Outline

- *Introduction: small cells in LTE-A;*
- *Small-cell backhaul configurations;*
- *State-of-the-art techniques for small cells wireless backhauling;*
- *The proposed TH-IR technique;*
- *Simulation results and backhaul coverage analysis;*
- *Conclusion and future works.*

Introduction: small cells in LTE-A

- **Definition of "small cell"**
  - In order to avoid the ambiguous (and misleading) definitions of the past, international standardization committees (ITU, ETSI, etc.) agreed the following definition of "small cell" [BLAN12]:

"A small cell is a low-power and low-cost radio base station, whose primary design target is to provide superior cellular coverage in residential enterprise and hot spot outdoor environments"

  - Given the above definition, four typologies of small cells have been individuated:
    - *Pico-cells*: smaller, lighter base stations which plug directly into an operator core network (location: outdoor – radius 300-400 meters);
    - *Femto-cell:* indoor micro base-station targeted at extending the coverage of the operator core network;
    - *Trusted WLAN cell* integrated into the LTE-A system;
    - *Relay nodes* aimed at extending the macro-cell coverage or fill a coverage hole.

[BLAN12] Blankenship Y. "Achieving high capacity with small cells in LTE-A," In: *2012 50th Annual Allerton Conference on Communication, Control, and Computing*, Monticello (IL, USA), 2012, pp. 1680–1687.

Introduction: small cells in LTE-A

- **Why “small cells” in LTE-A?**
  - Because of the augmented capacity reached in smaller areas with reduced power expense (thanks to the reduced size of the cell and to the reduced number of terminals) -> 25Gb/s/Km^2 are expected;
  - “Greener” coverage for a “smarter” environment (small cells are enabling technologies for “smart city” applications [CIM14]):

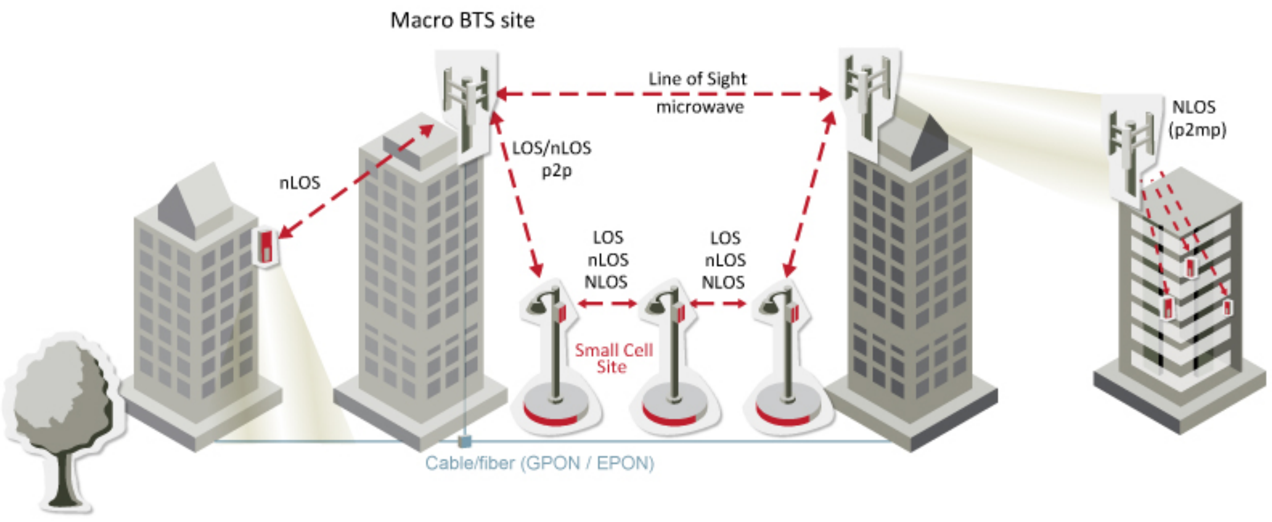
Conventional macro and microcellular coverage

“Greener” small-cellular coverage

[CIM14] A. Cimmino, T. Pecorella, R. Fantacci, F. Granelli, T.F. Rahman, C. Sacchi, C. Carlini and P. Harsh, “The Role of Small Cell Technology in Future Smart City Applications,” *Trans. Emerging Tel. Tech.*, Jan 2014, pp. 11-20.

Introduction: small cells in LTE-A

- **Small cell backhaul: <u>a critical issue</u>**
  - The figure below has been taken by http://www.ceragon.com:

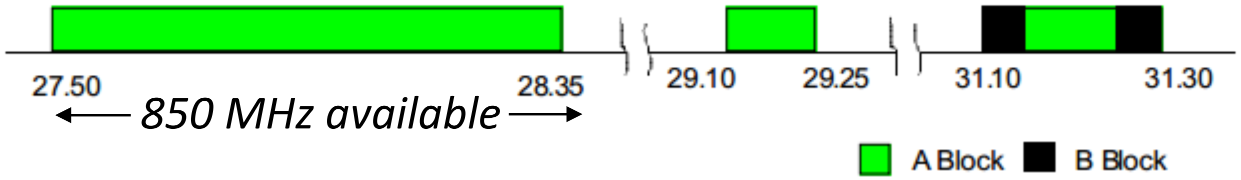


WIRELESS POINT-TO-POINT (P2P) AND POINT-TO-MULTI-POINT (P2MP) BACKHAULING IS RECOMMENDED FOR SMALL CELLS!

- Small cell BSs <u>are generally mounted on streetlamps</u> and/or installed closer to smaller buildings;
- Small cell BSs <u>may be far from optical fibers</u> and/or other wired connections commonly used to support backhaul links;
- <u>Latencies involved by the switch to the optical network</u> for backhauling (order of 1 msec.) configure a potential bottleneck for small cell networking.

