

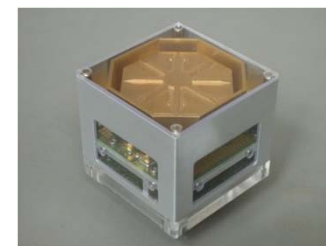
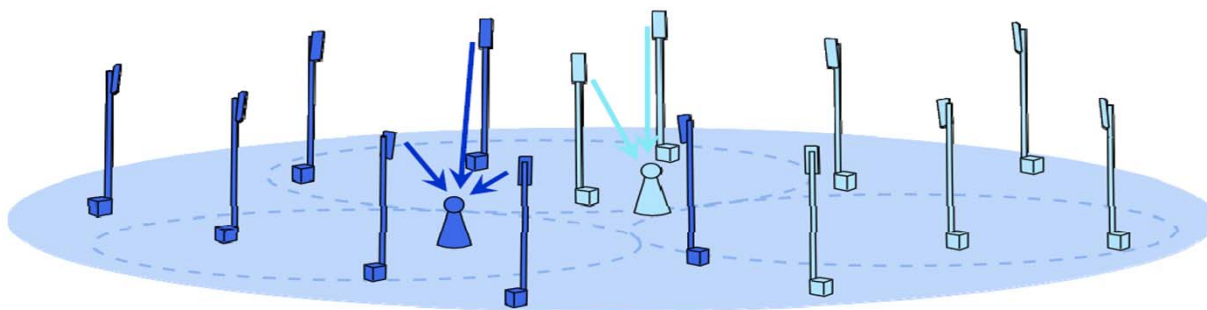
Cognitive LTE Small Cell Networks



Mérouane Debbah

The LTE Small Cells Flexible Framework

- **LTE:** (Long Term Evolution)
 - ❑ The new cellular communications standard aiming at very high data rates.
- **Idea:** A dense network of low-power base stations.

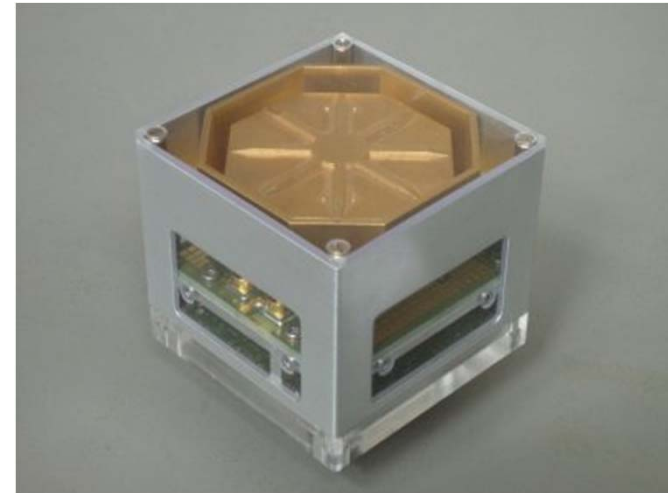


Bell Labs lightradio antenna module – the next generation small cell
(picture from www.washingtonpost.com)

- **Motivation:**
 - ❑ Higher spectral efficiency is achievable
 - ❑ “Green” technology:
 - ❑ Reduced energy consumption at the base stations
 - ❑ Reduced electromagnetic pollution (using beamforming to intended users)

Vision

- 1Gbps/Km² for 10 MHz
- Environment constraints = <1W EIRP
- Constraint: ~10 W power consumption



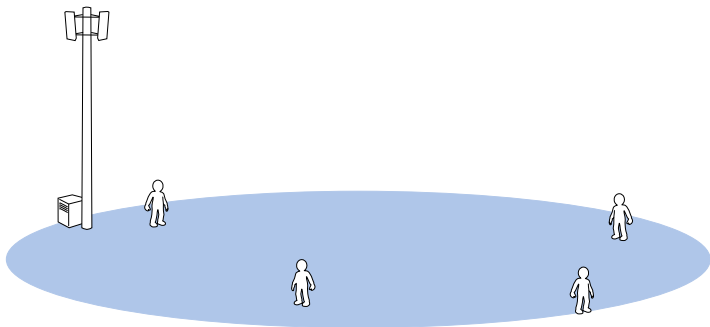
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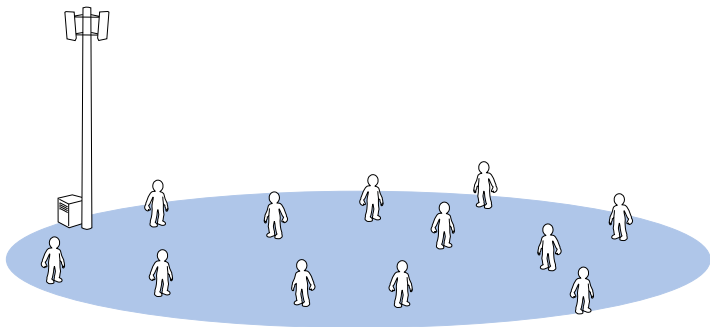
LightRadio Concept

- 2-inch cube that aims to replace unsightly cell towers
- LightRadio reduces energy consumption of mobile networks by up to 50% over current radio access network equipment
- Networks will be redesigned as a system of federated broadband hotspots that can be set up anywhere and can be powered by electricity, wind or sun.
- It is the end of the classical base station **if we can provide a new radio radio interface for non-interfering networks.**

