# Towards Optimized Planning, Operation, and Utilization of Heterogeneous Wireless Networks

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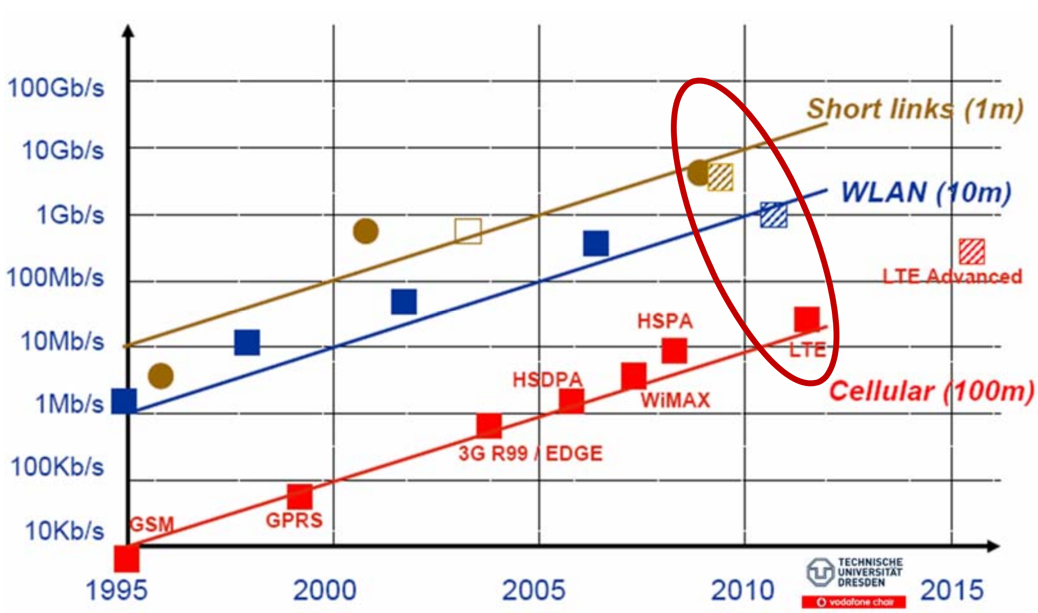
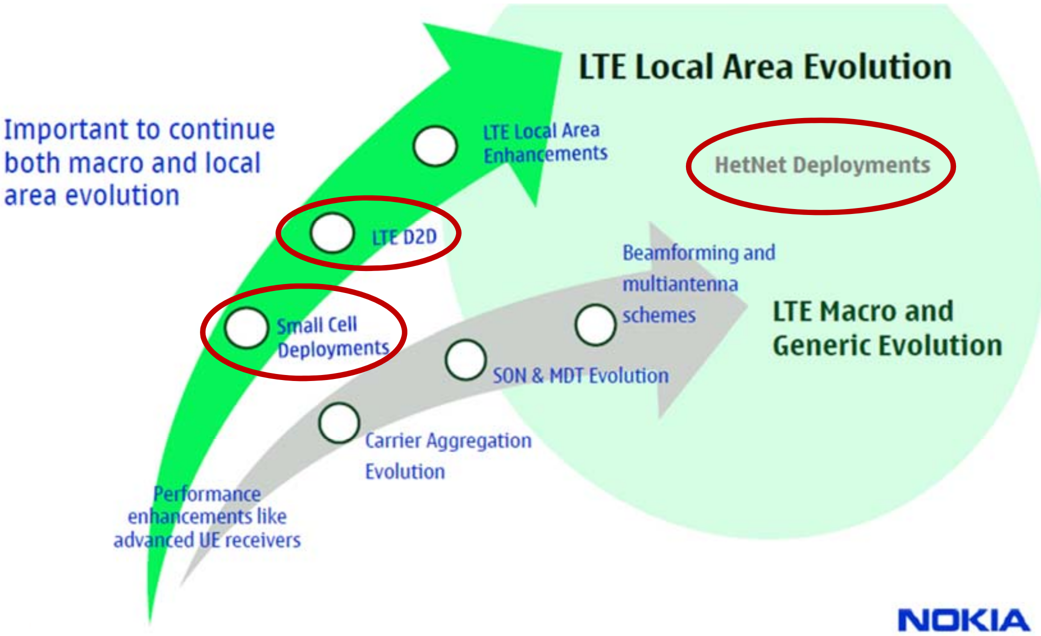
# Wireless technologies are evolving

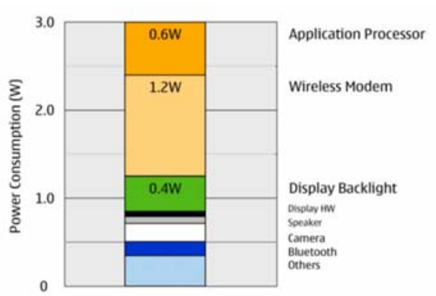


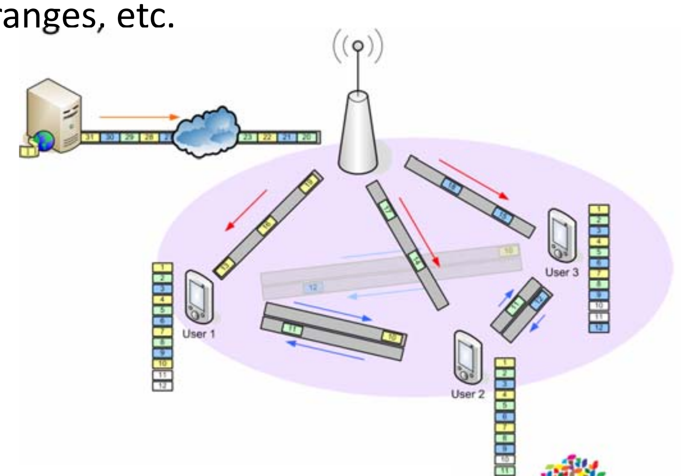
# LTE cellular technology is evolving



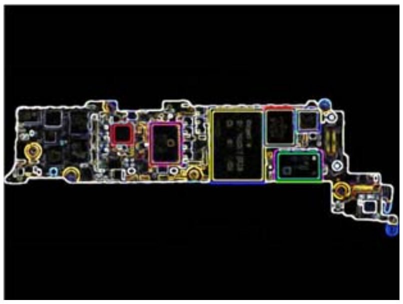

# Wireless networking: Research project I

- Multimedia apps require the wireless interfaces of APs/BSs and MTs to be active for long periods
- Mobile-to-mobile cooperation can provide gains in wireless networks
- Smartphones are equipped with multiple wireless interfaces with different designs, bit rates, ranges, etc.




NPRP 09 – 180 – 2 – 078: Optimized Energy Efficient Video Streaming for Wireless Networks with Cooperation among Mobile Devices [joint work with QMIC and LAU]

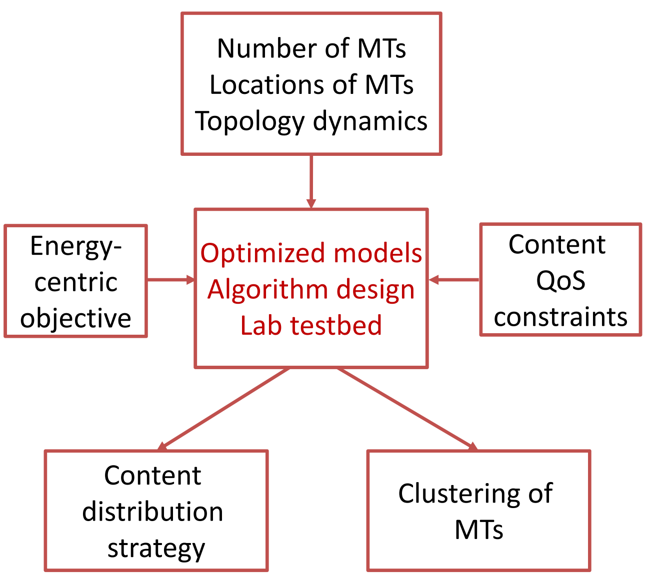


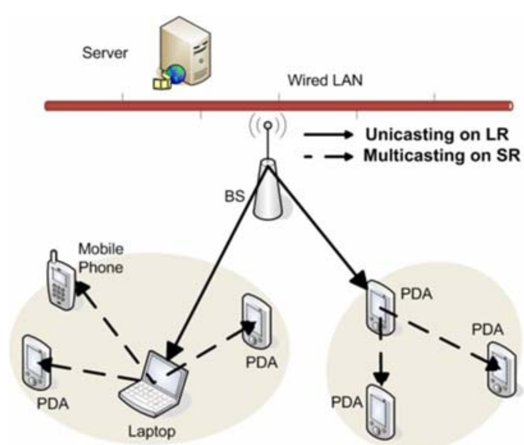
| | | |
|---|---|---|
| GENERAL | 2G Network | GSM 850 / 900 / 1800 / 1900 |
| | 3G Network | HSDPA 850 / 900 / 1900 / 2100 |
| | 4G Network | LTE (market dependent) |
| | SIM | Micro-SIM |
| | Announced | 2013, March |
| | Status | Available. Released 2013, April |
| BODY | Dimensions | 136.6 x 69.8 x 7.9 mm (5.38 x 2.75 x 0.31 in) |
| | Weight | 130 g (4.59 oz) |

| | | |
|---|---|---|
| MEMORY | Card slot | microSD, up to 64 GB |
| | Internal | 16/32/64 GB storage, 2 GB RAM |
| DATA | GPRS | Yes |
| | EDGE | Yes |
| | Speed | HSDPA, 42.2 Mbps; HSUPA, 5.76 Mbps |
| | WLAN | Wi-Fi 802.11 a/b/g/n/ac, dual-band, DLNA, Wi-Fi Direct, Wi-Fi hotspot |
| | Bluetooth | Yes, v4.0 with A2DP, EDR, LE |
| | NFC | Yes |
| | Infrared port | Yes |
| | USB | Yes, microUSB v2.0 (MHL 2), USB On-the-go, USB Host |

| | | |
|---|---|---|
| CAMERA | Primary | 13 MP, 4128 x 3096 pixels, autofocus, LED flash, check quality |
| | Features | Dual Shot, Simultaneous HD video and image recording, geo-tagging, touch focus, face and smile detection, image stabilization, HDR |
| | Video | Yes, 1080p@30fps, dual-video rec., check quality |
| | Secondary | Yes, 2 MP,1080p@30fps, dual video call |
| FEATURES | OS | Android OS, v4.2.2 (Jelly Bean) |
| | Chipset | Exynos 5 Octa 5410 |
| | CPU | Quad-core 1.6 GHz Cortex-A15 & quad-core 1.2 GHz Cortex-A7 |
| | GPU | PowerVR SGX 544MP3 |
| | Sensors | Accelerometer, gyro, proximity, compass, barometer, temperature, humidity, gesture |

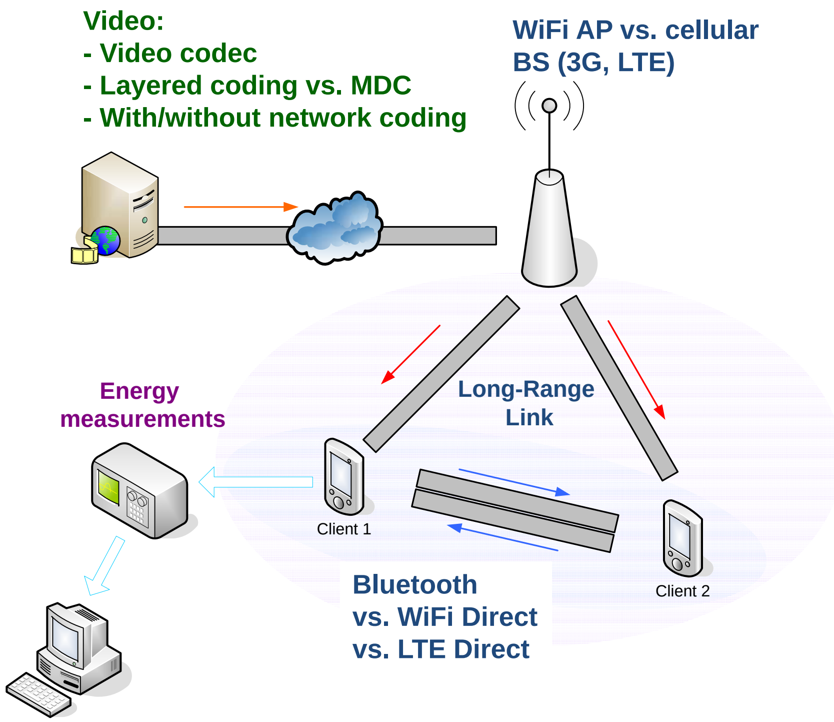
# Wireless networking: Research project I



