An Accurate and Efficient Analysis of a MBSFN Network

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Outline

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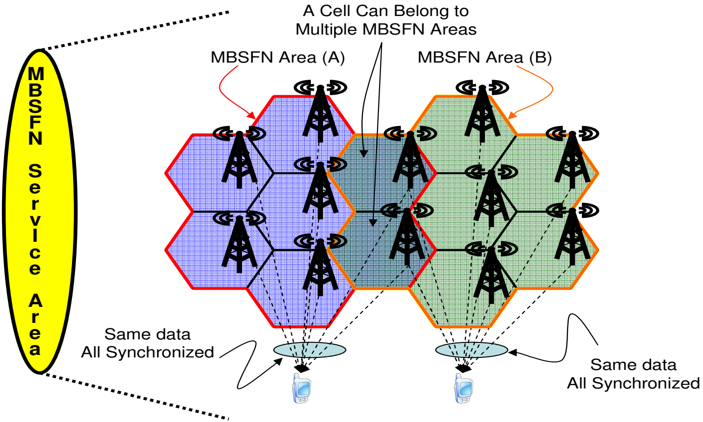
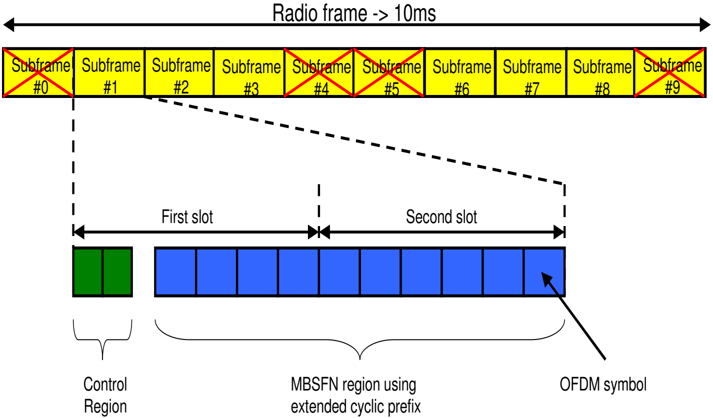
Multicast-Broadcast Single-Frequency Network (MBSFN)

- MBSFN is a transmission mode in the LTE standard.
- MBSFN allows multimedia content to be broadcast over a cellular network (no additional license spectrum, no new infrastructure and end-user devises).
- Different MBSFN Areas can broadcast different contents.
- A cell can be part of multiple (up to eight) MBSFN Areas.



MBSFN Subframes

- In an MBSFN area, it is also required the use of the same radio resources.
- The coordination is provided by a logical node called *Multi-cell/multicast Coordination Entity* (MCE).
- Inside a radio frame, certain sub-frames are reserved as MBSFN subframes.
- The MBSFN subframes use the *extended cyclic prefix* (16.7μs).



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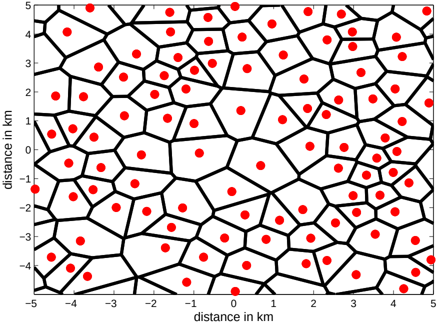
MBSFN Areas: Deployment

- In absence of real data, a MBSFN network can be created as follows:
  1. Deploy M base stations according to a *uniform clustering model* characterized by an exclusion zone of radius r_{bs} (•) [15];



[15] D. Torrieri, M. C. Valenti, and S. Talarico, "An analysis of the DS-CDMA cellular uplink for arbitrary and constrained topologies", *IEEE Trans. Commun.*, vol. 61, pp. 3318-3326, Aug. 2013.

