of neighbour cell lists

# Conclusion

## ■ Distribution of the Best Signal Quality

- Method: by means of the joint distribution of interference and max signal strength
- Stochastic geometry model: exact expression of the tail distribution
- Heavy-tail asymptotics: an approximation of the tail distribution

## ■ Level crossing of a stationary Gaussian process

- Length of an excursion above a very low level is exponentially distributed
- Mean number of crossings, length of an excursion of crossings of two successive levels

## ■ Mobility management

- Focus on handover measurement function
- Analytical model using developed results on best signal quality and level crossings
- Application to LTE Intra-frequency measurement



**Thank You**

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BACKUP

# Skeleton of solution finding (cont'd)

$$\mathbf{E}\{1(M_S \leq u) \exp(-zI)\}$$

=

$$\mathbf{E}\left\{1(M_S \leq u) \exp\left(-z \sum_i P_i(\mathbf{y})\right)\right\}$$

=

$$\mathbf{E}\left\{\exp\left(\sum_{i \in S} (\log 1(P_i(\mathbf{y}) \leq u) - zP_i(\mathbf{y})) - z \sum_{i \notin S} P_i(\mathbf{y})\right)\right\}$$

=

$$\mathbf{E}\left\{\exp\left(\sum_{(\mathbf{x}_i, p_i) \in \tilde{\Phi}_1} \log 1(P_i(\mathbf{y}) \leq u) - zP_i(\mathbf{y})\right)\right\}$$

×

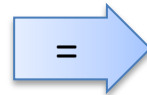
$$\mathbf{E}\left\{\exp\left(-z \sum_{(\mathbf{x}_i, p_i) \in \tilde{\Phi}_2} P_i(\mathbf{y})\right)\right\}$$

×

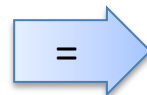
$$\mathbf{E}\left\{\exp\left(-z \sum_{(\mathbf{x}_i, p_i) \in \tilde{\Phi}_3} P_i(\mathbf{y})\right)\right\}$$



$$\mathcal{L} \text{ of } I_{\tilde{\Phi}_1}(\mathbf{y}) = \sum_{(\mathbf{x}_i, p_i) \in \tilde{\Phi}_1} \left( \frac{\log 1(L(\mathbf{y}, \mathbf{x}_i, p_i) \leq u)}{-z} + L(\mathbf{y}, \mathbf{x}_i, p_i) \right)$$



$$\mathcal{L} \text{ of additive SN } I_{\tilde{\Phi}_2}(\mathbf{y}) = \sum_{(\mathbf{x}_i, p_i) \in \tilde{\Phi}_2} L(\mathbf{y}, \mathbf{x}_i, p_i)$$



$$\mathcal{L} \text{ of additive SN } I_{\tilde{\Phi}_3}(\mathbf{y}) = \sum_{(\mathbf{x}_i, p_i) \in \tilde{\Phi}_3} L(\mathbf{y}, \mathbf{x}_i, p_i)$$

F. Baccelli and B. Blaszczyzyn. "Stochastic Geometry and Wireless Networks, Volume I – Theory". *Foundations and Trends in Networking*, vol. 3(3-4), pp.249-449, 2009.

Apply Laplace transform of additive shot noise given by Proposition 2.2.4 in [Baccelli2009]



# Overview of Applications

- Self-optimisation of Neighbour Cell Lists ([IEEE PIMRC 2010](#))
  - **Challenge:** Manual configuration of NCLs is a big every-day operator's concern
  - **Solution:** Propose measurement-based auto-configuration & self-optimisation
  - **Conclusion:** Attain 99% of scanning success without incurring signalling overhead
  - **Tools:** self-organisation paradigm
  
- Autonomous Scanning for Small Cell Networks ([EURASIP JWCN 2010](#))
  - **Challenge:** High-density and randomness of small cell networks require for new logic in the implementation of standardised mobility management mechanism
  - **Solution:** Propose and optimise autonomous scanning for max data throughput
  - **Conclusion:** Autonomously scan 30 cells is effective for a common network setting
  - **Tools:** **best signal quality** for **network densification scenario**
  
- Analytical Model of Handover Measurement ([IEEE ICC 2011](#))
  - **Challenge:** HO Measurement has strong impact on the whole system performance, its operation is complex while its state-of-the-art is weak
  - **Solution:** Generalised analytical model, then investigation of LTE HO measurement
  - **Conclusion:** Current LTE UE capability seems insufficient for reliable HO performance
  - **Tools:** **best signal quality** for **network extension & densification, level crossings**