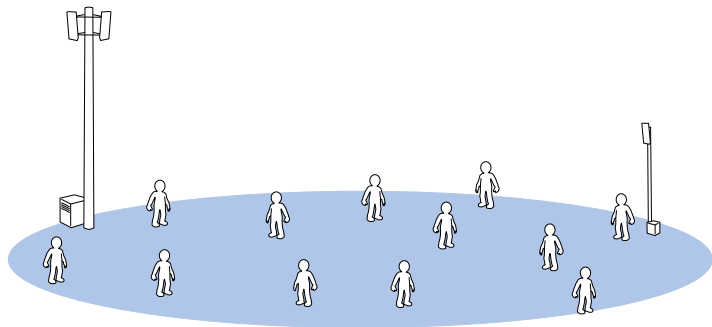
Motivation



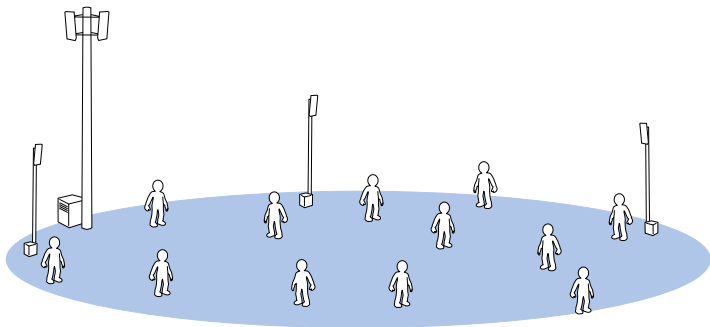
Motivation



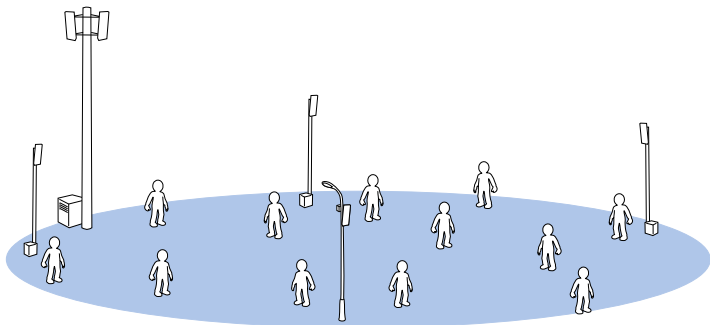
Motivation



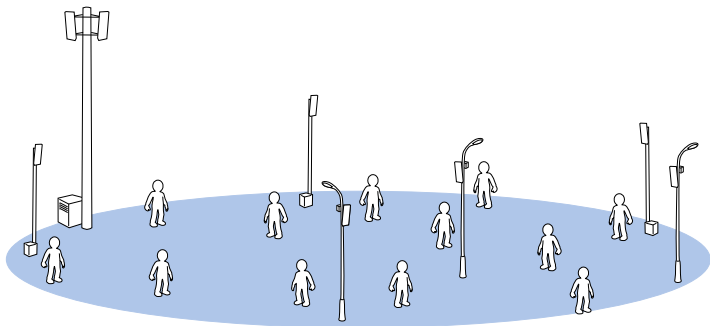
Motivation



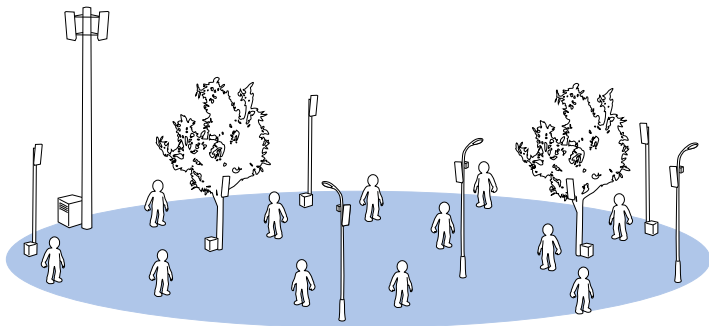
Motivation



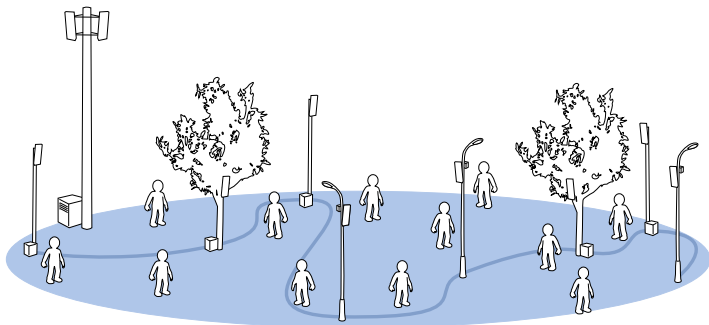
Motivation



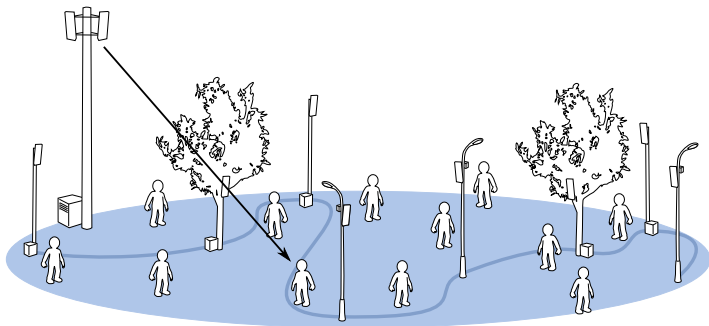
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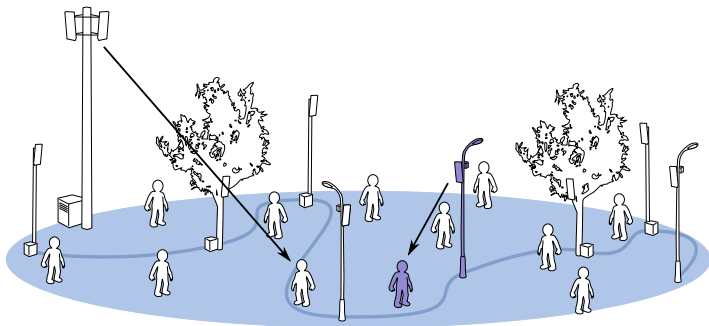
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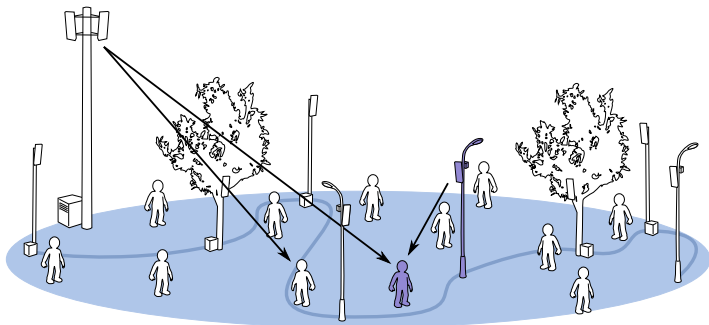
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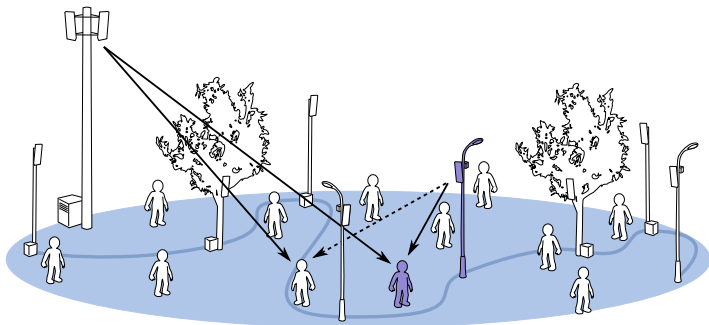
Motivation