State-of-the-art techniques for small cell wireless backhauling

- **Selected bandwidths**
  - NLOS backhaul [COLD13]
    - *Sub-6 GHz bandwidths* (ISM bandwidths or licensed bandwidth under 6 GHz);
    - *28 GHz licensed LMDS bandwidth* (license will expire in 2018):



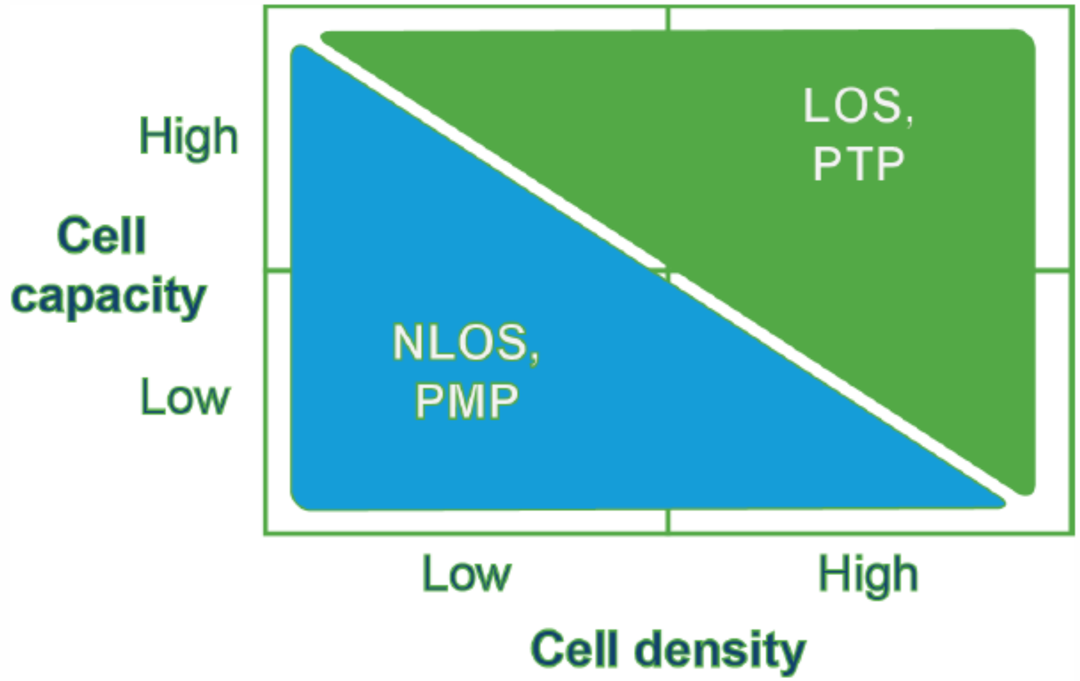
  - LOS backhaul [COL11]
    - *Licensed E-band bandwidth:* 71-76 GHz and 81-86 GHz **2x5 GHz AVAILABLE!!**

[COLD13] M. Coldrey, J-E. Berg, L. Manholm, C. Larsson, and J, Hansryd "Non-Line-of-Sight Small Cell Backhauling Using Microwave Technology," *IEEE Comm. Mag.*, Sept. 2013, pp. 78-84.

[COL11] C. Colombo and M. Cirigliano, "Next Generation Access Network: A Wireless Network Using E-band Radio Frequency (71-86 GHz) to Provide Wideband Connectivity," *Bell Labs Tech. Journal*, vol.16, no.1 (2011), pp. 187-206.

State-of-the-art techniques for small cell wireless backhauling

- **LOS vs. NLOS**
  - NLOS P2mp backhaul solutions are always deployable and cheaper, but they are unsuited for high-capacity small cells or for backhaul links supporting multiple cells;
  - When capacity requirements grow quickly (LTE-A backhaul traffic can reach 100 Gb/s per site), operators are likely to select LOS backhaul solutions in the busiest locations.

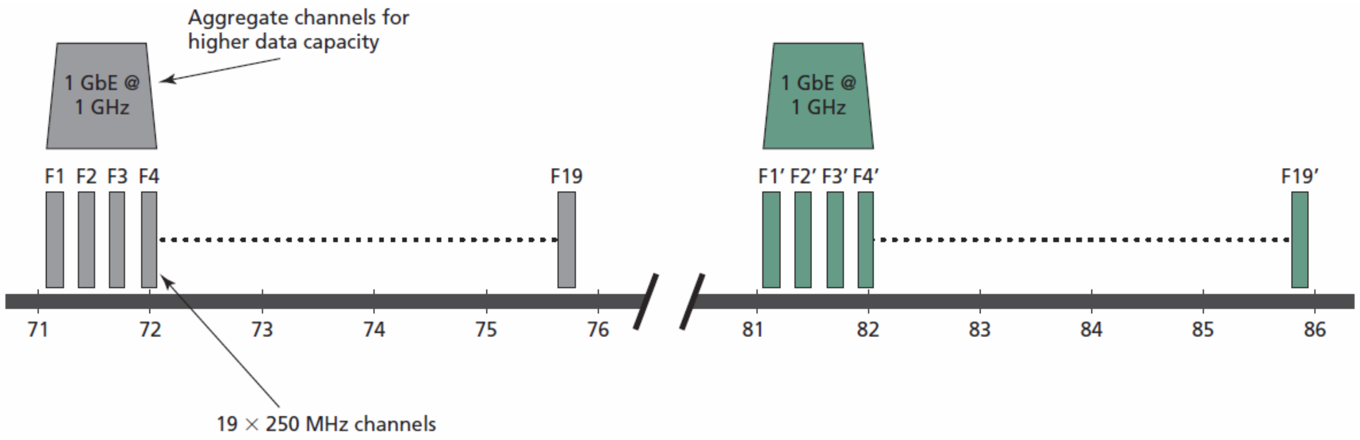


Source: "Senza Fili Consulting", http available

PROBLEM: the presence of LOS is not always guaranteed! Additional relays may be required when direct LOS is not available.