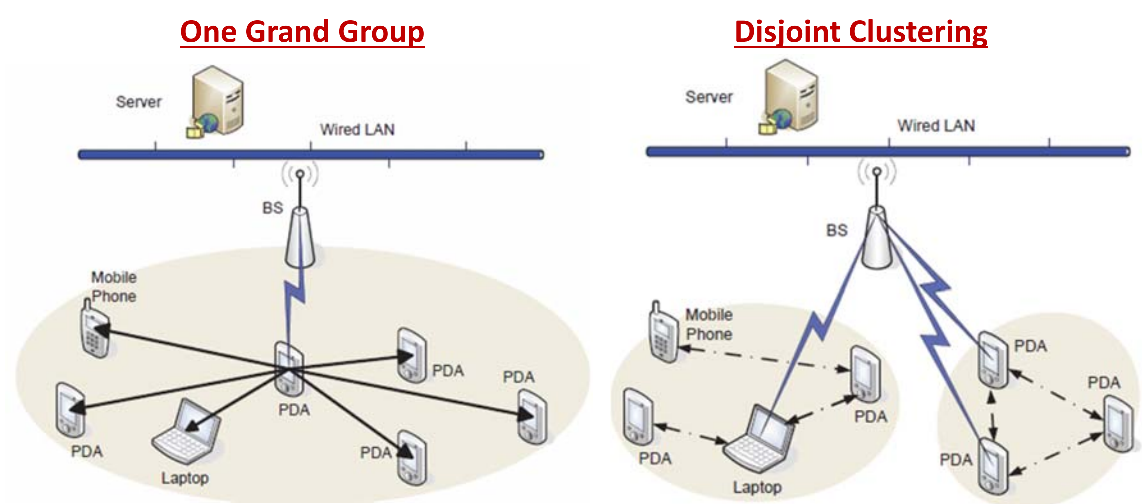




$$\min_{\mathbf{v},\mathbf{x},\mathbf{q}} E_{T,U} = S_T E_{\mathrm{Rx,L}} \sum_{k=1}^{K} \frac{x_k}{R_{L,k}} + S_T(E_{\mathrm{Tx,S}} + E_{\mathrm{Rx,S}}) \sum_{k=1}^{K} \sum_{j=1, j\neq k}^{K} \frac{q_{kj}}{R_{S,kj}}$$

# Research project I: Design parameters…

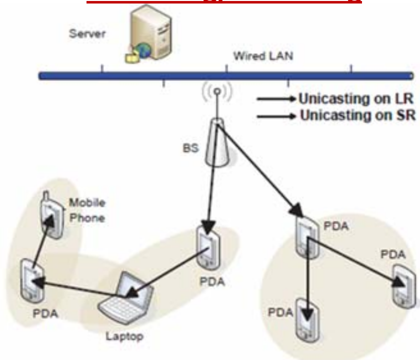



# Research project I: Design parameters…

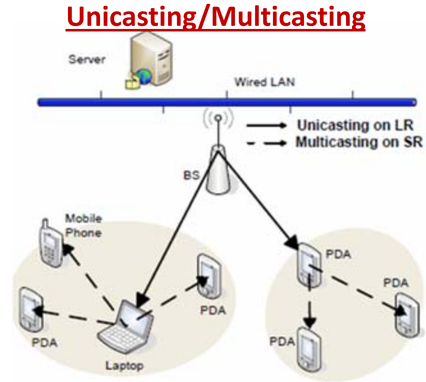


# Research project I: Design parameters…

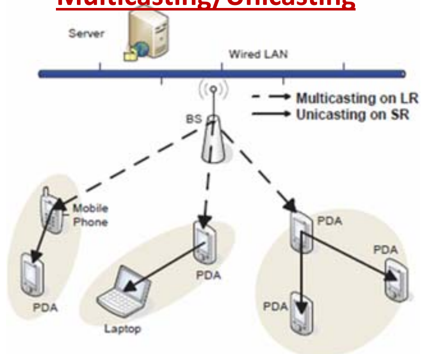
**Unicasting/Unicasting**



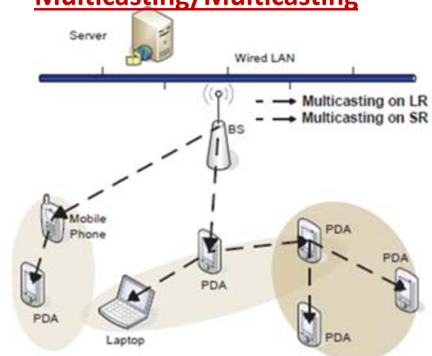

**Unicasting/Multicasting**




**Multicasting/Unicasting**

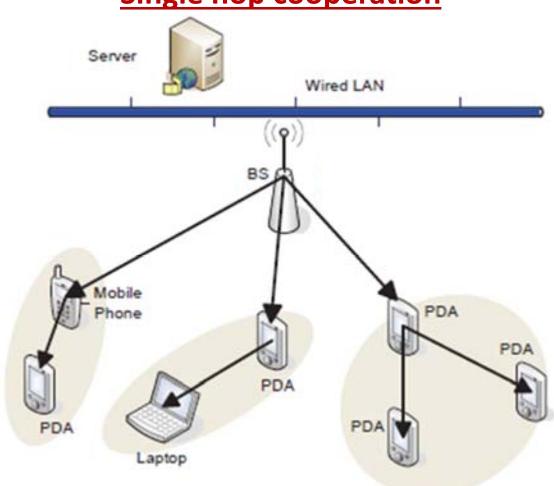



**Multicasting/Multicasting**

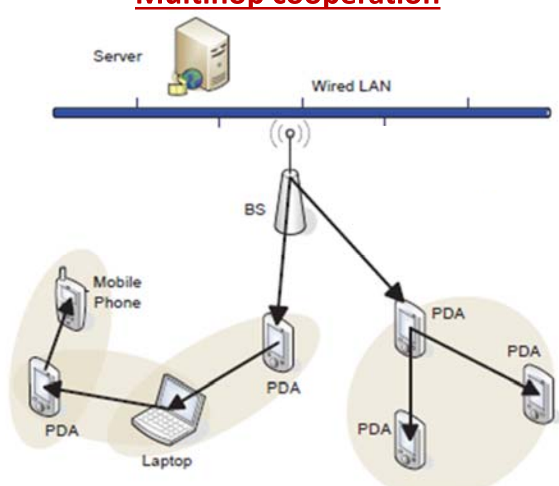



# Research project I: Design parameters…

**Single hop cooperation**

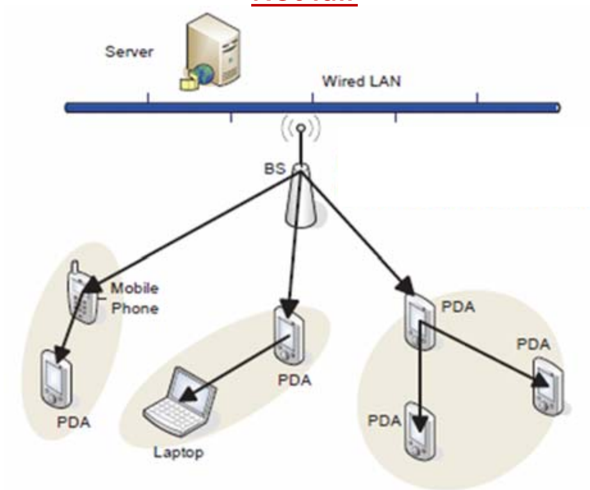



**Multihop cooperation**

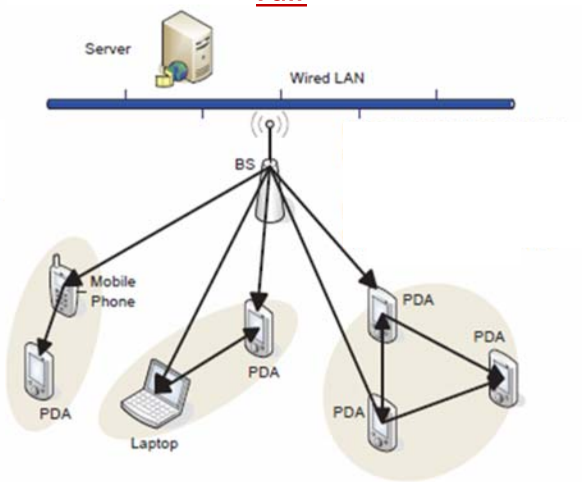


# Research project I: Design parameters…

**Not fair**




**Fair**




# Research project I: Sample formulation I

$$\min_{\mathbf{y},\mathbf{v}} \; E_{\mathrm{T,U}} = S_{\mathrm{T}} \sum_{k=1}^{K} \frac{E_{\mathrm{Rx,L}}}{R_{\mathrm{L},k}} y_k + S_{\mathrm{T}} \sum_{k=1}^{K} \sum_{j=1, j \neq k}^{K} \frac{E_{\mathrm{Tx,S}} + E_{\mathrm{Rx,S}}}{R_{\mathrm{S},kj}} v_{kj},$$

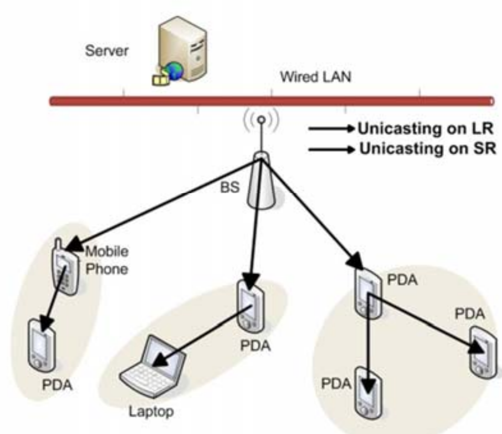
subject to

$$v_{kj} \leq y_k \;\; \forall k, \; \forall j,$$

$$\sum_{k=1, k \neq j}^{K} v_{kj} + y_j = 1, \;\; \forall j,$$

$$\mathbf{y} \in \{0,1\}^K, \;\; \mathbf{v} \geq \mathbf{0}.$$

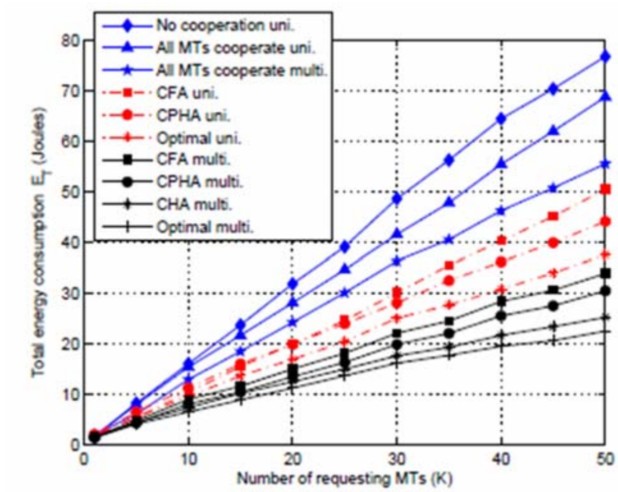
| | |
|---|---|
| $y_k$ | Binary variable that determines whether MT $k$ receives content on LR |
| $v_{kj}$ | Positive variable that determines whether MT $k$ transmits content to MT $j$ |




The optimal unicasting/unicasting problem is similar to the complete uncapacitated facility location (CUFL) problem which is NP-hard [1]

[1] S. Guha and S. Khuller, "Greedy strikes back: Improved facility location algorithms," *Journal of Algorithms*, vol. 31, no. 1, pp. 228–248, April 1999.

