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Design and Assessment of a CE-OFDM-based mm-Wave 5G Communication System

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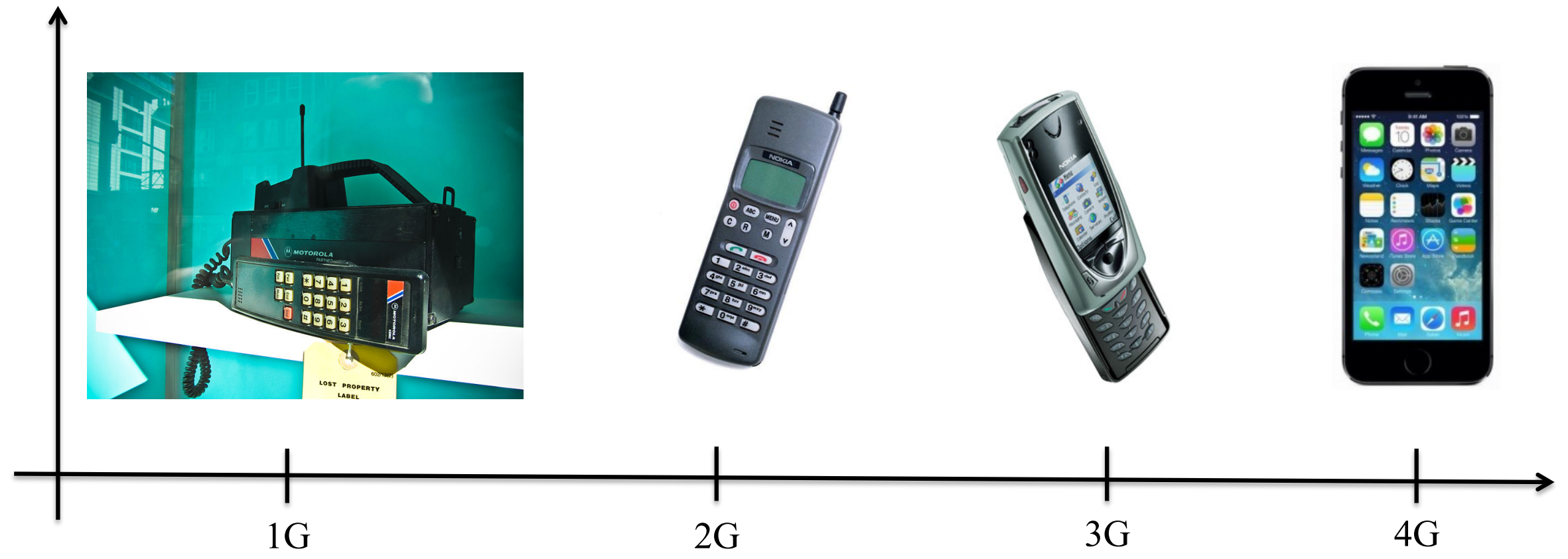
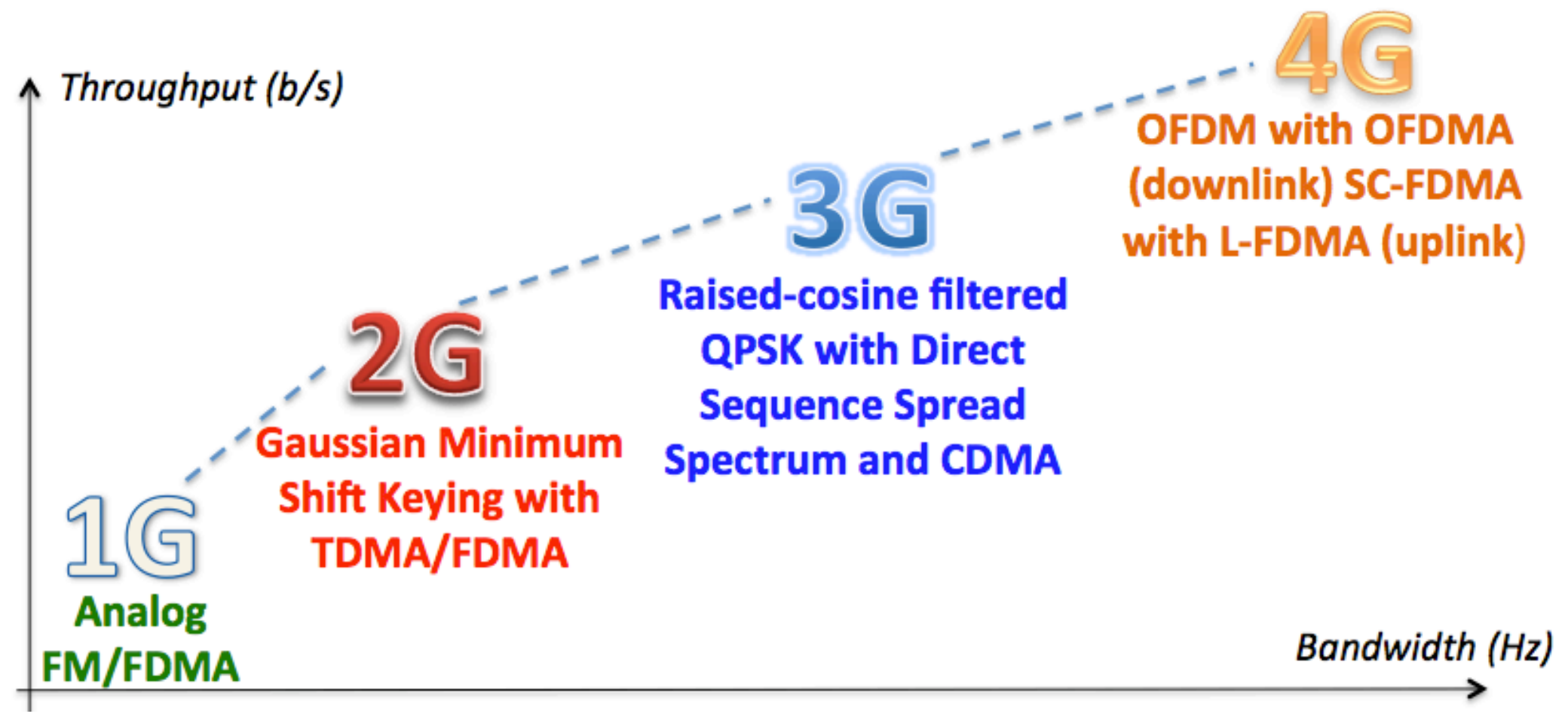
Fig. 9: Small cell coverage analysis: *SNR*.