State-of-the-art techniques for small cell wireless backhauling

- **PHY-layer solutions**
  - NLOS [COLD13]
    - *Sub 6GHz TX:* OFDM-based solution with adaptive modulation (from 4-QAM to 64-QAM), 2x2 MIMO and TDD over a 40 MHz bandwidth (reachable aggregate capacity: 100Mb/s);
    - *28 GHz TX:* single-carrier modulation with Nyquist waveforms, Viterbi channel coding, adaptive equalization and FDD over 2x56 MHz bandwidth (reachable aggregate capacity: 400 Mb/s).
  - LOS [COL11]
    - FDD (71-76 GHz for uplink and 81-86 GHz for downlink) with Frequency-Division-Multiplexing done over 19 channels of 250 MHz each, transmission solution based on single-carrier adaptive M-QAM with Nyquist waveforms and Viterbi coding (reachable aggregate capacity: 3 Gb/s).



The proposed TH-IR technique

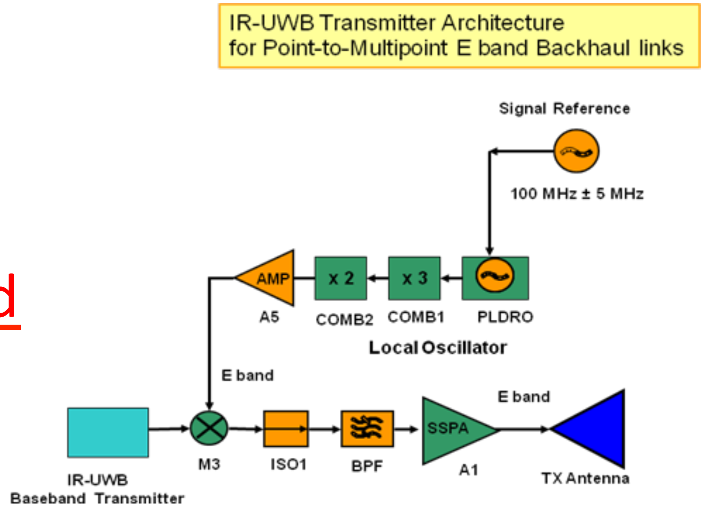
- **Weaknesses of state-of-the-art PHY-layer solutions**
  - Although well-established and cheap, single-carrier-based PHY-layer solutions for MM-wave small-cell backhauling present some weaknesses:
    - *Vulnerability with respect to link distortions:* M-QAM modulations with Nyquist waveforms cannot be transmitted with high-gain saturating power amplifiers. They require a significant power back-off;
    - *Phase-noise sensibility:* analog FDM may suffer from unwanted frequency shifts due to phase noise, which is particularly impacting in the E-band;
    - *Bandwidth and power resources exploitation is intrinsically inefficient* when single-carrier modulations and FDM are used: these are typically "narrowband" transmission techniques, not well suited to support multi-gigabit traffic;
    - *Implementation mostly hardware-based*, using complex (and expensive) analog circuitry like frequency shifters and phase-locked-loops (PLLs).

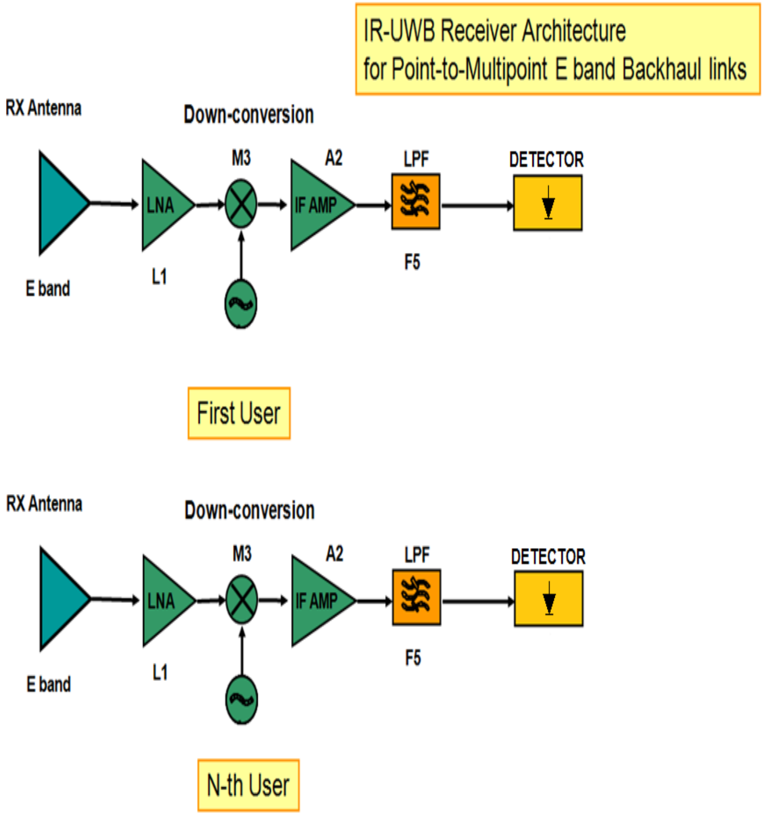
The proposed TH-IR technique

- **Why Impulse-Radio (IR) for MM-wave wireless backhauling?**
  - Some potential advantages can be taken by the use of Impulse-Radio:
    - *Efficient bandwidth exploitation:* being derived by UWB, IR is explicitly conceived to occupy large spectrum portions for robust multi-gigabit transmission;
    - *Low-power transmission:* IR is a wideband technique that occupies large spectrum portions with low power spectral density;
    - *Reduced costs and reduced size of the transceiver equipment:* it is possible to remove the expensive RF circuitry by avoiding oscillators and mixers;
    - *Low-complexity receiver:* the IR receiver is very simple and cheap;
    - *Efficient management of P2mP backhauling* using low-complexity time-hopping (TH) multi-user transmission and detection;
    - *Robustness against phase noise and link distortions* thanks to the impulsive waveform.