# Service Failure

## Formulation

$$\text{SINR} = Z + 10 \log \left( \frac{P_{\text{tx}}}{l(d)(1+I)} \right)$$

$$\text{SINR}(t) < \text{SINR}_{\text{fail}} \Leftrightarrow Z(t) > Z_{\text{fail}} \text{ where } Z_{\text{fail}} := 10 \log \left( \frac{P_{\text{tx}}}{l(d)(1+I)} \right) - \text{SINR}_{\text{fail}}$$

Service Failure  $\equiv$  Excursion of  $Z(t)$  above  $Z_{\text{fail}}$  with length longer than  $T_{\text{fail}}$

## Solution

- [Mandayam98]: result for the case of **constant**  $Z_{\text{fail}}$  assuming constant interference  $I$
- **We** generalised the result for the case of **random**  $Z_{\text{fail}}$  taking into account random  $I$

This solution is similarly applied for the probability of scanning withdrawal

N. Mandayam, P.-C. Chen, and J. Holtzman. "Minimum Duration Outage for CDMA Cellular Systems: A Level Crossing Analysis", *Wireless Pers. Commun., Springer Netherlands*, **1998**, vol.7, pp. 135-146



# Scanning Triggering (1/2)

## Step 1 – Representation in Basic Events

Computationally  
similar to Service  
Failure

$P(\text{SINR}(t) \text{ below } \text{SINR}_{\text{trig}} \text{ longer than } T_{\text{trig}} \text{ and Not Failure})$

=

$P(\text{SINR}(t) \text{ below } \text{SINR}_{\text{trig}} \text{ longer than } T_{\text{trig}})$

$$P(A * !B) = P(A) - P(A * B)$$

–

$P(\text{SINR}(t) \text{ below } \text{SINR}_{\text{trig}} \text{ longer than } T_{\text{trig}} \text{ and Failure})$



$P(\text{SINR}(t) \text{ below } \text{SINR}_{\text{trig}} \text{ longer than } T_{\text{trig}} \text{ and Failure})$

=

$P(\text{SINR}(t) \text{ below } \text{SINR}_{\text{trig}} \text{ longer than } T_{\text{trig}}, \text{ and } \text{SINR}(t) \text{ below } \text{SINR}_{\text{fail}} \text{ longer than } T_{\text{fail}})$

=

$P(Z(t) \text{ above } Z_{\text{trig}} \text{ longer than } T_{\text{trig}}, \text{ and } Z(t) \text{ above } Z_{\text{fail}} \text{ longer than } T_{\text{fail}})$

# Scanning Triggering (2/2)

## Step 2 – Application of Level Crossing Results

$$\begin{aligned} & \mathbf{P}(Z(t) \text{ above } Z_{\text{trig}} \text{ longer than } T_{\text{trig}}, \text{ and } Z(t) \text{ above } Z_{\text{fail}} \text{ longer than } T_{\text{fail}}) \\ &= \\ & \frac{\mathbf{E}\{\text{total time of } Z(t) > Z_{\text{trig}} \text{ with } t_1 \geq T_{\text{trig}}, \text{ and } Z(t) > Z_{\text{fail}} \text{ with } t_2 \geq T_{\text{fail}}, t \in [0, T]\}}{T} \end{aligned}$$



$$\begin{aligned} & \mathbf{E}\{\text{total time of } Z(t) > Z_{\text{trig}} \text{ with } t_1 \geq T_{\text{trig}}, \text{ and } Z(t) > Z_{\text{fail}} \text{ with } t_2 \geq T_{\text{fail}}, t \in [0, T]\} \\ &= \end{aligned}$$

Basic of service failure probability

$$\mathbf{E}\{\# \text{ excursions above } Z_{\text{trig}} \text{ with } t_1 \geq T_{\text{trig}} \text{ for } t \in [0, T]\}$$

×

$$\mathbf{E}\{\# \text{ excursions above } Z_{\text{fail}} \text{ with } t_2 \geq T_{\text{fail}} \mid \text{excursion above } Z_{\text{trig}} \text{ with } t_1 \geq T_{\text{trig}}\}$$

×

Mean number of crossings of successive levels

$$\mathbf{E}\{t_2 \mid t_2 \geq T_{\text{fail}}\}$$

Length of crossings of successive levels

# Suitable Target Found

## Formulation

$$Y_k \triangleq \max_{i=1, \mathbf{x}_i \in B}^k \text{SINR}_i$$

$$\mathbf{P}(\text{Suitable Target Found}) = \mathbf{P}(Y_k \geq \text{SINR}_{\text{req}})$$

