Analytical Performance Evaluation of Cooperative and Multi-Radio Concepts in Emerging Wireless Networks

W.I.N.T.E.R. Group

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Motivation

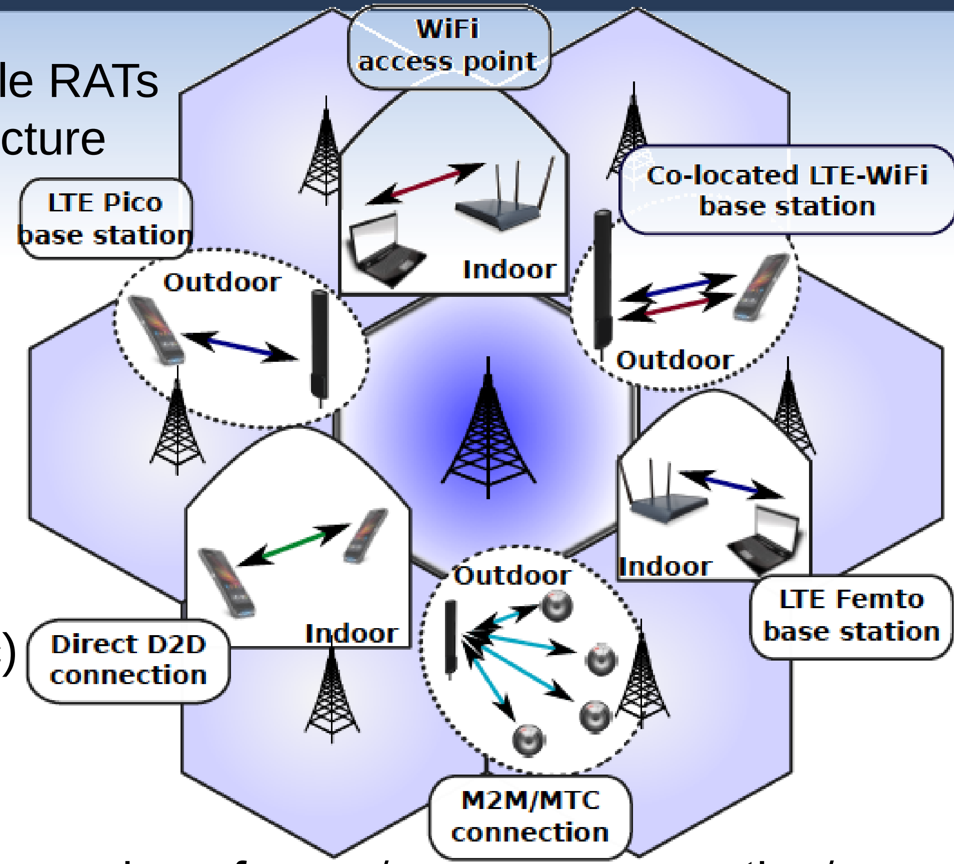
1. **5G**: integration of diverse techniques and solutions to improve performance of wireless systems

2. **Multi-RAT**: Multiple radios and associated device/ infrastructure intelligence will become a fundamental characteristic of 5G

3. **Cooperation**: Use of centralized cellular connectivity will help to manage direct links

Focus and Contributions of Proposed Research

Environment: integration between multiple RATs (WLAN and D2D) within HetNet architecture



Target: a **predictor** of flow-level **uplink** performance (stochastic traffic loads)

- Real-time data sessions with the minimum bitrate
- Files of random size (elastic traffic)

Evaluating: blocking probabilities/average number of users/energy consumption/…

Result: unified **Space-Time** methodology for modeling HetNet operation

Considering various degrees of **cellular-assistance**

Origin of the Proposed Mathematical Approach

TIME

SPACE

QUEUEING THEORY

Erlang published his first paper on queueing theory in 1909

STOCHASTIC GEOMETRY

geometric probability

Name is proposed by Frisch and Hammersley in 1963 as a name of a theory of "random irregular structures"

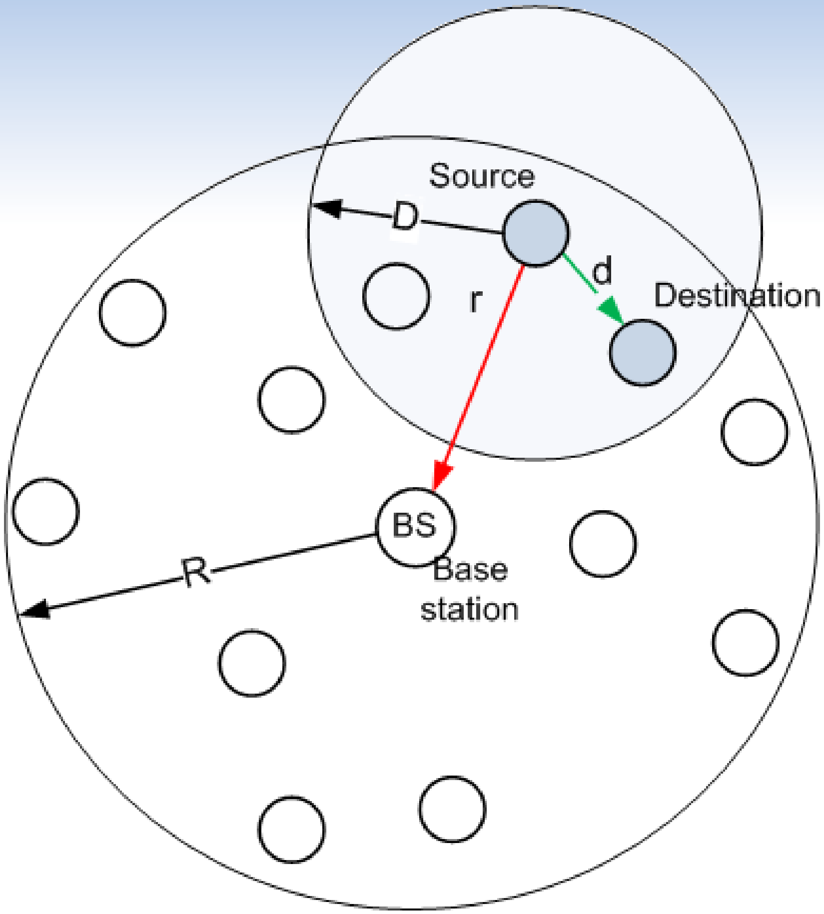
Methodology for Space-Time Network Analysis

Baseline model

Spatial network model: baseline

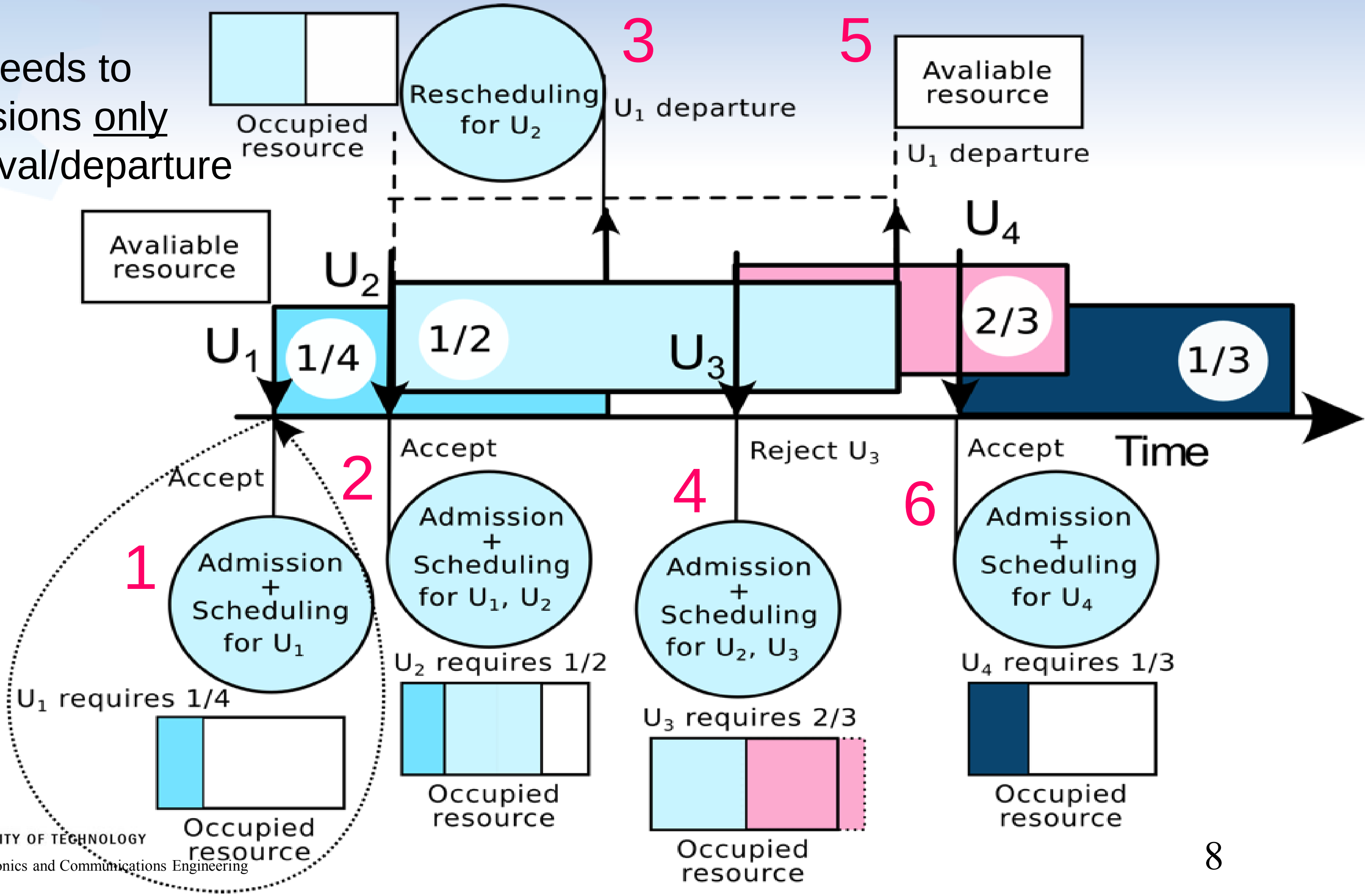
System model

1. Circle (sector) of radius R, base station.
2. Uniform user location,
   different channel characteristics.
   - Poisson arrivals of flows/sessions, λ
   - constant target bitrate, r
   - exponential holding time, μ
3. Admission/power control