- **The proposed TH-IR architecture for P2mP E-band backhauling**
  - We have considered a transceiver architecture for E-band LOS backhauling based on COTS components, so to minimize monetary and computational costs:

PROBLEM: the Phase-Locked Dielectric Resonator Oscillator (PLDRO) working at 80 GHz is a bad source of phase-noise





Transmitted baseband signal and generated waveforms:

Pulse Position Modulation (PPM) with Gaussian monocycle pulse waveform:

$$s(t)=\sum_{k=1}^{K}\sum_{j=-\infty}^{+\infty} \mathrm{A}^{k}_{d[j/N_s]}\, p\left(t - j\mathrm{T}_f - c_j^{(k)}T_c - \delta^{(k)}_{[j/N_s]}\right)$$

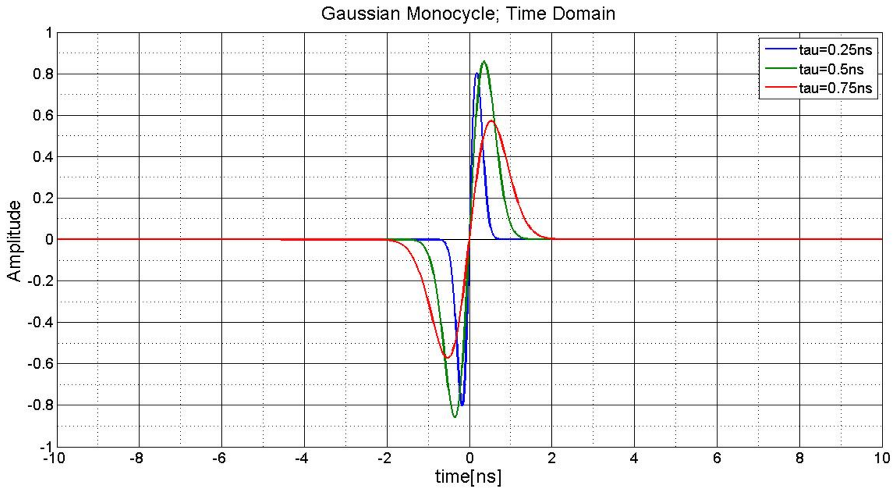
$\mathrm{A}^{(k)}$ Signal amplitude of k-th user

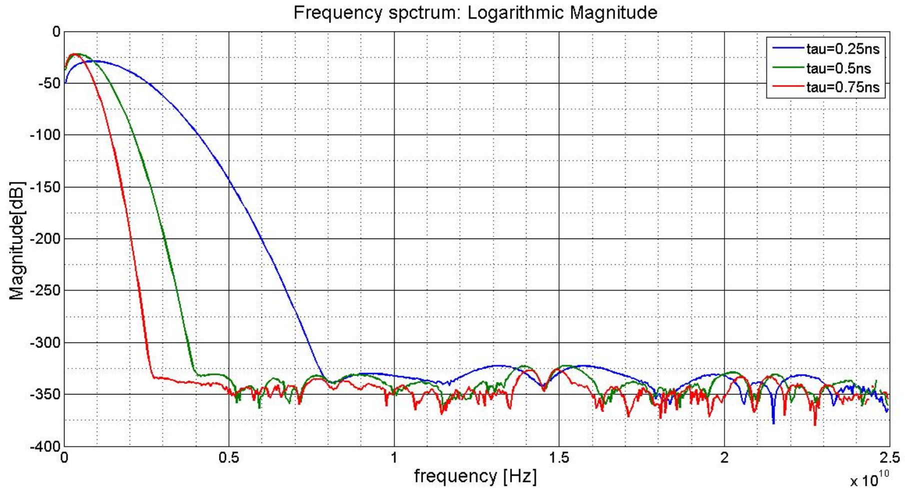
$p(t)=\frac{At}{\sigma^2}e^{-\frac{t^2}{2\sigma^2}}$ Pulse waveform (Gaussian Monocycle)

T_f Frame duration (a frame is divided into N_{TH} slots of duration T_c each)

$c_j^{(k)}$ Time-Hopping pseudo-random sequence of the user k (hop duration: T_c)

$\delta^{(k)}$ Additional time-shift introduced by the PPM



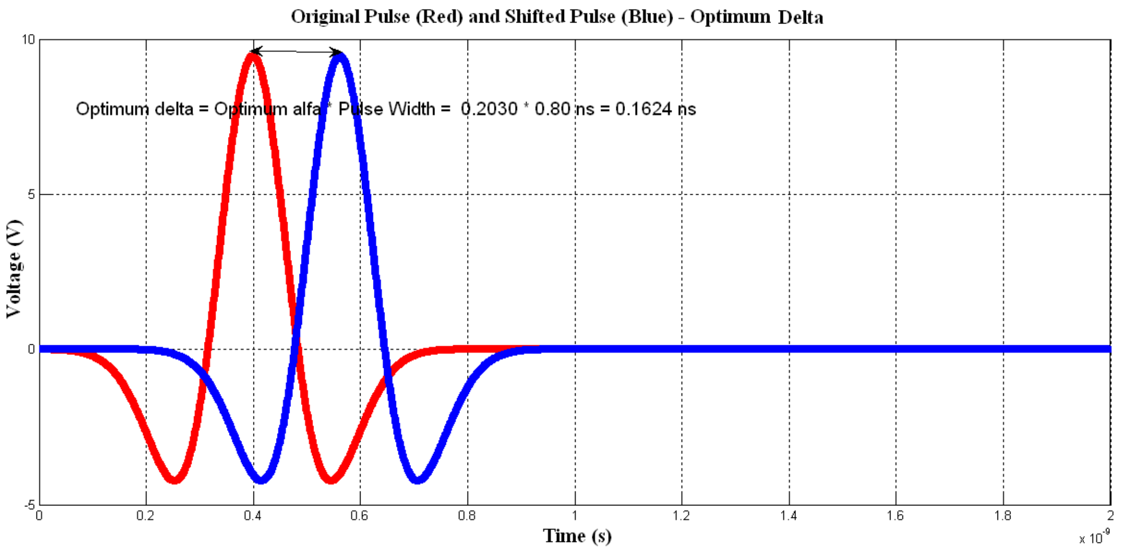


Optimum setting of the time-shift parameter:

$$R_1(\delta) = \frac{1}{E_p}\int_{-\frac{T_f}{2}}^{+\frac{T_f}{2}} p(t)\,p(t-\delta)\,dt \approx \frac{1}{E_p}\int_{-\infty}^{+\infty} p(t)\,p(t-\alpha 2\pi\sigma)\,dt$$

$$= \frac{A^2\sqrt{\pi}}{\vartheta E_p}\left(0.5-\pi^2\alpha^2\right)e^{-\pi^2\alpha^2} \qquad E_p = \int_{-\frac{T_f}{2}}^{\frac{T_f}{2}} |p(t)|^2\,dt$$

Normalized correlation function over a frame duration (it should be minimized with respect to the parameter a)



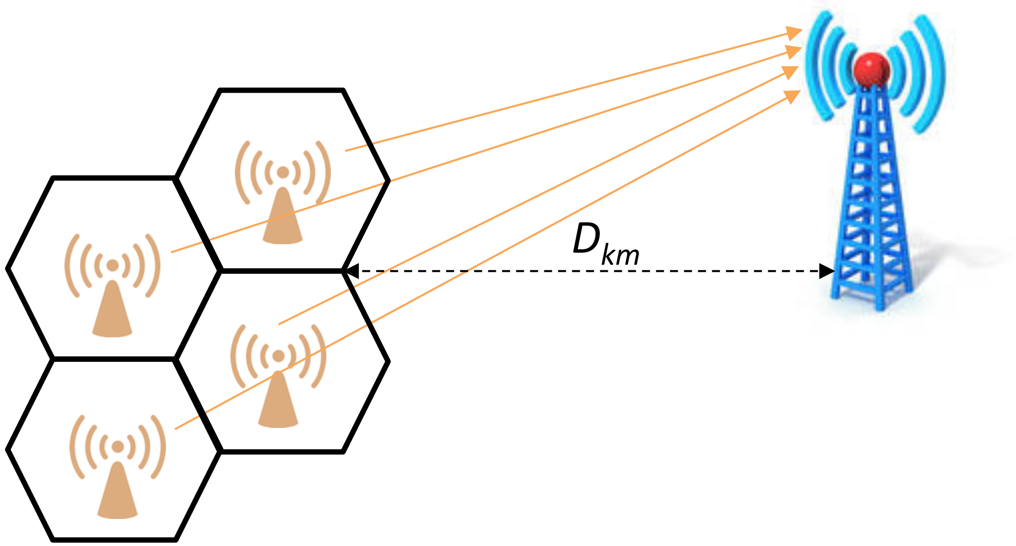
Assuming AWGN, *the problem of reducing the BER* becomes that of finding δ *that reduces* $R_1(\delta)$
The modulation index that yields the least possible correlation is called *optimum modulation index,* δ_{opt}

To obtain that value, $R_1(\delta)$ is differentiated and set to 0.

$$\delta_{opt} = \alpha_{opt} * PulseWidth$$

Simulation results and backhaul coverage analysis

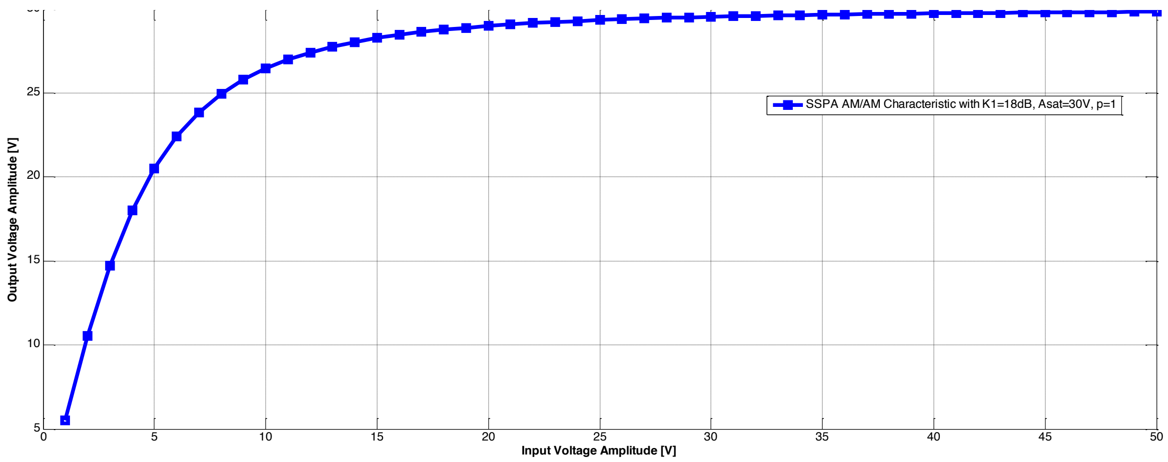
- **Simulation parameters and configurations**
  - Backhaul configuration: 4 small cells transmitting to 1 macro-cell;
  - Presence of LOS;
  - Bandwidth: 81-86 GHz (5GHz);
  - Transmitted RF power: 1W;
  - Channel data-rate: 4Gb/s;
  - TX/RX antenna gain: 24dBi;
  - Modulation/demodulation losses: 4dB;
  - Low-Noise amplifier (LNA) gain: 21dB;
  - Receiver noise figure: 3.5dB;
  - Gaseous absorption: 3dB/Km