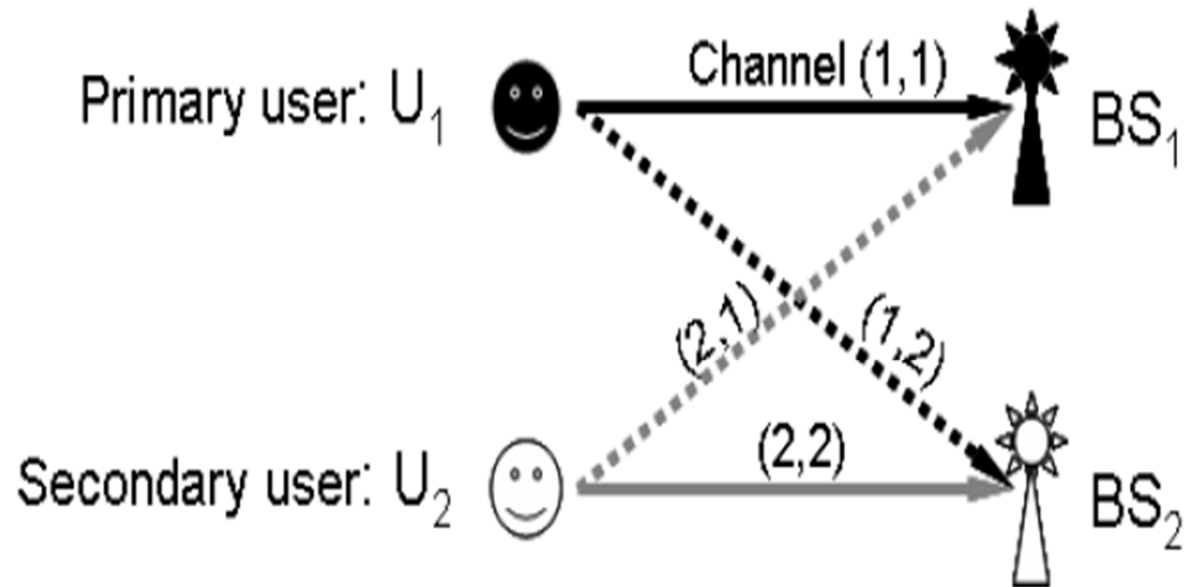
Motivation



Motivation



Toy scenario



A bit of history on the LTE interface

Shannon's point of view on OFDM

C. E. Shannon, "Communication in the presence of Noise", Proceeding of the IRE, vol. 37, no.1, pp. 10-21, Jan, 1949.

IX. ARBITRARY GAUSSIAN NOISE

If a white thermal noise is passed through a filter whose transfer function is $Y(f)$, the resulting noise has a power spectrum $N(f) = K Y(f)^2$ and is known as Gaussian noise. We can calculate the capacity of a channel perturbed by any Gaussian noise from the white-noise result. Suppose our total transmitter power is P and it is distributed among the various frequencies according to $P(f)$. Then

$$\int_0^W P(f) df = P, \quad (31)$$

We can divide the band into a large number of small bands, with $N(f)$ approximately constant in each. The total capacity for a given distribution $P(f)$ will then be given by

$$C_1 = \int_0^W \log\left(1 + \frac{P(f)}{N(f)}\right) df \quad (32)$$

since, for each elementary band, the white-noise result applies. The maximum rate of transmission will be found by maximizing C_1 subject to condition (31). This requires that we maximize

$$\int_0^W \left[\log\left(1 + \frac{P(f)}{N(f)}\right) + \lambda P(f) \right] df. \quad (33)$$

The condition for this is, by the calculus of variations, or merely from the convex nature of the curve $\log(1+x)$

$$\frac{1}{N(f) + P(f)} + \lambda = 0 \quad (34)$$

or $N(f) + P(f)$ must be constant. The constant is adjusted to make the total signal power equal to P . For frequencies where the noise power is low, the signal power should be high, and vice versa, as we would expect.

The situation is shown graphically in Fig. 8. The curve is the assumed noise spectrum, and the three lines correspond to different choices of P . If P is small, we cannot make $P(f) + N(f)$ constant, since this would require negative power at some frequencies. It is easily shown, however, that in this case the best $P(f)$ is obtained by making $P(f) + N(f)$ constant whenever possible, and making $P(f)$

Fourier

"We can divide the band into a large number of small bands, with $N(f)$ approximately constant in each"

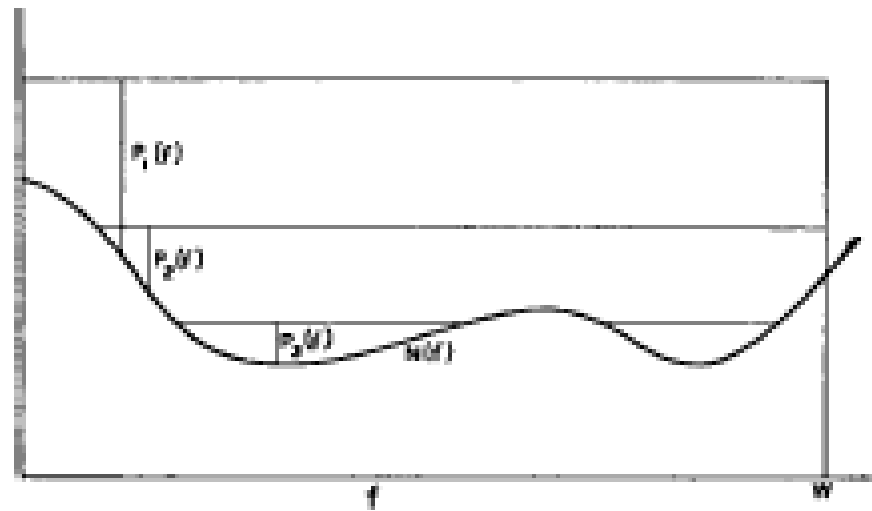


Fig. 8. Best distribution of transmitter power.

In Shannon's terms, $N(f)$ is the power spectrum.

- OFDM is the best you can do for a point to point scenario....but not in a multi-user setting....

First OFDM scheme

M. L. Doeltz, E. T. Heald and D. L. Martin, "Binary data transmission techniques for linear systems," Proc. IRE, vol. 45, pp. 656-661, May 1957.

- First system known as Kineplex (50 years ago!) for military purposes in the band [1.8-30Mhz].

Unfortunately, not much is known about this system...classified!

The Analog age of OFDM

B. R. Saltzberg, "Performance of an efficient Parallel Data Transmission System," IEEE Trans. Commun, Vol. Com-15, p. 805-811, Dec. 1967

S. B. Weinstein and P. M. Ebert, "Data Transmission by frequency Division Multiplexing", IEEE Trans. Commun, vol. COM-19, pp. 628-634, Oct, 1971.



Joseph Fourier, 1768-1830

The basic idea used the Fourier transform but the success was limited due to the high cost of orthogonal analog filters.

The digital age of OFDM

A. Peled and A. Ruiz, "Frequency domain data transmission using reduced computational complexity algorithms", in Proc. IEEE Int. Conf. Acoustics, Speech and Signal Processing, Apr. 1980, pp. 964-967

B. Hirosaki, "An Orthogonally multiplexed QAM system using the discrete Fourier Transform," IEEE Trans. Commun., vol. Com-29, pp. 982-989, Jul. 1981

The modulator was based on the FFT and had well celebrated features thanks to Cooley (IBM) and Tukey (Princeton) in 1965.

But how does one cope with frequency selective channels?

OFDM Afterwards

WO9004893, oct, 1989, First worldwide patent introducing the guard interval in OFDM



Tristan de Couason, 1946- ,Supelec then TH-CSF

The idea is based on the use of a **guard interval**.

The **unexploited** guard interval trades complexity for performance but this is exactly the degree of freedom we need

We have to exploit it!

Our proposal: VFDM

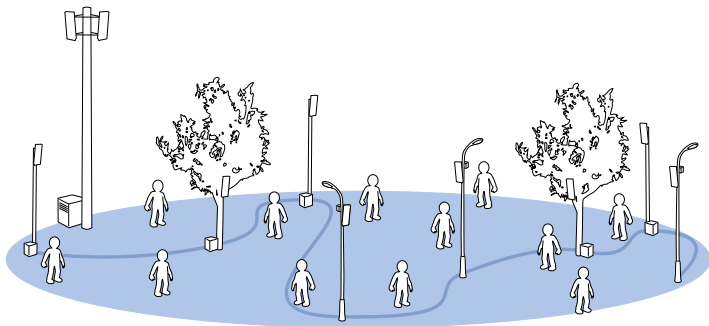
Vandermonde-subspace Frequency Division Multiplexing

A linear Vandermonde-based orthogonal precoder that generates zero interference on the primary network by exploiting the frequency selective nature of the channel.