# Sample formulation I: Results

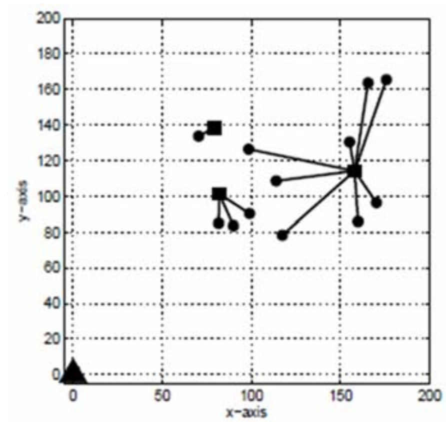



No cooperation

One cluster

Disjoint clustering: unicasting/unicasting

Disjoint clustering: unicasting/multicasting




# Sample formulation II

The optimal multicasting/multicasting problem with multihop connections is a mixed integer non-linear programming problem (MINLP)

$$\min \sum_{k=1}^{K} S_T \left[ T_k + Z_k + \sum_{j=1, j\neq k}^{K} C_{kj} \right]$$

subject to

$$v_{kj}^{1} \le y_k, \ \forall k, \ \forall j$$

$$v_{ji}^{h+1} \le \sum_{k=1}^{K} v_{kj}^{h}, \ \forall j, \forall i, \ \forall h$$

$$\sum_{k=1}^{K} \sum_{h=1}^{H} v_{kj}^{h} + y_j = 1, \ \forall j$$

$$q \ge y_k \frac{E_{\mathrm{Rx,L}}(R_{L,k})}{R_{L,k}}, \ \forall k$$

$$T_k \ge q - \max_k \left( \frac{E_{\mathrm{Rx,L}}(R_{\mathrm{L},k})}{R_{\mathrm{L},k}} \right) (1 - y_k), \ \forall k$$

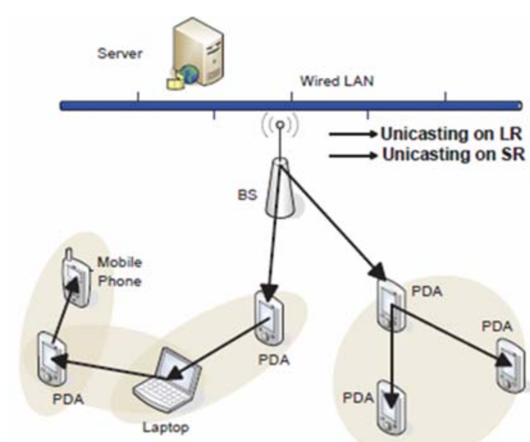
$$Z_k \ge \frac{E_{\mathrm{Tx,S}}(R_{\mathrm{S},kj})}{R_{\mathrm{S},kj}} \sum_{h=1}^{H} v_{kj}^{h}, \ \forall k, \ \forall j$$

$$Z'_k \ge \frac{E_{\mathrm{Rx,S}}(R_{\mathrm{S},kj})}{R_{\mathrm{S},kj}} \sum_{h=1}^{H} v_{kj}^{h}, \ \forall k, \ \forall j$$

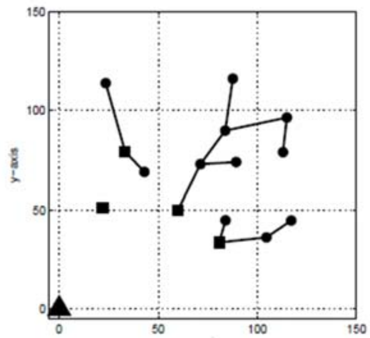
$$C_{kj} \ge Z'_k - \max_j \left( \frac{E_{\mathrm{Rx,S}}(R_{\mathrm{S},kj})}{R_{\mathrm{S},kj}} \right) (1 - \sum_{h=1}^{H} v_{kj}^{h}), \forall k, \forall j$$

$$y_k \in \{0,1\}, v_{kj}^{h} \in \{0,1\}$$

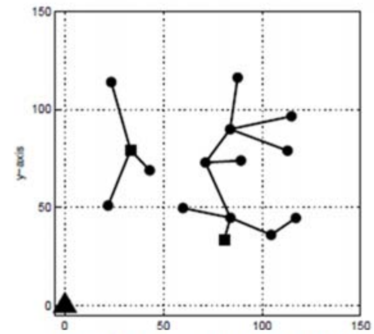
$$q \ge 0, T_k \ge 0, Z_k \ge 0, Z'_k \ge 0, C_{kj} \ge 0$$



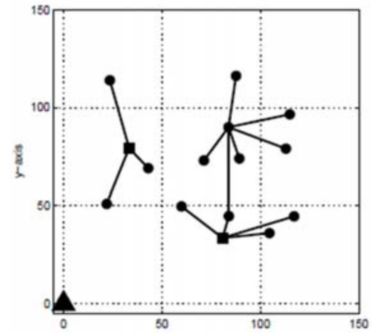
# Sample formulation II: Results



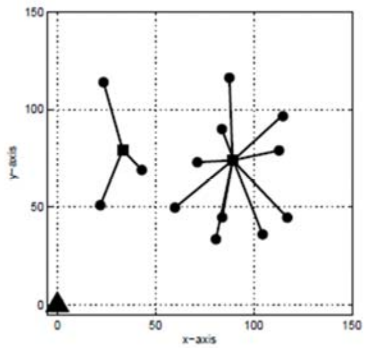
(a) Optimal uni./uni.



(b) Optimal multi./multi.



(c) SA multi./multi.



(d) SA multi./multi. with interference avoidance for $f_r = 2$

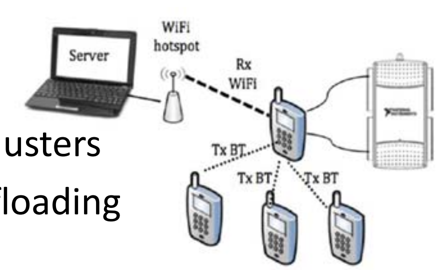
# Experimental results: WiFi + Bluetooth

| Devices | LR only | master Rx and Tx | master Tx | peer Rx |
|---|---|---|---|---|
| 1 device | 27.5 J | – | – | – |
| 2 devices | 32.0 J | 63.7 J | 36.2 J | 31.5 J |
| 3 devices | 43.9 J | 69.4 J | 41.9 J | NA |
| 4 devices | 54.1 J | 71.9 J | 44.4 J | 37.0 J |

TABLE II

EXPERIMENTAL RESULTS FOR A GIVEN SCENARIO WITH WIFI ON THE LR INTERFACE AND BLUETOOTH ON THE SR D2D LINKS.

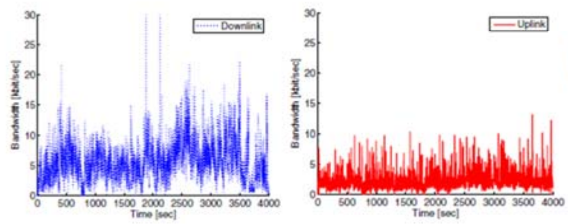
- Energy consumption does not increase linearly with the number of devices that the master device relays the content to on the SR links:
  - Relaying to one device consumes 36.2 J
  - Relaying to three devices consumes 44.4 J
- This favors forming larger cooperation clusters
- Demonstrates potential gains of D2D offloading

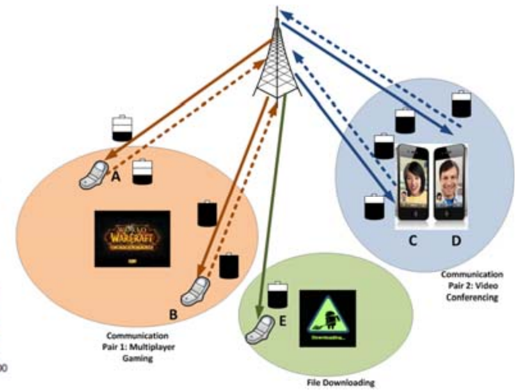


# Wireless networking: Research project II

- Resource allocation [slots, sub-channels, power, antennas] in cellular networks is performed independently between uplink and downlink
- Many emerging multimedia services require symmetrical uplink and downlink resources for adequate quality of experience
- Aim: develop and optimize joint uplink/ downlink resource allocation algorithms for 4G cellular networks

$$\max_{\mathbf{P^U},\mathbf{P^D},\mathbf{W^U},\mathbf{W^D}} \sum_{i=1}^{M} Q_i^U(t)R_i^U(t) + \sum_{i=1}^{M} Q_i^D(t)R_i^D(t) - \alpha \left\|\mathbf{R^D}(t) - \mathbf{R^U}(t)\right\|_1$$

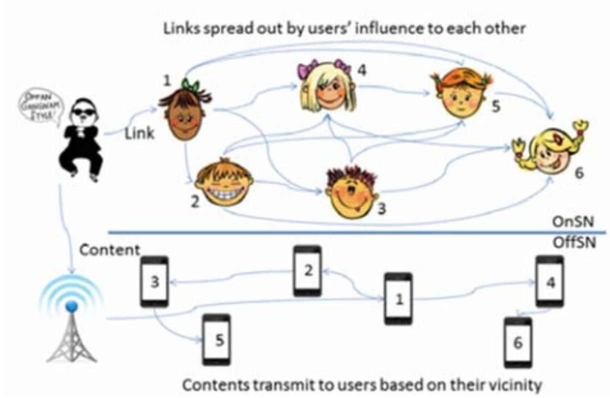


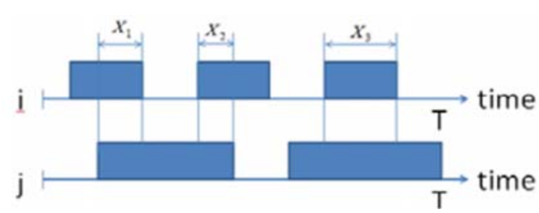




NPRP 4 – 347 – 2 – 127: A Context Aware Framework for Optimized Resource Management in Fourth Generation Wireless Systems [joint work with QMIC and University of Houston]

# Wireless networking: Research project II

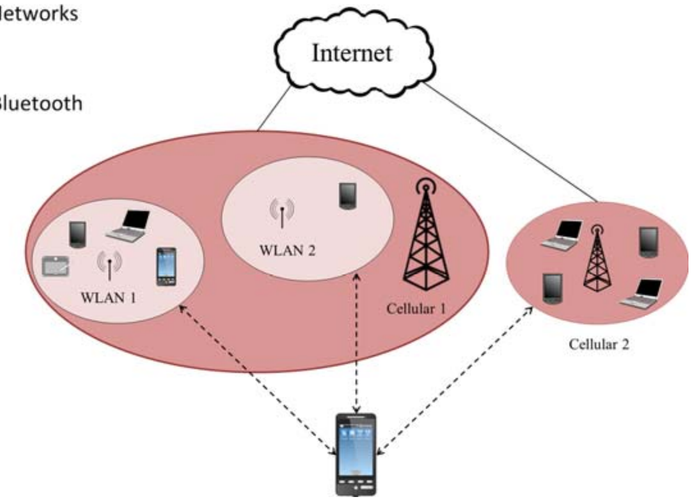
Exploring Social Ties for Enhanced Device-to-Device Communications in Wireless Networks



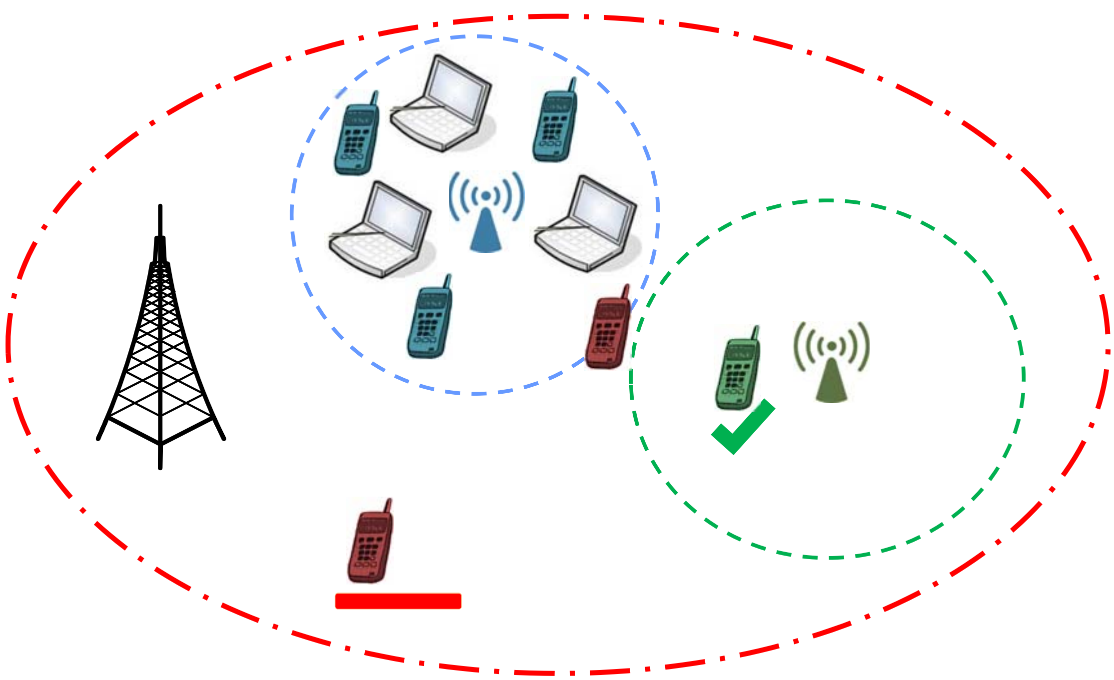

NPRP 4 – 347 – 2 – 127: A Context Aware Framework for Optimized Resource Management in Fourth Generation Wireless Systems [joint work with QMIC and University of Houston]