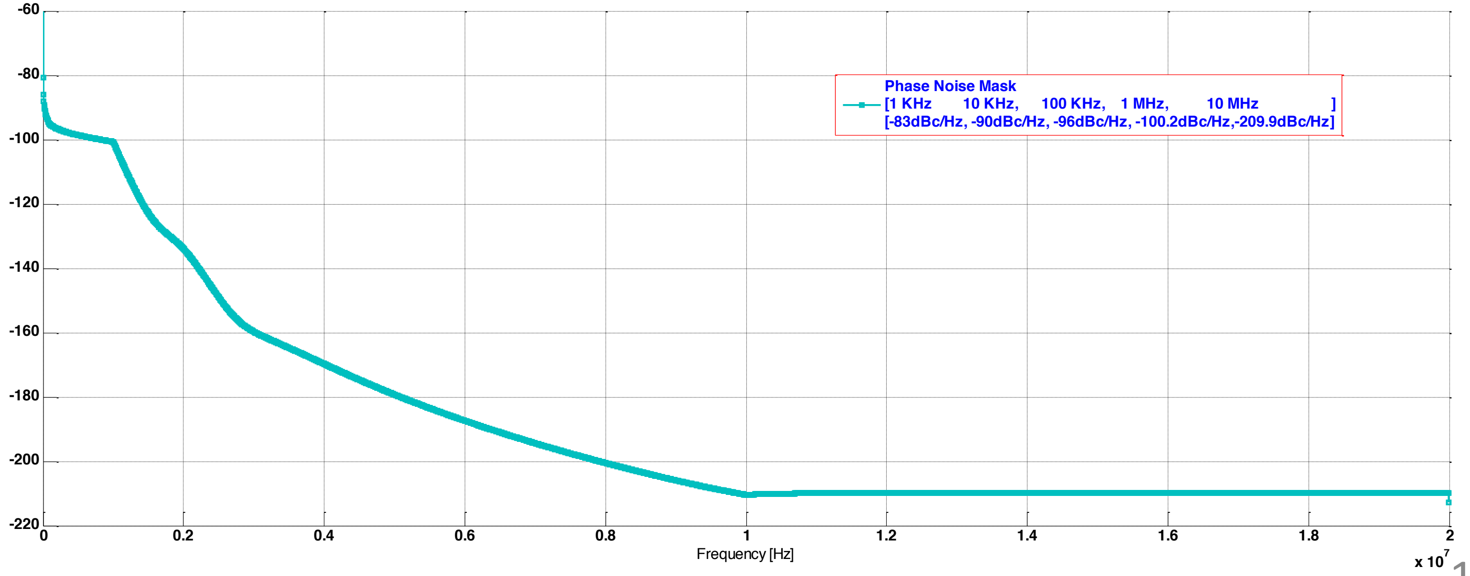
Simulation results and backhaul coverage analysis

- **Link impairments: amplifier distortion and phase noise**
  - SSPA modelled using Rapp nonlinear function:

$$G(\rho)=\frac{K_1\rho}{\left[1+\left(\frac{K_1\rho}{A_{sat}}\right)^{2p}\right]^{1/2p}}$$



  - Phase-noise mask of the PLDRO:



Simulation results and backhaul coverage analysis

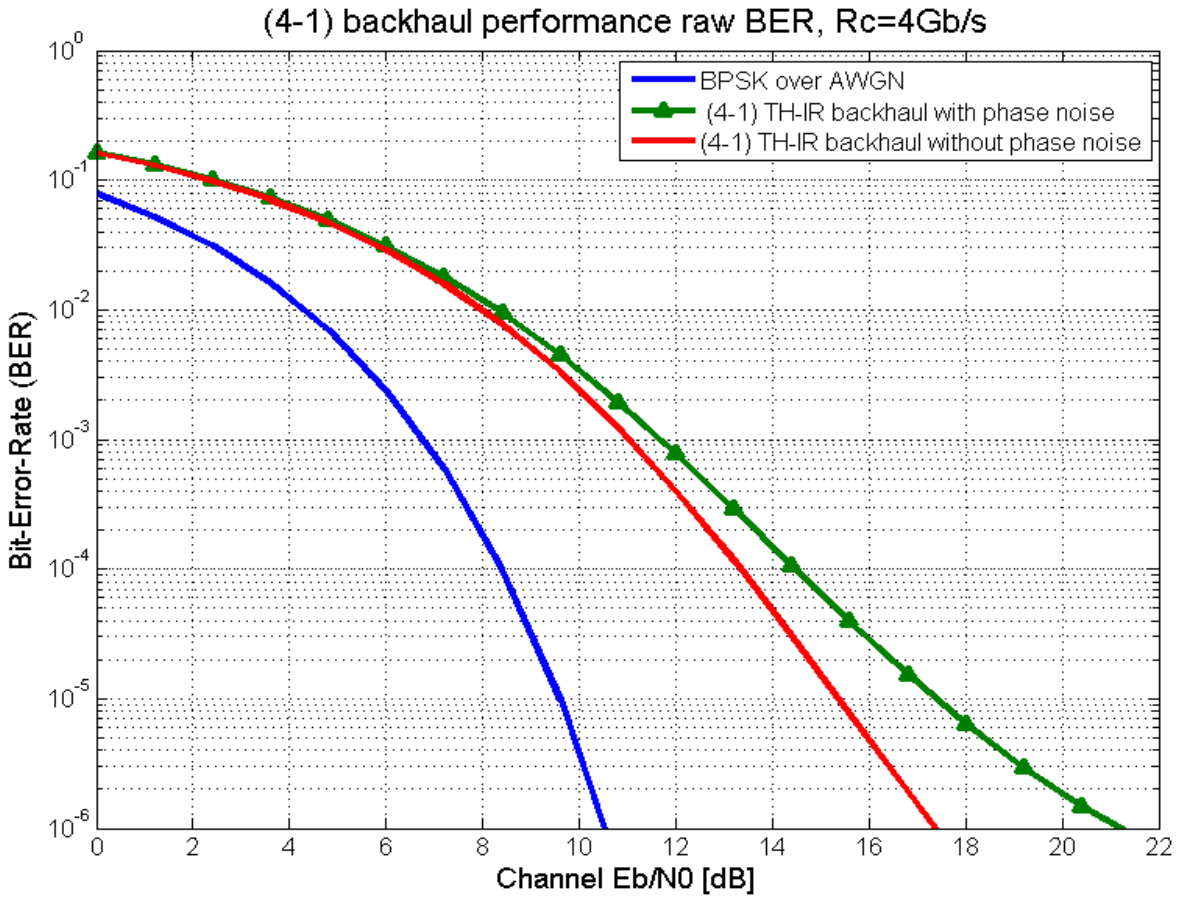
- **Rain attenuation**
  - ITU model for rain attenuation [ITU-R]: $A_R = \mu F^{\xi} \, (dB/Km)$
  - *m* and *x* are frequency-dependent parameters (1.2387 and 0.6968 respectively for 86 GHz frequency);
  - *F* is the rainfall intensity, exceeded with a probability P_{exc};
  - According to [LUI12], we selected *F*=45 mm/h and P_{exc}=0.0001;
  - The resulting rain attenuation is therefore **17.6 dB/Km** exceeded with 0.0001 probability.