INTRODUCTION

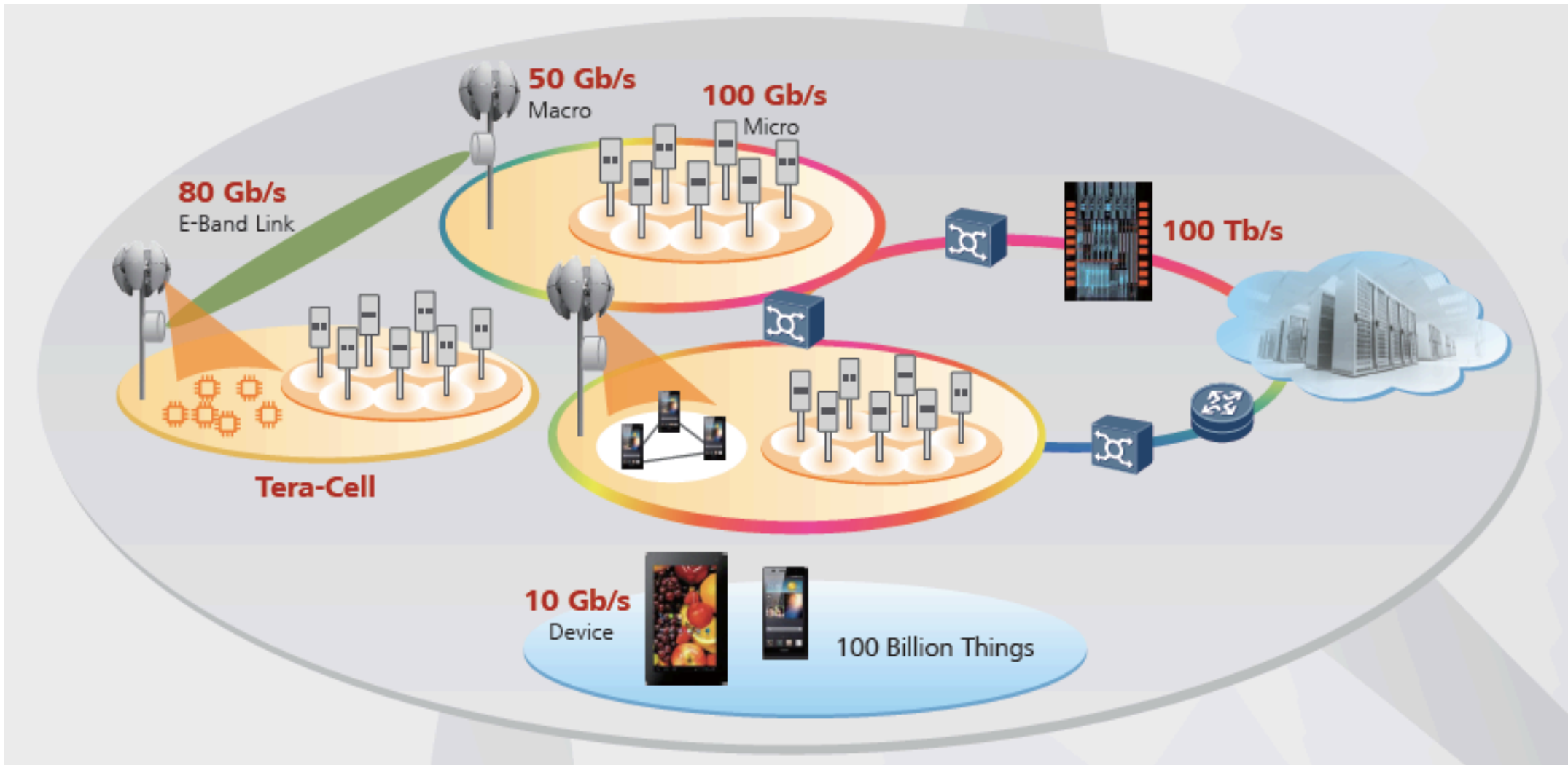
The evolution of cellular networking from 1G to 4G evidences some non-equivocal trends concerning available services and devices:



The evolution of waveform design has been consequential:



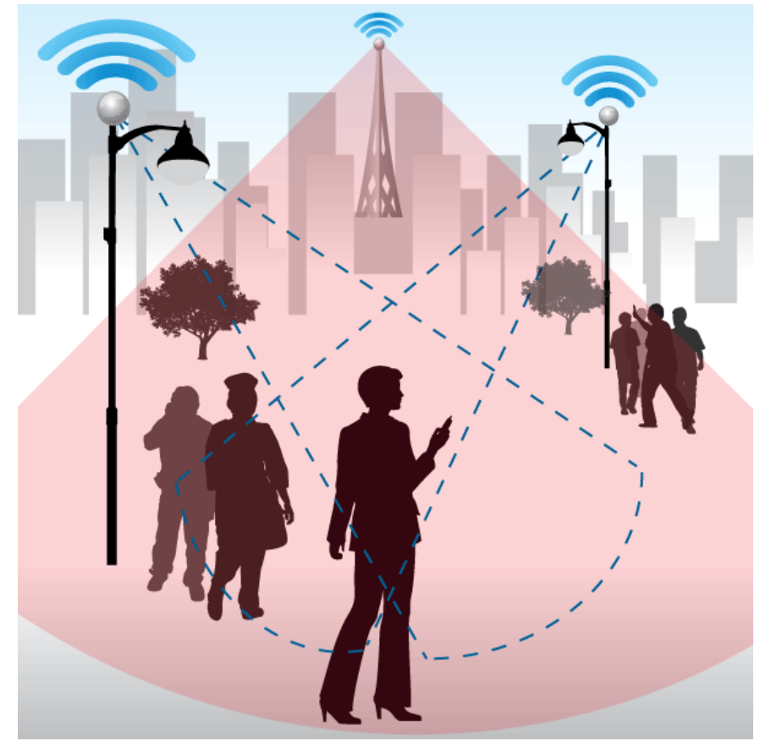
5G considers all-spectrum access, including **mm-wave bandwidths**:



E-band (71-76 GHz, 81-86 GHz) licensed for 5G applications is characterized by higher pathloss, as compare to sub 6GHz bandwidths, in particular in case of NLOS. Power resources should be exploited at maximum by means of **power-efficient nonlinear amplifiers**. Despite this, **OFDM and "OFDM inspired" waveforms (SC-OFDM, SC-FDMA, FBMC, etc.) are still in pole-position for supporting 5G applications** [1] [4], because they are flexible, intrinsically smart and allow broadband transmission over frequency-selective channels.