# Wireless networking: Research project III

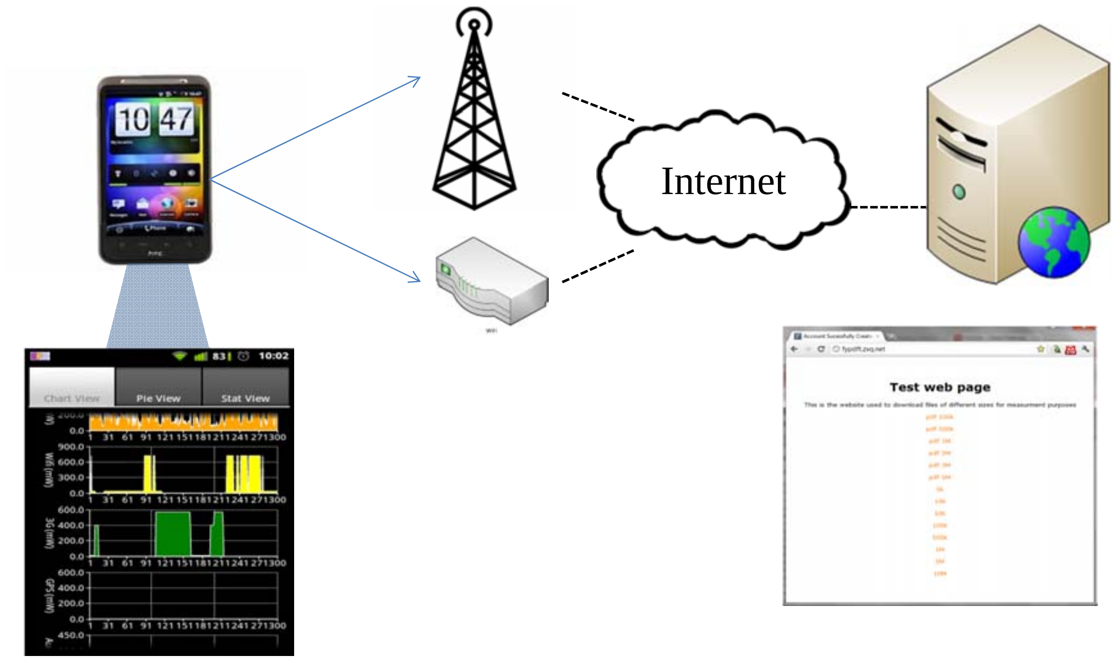




Network selection and traffic splitting in WiFi/cellular heterogeneous networks

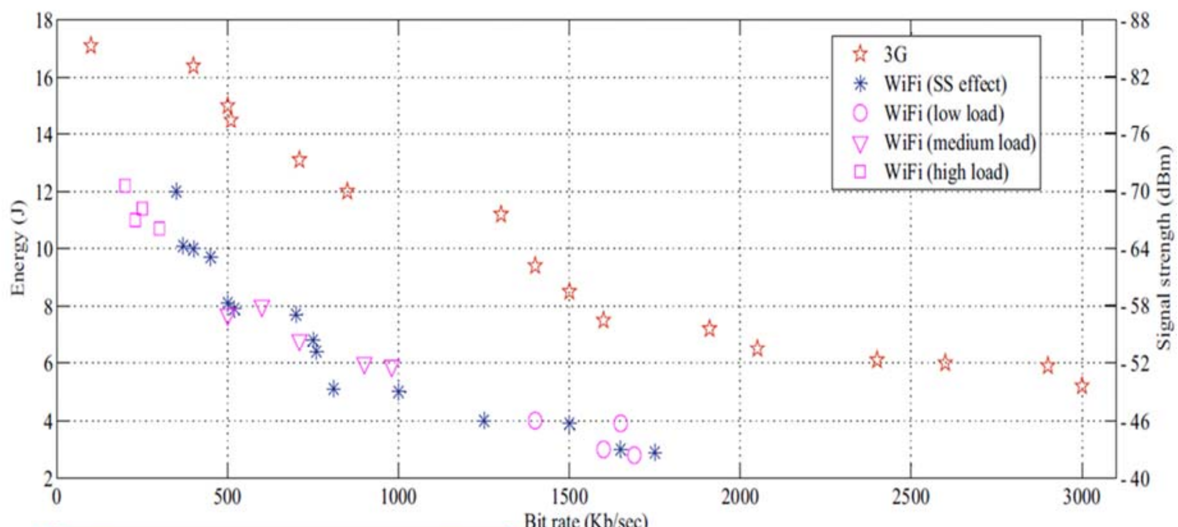
# On network selection in hetnets



# Hetnets testbed: Design components

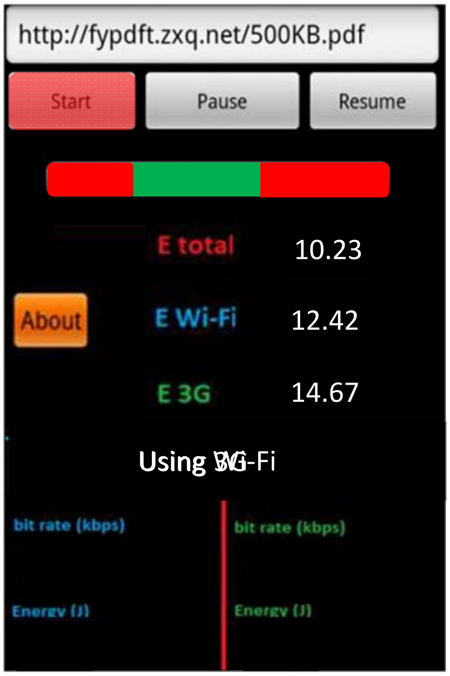



# Hetnets testbed: Sample results




$$E = \frac{C}{R + D} + (M - 1000)$$

# Hetnets testbed: HetApp

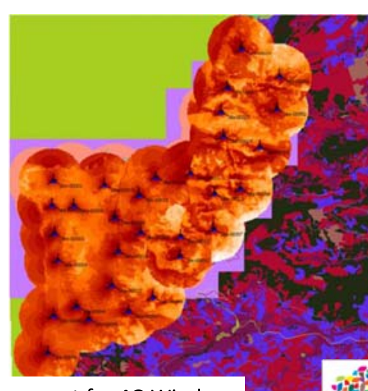



| Slot | R(WiFi) Kb/sec | E(WiFi) J | R(3G) Kb/sec | E(3G) J | Choose |
|---|---|---|---|---|---|
| 1 | 1460 | 2.79 | 1980 | 5.68 | Wi-Fi |
| 2 | 690 | 6.08 | 2920 | 3.89 | 3G |
| 3 | 1180 | 3.55 | 2230 | 5.10 | Wi-Fi |

- Energy using Wi-Fi in the three slots = 12.42 Joules
- Energy using 3G in the three slots = 14.67 Joules
- Energy using HetApp = 10.23 Joules
  - 18% energy saved with respect to Wi-Fi
  - 30% energy saved with respect to 3G

# Wireless networking: Research project IV

- Existing planning approaches for 2G/3G networks based on static link budget analysis with Monte-Carlo simulations
- LTE/LTE-A: dynamic adaptive operation in multi-RAT multi-tier heterogeneous environment with advanced features
- Opportunity to develop a new radio planning framework to capture dynamic operation and advanced features of LTE-A



NPRP 4 – 353 – 2 – 130: Holistic Network Planning, Optimization, and Management for 4G Wireless Systems [joint work with QMIC and KAUST]

# Wireless networking: Research project IV

- How to statistically model interference in LTE-A networks?
- How to capture dynamic cellular network variation as part of the planning process?
  - Users' number and locations are time varying
  - Users' wireless channel conditions are time varying
- How to capture emerging LTE-A features as part of the planning process?
  - How to perform optimized radio network planning if cellular operator supports WiFi offloading, femtocells, D2D connections, green BS on/off switching, etc.?
- How to implement the developed framework and algorithms in a prototype planning tool with real maps and traffic conditions?

# Interference modeling: Approach

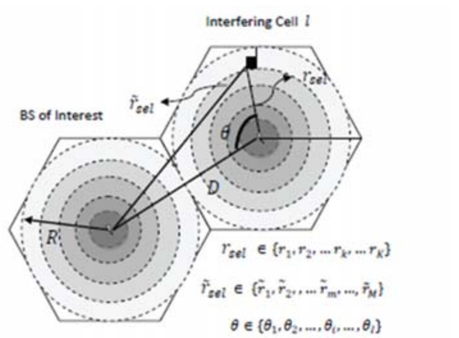


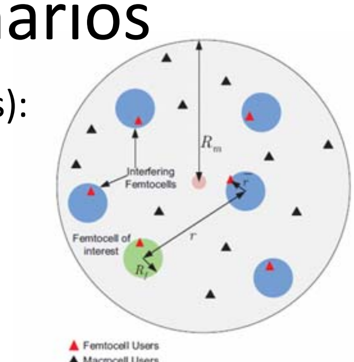

Figure 4: Cellular network model with each cell divided into multiple rings.

- Derive the distribution of the distance of the allocated user from its serving BS in a cell considering various scheduling scheme, i.e., $f_{r_{\text{sel}}}(r)$.
- Derive the distribution of the distance between the allocated users in the neighbor interfering cells and the BS of the cell of interest, i.e., $f_{\tilde{r}_{\text{sel}}}(\tilde{r})$.
- Derive the distribution and MGF of the interference $X_l = \tilde{r}_{\text{sel}}^{-\beta}\zeta$ considering a single interfering cell $l$.
- Derive the MGF of the cumulative interference $Y = \sum_{l=1}^{L} X_l$ caused by the users in all interfering cells.

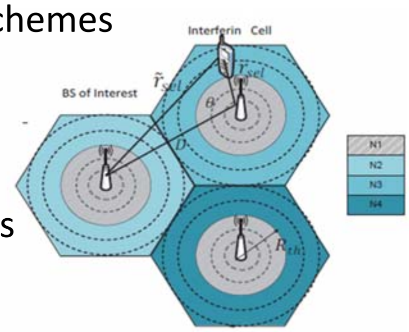
# Interference modeling: Approach

| | | |
|---|---|---|
| $\Pr(r_{\text{sel}} = r_k)$ | Modified Fast PC | $\sum_{b \in \mathcal{B}} p_k \prod_{j=1}^{k-1} p_j^{b(j)} (1-p_j)^{1-b(j)} \frac{\prod_{j=k+1}^{K'} p_j^{b(j-1)} (1-p_j)^{1-b(j-1)}}{1+\sum_{j=1}^{K'-1} b(j)}$ |
| | Modified Slow PC | $\sum_{b \in \mathcal{B}} \tilde{p}_k \prod_{j=1}^{k-1} \tilde{p}_j^{b(j)} (1-\tilde{p}_j)^{1-b(j)} \frac{\prod_{j=k+1}^{K'} \tilde{p}_j^{b(j-1)} (1-\tilde{p}_j)^{1-b(j-1)}}{1+\sum_{j=1}^{K'-1} b(j)}$ |
| | Conventional Fast PC | $1/K$ |
| $f_S(s)$ | Modified Fast PC | $\delta(s-P_0) \sum_{k=1}^{K'} \Pr(r_{\text{sel}} = r_k) + \delta(s)\Pr(\mathbb{A})$ |
| | Modified Slow PC | $\sum_{k=1}^{K'} \frac{1}{P_0} f_\eta \left(\frac{s}{P_0}\right) \Pr(r_{\text{sel}} = r_k) + \delta(s)\Pr(\mathbb{A})$ |
| | Conventional Fast PC | $\sum_{k=1}^{K'} \left( \frac{r_k^\beta}{P_{\max}} \mathrm{U}(P_0 - s) f_\zeta \left( \frac{r_k^\beta s}{P_{\max}} \right) + \delta(s-P_0) \left( 1 - F_\zeta \left( \frac{P_0 r_k^\beta}{P_{\max}} \right) \right) \right) \Pr(r_{\text{sel}} = r_k)$ |
| $\mathcal{M}_S(t)$ | Modified Fast PC | $e^{-tP_0} \sum_{k=1}^{K'} \Pr(r_{\text{sel}} = r_k) + \Pr(\mathbb{A})$ |
| | Modified Slow PC | $\sum_{k=1}^{K'} \mathcal{M}_\eta(tP_0) \Pr(r_{\text{sel}} = r_k) + \Pr(\mathbb{A})$ |
| | Conventional Fast PC | $\sum_{k=1}^{K'} \left( e^{-tP_0} \left( 1 - F_\zeta \left( \frac{P_0 r_k^\beta}{P_{\max}} \right) \right) + \frac{r_k^\beta}{P_{\max}} \int_0^{P_0} e^{-tS} f_\zeta \left( \frac{r_k^\beta S}{P_{\max}} \right) dS \right) \Pr(r_{\text{sel}} = r_k)$ |
| $f_I(i)$ | Modified Fast PC | $\sum_{n=1}^{\mathcal{N}} \sum_{\tilde{r}_{\text{sel}}=\tilde{r}_{n,1}}^{\tilde{r}_{n,K'}} A f_{W\mid\mathbb{B}}(Ai) \Pr(\tilde{r}_{\text{sel}} = \tilde{r}_{n,k}) + \Pr(\mathbb{A})\delta(i)$ |
| | Modified Slow PC | $\sum_{n=1}^{\mathcal{N}} \sum_{\tilde{r}_{\text{sel}}=\tilde{r}_{n,1}}^{\tilde{r}_{n,K'}} A f_{W\mid\mathbb{B}}(Ai) \Pr(\tilde{r}_{\text{sel}} = \tilde{r}_{n,k}) + \Pr(\mathbb{A})\delta(i)$ |
| | Conventional Fast PC | $\sum_{n=1}^{\mathcal{N}} \sum_{\tilde{r}_{\text{sel}}=\tilde{r}_{n,1}}^{\tilde{r}_{n,K'}} \left( A f_{W\mid\mathbb{B}}(Ai) p_k + (1-p_k) B f_X(Bi) \right) \Pr(\tilde{r}_{\text{sel}} = r_{n,k})$ |
| $\mathcal{M}_I(t)$ | Modified Fast PC | $\sum_{n=1}^{\mathcal{N}} \sum_{\tilde{r}_{\text{sel}}=\tilde{r}_{n,1}}^{\tilde{r}_{n,K'}} \mathcal{M}_{W\mid\mathbb{B}}(t/A) \Pr(\tilde{r}_{\text{sel}} = \tilde{r}_{n,k}) + \Pr(\mathbb{A})$ |
| | Modified Slow PC | $\sum_{n=1}^{\mathcal{N}} \sum_{\tilde{r}_{\text{sel}}=\tilde{r}_{n,1}}^{\tilde{r}_{n,K'}} \mathcal{M}_{W\mid\mathbb{B}}(t/A) \Pr(\tilde{r}_{\text{sel}} = \tilde{r}_{n,k}) + \Pr(\mathbb{A})$ |
| | Conventional Fast PC | $\sum_{n=1}^{\mathcal{N}} \sum_{\tilde{r}_{\text{sel}}=\tilde{r}_{n,1}}^{\tilde{r}_{n,K'}} \left( \mathcal{M}_{W\mid\mathbb{B}}(t/A) p_k + (1-p_k) \mathcal{M}_X(t/B) \right) \Pr(\tilde{r}_{\text{sel}} = r_{n,k})$ |