[ITU-R] "Specific attenuation model for rain for use in prediction methods," Recommendation ITU-R P.838-3, 2005.

[LUI12] L. Luini, and C. Capsoni, "Estimating the spatial cumulative distribution of rain from precipitation amounts," *Radio Science*, vol.47, no.1, pp.1-9, Jan. 2012.

Simulation results and backhaul coverage analysis

- **Simulation* results: uncoded BER vs. channel E_b/N_0**

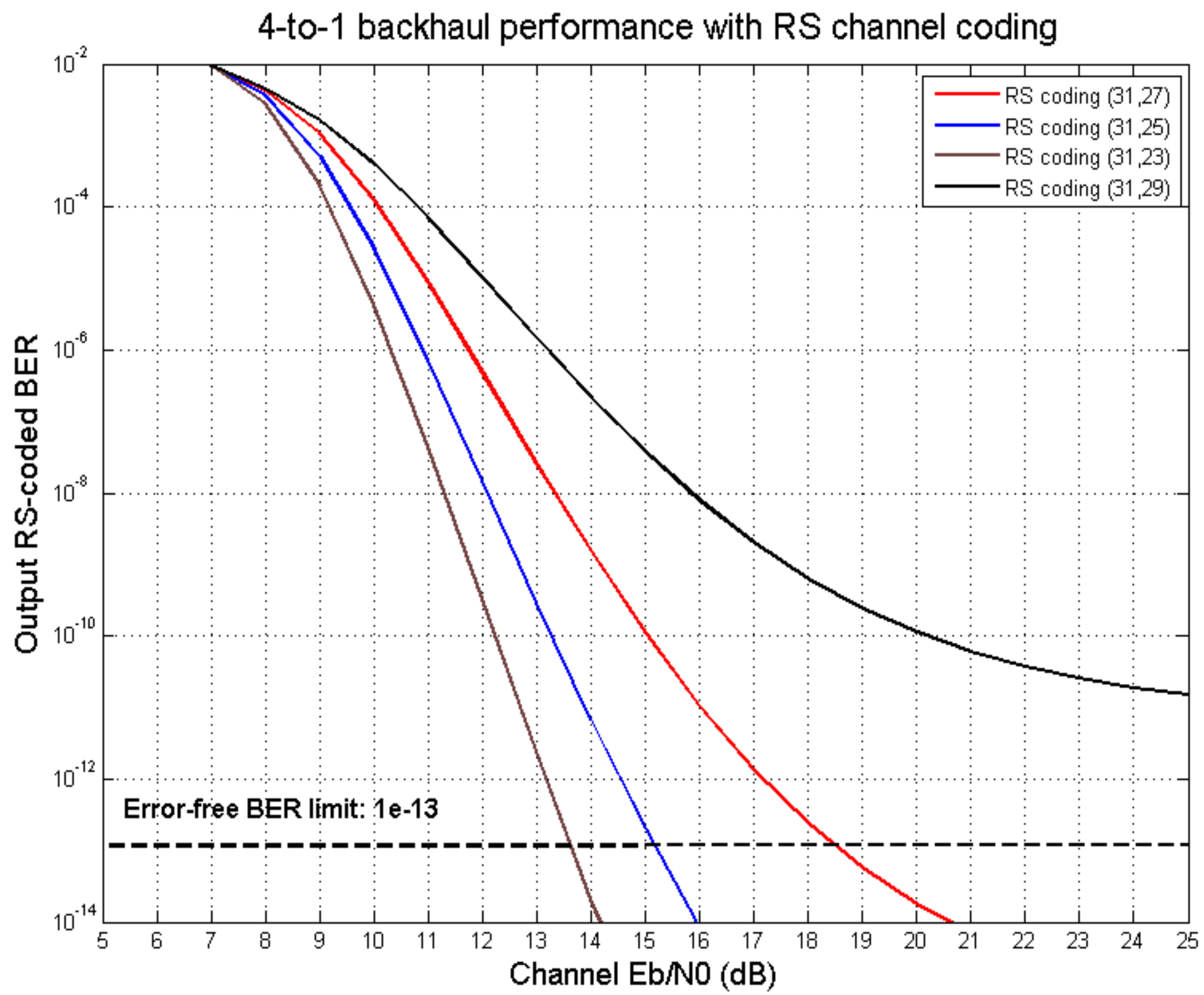


Simulations in MATLAB R2014a environment

- The impact of multi-user interference on link performance is evident and noticeably increased by the presence of phase-noise (phase noise involves additional time jitters that increases MUI);
- Nonlinear distortions does not significantly degrade link performance, as expected;
- As an irreducible error-floor bounds the link performance, we need some kind of channel coding to increase link availability.