Tail of the Best  
Signal Quality

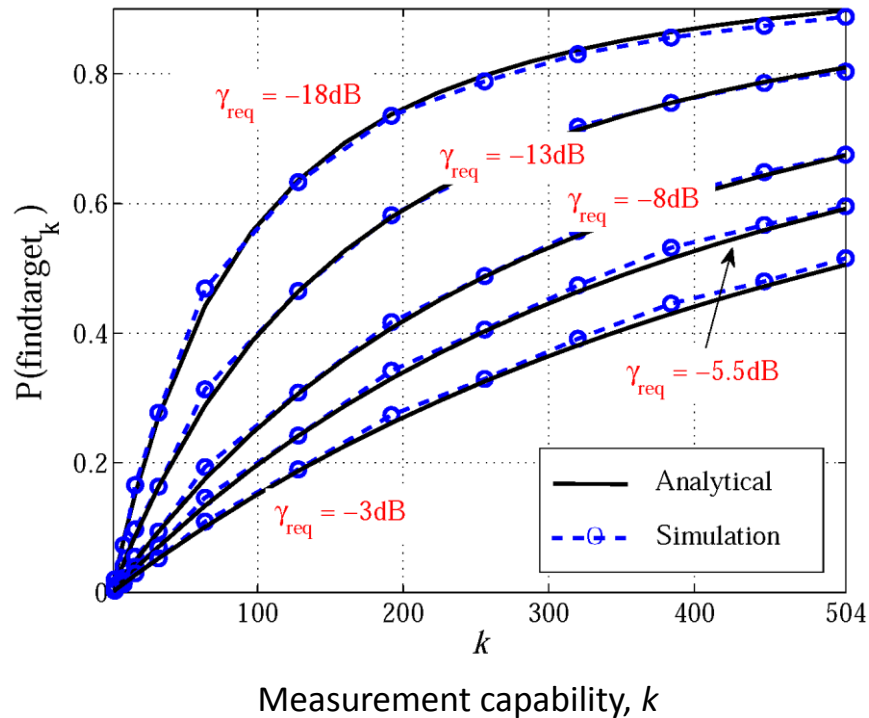
## Unlimited candidate set

- No restriction on the set of cells to be measured, e.g. intra-freq in WCDMA and LTE
- Apply the result on **the tail distribution of the best signal quality** for **network extension scenario** (obtained with stochastic geometry model)

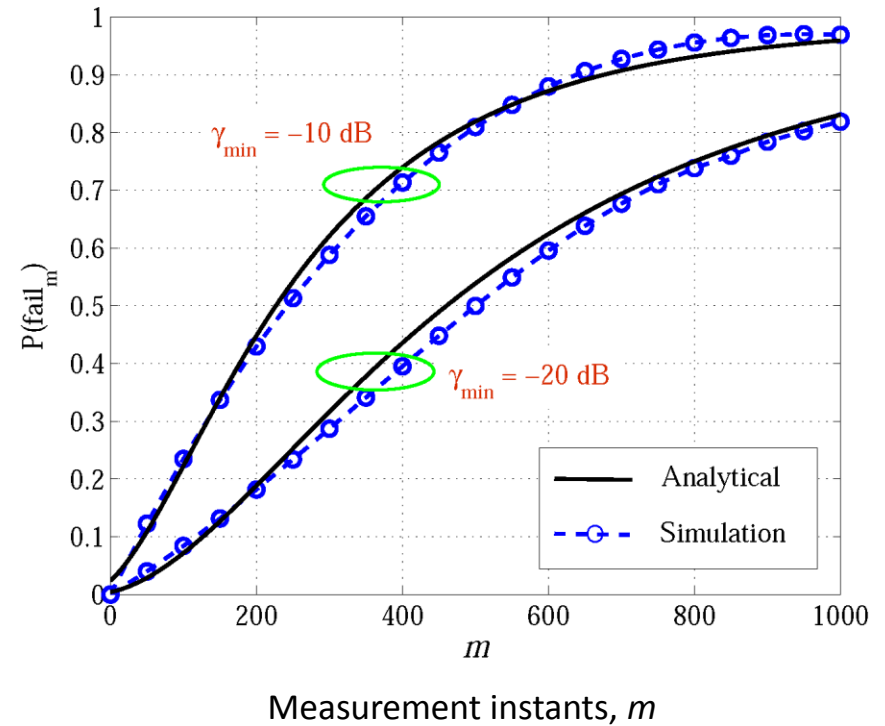
## Limited candidate set

- The mobile only measures cells belonging to a predefined set, e.g. neighbour cell list
- Apply the result on the **tail distribution of the best signal quality** for **network densification scenario** (obtained with heavy-tail asymptotics)