# Interference modeling: Scenarios




- Interference distributions (PDFs, CDFs, and MGFs):
  - Resource allocation (RR, PF, greedy)
  - Uplink and downlink
  - Generic fading channel models
  - With/without power control [slow and fast power control]
  - Single carrier and multicarrier systems
  - With/without interference coordination schemes
  - Universal and fractional frequency reuse
  - With femtocell deployments
  - With heterogeneous network deployments
  - …



# Interference modeling: Sample results

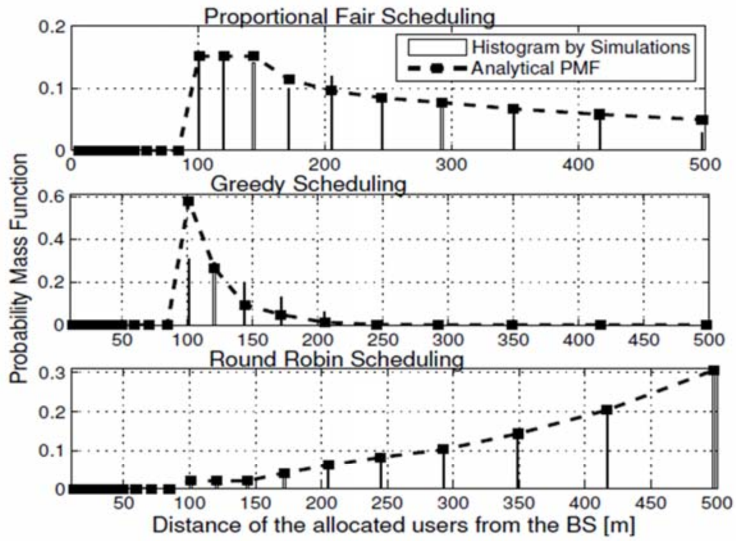
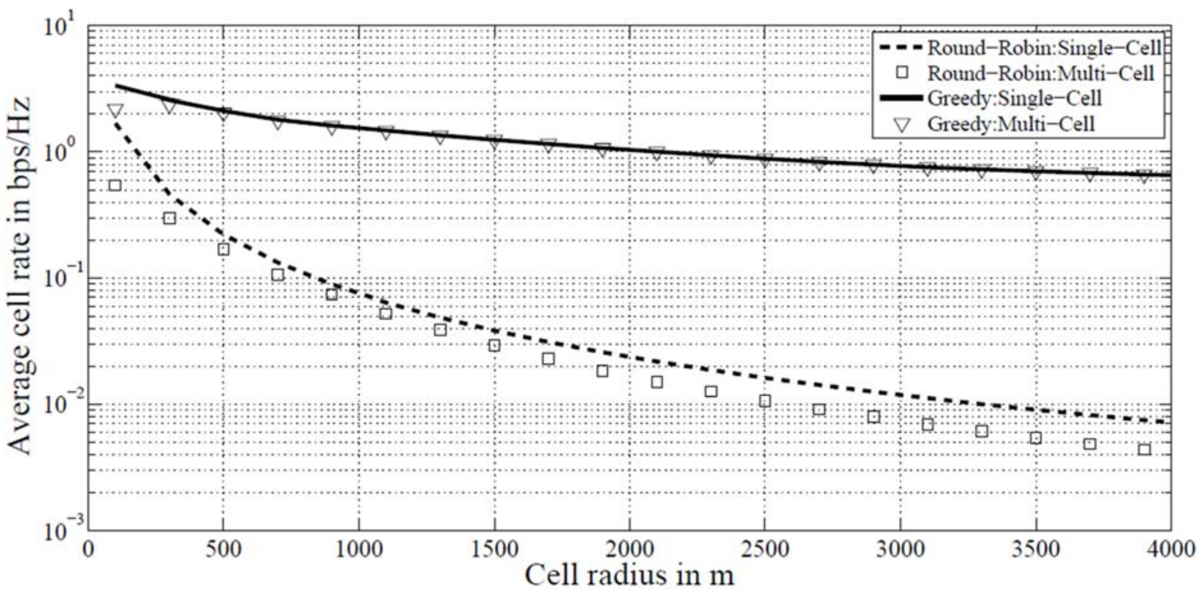


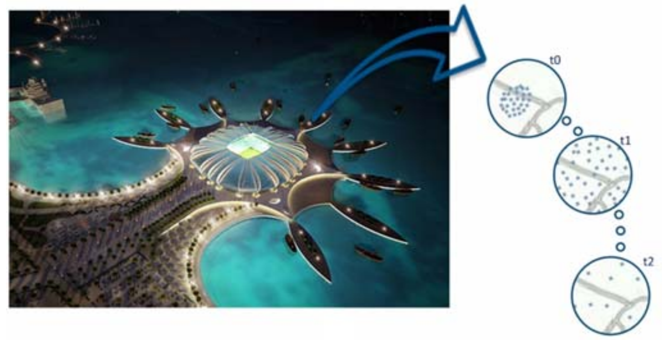

Figure 5: PMF of the distance of the allocated users in a given cell (i.e., PMF of $r_{\mathrm{sel}}$) for proportional fair, greedy and round robin scheduling schemes with path loss exponent $\beta = 2.6$, $U = 50$, Number of Monte-Carlo simulations =100,000, $C$=60 dB, $P_{\max}$=1W, $\sigma^2$=-174 dBm/Hz.

# Interference modeling: Sample results



# From interference modeling to planning…

- In a given geographical area:
  - Number of users vary
  - Locations of users vary
  - Distribution of users vary




- How to capture this variation as part of the planning problem?
- Approach:
  - Optimization problem formulation
  - Solution: robust optimization and stochastic optimization
  - Solution: sub-optimal search-based algorithms

# Robust cellular planning under uncertainty

➢ A chance-constraint approach:

$$\min_{s,c} \alpha \sum_{i=1}^{N_0} c_i - (1-\alpha) \sum_{t=1}^{T} p(t) \sum_{k=1}^{K_t} \sum_{i=1}^{N_0} s_{k,i,t} P_{k,i,t} \quad (1)$$

subject to

$$\Pr\{\Gamma_p \geq \Gamma_{\text{thr}}\} \geq (1-\epsilon) \quad (2)$$

$$c_i \in \{0,1\} \quad (3)$$

➢ SNR PDF [6]:

$$f_\Gamma(\gamma|(x_k, y_k)) = \int_0^\infty \frac{\sigma^2 + \eta}{P_{k,i}} f_A\left(\frac{(\sigma^2+\eta)\gamma}{P_{k,i}}\right) f_{I_{\text{total}}}(\eta) d\eta$$

interfering power

noise

received power

fading PDF

interference PDF

# Robust cellular planning: Sample results

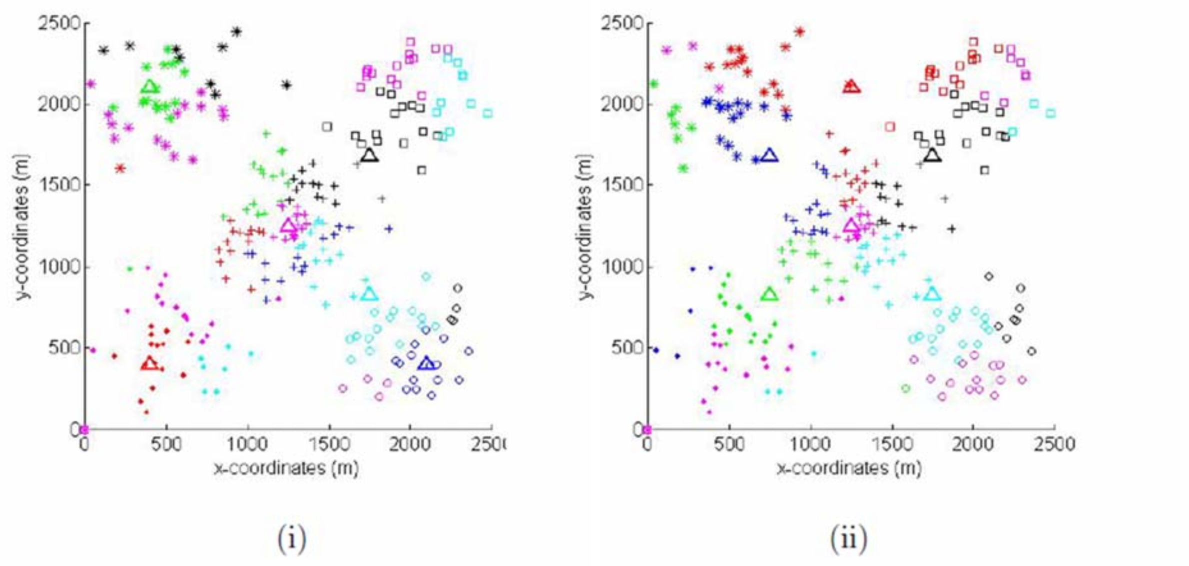
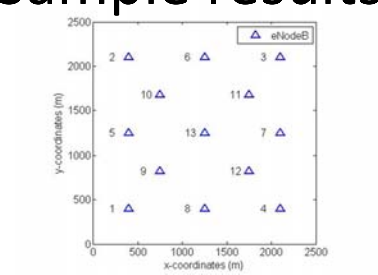


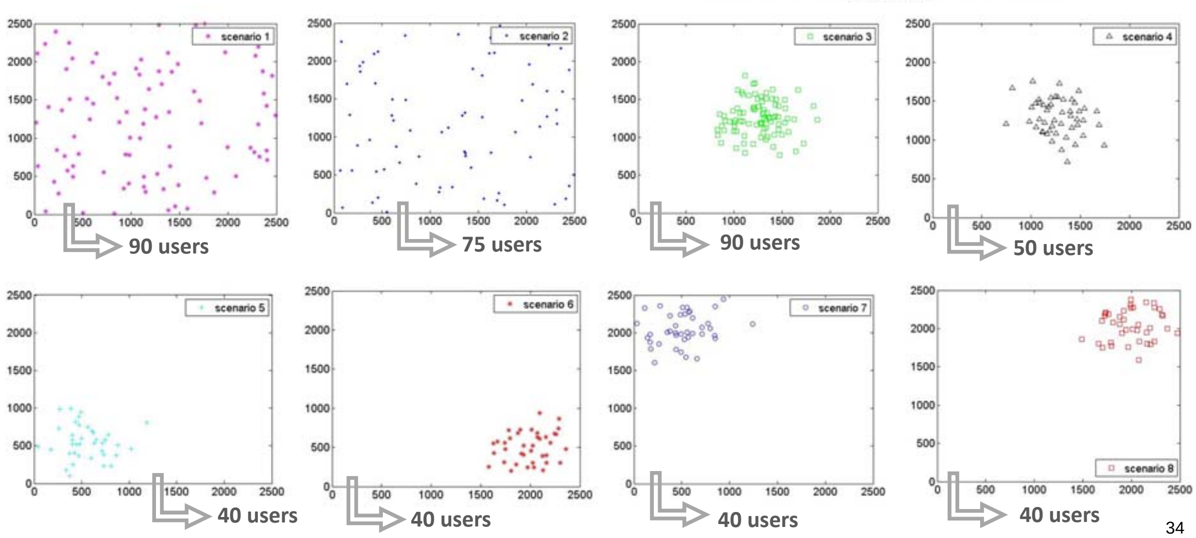

Figure 5: The optimal subset of eNodeBs and allocation of users (i) when the scenarios occur with equal probability and (ii) when the scenario at the center occurs with a higher probability.