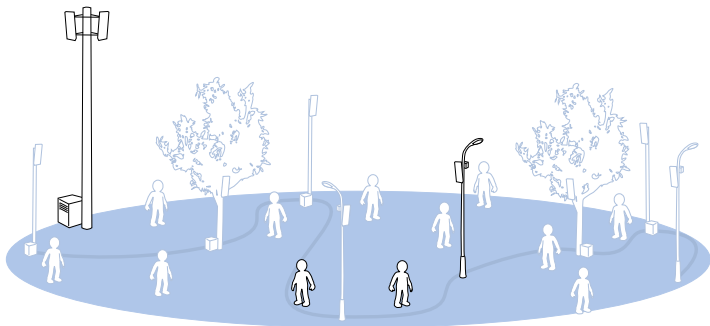
[1] L. S. Cardoso, M. Kobayashi, Ø. Ryan, and M. Debbah, "Vandermonde frequency division multiplexing for cognitive radio," SPAWC 2008

[2] L. S. Cardoso, R. Calvacanti, M. Kobayashi and M. Debbah, "*Vandermonde-Subspace Frequency Division Multiplexing Receiver Analysis*," PIMRC 2010

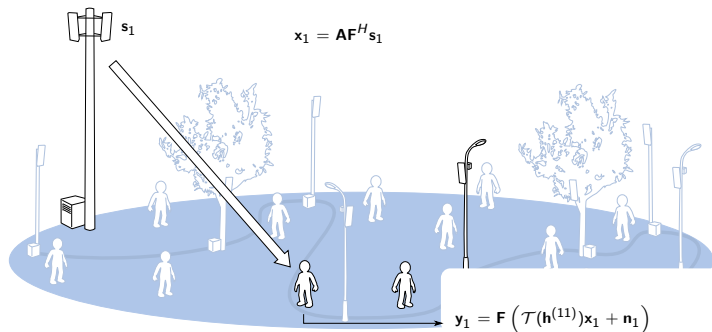
System Model



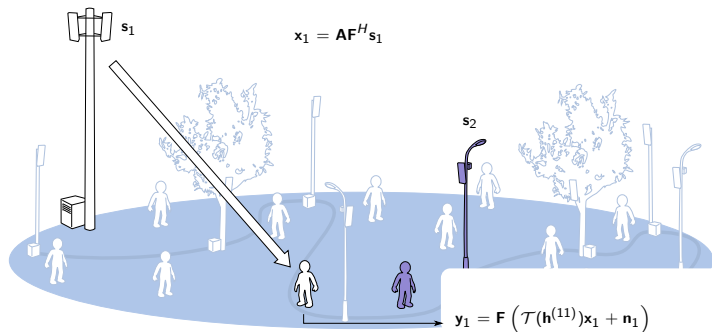
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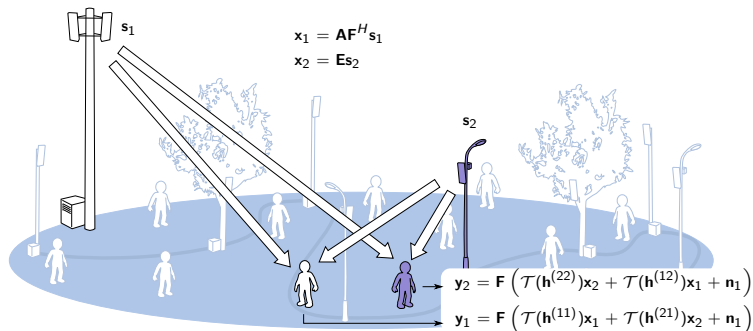
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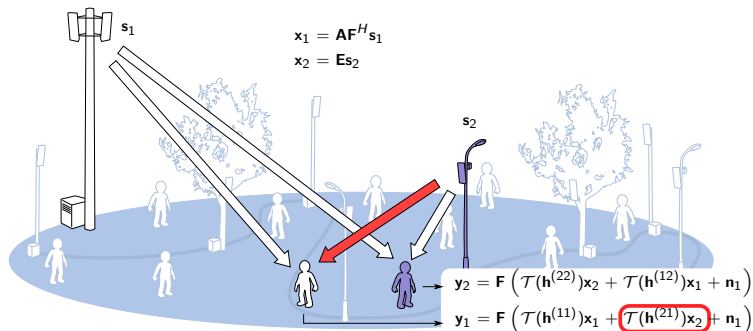
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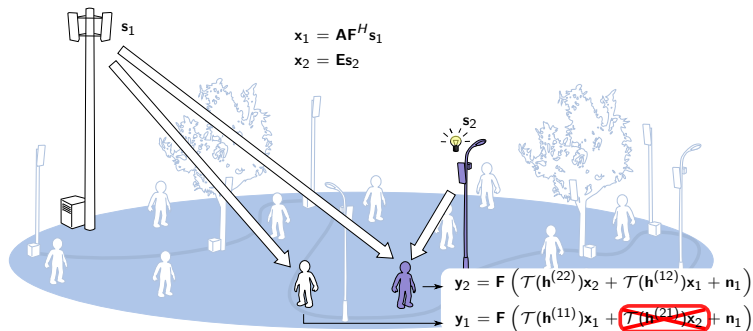
System Model



System Model



System Model



Precoder

Our objective is to find an $\mathbf{E} \in \mathcal{C}^{(N+L) \times L}$ such that for any \mathbf{s}_2 :

$$\mathcal{T}(\mathbf{h}^{(21)})\mathbf{E} = \mathbf{0}. \quad (1)$$

Our objective is to find an $\mathbf{E} \in \mathcal{C}^{(N+L) \times L}$ such that for any \mathbf{s}_2 :

$$\mathcal{T}(\mathbf{h}^{(21)})\mathbf{E} = \mathbf{0}. \quad (1)$$

One solution to (1) is given by the Vandermonde-subspace matrix:

$$\mathbf{v} = \begin{bmatrix} 1 & \dots & 1 \\ a_1 & \dots & a_L \\ a_1^2 & \dots & a_L^2 \\ \vdots & \ddots & \vdots \\ a_1^{N+L-1} & \dots & a_L^{N+L-1} \end{bmatrix}, \quad (2)$$

where $\{a_1, \dots, a_L\}$ are the roots of $S(z) = \sum_{i=0}^L h_i^{(21)} z^{L-i}$.