Flow-level dynamic example

Predictor needs to make decisions only at user arrival/departure



Power/rate model

Assumption

The channel gain between Tx i and Rx j depends on the distance between them:

$$\gamma_{i,j} = \frac{G}{d_{i,j}^{\kappa}}$$

k is *propagation exponent*,
G is *propagation constant*.

Assumption

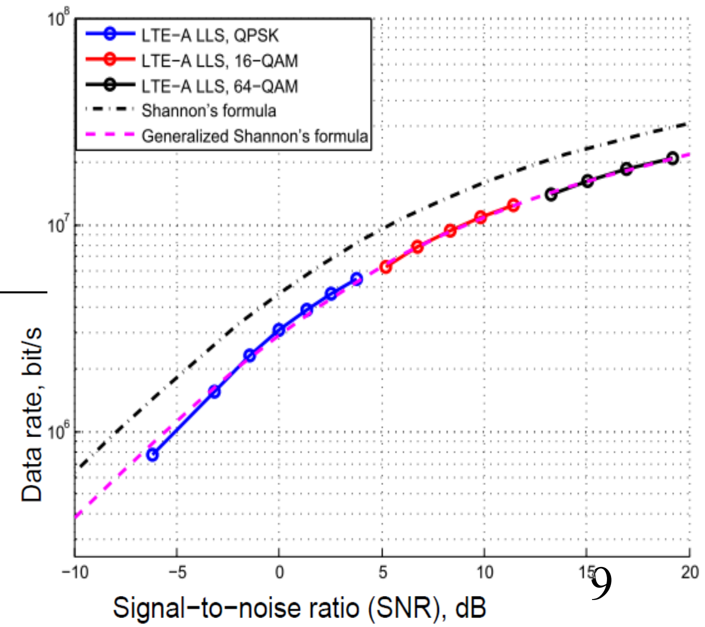
User transmit power and rate are coupled by *Shannon's formula*:

$$r_i = B\,\log(1 + A p_i)$$

p_i is output power of the RF power amplifier,
A, B are additional parameters, depending on wireless system implementation and configuration

$$A = \frac{\eta\gamma_{i,i}}{N_0 + I}, \quad B = w$$

Shannon's formula
for QPSK, 16-QAM, 64-QAM

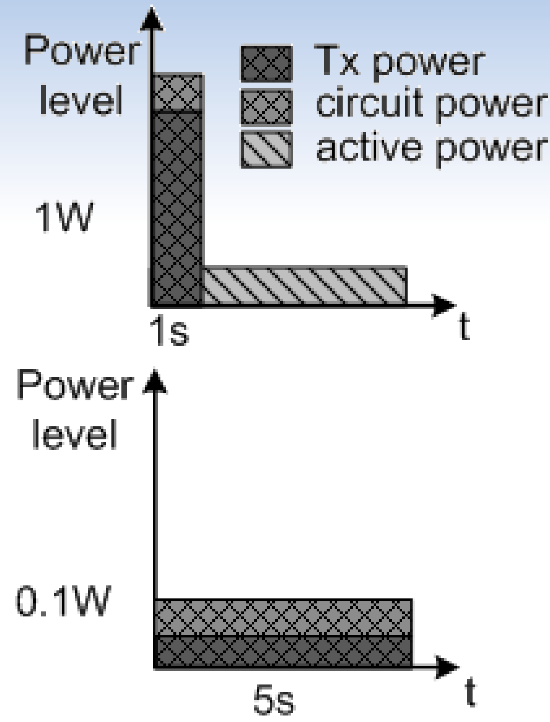


Power/resource allocation

Assumption:

Three different power levels for every transmitter:

- transmit power consumption p_i
- circuit power p_c,
- active power consumption p_a
- idle power consumption (set for simplicity p_{idle} = 0)



Assumption (power/resource allocation policies):

1. *"Maximum power"* = fixed maximum power
2. *"Full utilization"* = system resource is used completely
   Each session is allocated resource portion $\frac{r_0}{r_i} = \frac{1}{n}$
   (***n*** users in service adjust transmit power to match target bitrate $\boldsymbol{r_0}$)

System model analysis

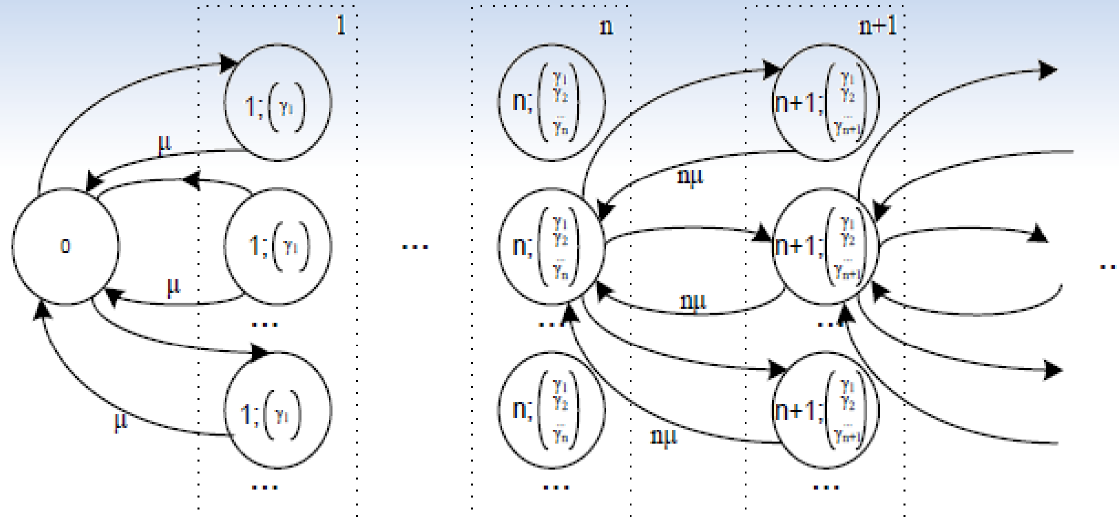
1. Describe and analyze the **generalized system model**

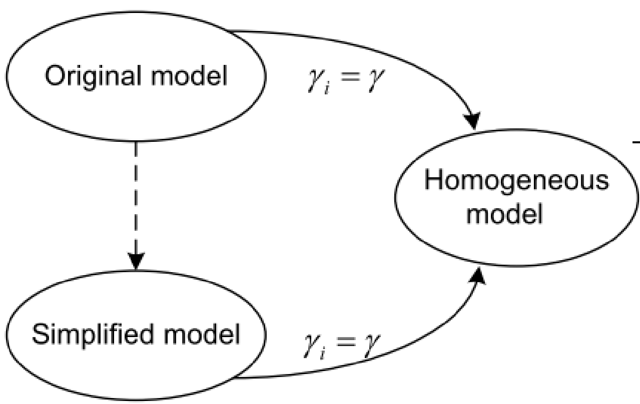
2. Markov process S(t):
number of users + vector SNR

$$n, (\gamma_1, \dots, \gamma_n)$$

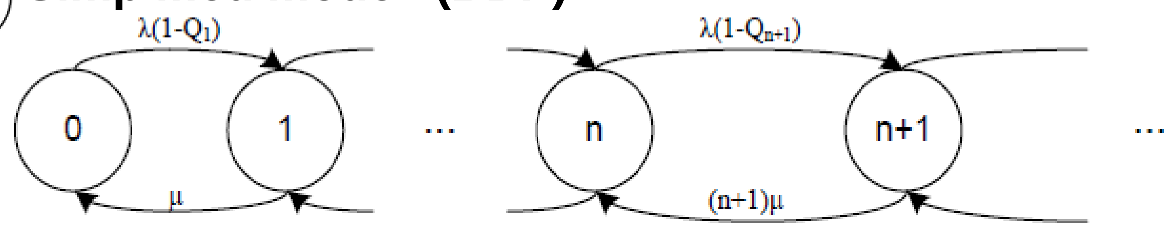
3. Set of states is uncountable

Use state aggregation





Simplified model (BDP)