### Probability of finding suitable target



### Probability of service failure



- Analytical results agree with simulation
- High *measurement capability* increases the probability of finding a suitable target
- Robust service, i.e. low  $\text{SINR}_{\text{fail}} (\equiv \gamma_{\text{min}})$ , reduces the service failure probability

# Bibliography

## Articles

- ❖ V. M. Nguyen, F. Baccelli, L. Thomas, and C. S. Chen.  
Best signal quality in cellular networks: asymptotic properties and applications to mobility management in small cell networks.  
*EURASIP J. Wireless Commun. Netw. (JWCN), spec. issue on femtocell networks*, pp. 1-14, Mar. 2010.
- ❖ V. M. Nguyen, C. S. Chen, and L. Thomas.  
Handover measurement in mobile cellular networks: analysis and applications to LTE'.  
*In Proceedings of IEEE International Conference on Communications (ICC) 2011*. Japan, June 2011.
- ❖ V. M. Nguyen and F. Baccelli.  
A stochastic geometry model for the best signal quality in a wireless network.  
*Proceeding of IEEE International Symposium on Modeling and Optimization in Mobile, Ad-Hoc and Wireless Networks (WiOPT) 2010*, pp. 465-471. France, June 2010
- ❖ V. M. Nguyen and H. Claussen.  
Efficient self-optimization of neighbour cell lists in macrocellular networks.  
*Proceedings of IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC) 2010*, pp. 1921-1926. Turkey, Sept. 2010.
- ❖ V. M. Nguyen and L. Thomas.  
Efficient dynamic multi-step paging for cellular wireless networks.  
*Bell Labs Tech. J., special issue on Core and Wireless Networks*, vol.14(2), pp. 203-221. Aug. 2009.

## Articles (cont'd)

- ❖ V. M. Nguyen.

Extreme value modeling of the best signal quality and applications for small cell networks.

*Joint workshop of Bell Labs, Fraunhofer HHI, and Deutsche Telekom Labs on The Future of Communications: Science, Technologies, and Services.* Berlin, June 2010.

- ❖ V. M. Nguyen.

Some properties of level crossings of a stationary process and applications. *In preparation.*

- ❖ V. M. Nguyen, C. S. Chen, and L. Thomas.

A unified analytical model of handover measurement for mobile cellular networking.

*In preparation for IEEE /ACM Trans. Netw.*

## Standard Contributions

- ❖ Alcatel-Lucent/V. M. Nguyen.

Identifying coverage islands.

3GPP LTE Standard Contribution. TSG-RAN WG3\#66, R3-092949. Nov. 2009.

- ❖ Alcatel-Lucent/V. M. Nguyen.

UE measurements in coverage islands.

3GPP LTE Standard Contribution. TSG-RAN WG3\#66, R3-092950. Nov. 2009.

- ❖ Alcatel-Lucent/V. M. Nguyen.

Handling of UE measurements and transfer of UE history for mobility robustness optimization.

3GPP LTE Standard Contribution. TSG-RAN WG3\#66, R3-092951. Nov. 2009.

## Patent Applications

❖ V. M. Nguyen and H. Claussen.

Method for automatically configuring a neighbor cell list for a base station in a cellular wireless network.

European Patent Appl. No.08291260.1 (31.12. 08). International Patent Appl, No.PCT/EP2009/009204 (21.12.09)

❖ V. M. Nguyen and O. Marcé.

Adaptive time allocation to reduce impacts of scanning.

European Patent Appl, No.08291265.0 (31.12.08). International Patent Appl. No.PCT/EP2009/009205 (21.12.09)

❖ V. M. Nguyen and Y. El Mghazli.

Method and equipment for dynamically updating neighboring cell lists in heterogenous networks.

European Patent Application, No. 09290135.4 (25.02.09).

❖ V. M. Nguyen and Y. El Mghazli.

Method and apparatus for new cell discovery.

US Patent Appl, No.12/383,907(30.03.09). International Patent Appl, No.PCT/US2010/026496 (08.03.10)

❖ V. M. Nguyen, L. Thomas, and O. Marcé.

Method and controller for paging a mobile set in a cellular network.

European Patent Application, No. 09305029.2 (12.01.09)

❖ O. Marcé, A. Petit, and V. M. Nguyen.

Method for enhancing the handover of a mobile station and base station for carrying out the method.

European Patent Appl, No.09305189.4 (02.03.09). International Patent Appl, No.PCT/EP2010/052425 (25.02.10)