Precoder

A bit of linear algebra

$$\begin{bmatrix} h_2 & h_1 & h_0 & 0 & 0 & 0 \\ 0 & h_2 & h_1 & h_0 & 0 & 0 \\ 0 & 0 & h_2 & h_1 & h_0 & 0 \\ 0 & 0 & 0 & h_2 & h_1 & h_0 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ a_1 & a_2 & a_3 & a_4 \\ a_2 & a_3 & a_4 & a_1 \\ a_3 & a_4 & a_1 & a_2 \\ a_4 & a_1 & a_2 & a_3 \\ a_1 & a_2 & a_3 & a_4 \end{bmatrix}$$

Precoder

A bit of linear algebra

$$\begin{bmatrix} h_2 & h_1 & h_0 & 0 & 0 & 0 \\ 0 & h_2 & h_1 & h_0 & 0 & 0 \\ 0 & 0 & h_2 & h_1 & h_0 & 0 \\ 0 & 0 & 0 & h_2 & h_1 & h_0 \end{bmatrix} \times \begin{bmatrix} 1 & 1 & 1 & 1 \\ a_1 & a_2 & a_3 & a_4 \\ a_2 & a_3 & a_4 & a_5 \\ a_3 & a_4 & a_5 & a_1 \\ a_4 & a_5 & a_1 & a_2 \\ a_5 & a_1 & a_2 & a_3 \end{bmatrix}$$

$\rightarrow = h_2 + h_1 a_1 + h_0 a_1^2$

Precoder

A bit of linear algebra

$$\begin{bmatrix} h_2 & h_1 & h_0 & 0 & 0 & 0 \\ 0 & h_2 & h_1 & h_0 & 0 & 0 \\ 0 & 0 & h_2 & h_1 & h_0 & 0 \\ 0 & 0 & 0 & h_2 & h_1 & h_0 \end{bmatrix} \times \begin{bmatrix} 1 & 1 & 1 & 1 \\ a_1 & a_2 & a_3 & a_4 \\ a_2 & a_3 & a_4 & a_5 \\ a_3 & a_4 & a_5 & a_1 \\ a_4 & a_5 & a_1 & a_2 \\ a_5 & a_1 & a_2 & a_3 \end{bmatrix}$$

$\rightarrow = h_2 + h_1 a_1 + h_0 a_1^2 = 0$

Precoder

A bit of linear algebra

$$\begin{bmatrix} h_2 & h_1 & h_0 & 0 & 0 & 0 \\ 0 & h_2 & h_1 & h_0 & 0 & 0 \\ 0 & 0 & h_2 & h_1 & h_0 & 0 \\ 0 & 0 & 0 & h_2 & h_1 & h_0 \end{bmatrix} \times \begin{bmatrix} 1 & 1 & 1 & 1 \\ a_1 & a_2 & a_3 & a_4 \\ a_2 & a_3 & a_4 & a_5 \\ a_3 & a_4 & a_5 & a_1 \\ a_4 & a_5 & a_1 & a_2 \\ a_5 & a_1 & a_2 & a_3 \end{bmatrix}$$

$\rightarrow = h_2 a_1 + h_1 a_1^2 + h_0 a_1^3 = 0$

Precoder

A bit of linear algebra

$$\begin{bmatrix} h_2 & h_1 & h_0 & 0 & 0 & 0 \\ 0 & h_2 & h_1 & h_0 & 0 & 0 \\ 0 & 0 & h_2 & h_1 & h_0 & 0 \\ 0 & 0 & 0 & h_2 & h_1 & h_0 \end{bmatrix} \times \begin{bmatrix} 1 & 1 & 1 & 1 \\ a_1 & a_2 & a_3 & a_4 \\ a_2 & a_3 & a_4 & a_5 \\ a_3 & a_4 & a_5 & a_1 \\ a_4 & a_5 & a_1 & a_2 \\ a_5 & a_1 & a_2 & a_3 \end{bmatrix}$$

$\rightarrow = h_2 a_1^2 + h_1 a_1^3 + h_0 a_1^4 = 0$

Precoder

A bit of linear algebra

$$\begin{bmatrix} h_2 & h_1 & h_0 & 0 & 0 & 0 \\ 0 & h_2 & h_1 & h_0 & 0 & 0 \\ 0 & 0 & h_2 & h_1 & h_0 & 0 \\ 0 & 0 & 0 & h_2 & h_1 & h_0 \end{bmatrix} \times \begin{bmatrix} 1 & 1 & 1 & 1 \\ a_1 & a_2 & a_3 & a_4 \\ a_2 & a_3 & a_4 & a_5 \\ a_3 & a_4 & a_5 & a_1 \\ a_4 & a_5 & a_1 & a_2 \\ a_5 & a_1 & a_2 & a_3 \end{bmatrix}$$

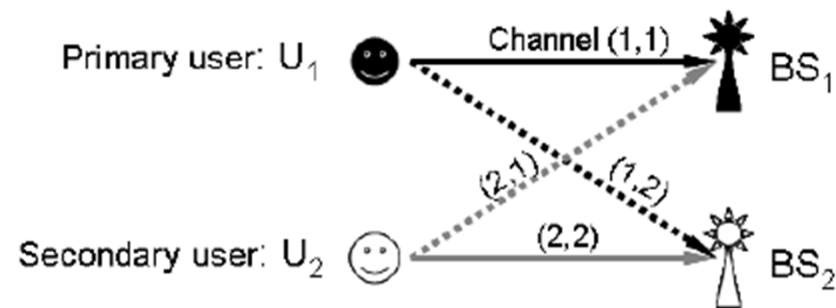
$$\rightarrow = h_2 a_1^3 + h_1 a_1^4 + h_0 a_1^5 = 0$$

Think Vandermonde!



Alexandre-Thophie Vandermonde, 1735-1796

- The general idea here is to **exploit the redundancy of the cyclic prefix to null the interference**.
- Mainly, the secondary user will try to send his information in the nulls of the channel (2,1) in order to not interfere with the primary user (**and we can prove that there are L nulls**).
- Since the channels (2,1) and (2,2) are statistically different, the nulls have probability zero to be the same and therefore information from the secondary user U_2 to BS_2 will go through.



TDD Mode required

- Interestingly, the secondary estimates channel (2,1), derives the zeros of the channel and constructs adaptively the vandermonde modulator.
- Interestingly, **with any input power**, the secondary user will never interfere with the primary user.
- In some sense, the vandermonde modulator plays the role of a beamformer in the frequency domain.
- Note finally that the secondary user will send only a signal of dimension L , corresponding to the degrees of freedom left by the system.

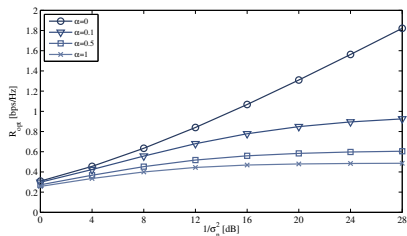
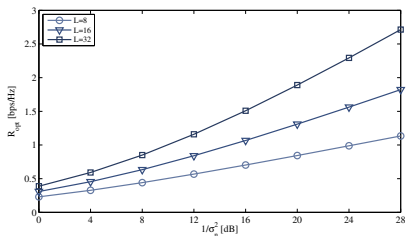
We are able to create a world where non-interfering communications can take place.

In this world,

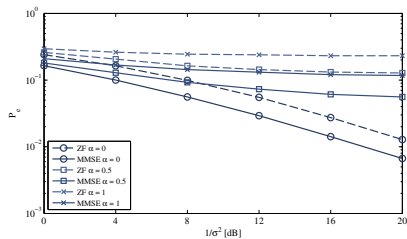
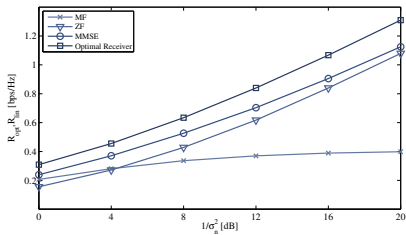
- Primary users use FFT modulators.
- Secondary users use Vandermonde based modulators.

These modulators should adapt to the environment and be able to be software defined.

Equalizers for VFDM



Optimal Receiver — $N = 64$ and $L = 16$.