4. Steady-state distribution via calculating all probability integrals

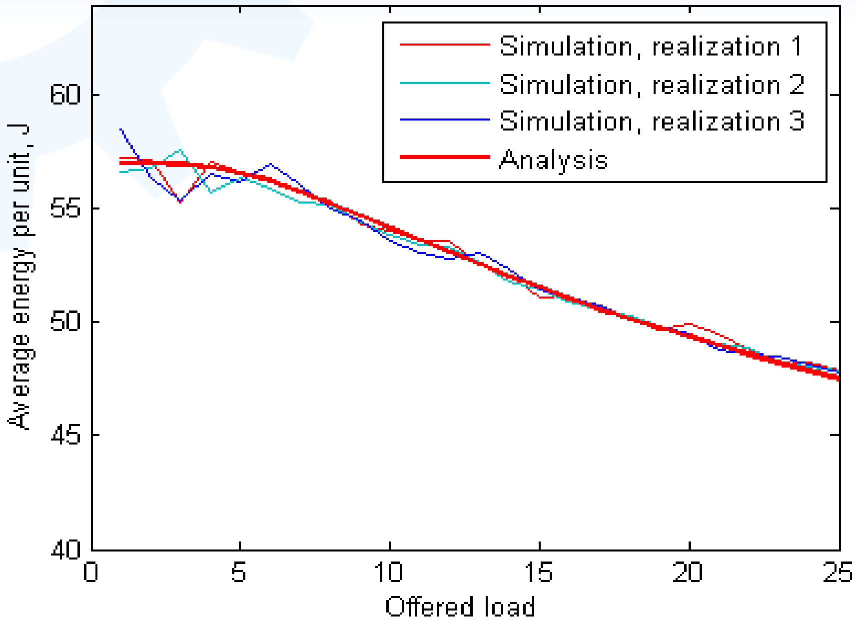
Q_{n+1} - probability of rejection at the stage n

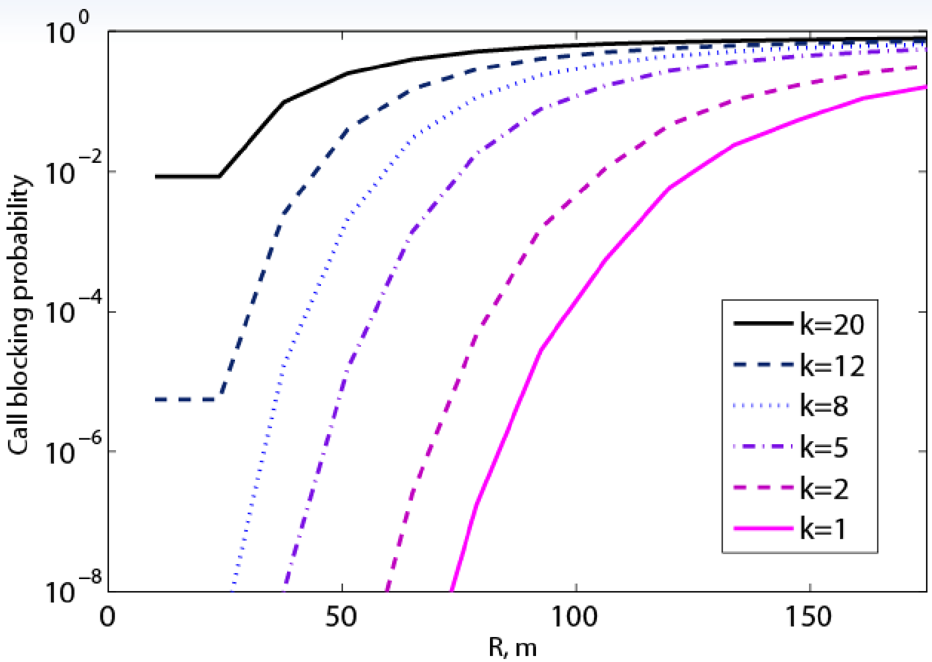
Numerical results

Average energy consumption (per flow), *E*[*J*]

$$E[J] = \frac{E[P]}{\lambda(1 - P_{block})}$$

Blocking probability





Average energy vs. offered load

Иlocking probability vs. distance (FU)

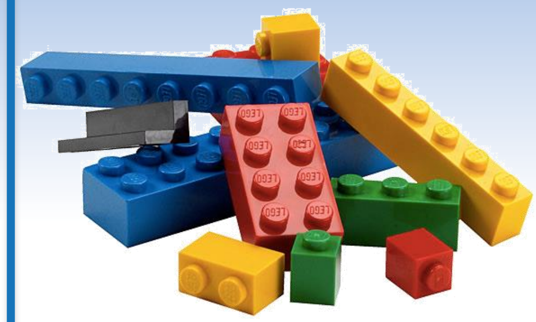
Proposed methodology

"Construction toy" for UL performance prediction

Blocks:

Space

- Spatial distribution of infrastructure
- Spatial distribution of users
- Area of interest



"Construction toy" for UL performance prediction

<u>**Blocks**</u>:

Space

- Spatial distribution of infrastructure
- Spatial distribution of us
- Area of interest

- Poisson point process (PPP)
- Poisson cluster process
- Hard core point process
- Determinantal (e.g. Ginibre)
- …

"Construction toy" for UL performance prediction

Blocks:

Space

- Spatial distribution of infrastructure
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- Poisson point process (PPP)
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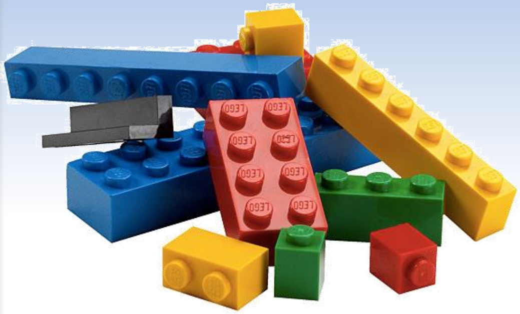
- Determinantal (e.g. Ginibre)
- …

"Construction toy" for UL performance prediction

Blocks:

Space

- Spatial distribution of infrastructure
- Spatial distribution of users
- Area of interest
  - Circle
  - Voronoi cell
  - Hexagon
  - …



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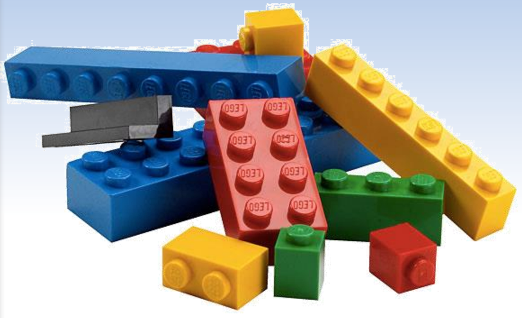


[Outcomes]

- Distribution of the **distance** between transmitters and receivers
- Distribution of the **instantaneous rates**
- Distribution of the **actual transmission rates**
- Distribution of **occupied individual shares** of the total resource
- Distribution of the **total occupied resource**

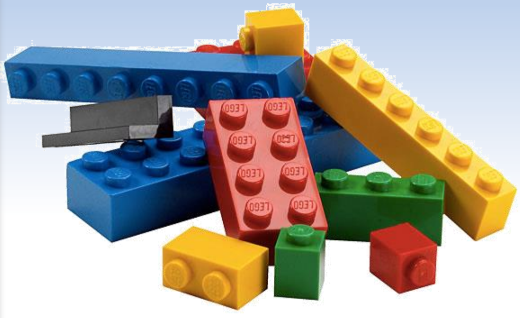
“Construction toy” for UL performance prediction

Blocks:

Time:

- User arrival process
- Type (QoS class)
- File-based traffic | Session-based
- Schedule/admission/power control

- Interference
- Channel model



"Construction toy" for UL performance prediction

Blocks:

Time

- User arrival process
- Type (QoS class)
- File-based traffic | Session-
- Schedule/admission/power control
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- Channel model

- Poisson process
- Markov-modulated PP
- D-BMAP arrival process
- …

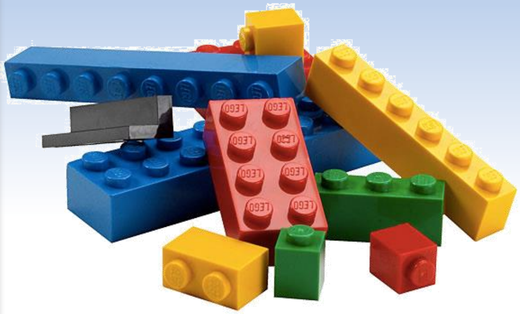
"Construction toy" for UL performance prediction

Blocks:

Time

- User arrival process
- Type (QoS class)
- File-based traffic | Session-based
- mission/power control
- terference
- Channel model

- Exponential file size
- Erlang-k file size
- Heavy-tailed distributions
- …



"Construction toy" for UL performance prediction

Blocks:

Time

User arrival process

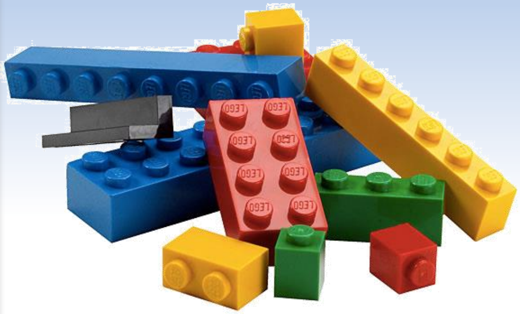
Type (QoS class)

File-based traffic

Session-based

Schedule/admissio

- Exponential service time
- Erlang-k service time
- Hyperexponential
- …



"Construction toy" for UL performance prediction

Blocks:

Time

- User arrival process
- Type (QoS class)
- File-based traffic | Session-based
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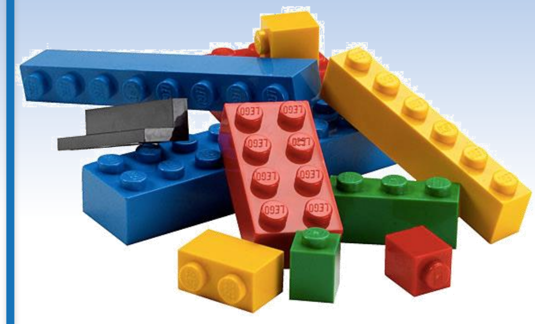


- Round robin
- Weighted RR
- …

- Check resource
- Check bitrate
- …

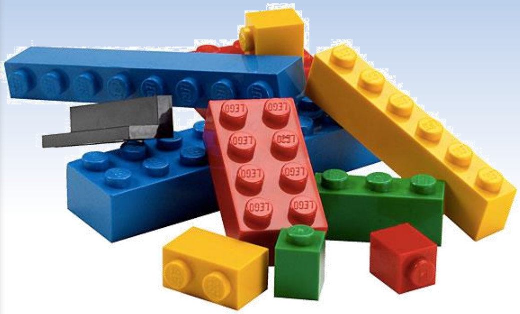
- Fixed power
- Power control
- …

"Construction toy" for UL performance prediction

Blocks:

Time

- User arrival process
- Type (QoS class)
- File-based traffic | Session-based
- Schedule/admission/power control
- Interference
  - Yes/No
- Channel model



"Construction toy" for UL performance prediction

Blocks:

Time

User arrival process

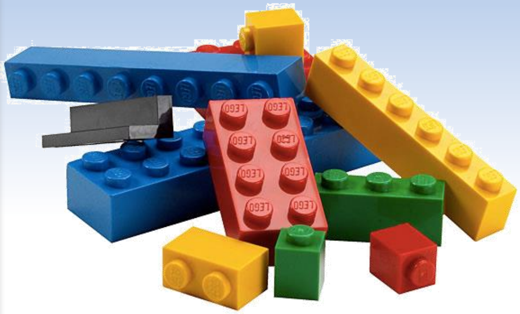
Type (QoS class)

File-based traffic	Session-based

Schedule/admission/power control

Interference

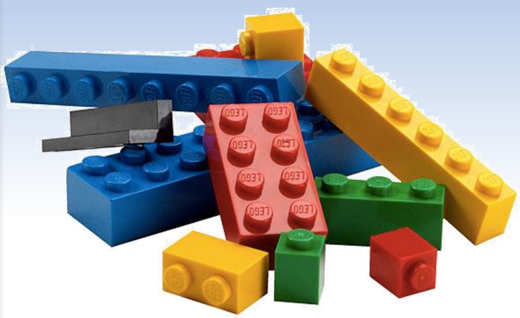
Channel model



- Shannon + power function of d
- …

"Construction toy" for UL performance prediction

Blocks:



Time:
- User arrival process
- Type (QoS class)
- File-based traffic | Session-based
- Schedule/admission/power control

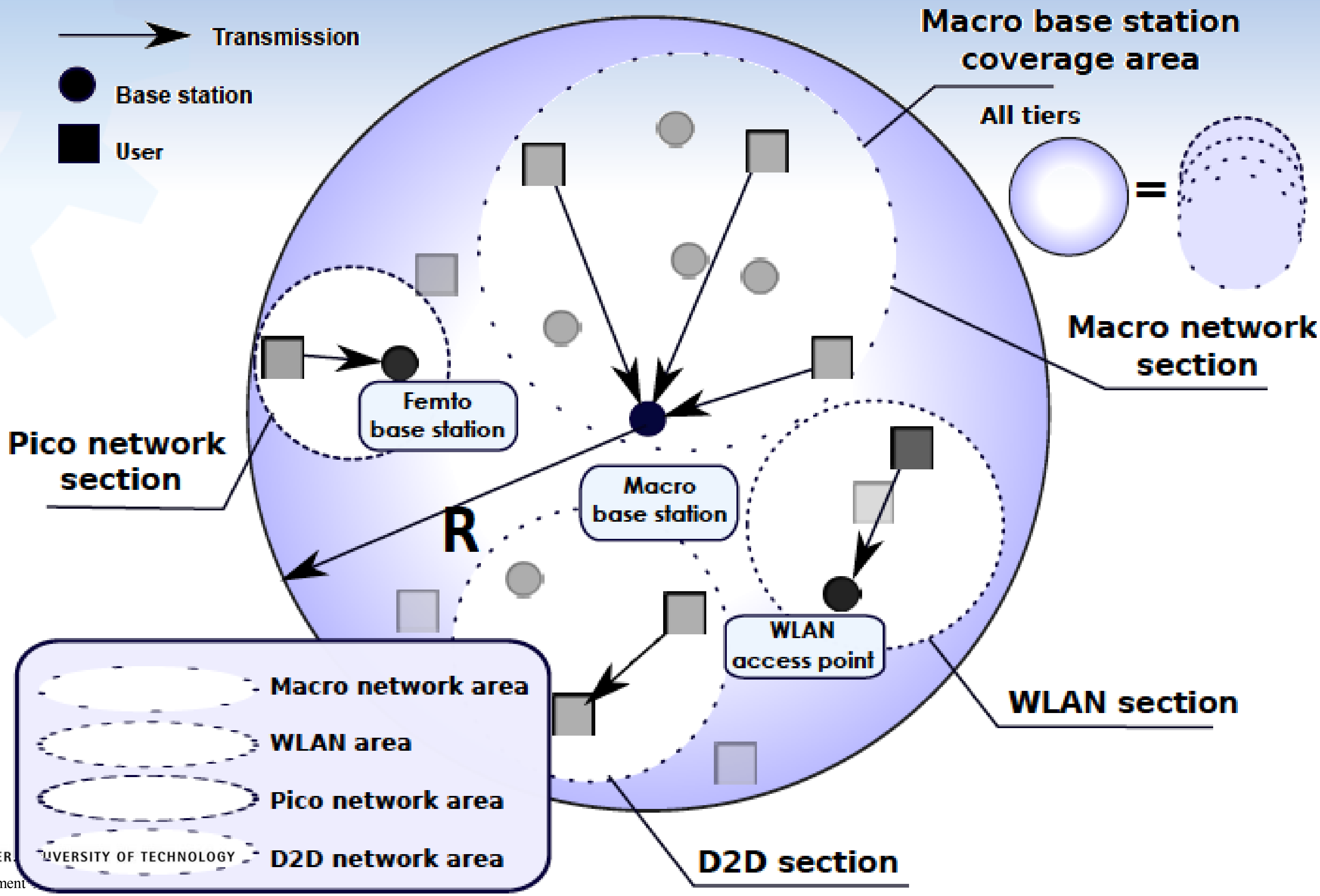
- Interference
- Channel model

↓

- Queueing system A/S/c/K/N/D
- Stationary distribution of ongoing users
- Averaged by space and time system characteristics