Simulation results and backhaul coverage analysis

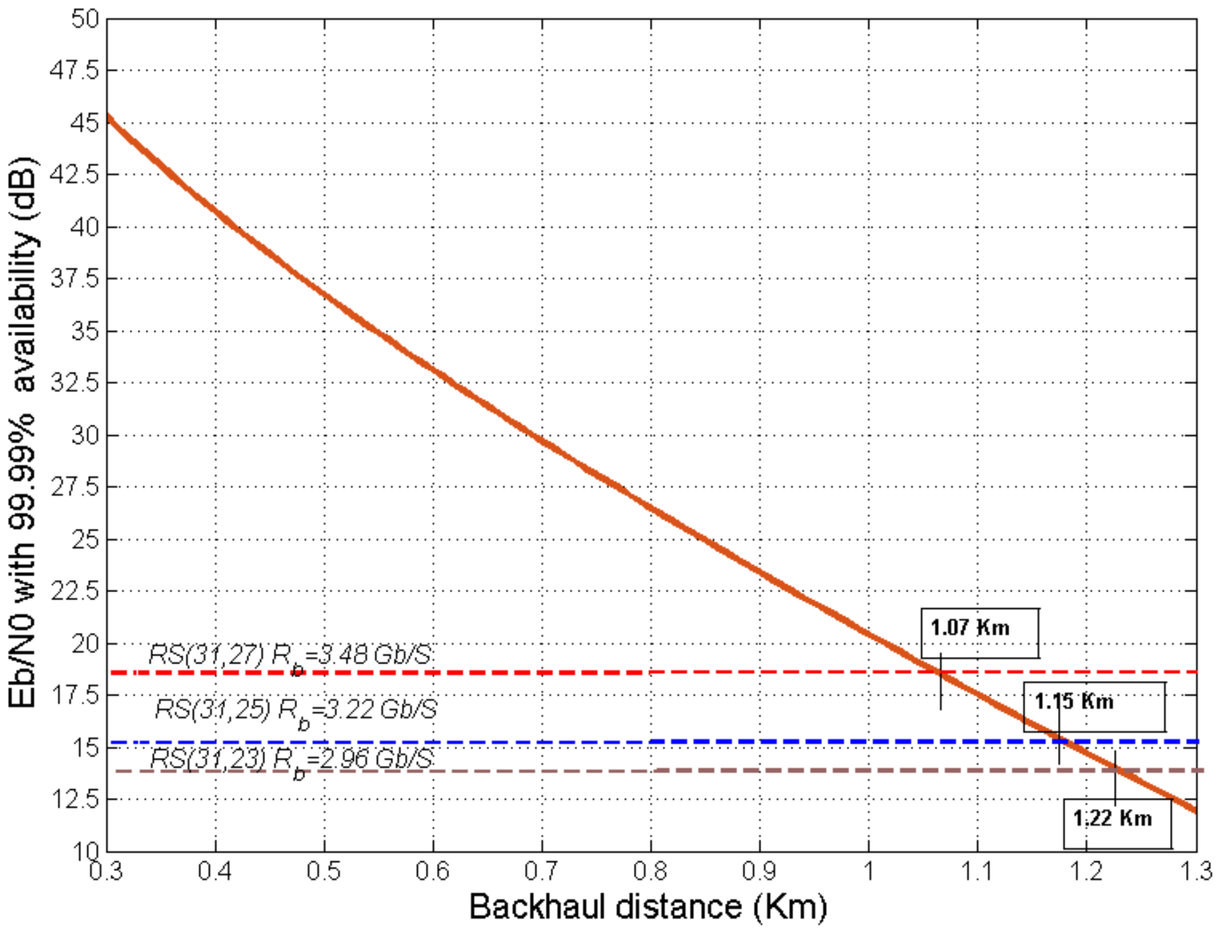
- **BER performance after Reed-Solomon channel coding**



- Different RS correction codes have been tested:
  - *RS(31,29):* code-rate R_c=0.935;
  - *RS(31,27):* code-rate R_c=0.871;
  - *RS(31,25):* code-rate R_c=0.806;
  - *RS(31,23):* code-rate R_c=0.742.
- An "error-free" BER limit has been fixed to 10^{-13};
- Error-free is reached at: E_b/N_0=13.75dB with RS(31,23), E_b/N_0=15.1dB with RS(31,25), and E_b/N_0=18.5dB with RS(31,27) respectively.

Simulation results and backhaul coverage analysis

Available E_b/N_0 vs. backhaul distance and capacity availability



- Given the link budget of slide 13, the E_b/N_0 vs. backhaul distance with an availability percentage of 99.99% is:

$$\left(\frac{E_b}{N_0}\right)_{av} = 41 - 20\log_{10}\left(D_{km}\right) - 20.6D_{km}\ (dB)$$

- In the figure aside, the above expression is plotted and checked against the error-free aggregate net data rates reachable by the different RS coding systems;
- The maximum capacity of 3.48 Gb/s can be reached at a backhaul distance of about 1.07 Km, using the RS(31,27) code.

Conclusion

- The use of robust TH-IR techniques for MM-wave P2mP LOS backhaul has been considered in the framework of broadband LTE-A small cell networking;
- A TH-IR transceiver implemented with COTS hardware, using low-complexity detection techniques has been simulated;
- The most significant impairments of the backhaul link (nonlinear distortions, phase-noise, oxygen absorption, rain fading, time-jitters) have been thoroughly considered in the simulations;
- Simulation results have shown that a net aggregate capacity higher than 3 Gb/s can be reached by a 4-1 backhaul @ backhaul distance of 1Km (reasonable in dense urban environment);
- TH-IR represents a cost-effective alternative to single-carrier and FDM-based state-of-the-art solutions and a step-ahead in terms of improved spectral and power efficiency;
- Future works may be related to the development of efficient detection techniques aimed at reducing the impact of Multi-User Interference, external interference, phase-noise and jittering.