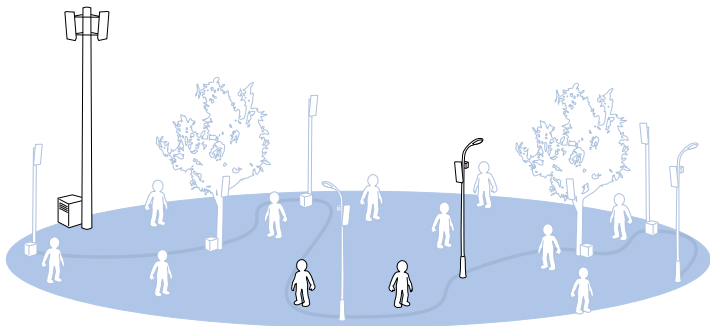
Optimal and linear receivers — $N = 64$ and $L = 16$.

Multi-user Vandermonde-subspace Frequency Division Multiplexing

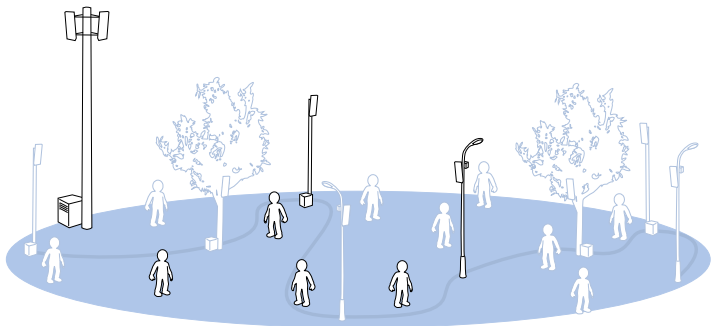
A linear cascaded precoder that generates zero interference on the primary network and manages multi-user interference in the secondary network

- [4] L. S. Cardoso, M. Maso, M. Kobayashi, and M. Debbah. "Orthogonal LTE two-tier cellular networks". To appear in proceedings of International Conference on Communications 2011
- [5] M. Maso, L. S. Cardoso, M. Debbah, and L. Vangelista. "Orthogonal precoder for LTE Small-Cells networks". IEEE Journal on Selected Areas in Communications (submitted), 2011.

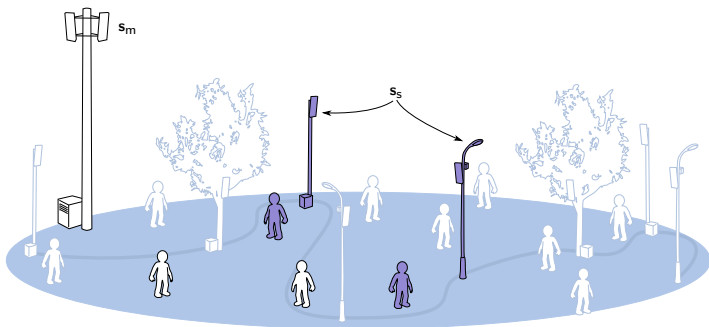
System Model



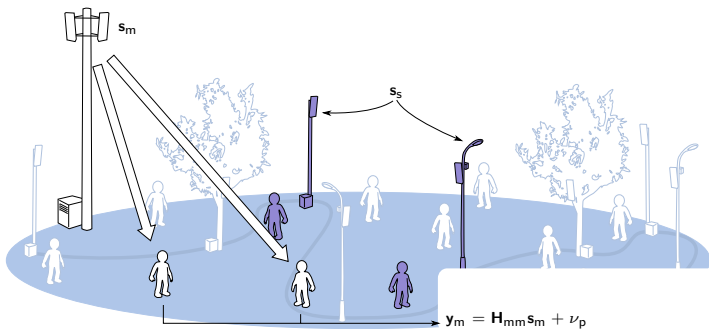
System Model



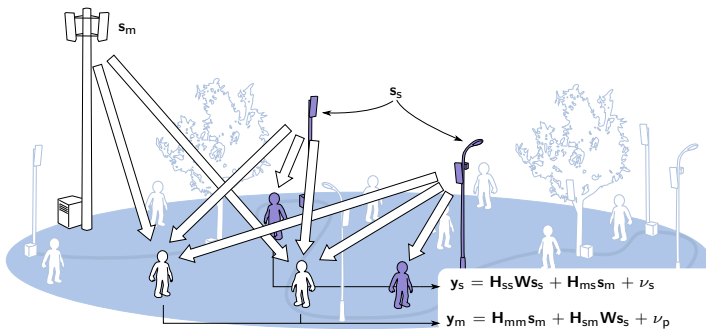
System Model



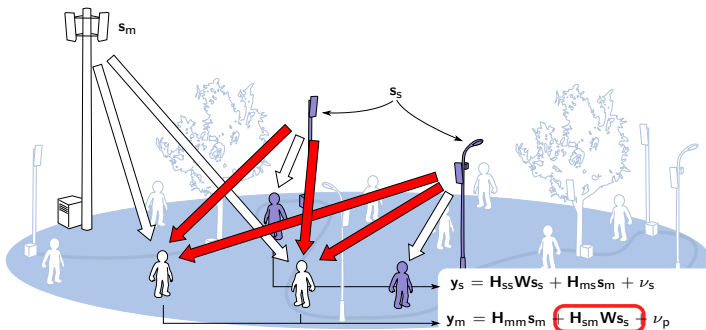
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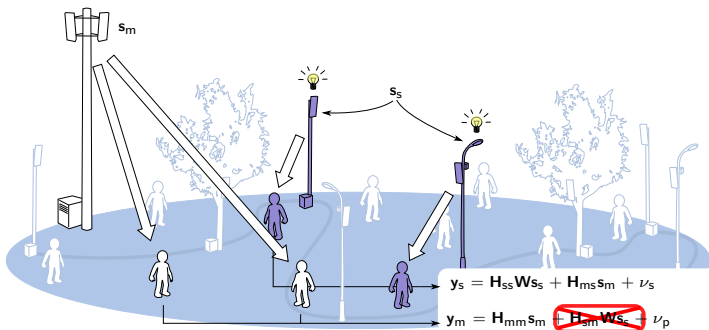
System Model



System Model



System Model



Precoder

$$\mathbf{W} = \mathbf{Z}\mathbf{E}$$

$$\mathbf{W} = \mathbf{Z}\mathbf{E}$$

- ▶ Inner precoder \mathbf{E} (Vandermonde)

$$\mathbf{H}_{\text{sm}}\mathbf{E} = \mathbf{0}, \quad (4)$$

where \mathbf{E} is defined as $\mathbf{E} = \bigoplus_{i=1}^K \mathbf{E}_i$. (4) is satisfied when

$$\mathbf{H}_{\text{sm}}^{(i,\cdot)} \mathbf{E}_i = \mathbf{0} \quad \forall i \in [1, K].$$

Channel estimation

Channel estimation protocol

Design of a channel estimation protocol, that takes into consideration the primary system's own channel estimation, and tries to minimize errors.