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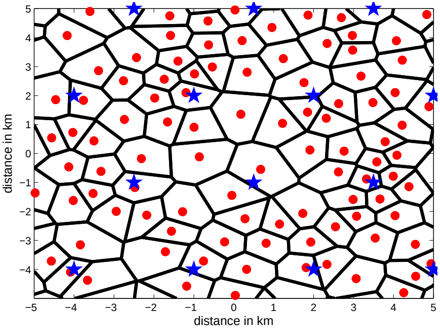
  2. Pick Z points $\{Z_1, ..., Z_S\}$ according to a regular hexagonal grid, which are equally separated by d_{sfn} (★);



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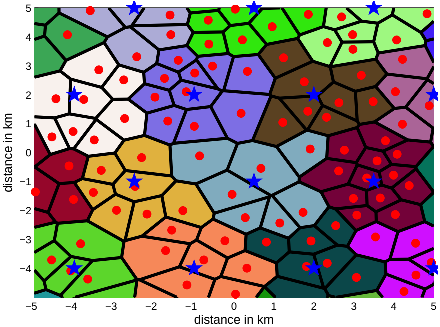
  2. Pick Z points $\{Z_1, ..., Z_S\}$ according to a regular hexagonal grid, which are equally separated by d_{sfn} (★);
  3. Form MBSFN areas by grouping the radio cells of all base stations that are closer to each of the points $\{Z_1, ..., Z_S\}$.



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Network Model

- The Network comprises:
  - S MFSFN areas $\{Z_1, ..., Z_S\}$ which are equally separated by d_{sfn};
  - M cellular base stations $\{X_1, ..., X_M\}$.
- Finite network area discretized into N points, $\{Y_1 ..., Y_N\}$.
- The instantaneous power of X_i received at position Y_j is

$$\rho_{i,j} = P_0 g_{i,j} 10^{\xi_{i,j}/10} f\left(||X_i - Y_j||\right) \quad (1)$$

where

- P_0 is the transmit power;
- $g_{i,j}$ is the power gain due to Nakagami fading;
- $f(\cdot)$ is a path-loss function:

$$f(d) = \left(\frac{d}{d_0}\right)^{-\alpha}$$

  - α is the path loss exponent;
  - $d \geq d_0$;
- $\xi_{i,j}$ is a *shadowing factor* and $\xi_{i,j} \sim N\left(0, \sigma_s^2\right)$ with Gudmundson's autocorrelation function

$$\mathcal{R}(\Delta x) = \exp\left\{-\frac{||\Delta x||}{d_{\text{corr}}} \ln 2\right\} \quad (2)$$

with the decorrelation length $d_{\text{corr}} = 20$ m as suggested by the 30.03 UMTS standard.

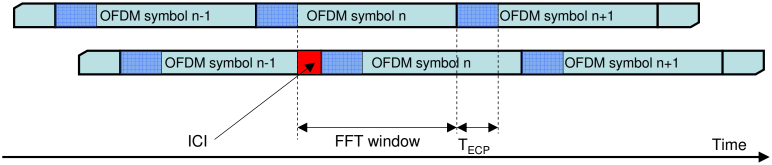
Inter-Symbol Interference (ISI)

- In a MBSFN OFDMA network, given a MBSFN area Z_k there are two sources of ISI:
  - *Inter-MBSFN area interference*: all the base stations outside Z_k;
  - *Intra-MBSFN area interference*: a transmission results in ISI if

$$||X_i - Y_j|| > \frac{c}{T_{\text{ECP}}} \approx 5 \text{ km}$$

where

- $c = 3 \times 10^8$ m/s, which is the speed of light;
- $T_{\text{ECP}} = 16.7\mu$s, which is the *extended cyclic prefix*.



Signal-To-Interference-And-Noise Ratio (SINR)

- Let $\mathcal{G}_{j,z}$ denote the set of the indexes of the base stations that belong to the z^{th} MBSFN area and serving location Y_j, and let $N_j = |\mathcal{G}_{j,z}|$ denote the cardinality of $\mathcal{G}_{j,z}$.
- The signal from base station $X_i, i \in \mathcal{G}_{\mathcal{Z}_j}$ to the UE at location Y_j is included in the *maximal-ratio combining* (MRC) combined signal passed to the demodulator and the instantaneous SINR at location Y_j by using (1) and (2) can be expressed as

$$\gamma_j = \frac{\sum_{i \in \mathcal{G}_{j,\mathcal{Z}_j}} g_{i,j}\Omega_{i,j}}{\Gamma^{-1} + \sum_{i \notin \mathcal{G}_{j,\mathcal{Z}_j}} g_{i,j}\Omega_{i,j}} \quad (3)$$

  where

  - $\Gamma = d_0^{\alpha} N_j P_0 / \mathcal{N}$ is the signal-to-noise ratio (SNR) at a mobile located at unit distance when fading and shadowing are absent, where $\mathcal{N}$ is the noise power;
  - $\Omega_{i,j} = \dfrac{10^{\xi_{i,j}/10}||X_i - Y_j||^{-\alpha}}{N_j}$ is the normalized power of X_i at receiver Y_j.