# Robust cellular planning: Sample results

- Initial set of base stations:

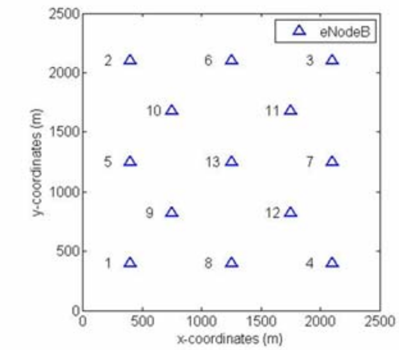



- 8 different traffic states:



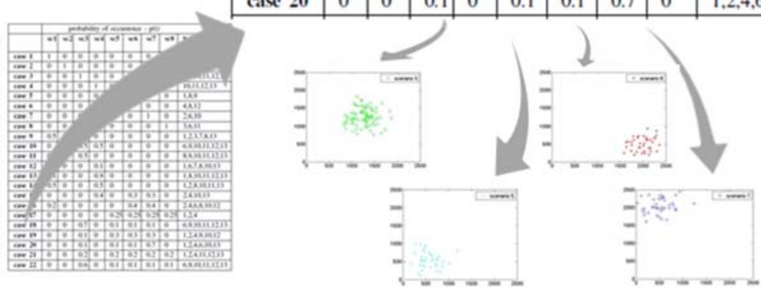
# Robust cellular planning: Sample results

| | probability of occurrence - p(t) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | sc1 | sc2 | sc3 | sc4 | sc5 | sc6 | sc7 | sc8 | Selected eN-odeBs |
| case 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1,6,7,8,10,13 |
| case 2 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1,2,3,7,8 |
| case 3 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 5,9,10,11,12,13 |
| case 4 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 10,11,12,13 |
| case 5 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1,8,9 |
| case 6 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 4,8,12 |
| case 7 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 2,6,10 |
| case 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3,6,11 |
| case 9 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 1,2,3,7,8,13 |
| case 10 | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 6,9,10,11,12,13 |
| case 11 | 0.5 | 0 | 0.5 | 0 | 0 | 0 | 0 | 0 | 8,9,10,11,12,13 |
| case 12 | 0.9 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 1,6,7,8,10,13 |
| case 13 | 0.1 | 0 | 0 | 0.9 | 0 | 0 | 0 | 0 | 1,8,10,11,12,13 |
| case 14 | 0.5 | 0 | 0 | 0.5 | 0 | 0 | 0 | 0 | 1,2,8,10,11,13 |
| case 15 | 0 | 0 | 0 | 0.4 | 0 | 0.3 | 0.3 | 0 | 2,4,10,13 |
| case 16 | 0.2 | 0 | 0 | 0 | 0 | 0.4 | 0.4 | 0 | 2,4,6,8,10,12 |
| case 17 | 0 | 0 | 0 | 0 | 0.25 | 0.25 | 0.25 | 0.25 | 1,2,4 |
| case 18 | 0 | 0 | 0.7 | 0 | 0.1 | 0.1 | 0.1 | 0 | 6,9,10,11,12,13 |
| case 19 | 0 | 0 | 0.1 | 0 | 0.3 | 0.3 | 0.3 | 0 | 1,2,4,9,10,12 |
| case 20 | 0 | 0 | 0.1 | 0 | 0.1 | 0.1 | 0.7 | 0 | 1,2,4,6,10,13 |
| case 21 | 0 | 0 | 0.2 | 0 | 0.2 | 0.2 | 0.2 | 0.2 | 1,2,4,11,12,13 |
| case 22 | 0 | 0 | 0.6 | 0 | 0.1 | 0.1 | 0.1 | 0.1 | 6,9,10,11,12,13 |



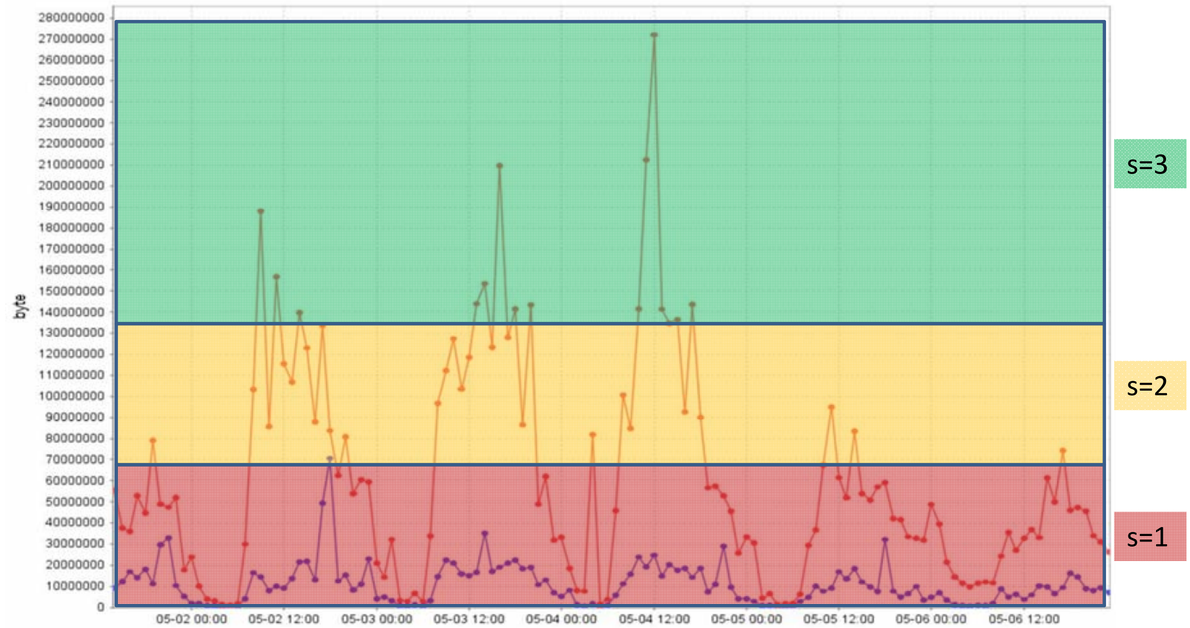

# Robust cellular planning: Sample results

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| case 18 | 0 | 0 | 0.7 | 0 | 0.1 | 0.1 | 0.1 | 0 | 6,9,10,11,12,13 |
| case 19 | 0 | 0 | 0.1 | 0 | 0.3 | 0.3 | 0.3 | 0 | 1,2,4,9,10,12 |
| case 20 | 0 | 0 | 0.1 | 0 | 0.1 | 0.1 | 0.7 | 0 | 1,2,4,6,10,13 |

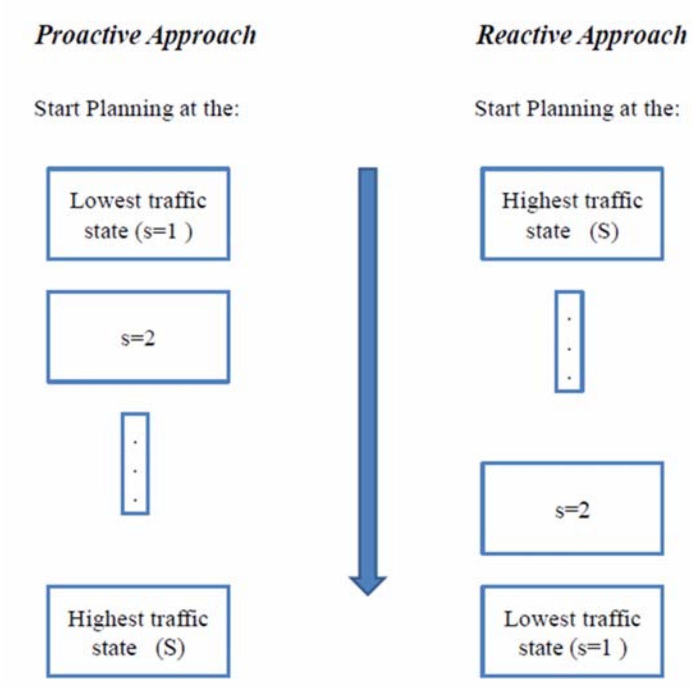


| | Conventional approach | Stochastic approach |
|---|---|---|
| Case 18 | 0.33 bps/Hz | 0.34 bps/Hz |
| Case 19 | 0.32 bps/Hz | 0.41 bps/Hz |
| Case 20 | 0.33 bps/Hz | 0.41 bps/Hz |

# Green cellular planning: Motivation




# Green cellular planning: BS On/Off switching



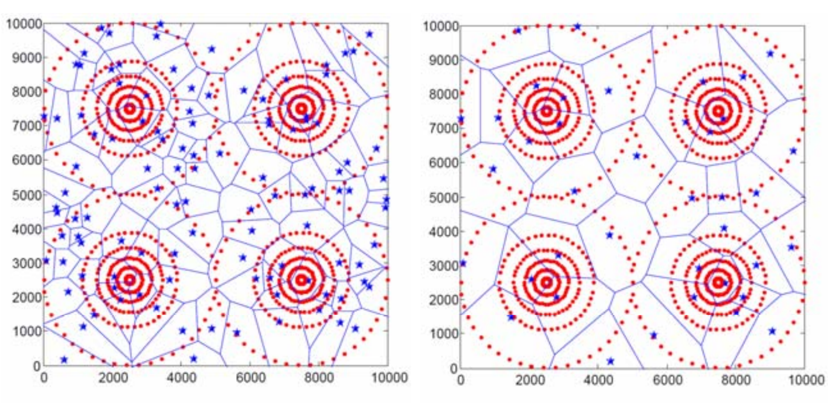
**Algorithm 1** LTE RNP Solution

**Input:** $N_0$ ; $K$ ; $\{x_i, y_i, i = 1, ..., N_0\}$ ; $\{u_k, v_k, k = 1, ..., K\}, \mathcal{F} = \emptyset, \mathcal{I} = \emptyset$ .
**while** true **do**
  **for** $i = 1 : N_0$ {Try eliminating base station $i$} **do**
    $x_{temp} = \{x_1, ..., x_{i-1}, x_{i+1}, ..., x_{N_0}\}$
    $y_{temp} = \{y_1, ..., y_{i-1}, y_{i+1}, ..., y_{N_0}\}$
    **Step 1.** Construct the new Voronoi tessellation corresponding to the base station locations and find the distance between each (BS , MS) pair
    **Step 2.** Calculate the SINR expressions based on the estimated pathloss for each (BS , MS) pair as given in (3)
    **Step 3.**
    **if** SINR $<$ $\mathrm{SINR_{thr}}$ {If eliminating the base station causes outage} **then**
      $i \in \mathcal{I}$ {Place BS $i$ in the infeasible set}
    **else**
      $i \in \mathcal{F}$ {Place BS $i$ in the feasible set}
      Calculate the total SINR which is the sum of the users' SINR for the given BS configuration.
    **end if**
  **end for**
  **if** $\mathcal{F} \neq \emptyset$ {If some base station can be eliminated and $e$ represents the BS $i$ that when eliminated led to the highest total SINR that was calculated in **Step 3.**} **then**
    $x = \{x_1, ..., x_{e-1}, x_{e+1}, ..., x_{N_0}\}$
    $y = \{y_1, ..., y_{e-1}, y_{e+1}, ..., y_{N_0}\}$
    $N_0 = N_0 - 1$
  **else**
    break{Converged: No BS can be eliminated without causing outage}
  **end if**
**end while.**
**Output:** $N$