[7] M. Maso, L. Cardoso, M. Debbah, and L. Vangelista. "Channel Estimation Impact for MU-VFDM LTE Small Cells". IEEE Global Communications Conference (submitted), 2011

Imperfect CSIT

Model

- ▶ Block fading channel of coherence time T
- ▶ Channel estimation in the MC is performed during $\tau \leq T$
- ▶ τ is divided into two parts, τ_1 (UL channel estimation phase) and τ_2 (DL channel estimation phase)

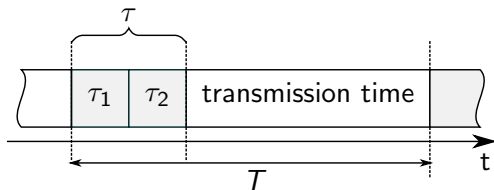
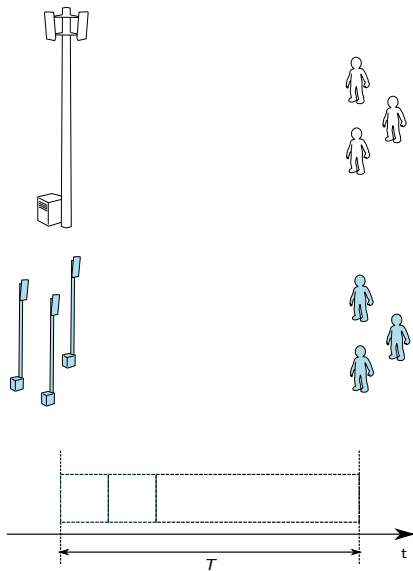
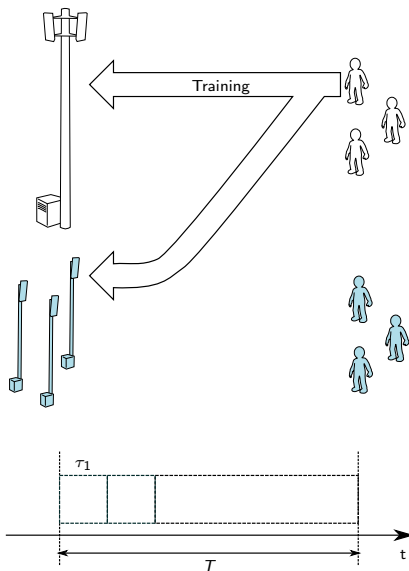


Figure: Channel estimation and transmission times.

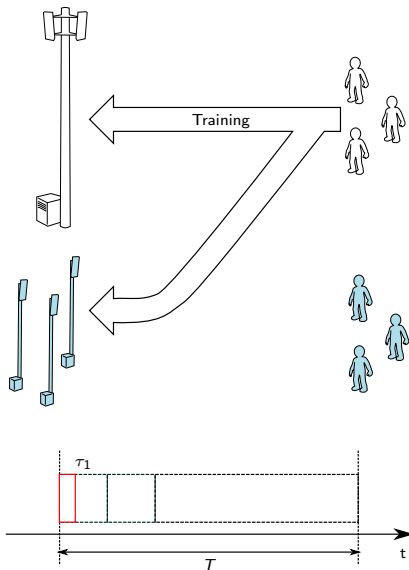
Protocol



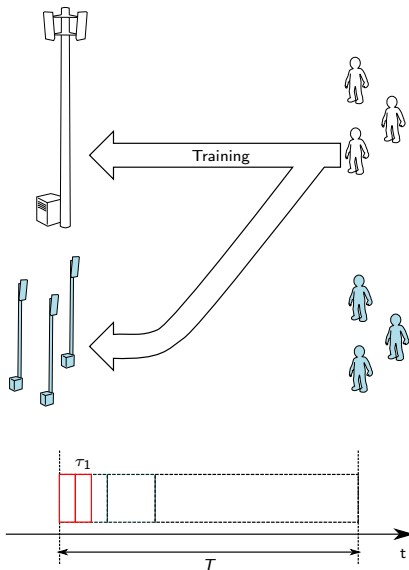
Protocol



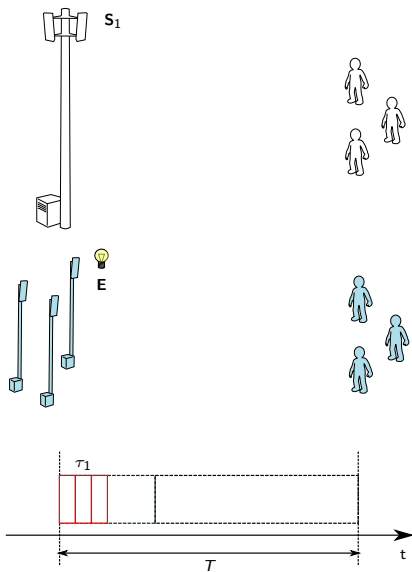
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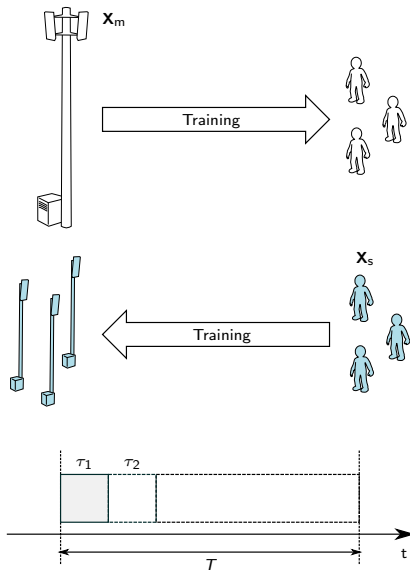
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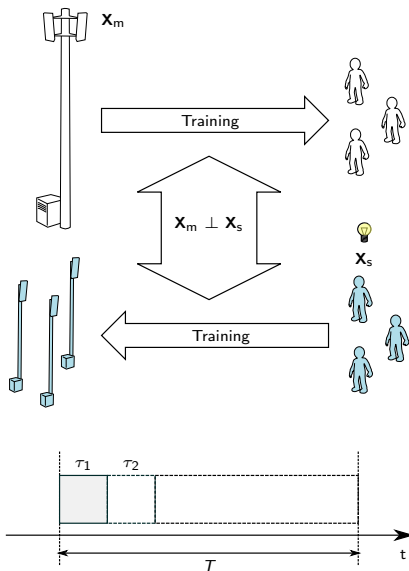
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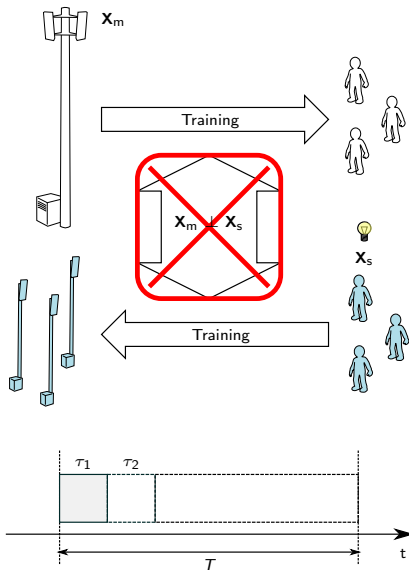
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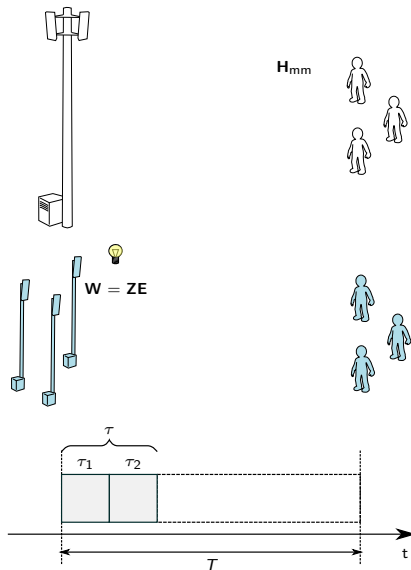
Protocol