Conditional Outage Probability

- An *outage* occurs when the SINR is below a threshold β.
  - β depends on the choice of modulation and coding.
- The *outage probability* for the mobile Y_j conditioned over the network is

$$\epsilon_j \quad = \quad P\left[\gamma_j \leq \beta_j \middle| \mathbf{\Omega}_j\right]. \tag{4}$$

- The conditional outage probability is found in closed form [5] for non-identical Nakagami-m parameters $\{m_{i,j}\}$:
  - characterize the fading from the base station X_k to the mobile Y_j;
  - selected based on a *distance-depending fading* model:

$$m_{i,j} = \begin{cases} 3 & \text{if } \ ||X_i - Y_j|| \leq r_{\mathsf{f}}/2 \\ 2 & \text{if } \ r_{\mathsf{f}}/2 < ||X_i - Y_j|| \leq r_{\mathsf{f}} \\ 1 & \text{if } \ ||X_i - Y_j|| > r_{\mathsf{f}} \end{cases} \tag{5}$$

  where r_{f} is the *line-of-sight radius*.

[5] S. Talarico, M. C. Valenti, and D. Torrieri, "Analysis of multi-cell downlink cooperation with a constrained spatial model",

Proc. IEEE Global Telecommun. Conf (GLOBECOM), Atlanta, GA, Dec. 2013.

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Area Below An Outage Threshold (ABOT)

- The *area below an outage threshold* (ABOT) is defined as the fraction of the network realization t that provides an outage probability (averaged over the fading) that meets a threshold $\hat{\epsilon}$ following

$$\mathcal{A}_{\text{bot}}^{(t)} = P\left[\epsilon_j < \hat{\epsilon}\right]. \quad (6)$$

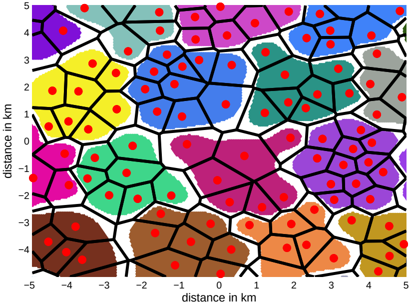

Figure: *Close-up of an example network topology. The white areas are the portion of the network for which the outage probability is above a typical value of $\hat{\epsilon} = 0.1$.*

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- After computing $\mathcal{A}_{\text{bot}}^{(t)}$ for Υ network topologies, its *spatial average* can be computed as

$$\bar{\mathcal{A}}_{\text{bot}} = \frac{1}{\Upsilon}\sum_{t=1}^{\Upsilon}\mathcal{A}_{\text{bot}}^{(t)}. \quad (7)$$

- Let $R = C(\beta_j)$ represent the relationship between the code rate R (in bit per channel used [bpcu]) and SINR threshold β_j. For modern cellular systems, it is reasonable to use:

$$C(\beta_j) = \log_2(1 + \beta_j)$$

ABOT vs Rate

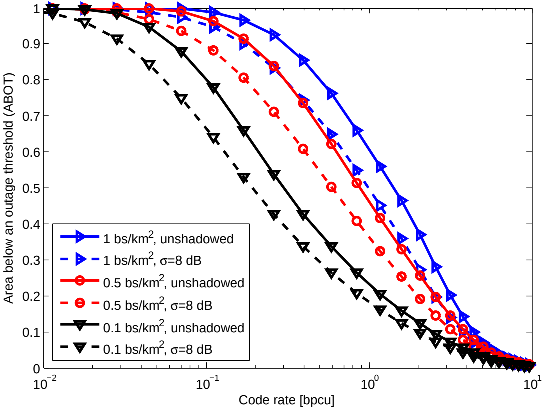

Figure: *ABOT as function of the rate for both a shadowed ($\sigma_s = 8$ dB) and unshadowed environment.*