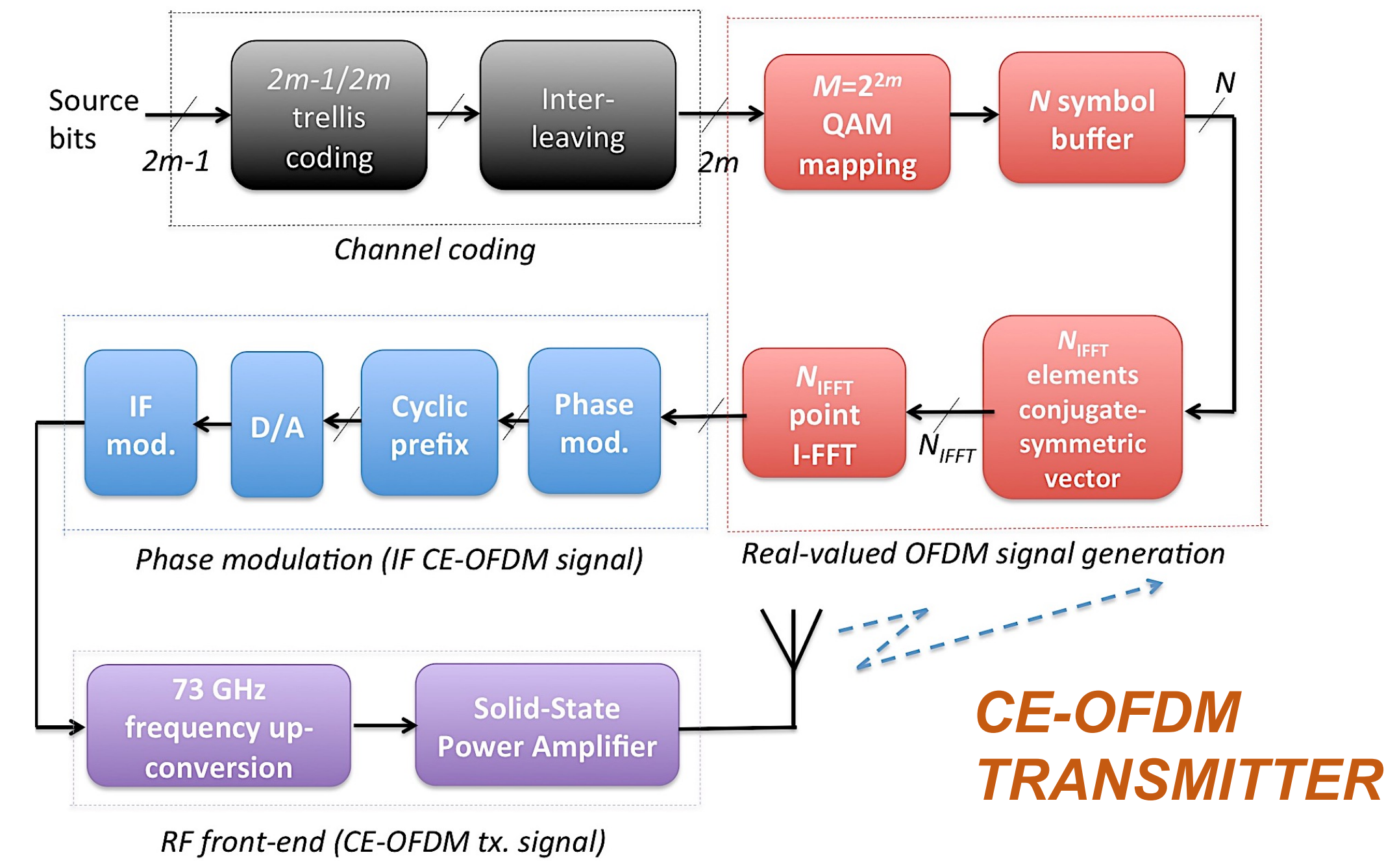
OUR PROPOSAL:

- A novel mm-wave 5G transmission system, working at 73 GHz, **characterized by power efficiency and robustness**;
- The system is based on **CONSTANT-ENVELOPE ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING (CE-OFDM)** [5] and the use of a **SUBSTRATE INTEGRATED WAVEFORM (SIW) SLOTTED ANTENNA ARRAY** with a squared cosecant pattern;
- Application scenarios: small-cell downlink, information shower.