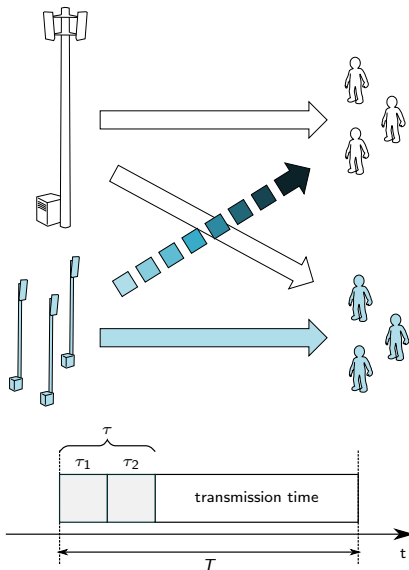
Protocol



Protocol



Protocol



Performance

The precoder \mathbf{W} is based on an imperfect channel estimation affecting the performance of both systems.

$$C_m^{\text{SUM, I}} = \frac{T - \tau}{T(N + L)} \sum_{i=1}^N \log_2(1 + \text{SINR}_i(\tau)) \text{ and}$$

$$C_s^{\text{SUM, I}} = \frac{T - \tau}{T(N + L)} \sum_{i=1}^{\gamma_{rx} KN} \log_2(1 + \text{SINR}_i(\tau))$$

Performance

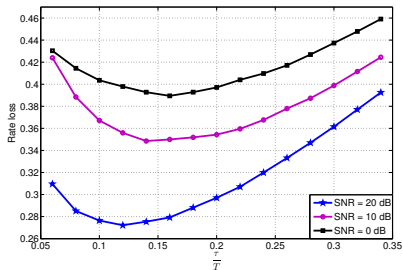


Figure: Rate loss of the MC due to imperfect CSIT as τ changes.

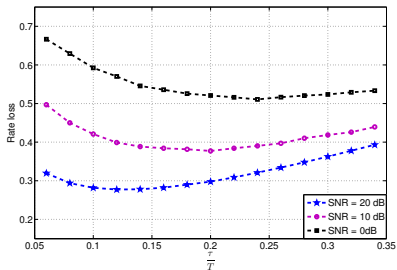


Figure: Rate loss of the SCs due to imperfect CSIT as τ changes.

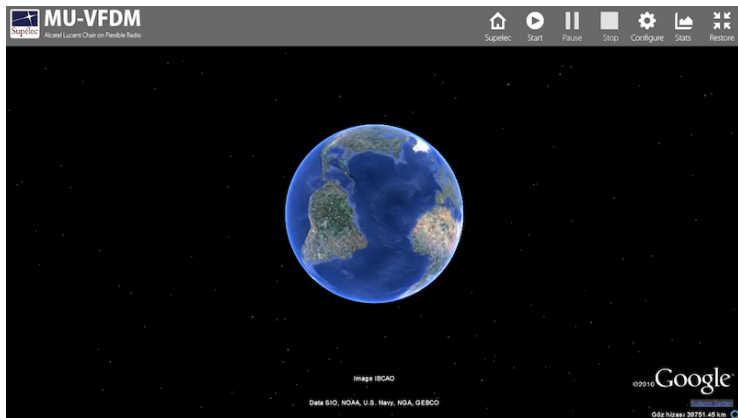
Demo

Introduction

- ▶ MU-VFDM case;
- ▶ User configurable: physical layer and network parameters;
- ▶ Macro Cell and Small Cells randomly deployed on a 3D map representing a realistic scenario;
- ▶ Mobility of all user equipments (Random Walk @ 3km/h);
- ▶ Instantaneous and time evolving capacity user equipments;
- ▶ Developed in MATLAB and exported to C#

Demo

Init



MU-VFDM demo, opening screen.

Demo

Configuration

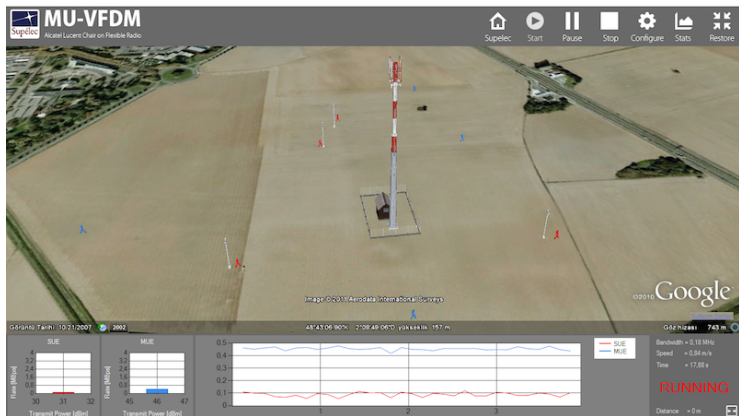
The screenshot displays the MU-VFDM configuration interface. The main window shows an aerial map of a rural area with a red triangle indicating a location. The interface includes a top navigation bar with icons for Home, Start, Pause, Stop, Configure, Stats, and Restore. A settings panel on the right side contains the following parameters:

N	12	SAPs	4
L	3	MUGs	4
MBS Tx Power [dBm]	46	<input checked="" type="checkbox"/> Small Cells	
SAP Tx Power [dBm]	33	<input checked="" type="checkbox"/> Macro Cell	
Tx Antenna	0	<input checked="" type="checkbox"/> Perfect CSIT	
Rx Antenna	1	<input checked="" type="checkbox"/> Realistic On MC	
Shadowing var MC [dB]	10	<input checked="" type="checkbox"/> Realistic On SC	
Shadowing var SC [dB]	3	<input checked="" type="checkbox"/> Force Speed	
Channel Type MC	3		
Channel Type SC	3		

At the bottom of the map, there is a copyright notice: "Image © 2015 Amdata International, S.p.A." and coordinates: "48°43'00.846\" N 2°11'00.54\" E UTM34QK155".

MUVFDM demo, configuration panel.

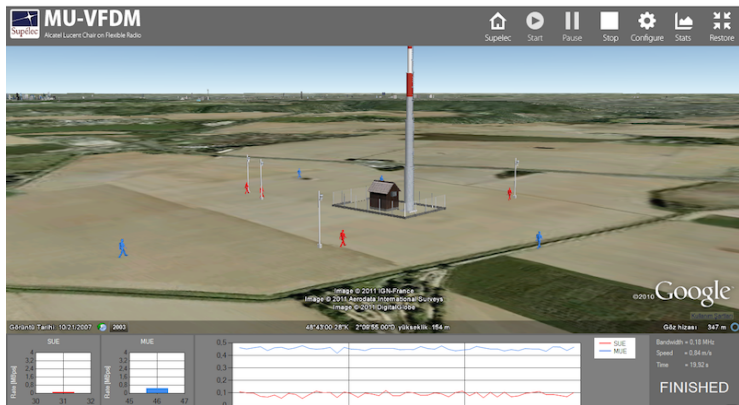
Demo Running



MU-VFDM demo, simulation running.

Demo

Results



MU-VFDM, single MUE and SUE performance.

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The road ahead