Heterogeneous network

Envisioned multitier network



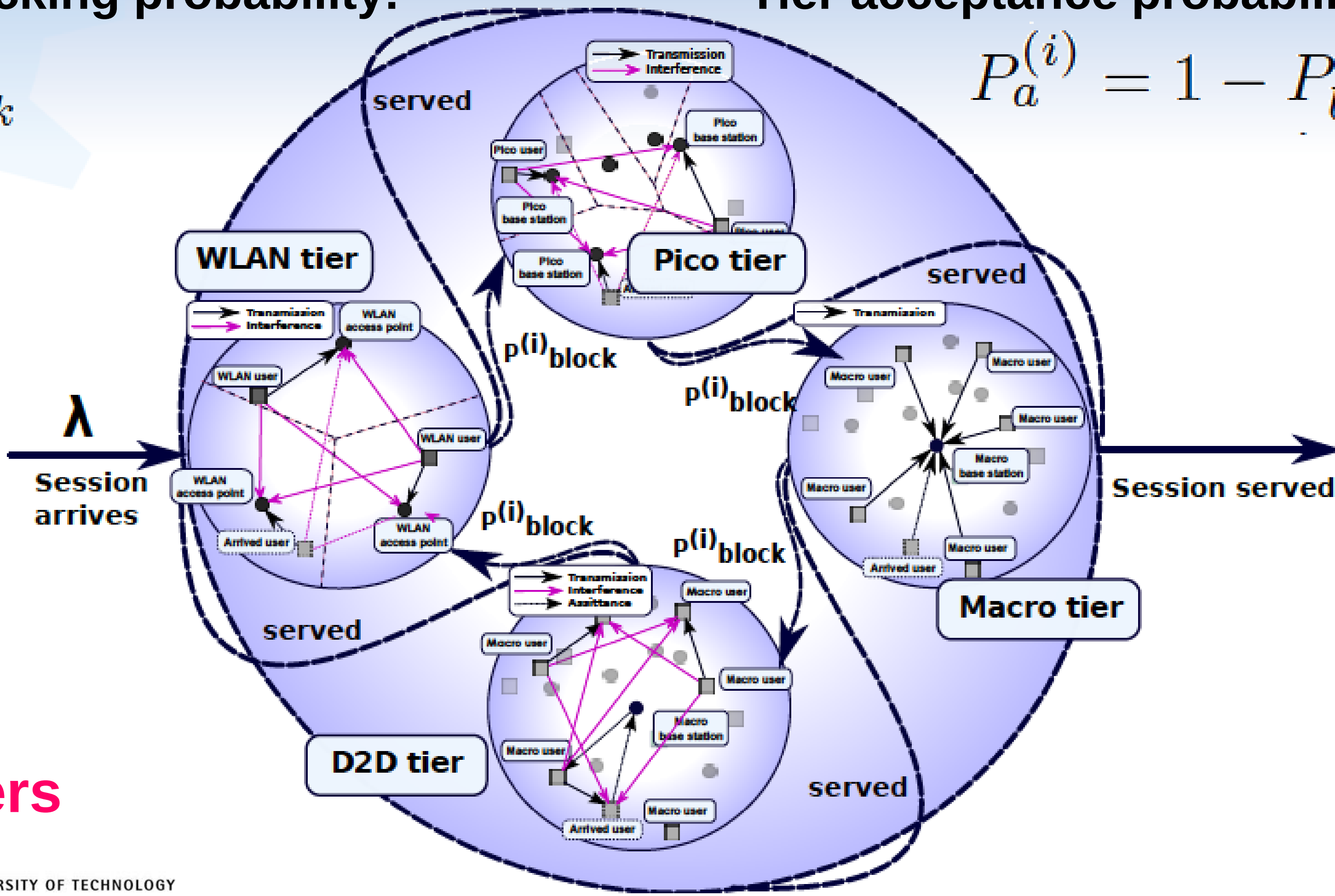
Example service discipline

Tier blocking probability:

$$P_{block}^{(i)}$$

Tier acceptance probability:

$$P_a^{(i)} = 1 - P_{block}^{(i)}$$

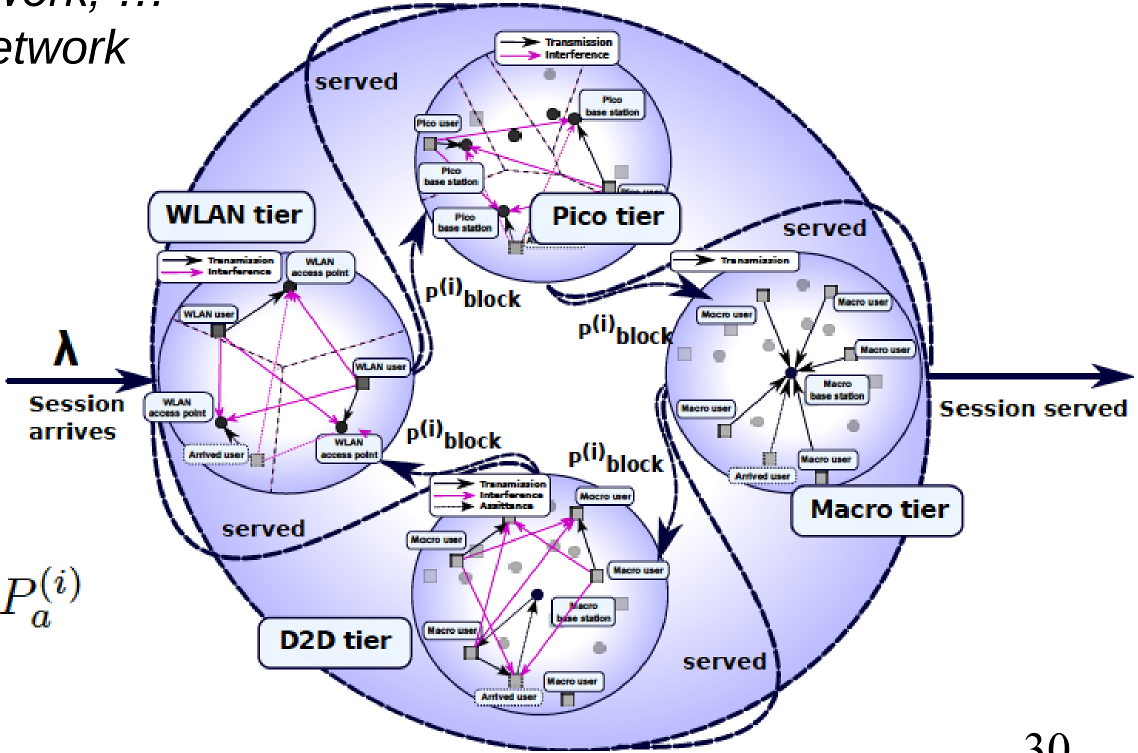


T tiers

Multiple tiers

Several tiers based on diverse technologies: e.g., Macro cellular, WLAN, Pico cellular

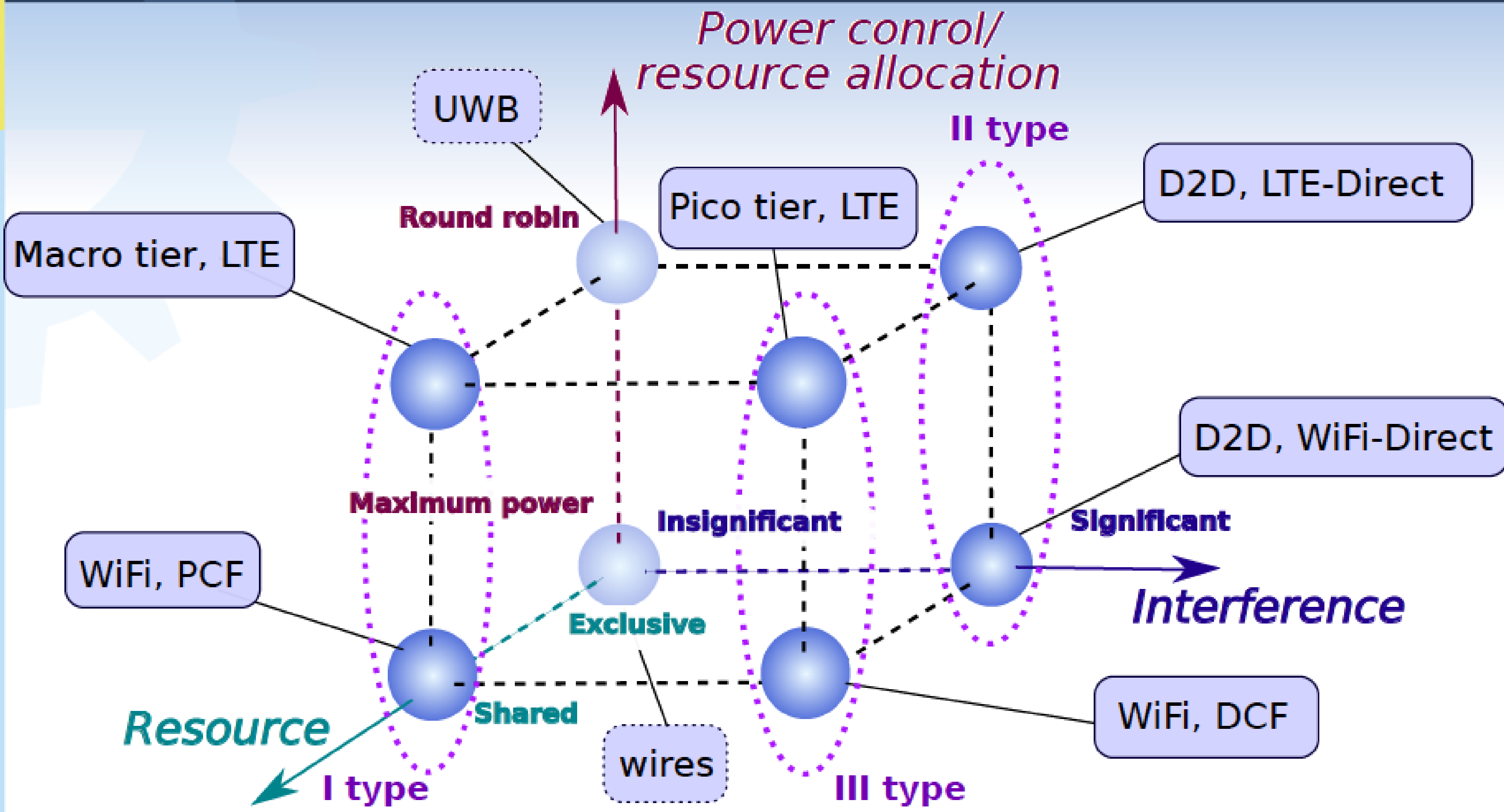
1. Attempt to offload new session onto the *D2D network* (by admission control).
2. If accepted, served by the network without interruption
3. Otherwise, attempt to *WLAN network, …*
2. Otherwise, attempt to *Pico network, …*
3. Otherwise, attempt to *Macro network*
4. If session is *not admitted*, it is considered **blocked**



System block probability:

$$P_{block} = 1 - \sum_{i=1}^{T} \prod_{j=1}^{i-1} (1 - P_a^{(j)}) P_a^{(i)}$$

Proposed taxonomy for HetNets



Example system model

Isolated cell of radius R:

- macro BS + **several** femto BSs + **several** WiFi APs

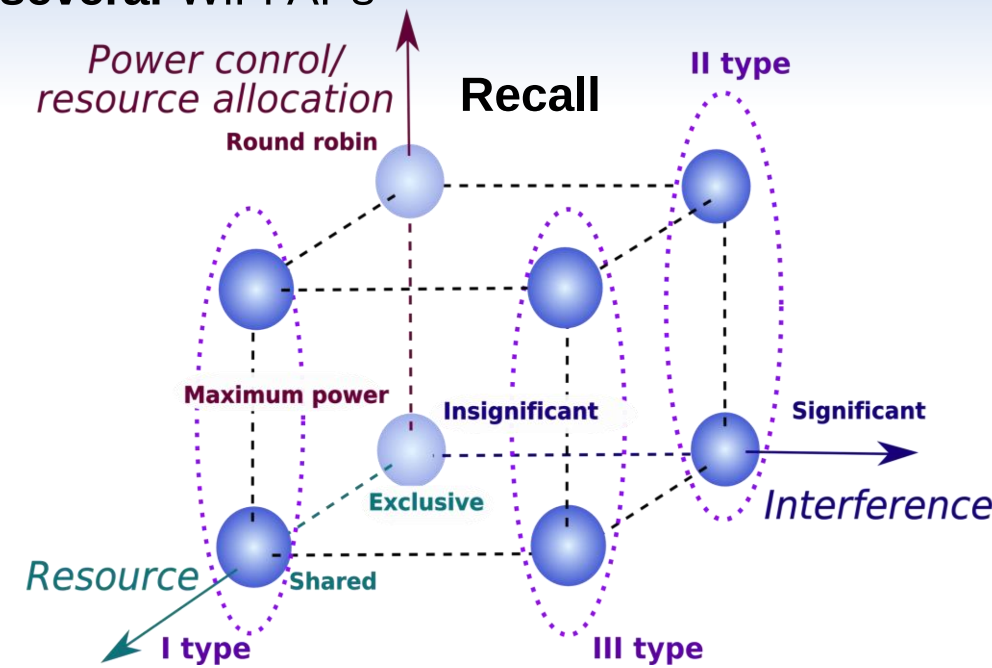
Uplink, real-time sessions:

•Poisson arrivals of sessions, λ

•constant target bitrate, r_0

and exponential holding time, μ

- or elastic traffic



•Three types of systems:

•Type I (no interference, shared resource)

•Type II (interference, exclusive resource)

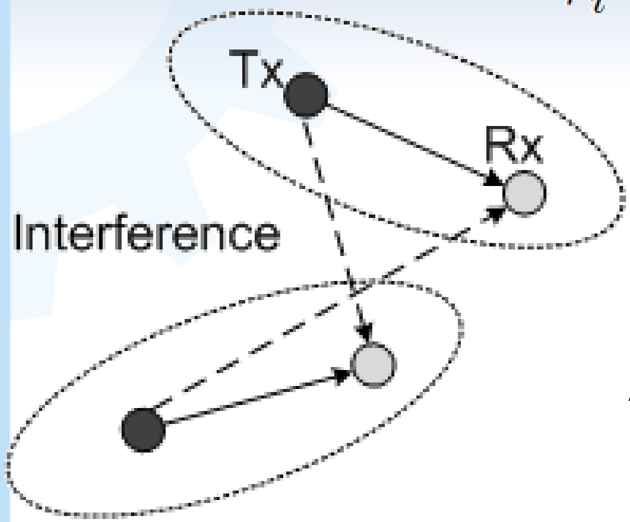
•Type III (interference, shared resource)

Are more complex and require further assumptions

Additional assumptions for T.II

Instantaneous rate Shannon's theorem for interference-limited environment

$$r_i = w \log\left(1 + SINR_i\right) = w \log\left(1 + \frac{p_i \gamma_{i,i}}{N_0 + I}\right)$$



Assumption

Noise plus interference power does not exceed some threshold

$$N_0 + I \leq KN_0$$

Assumption

D2D network of (**n-1**) users admits new session **n**
if for the set of transmitters *at each receiver*:

$$\frac{p_{max}\gamma_{i,i}}{KN_0} \geq e^{\frac{r}{w}} - 1$$

$$p_{\max}\gamma_{j,i} \leq N_0, \forall j, i \neq j$$

K is fixed throughout the D2D network

Transitions for T.I

We formulate Theorems connecting the obtained distributions and sought transitions rates

Theorem 1 *For tier type I under the RR policy, the accept probabilities* $\Pr\{accepted \mid arrived\} = 1 - Q_{n+1}$ *can be obtained by:*

$$1 - Q_{n+1} = \Pr\left\{r_{n+1}^{\max} \geq \frac{r_0(n+1)}{\delta_m}\right\}\left(\frac{\Pr\left\{r_i^{\max} \geq \frac{r_0}{\delta_m}(n+1)\right\}}{\Pr\left\{r_i^{\max} \geq \frac{r_0 n}{\delta_m}\right\}}\right)^n,$$

where

$$\Pr\{r \geq x\} = 1 - \Pr\{r < x\} = 1 - F_r(x),$$

and

$$F_r(x) = 1 - \frac{1}{R^2}\left[\frac{\eta G p}{N_0}\right]^{2/\kappa}\left(e^{r/w} - 1\right)^{-2/\kappa}, r_R \leq x < r_{lim}; \quad F_r(x) = 1, x \geq r_{lim}.$$

Transitions for T.II

Connections between the obtained distributions and sought transitions rates are dependent on the considered type

Theorem 2 *For tier type II under the MP policy, if admission control is performed according to (1.5) and, in particular, accounting for (1.14), then the reject probabilities* Q_{n+1} *can be closely approximated by:*

$$Q_{n+1} = 1 - \Pr\{accepted \mid arrived\} = \left[F_\gamma\left(\frac{N_0}{p_{\max}}\right)\right]^{2n-1}\left[1 - F_\gamma\left(\frac{\theta_0}{p_{\max}}\right)\right],$$

where $\theta_0 = KN_0\left(e^{\frac{r}{w}} - 1\right)$ *and the cumulative distribution function (CDF) for the SNR per a power unit* γ *is given as:*

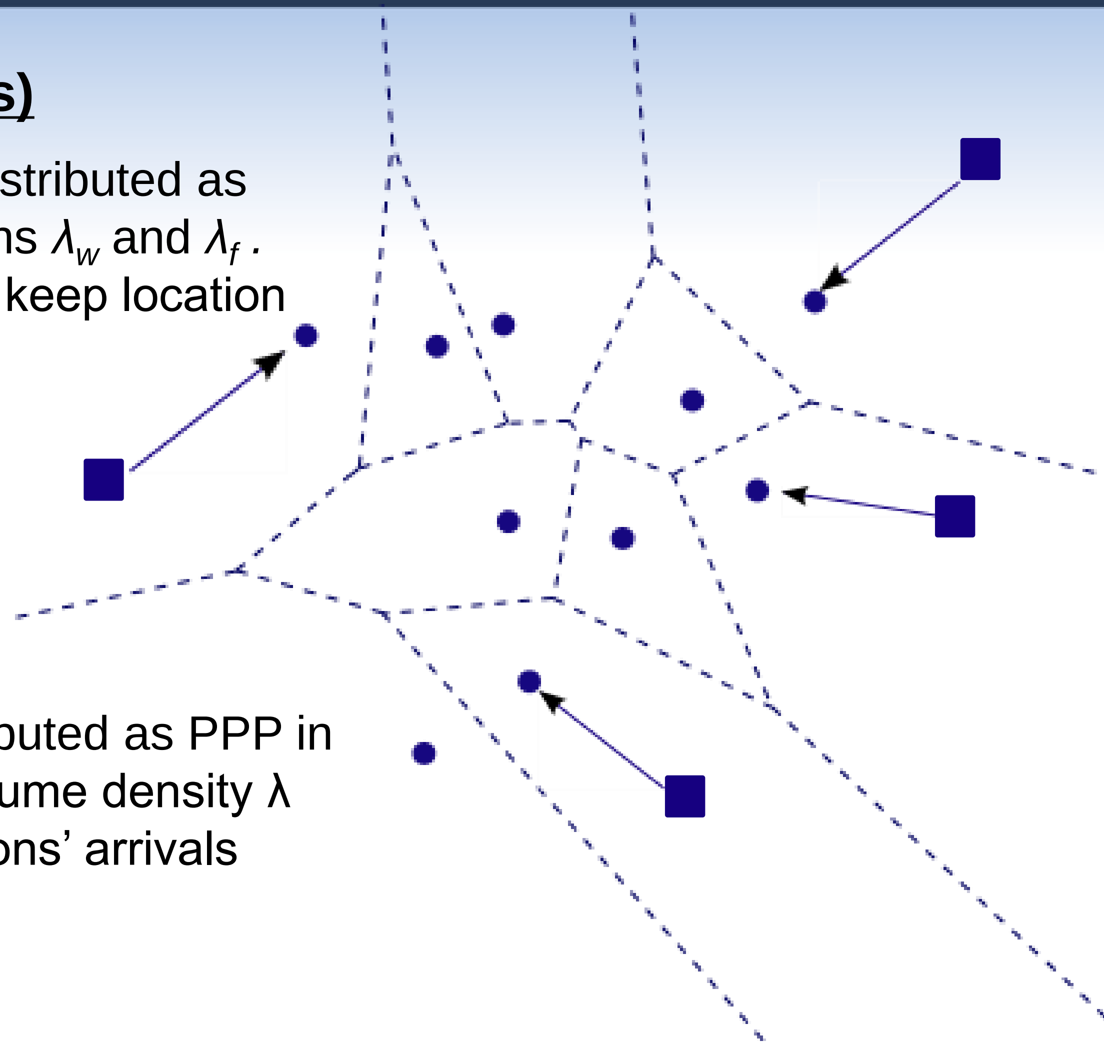
$$F_\gamma(\gamma) = 1 + \frac{G^{\frac{4}{k}}\gamma^{-\frac{4}{k}}}{8R^4} - \frac{G^{\frac{2}{k}}\gamma^{-\frac{2}{k}}}{R^2}\ln 2,\ \textit{if}\ \frac{G}{(2R^2)^{\frac{k}{2}}} \le \gamma \le \gamma_{\max}, \gamma_{\max} = \frac{KN_0}{p_{\max}}\left(e^{\frac{r_{\max}}{w}} - 1\right)$$

$$F_\gamma(\gamma) = 1 - \frac{1}{R^2}\left(\frac{G^{\frac{4}{k}}\gamma^{-\frac{4}{k}}}{8R^2} + G^{\frac{2}{k}}\gamma^{-\frac{2}{k}}\ln\frac{4R^2\gamma^{\frac{2}{k}}}{G^{2k}}\right),\ \textit{if}\ \frac{G}{(2R)^k} \le \gamma \le \frac{G}{(2R^2)^{\frac{k}{2}}}.$$