CONSTANT-ENVELOPE OFDM RADIO INTERFACE

Constant-Envelope OFDM is based on the non-linear phase modulation of a real-valued OFDM signal [5]:

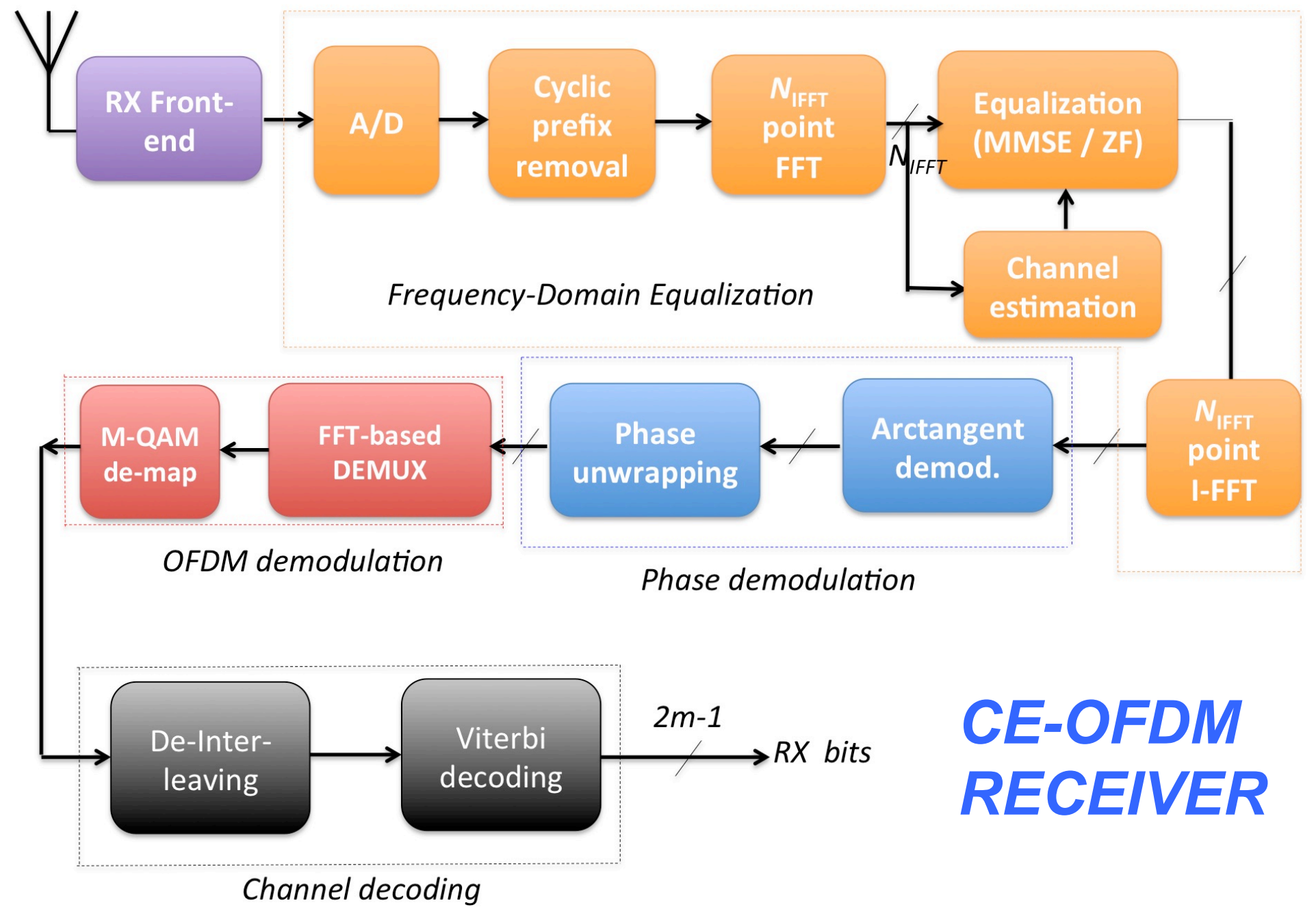


$$u_n = 2\sum_{k=1}^{N}\Re\{S_k\}\cos\left(2\pi nk/N_{IFFT}\right) - \Im\{S_k\}\sin\left(2\pi nk/N_{IFFT}\right)$$ ***Real-valued OFDM signal***

$$x_n = \exp\left\{j2\pi h\left(Lu_n\right)\right\} \quad n = 0,\ldots,\left(N_{IFFT}-1\right)$$ ***Phase-modulated signal (L: normalization constant, 2*pi*h: radian modulation index)***

$$s(t) = A_S\Re\left\{x(t)\exp\left(j2\pi f_c t\right)\right\} \quad -T_{CP} \le t \le T$$ ***RF transmitted signal***

$$N_{IFFT} = 2\left(N+1\right)F_O$$ ***F_O oversampling factor (oversampling obtained with zero-padding in order to limit phase jumps)***