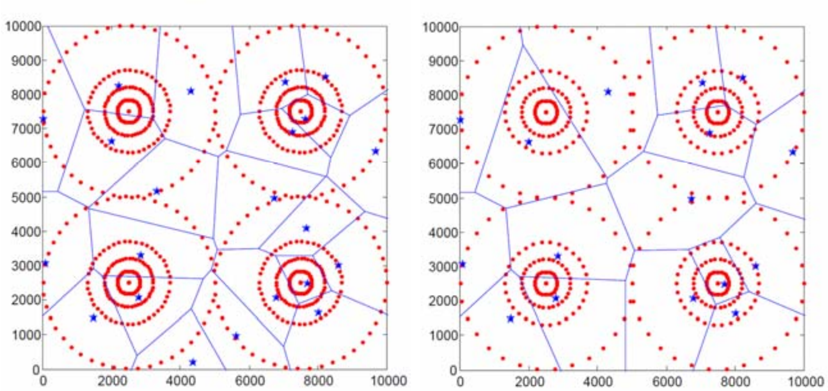
$$\min_{\mathbf{c}} \sum_{i=1}^{N_0} c_i$$

s.t.

$$\min \sum_{k=1}^{U} c_{b(k)} \cdot P^d_{k,b(k)} + \alpha \sum_{k=1}^{U} c_{b(k)} \cdot (P^u_k - P^u_{\max})^+$$

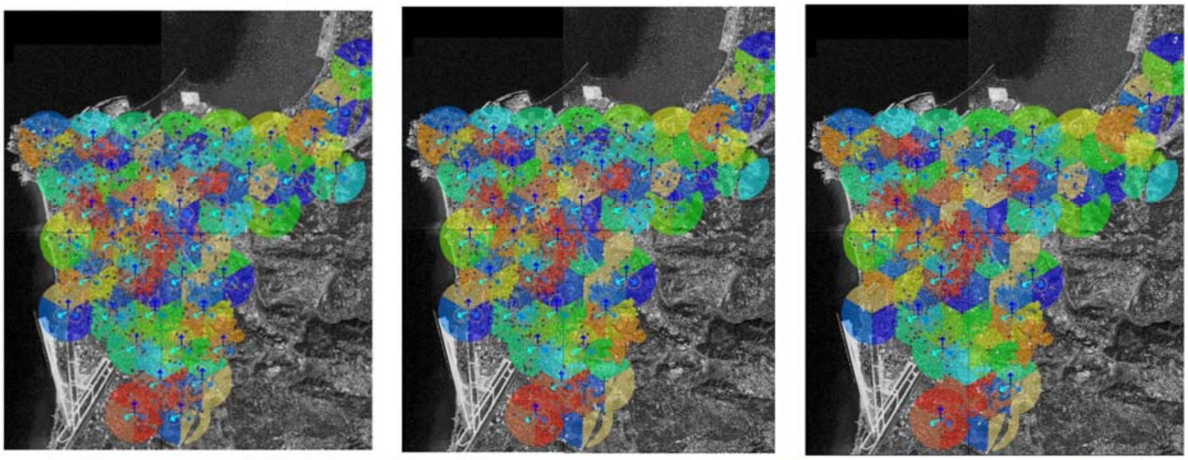


(a) BSs initial location  (b) BSs deployment for $s$=3



(c) BSs deployment for $s$=2  (d) BSs deployment for $s$=1

# Green cellular planning: Sample results

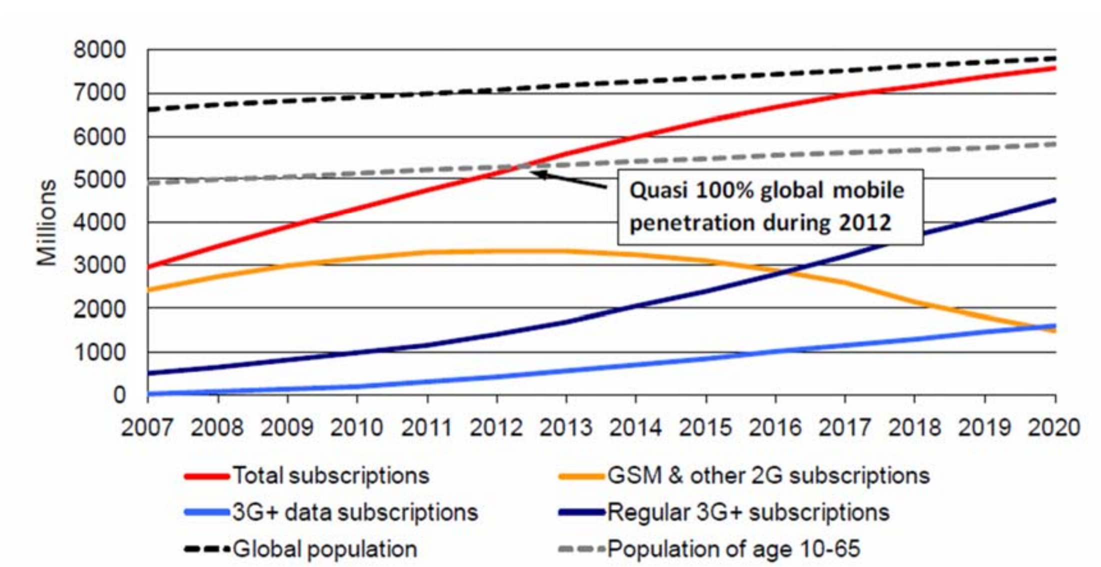


| Traffic states | Number of BSs | Coverage percentage | $CO_2$ emissions in $KgCO_2$/day |
|---|---|---|---|
| $s$=3 | 40 | 90% | 1.996 |
| $s$=2 | 33 | 91% | 0.818 |
| $s$=1 | 23 | 90% | 1.488 |

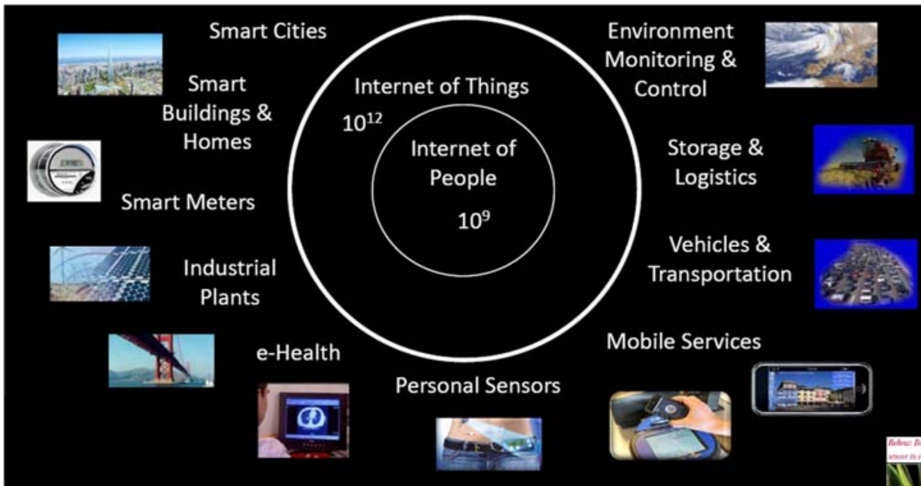
As for the traditional planning, where all the 40 BSs are always on 5.952 Kg $CO_2$ /day are emitted.

Using green planning, $CO_2$ emissions are decreased by 28% compared to traditional planning.

# From wireless network planning/operation to wireless network utilization…

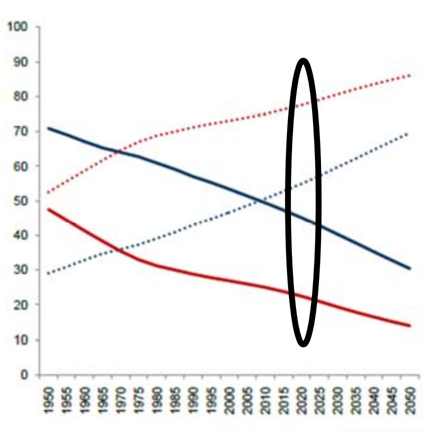


# “machines” are becoming connected

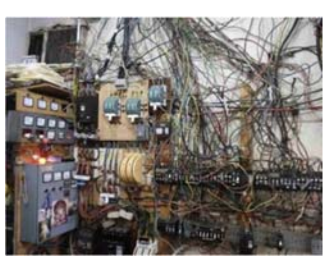




# Most global challenges are in cities…







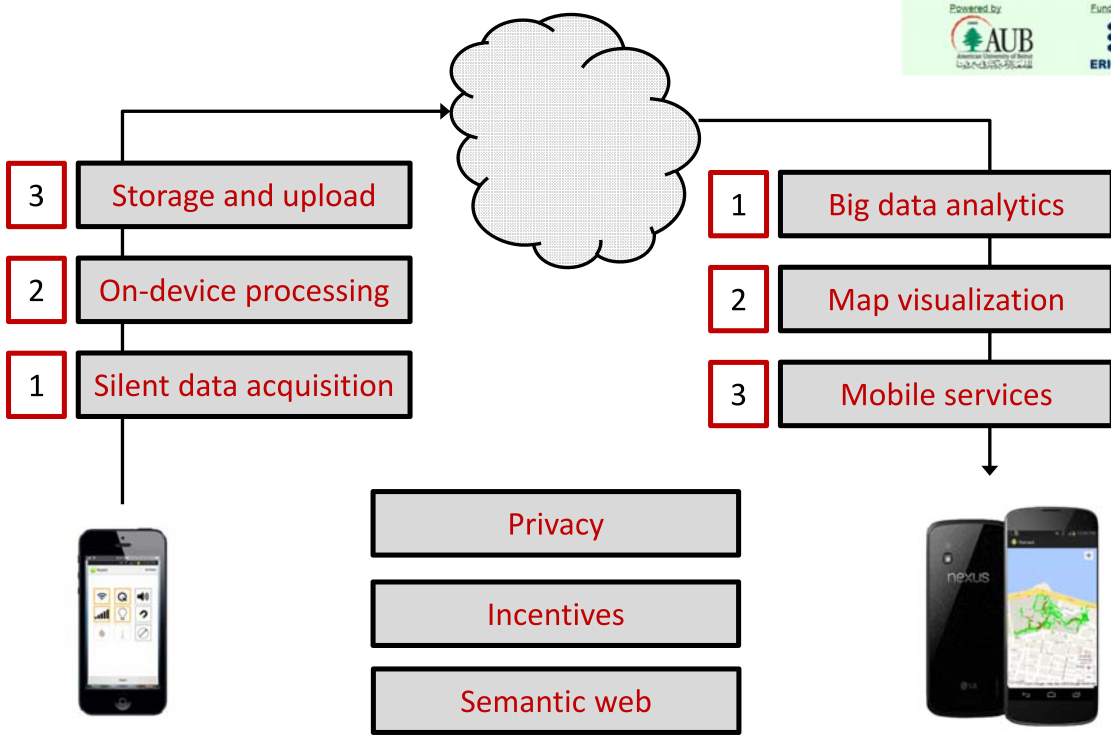

Source: U.S. Energy Information Administration Annual Outlook 2008; IBM Institute for Business Value estimates.

*Figure 7.* Global $CO_2$ emissions (metric tons), 1990, 2010 and 2030, urban/non-urban.