Settings:

- Square arena of side $d_{\text{net}} = 20$ km;
- SNR: $\Gamma = 10$ dB;
- Path loss exponent: $\alpha = 3.5$;
- Distance among MBSFN areas: $d_{\text{sfn}} = 6$ km;
- Line-of-sight radius: $r_{\text{f}} = 0.5$ km;
- Exclusion zone: $r_{\text{bs}} = 0.5$ km;
- Outage constraint: $\hat{\epsilon} = 0.1$.

ABOT vs Minimum Separation Among Base Stations

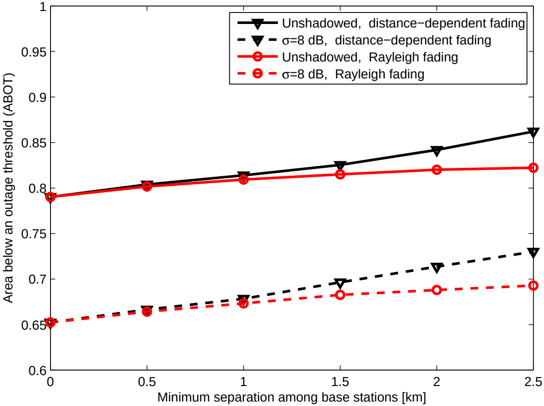

Figure: *ABOT as a function of the minimum separation among base stations, for both Rayleigh fading and a distance-depending fading when* $r_{\mathsf{bs}} = r_{\mathsf{f}}$.

Settings:

- Square arena of side $d_{\mathsf{net}} = 20$ km;
- SNR: $\Gamma = 10$ dB;
- Path loss exponent: $\alpha = 3.5$;
- Distance among MBSFN areas: $d_{\mathsf{sfn}} = 6$ km;
- Code Rate: $R = 0.1$;
- Density of base station: $\lambda = 0.1$ #bs/km^2
- Outage constraint: $\hat{\epsilon} = 0.1$.

ABOT vs Outage Constraint

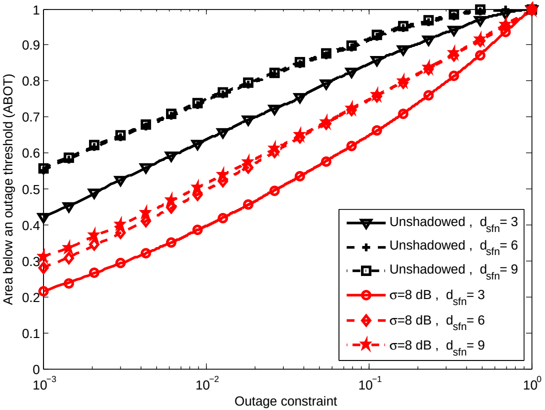

Figure: *ABOT as a function of the outage threshold $\hat{\epsilon}$ for both a shadowed ($\sigma_s = 8$ dB) and unshadowed environment.*

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- Square arena of side $d_{\text{net}} = 20$ km;
- SNR: $\Gamma = 10$ dB;
- Path loss exponent: $\alpha = 3.5$;
- Code Rate: $R = 0.5$;
- Density of base station: $\lambda = 0.5$ #bs/km^2
- Line-of-sight radius: $r_{\text{f}} = 0.5$ km;
- Exclusion zone: $r_{\text{bs}} = 0.5$ km;

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Conclusions

- A new approach for modeling and analyzing the performance of multicast-broadcast single-frequency network (MBSFN) has been presented.
- The analysis is driven by a new outage probability closed form expression, which is exact for a given network realization and accounts for path loss, correlated shadowing, and Nakagami-m fading with non-identical parameters.
- Despite other works that characterize the performance of a MBSFN network, the topology of the network is determined by a constrained random spatial model.
- The results show:
  - An increase in the size of an MBSFN areas leads to an improvement in performance until the inter-MBSFN area ISI begins to degrade performance;
  - As expected, densification or an increase in the minimum separation among base stations improve performance.

Thank You