Additional assumptions for T.III

Assumption (BS/AP locations)

APs and femto BSs are spatially distributed as PPP on **2D plane** with rate functions λ_w and λ_f . APs/BSs are considered fixed and keep location all the time during **one** realization.



Assumption (user location)

Users locations are spatially distributed as PPP in the 3D space (X × Y × t) . We assume density λ for the time component (i.e. sessions' arrivals follow Poisson process of rate λ).

Additional assumptions for T.III

Assumption (admission control)

System admits *arrived session* if it has sufficient resources to serve it.
Each ongoing session i has to occupy exactly r_0/r_i of resource:

$$\sum_{all\ sessions} \left(\frac{r_0}{r_i}\right) \leq \delta$$

δ ≤ 1 – available resource

$r_i \leq r_{max}$ - instantaneous data rate
r_{max} - maximum achievable rate at the maximum power level.

Assumption (interference)

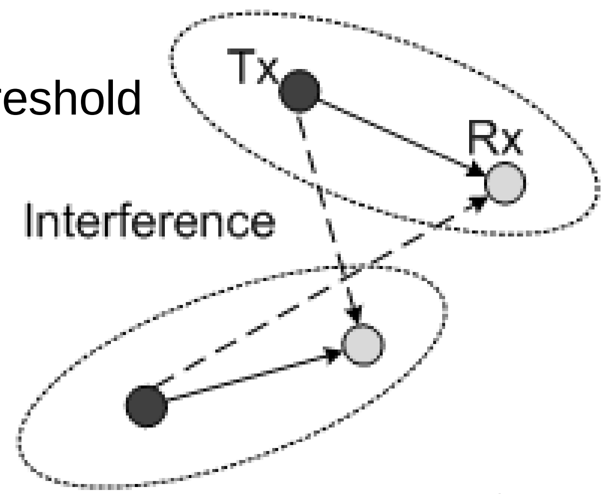
Noise plus interference power does not exceed some threshold

$$N_0 + I \leq KN_0$$

K is fixed

Network of (**n-1**) users admits new session **n**
if for the set of transmitters *at each receiver*:

$$p_j \gamma_{j,i} \leq N_0, \forall j, i \neq j$$



Transitions for T.III

Theorem 3 *[Galinina et al. (2014)] For tier type III, the average number of sessions per receiver (AP/BS) n_0 tends to $\frac{n}{L_i(\pi R^2)} = \frac{n}{E[N_i]}$ for large areas, where $E[N_i]$ is the expected number of receivers of tier i within the circle R.*

Theorem 4 *For tier type III under the MP policy, the corresponding transition rates may be calculated as $\Pr\{accepted \mid arrived\} = 1 - Q_{n+1}$ accounting for the following:*

$$1-Q_{n+1}=\frac{\left(1-e^{-\pi L_w d^2_{r,n+1}}\right)^{n+1}}{\left(1-e^{-\pi L_w d^2_{r,n}}\right)^{n}}\left(L_w \pi d^2_{thr} e^{-L_w \pi d^2_{thr}} + e^{-L_w \pi d^2_{thr}}\right),$$

where $d_{thr} = \left[\frac{Gp_{\max}}{N_0}\right]^{\frac{1}{\kappa}}$ and the constant value $d_{r,n}$ is defined as $\left(\frac{p_{\max}\eta G}{KN_0}\right)^{\frac{1}{\kappa}}\left(e^{\frac{\tilde{r}_{0,n}}{w}}-1\right)^{-\frac{1}{\kappa}}$.

$$\tilde{r}_{0,n} = r_0/(\delta_w - \sigma_n)$$

$$\sigma_n = E\left[\frac{r_0}{r_i^{\max}}\,\middle|\,\frac{r_0}{r_i^{\max}} \le \delta_w\right]\frac{n}{E[N_i]} = E[y|y \le \delta_i]\frac{n}{E[N_i]},$$

and $E[y|y \le \delta_i]$ may be found as:

$$E[y|y \le \delta_i] = \int_{y_0}^{\delta_i} y f_y(y|y \le \delta_i)dy = \frac{2\pi L_w}{C_3}\int_{y_0}^{\delta_i} y d(y) d'(y) e^{-\pi L_w \left(\frac{p_{\max}\eta G}{KN_0}\right)^{\frac{2}{\kappa}}\left(e^{\frac{r_0}{wy}}-1\right)^{-\frac{2}{\kappa}}} dy +$$

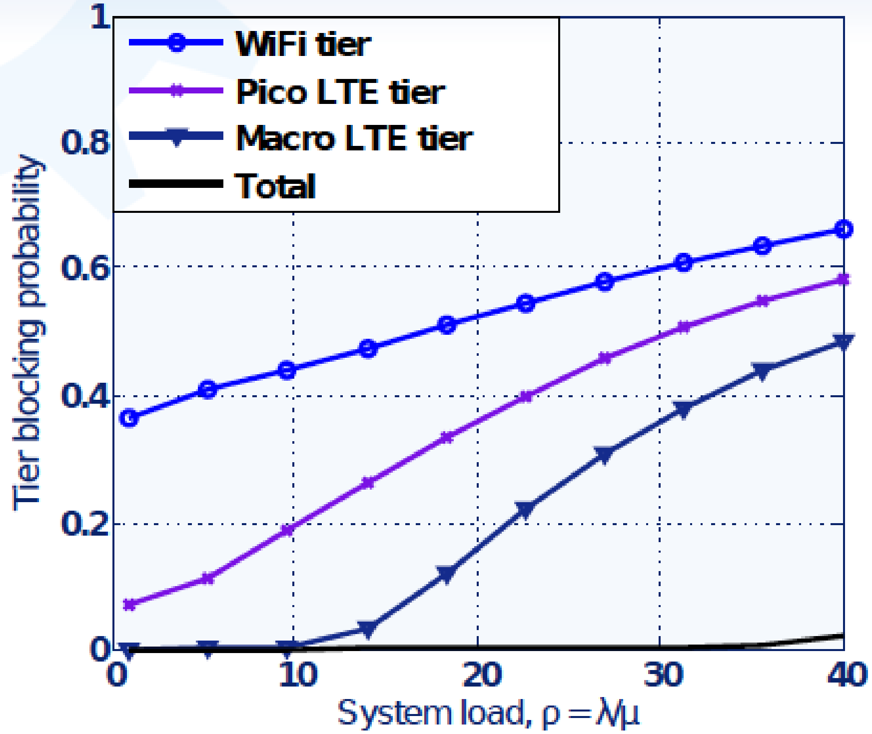
$$+\frac{2\pi L_i}{C_3} y_0 \int_0^{y_0} d(y) d'(y) e^{-\pi L_w \left(\frac{p_{\max}\eta G}{KN_0}\right)^{\frac{2}{\kappa}}\left(e^{\frac{r_0}{wy}}-1\right)^{-\frac{2}{\kappa}}} dy,$$

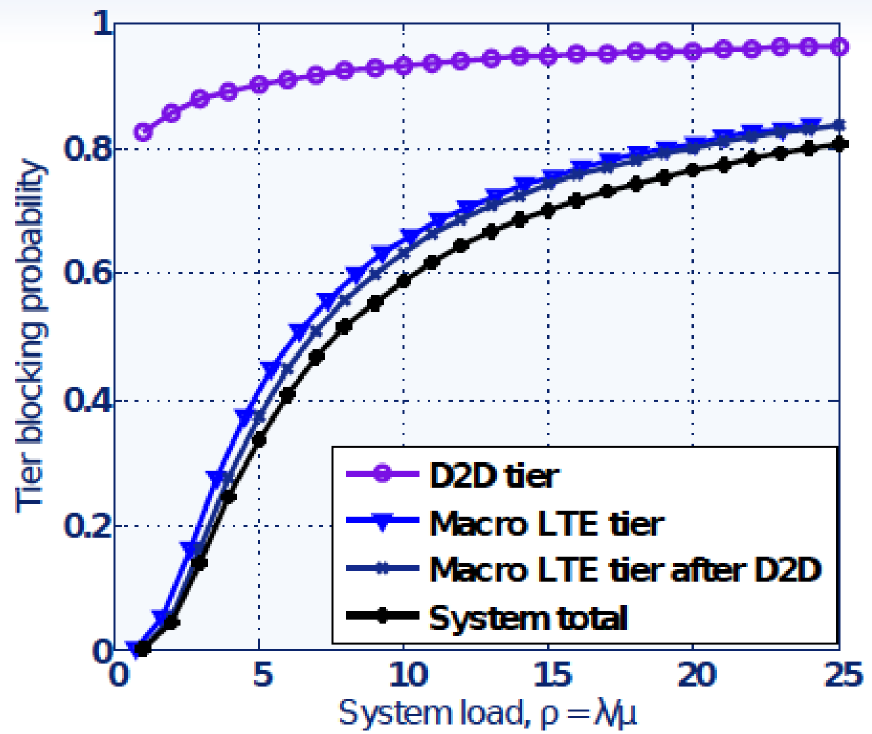
Numerical examples

Numerical results 1/2

Analyzing blocking probabilities in:

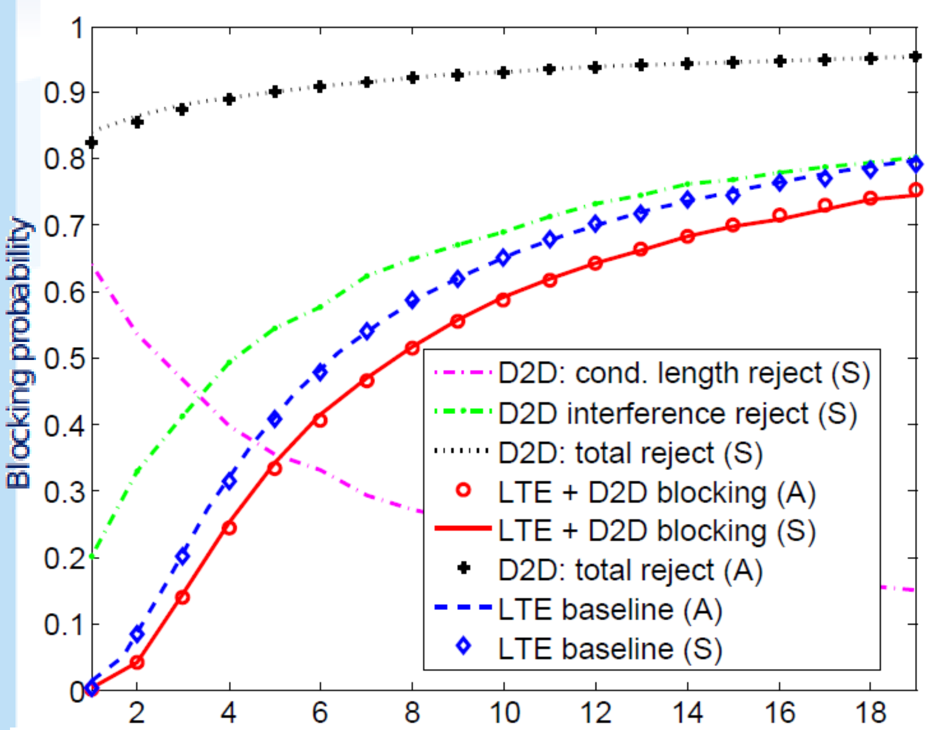
three-tier (left), and **two-tier** (right) HetNets

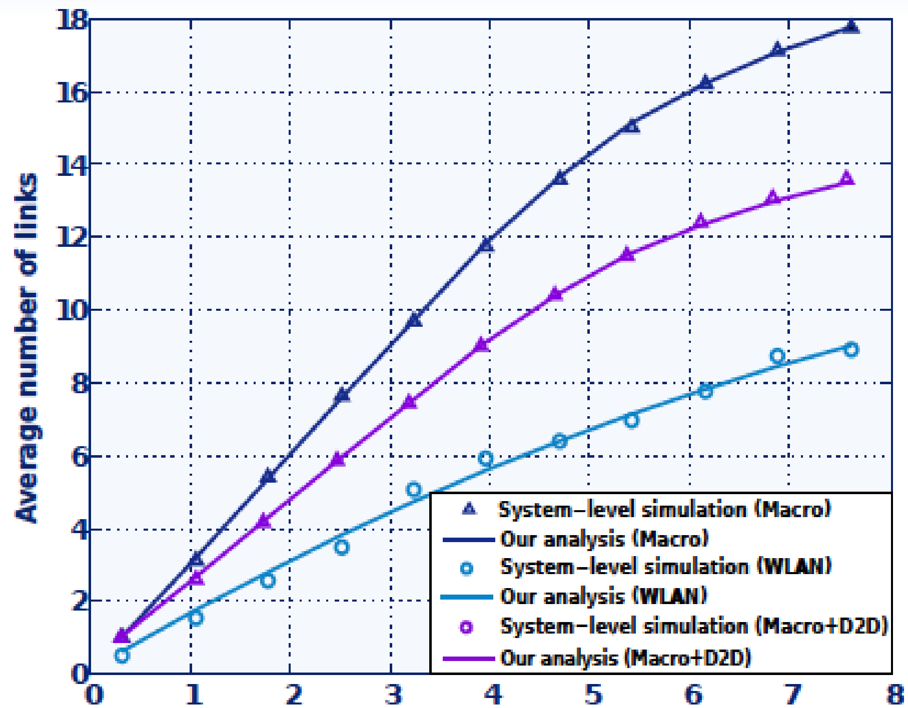




Numerical results 2/2

Session **blocking/reject probabilities** (left) and **system capacity** (right) vs. **system load**



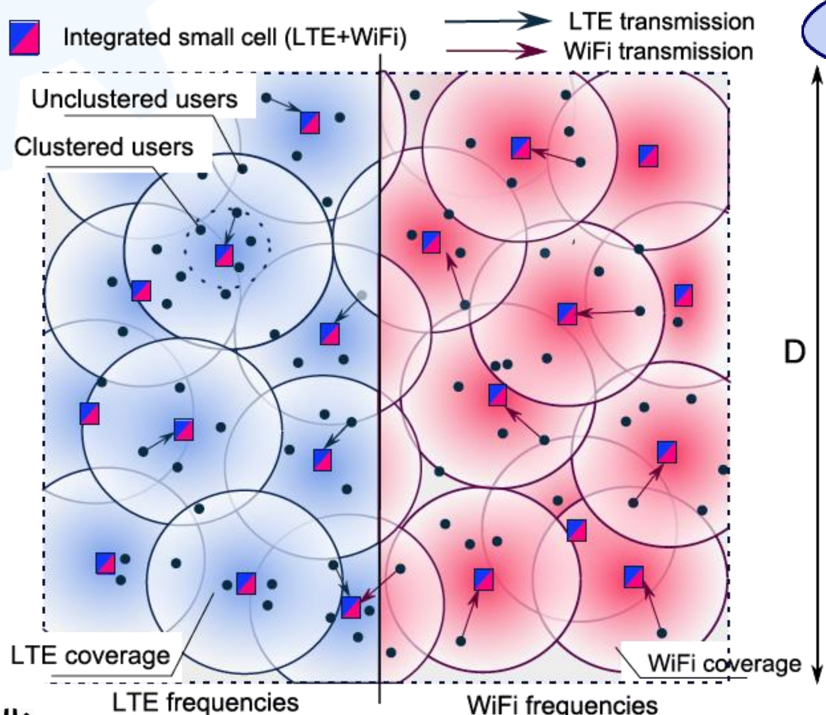


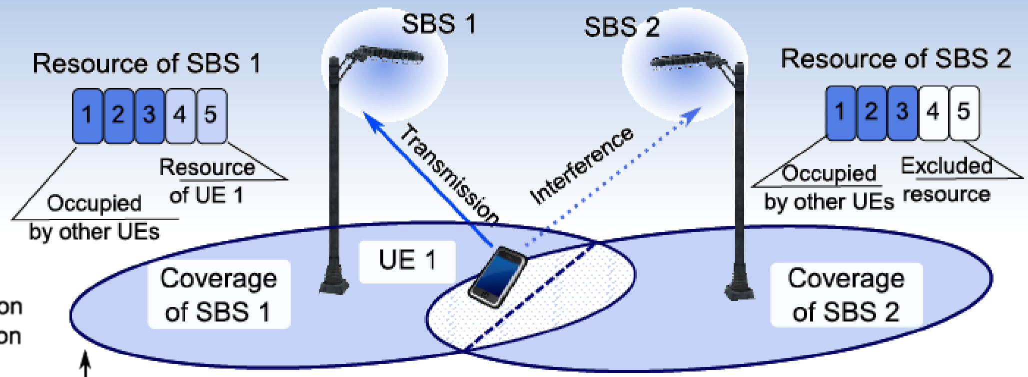
Main outcomes

- A unified mathematical methodology capturing :
  - the crucial HetNet dynamics, and
  - geometrical randomness of user deployment
- A classification of practical HetNet components
- Analytical methods of calculating main performance measures

Ultra-Dense Small Cells with co-located LTE and WiFi

Envisioned system topology





Interference coordination

Interference coordination

$$\frac{i}{E\left[\frac{s_j}{\frac{\tilde{\delta}_w r_w}{i} + \frac{\tilde{\delta}_l r_l}{i}}\right]}$$

Comparison co-located LTE and WiFi and WiFi-preferred scheme

Average transmission time for a file trasnfer