Mapibi

Powered by AUB

Funded by ERICSSON




Mapibi

Powered by AUB

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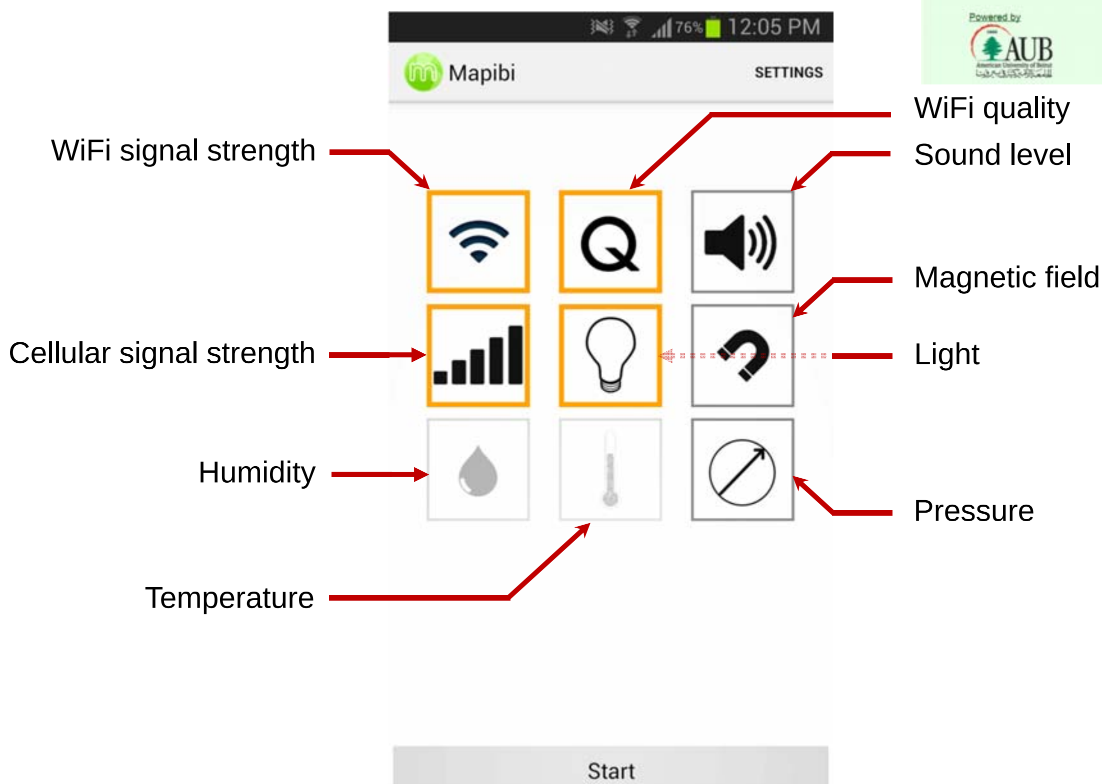
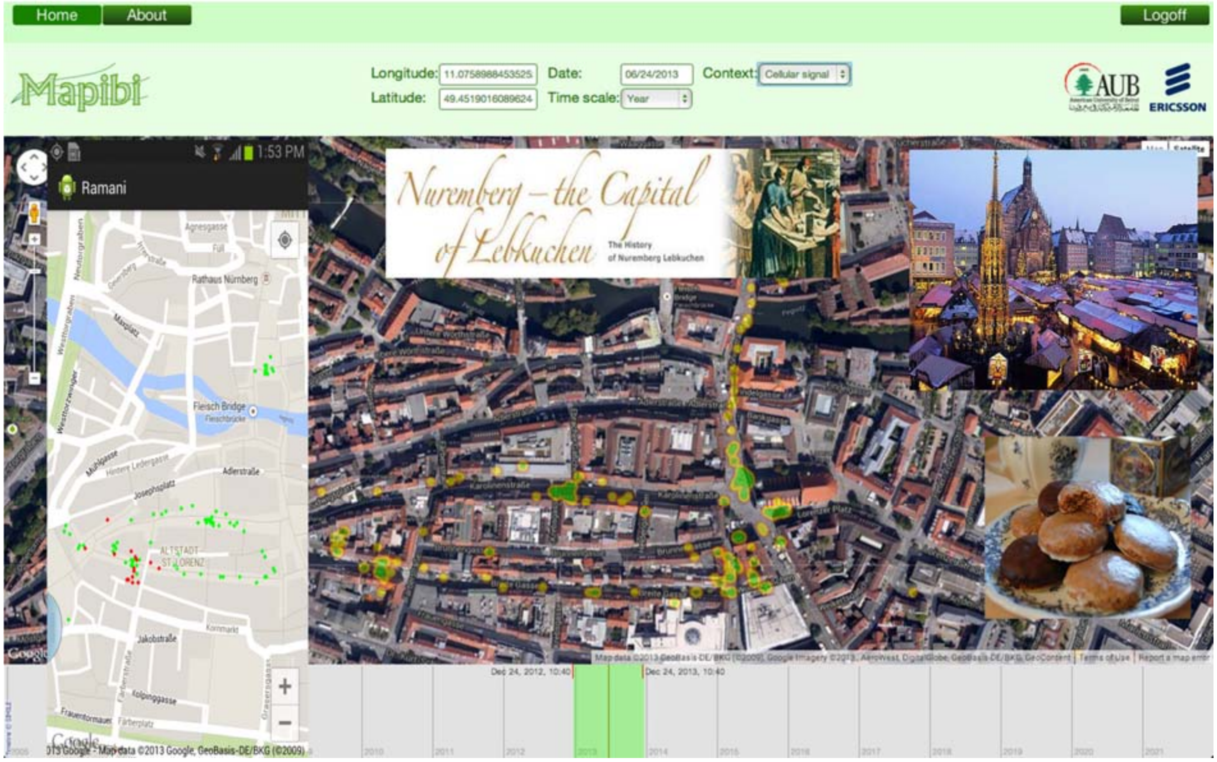
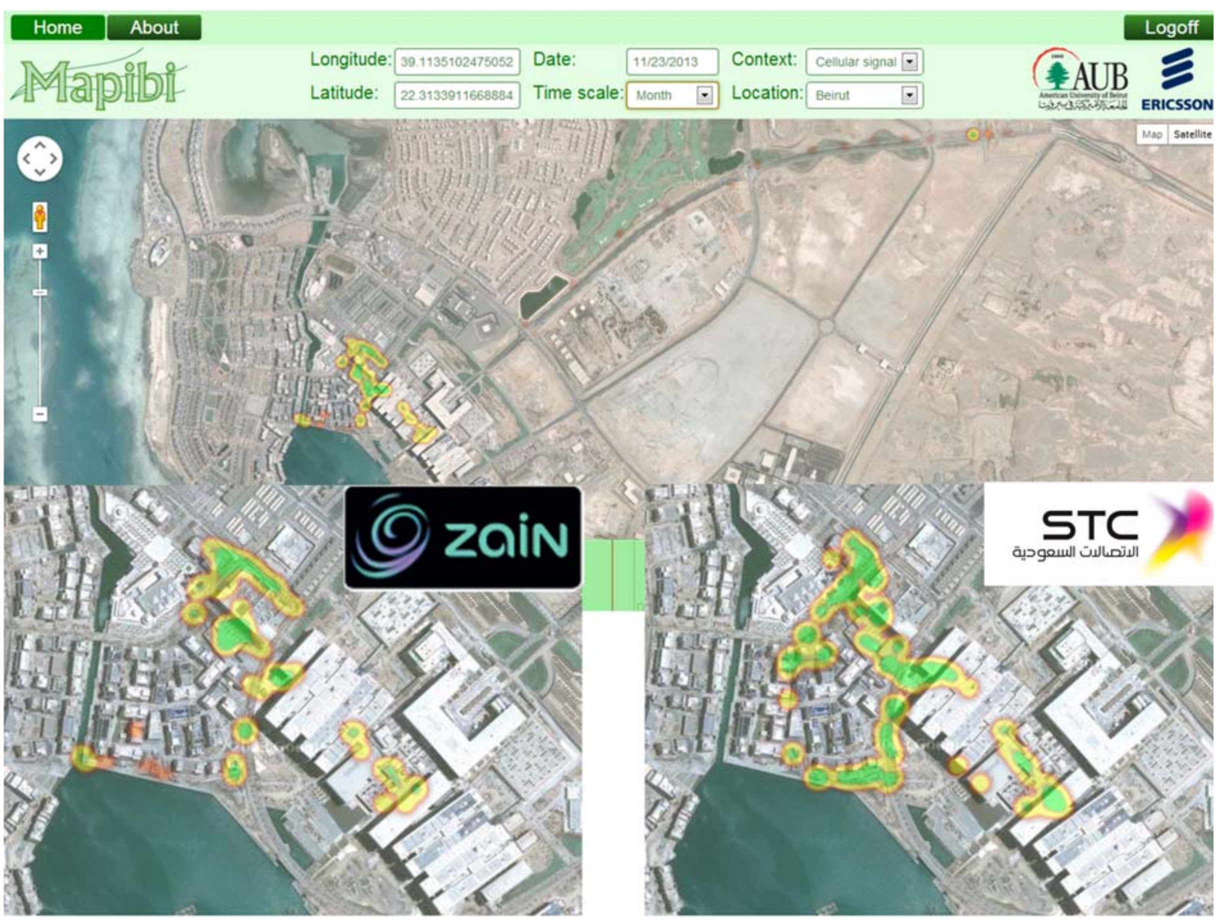






# Cross-platform web and mobile solutions…


Home
About
Logoff
Mapibi
Longitude: 11.0758988453525
Date: 06/24/2013
Context: Cellular signal
Latitude: 49.4519016089624
Time scale: Year
AUB
ERICSSON
Ramani
1:53 PM
Nuremberg – the Capital of Lebkuchen
The History of Nuremberg Lebkuchen
Dec 24, 2012, 10:40
Dec 24, 2013, 10:40


Home
About
Logoff
Mapibi
Longitude: 39.1135102475052
Date: 11/23/2013
Context: Cellular signal
Latitude: 22.3133911668884
Time scale: Month
Location: Beirut
AUB
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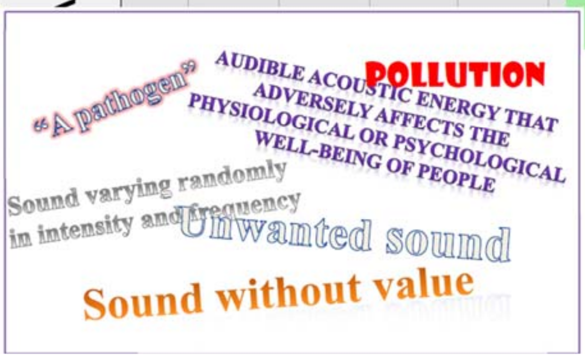
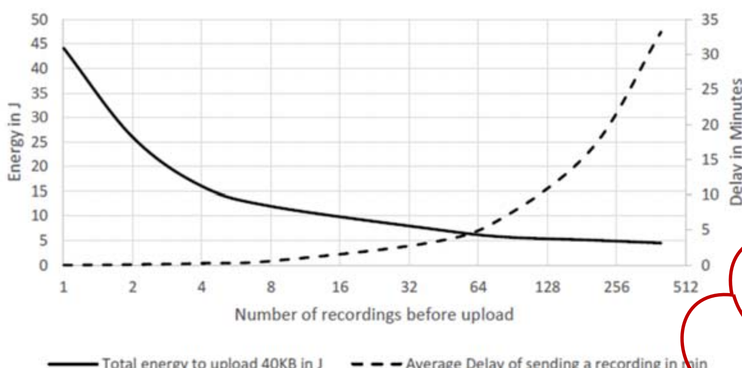
Satellite
zain
STC
الاتصالات السعودية

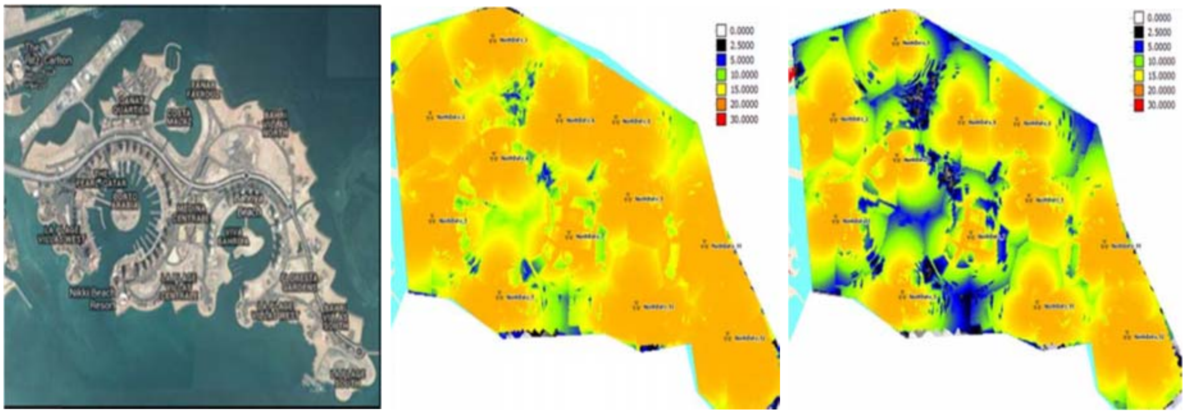




| Range | Intensity Ratio (re: $10^{-12}$ watts/m$^2$) | Level (dBA) | Sound Source |
|---|---|---|---|
| Harmful | 100 000 000 000 000 | 140 | Jet engine |
| | 10 000 000 000 000 | 130 | Riveting hammer |
| | | | THRESHOLD OF FEELING |
| | 1 000 000 000 000 | 120 | Propeller aircraft |
| | 100 000 000 000 | 110 | Rock drill |
| Critical Zone | 10 000 000 000 | 100 | Plage fabrication shop |
| | 1 000 000 000 | 90 | Heavy vehicle |
| | 100 000 000 | 80 | Very busy traffic |
| | 10 000 000 | 70 | Private car |
| | 1 000 000 | 60 | Ordinary conversation |
| Safe | 100 000 | 50 | |
| | 10 000 | 40 | Soft music from radio |
| | 1 000 | 30 | Quiet whisper |
| | 100 | 20 | Quiet urban dwelling |
| | 10 | 10 | Rustle of a leaf |
| | 1 | 0 | THRESHOLD OF HEARING |

# Addressing the challenges… @ device level




# Addressing the challenges…
# @ network level




# Towards Optimized Planning, Operation, and Utilization of Heterogeneous Wireless Networks

Thank You