PROS:

- ❑ Fixed 0dB PAPR: the signal can be transmitted with saturating amplifiers without amplitude distortion and spectral regrowth;
- ❑ Advantages of OFDM are still maintained, but with augmented diversity due to FDE applied to the tx single-carrier signal [7];
- ❑ Augmented robustness against phase noise with respect to conventional OFDM (phase noise is additive and not multiplicative) [8];
- ❑ Trellis coding and interleaving improves a lot performance of CE-OFDM when low modulation indexes are used [9].

CONS:

- ❑ At least 50% throughput (b/s/Hz) reduction w.r.t. OFDM (due to the two-sided real-valued OFDM RF spectrum [8]):

$$\eta_{TC-CEOFDM} = \frac{\left(2m-1\right)}{2\left[\max\left(2\pi h,1\right)\right]}$$

$$\eta_{TC-OFDM} = \left(2m-1\right) \quad \text{(b/s/Hz)}$$

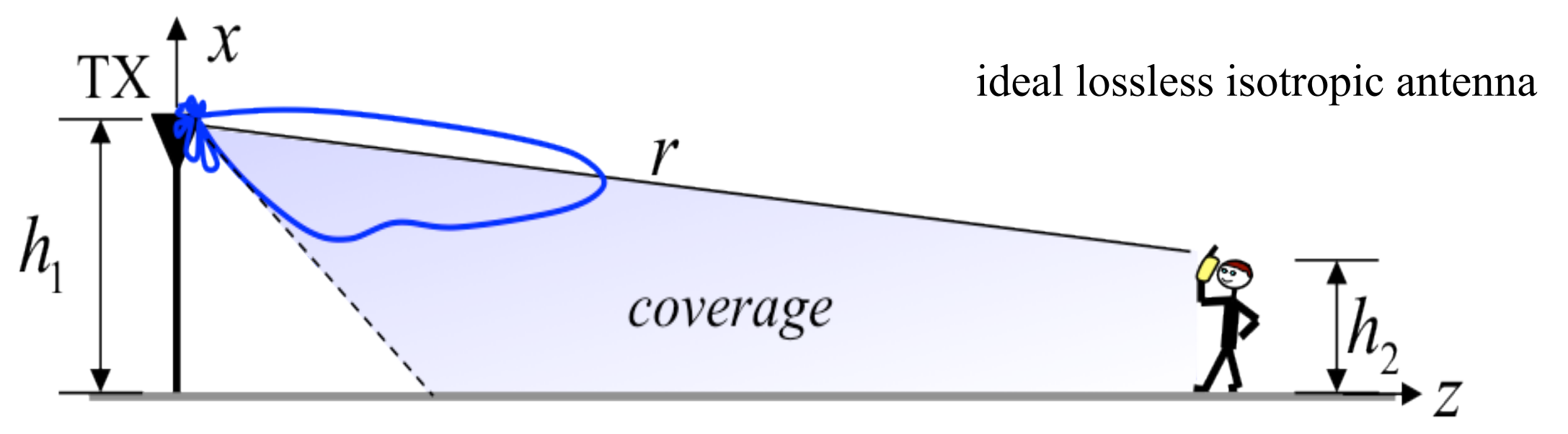
- ❑ Adaptive subcarrier allocation to OFDMA users is possible only in the downlink;
- ❑ Sidelobe power level higher than OFDM one (spectral precoding [10] provides a reliable solution to this issue).

ANTENNA SYSTEM

The transmission system considered in the model makes use of a surface integrated waveguide (**SIW**) slot array antenna. This solution is realized, at low cost, with two rows of metallic via-holes in a metal-clad dielectric substrate using standard print-circuit-board fabrication technique. At 73GHz multi-layer fabrication techniques with LTCC (Low Temperature Co-fired Ceramics) can be conveniently used for large mass production.

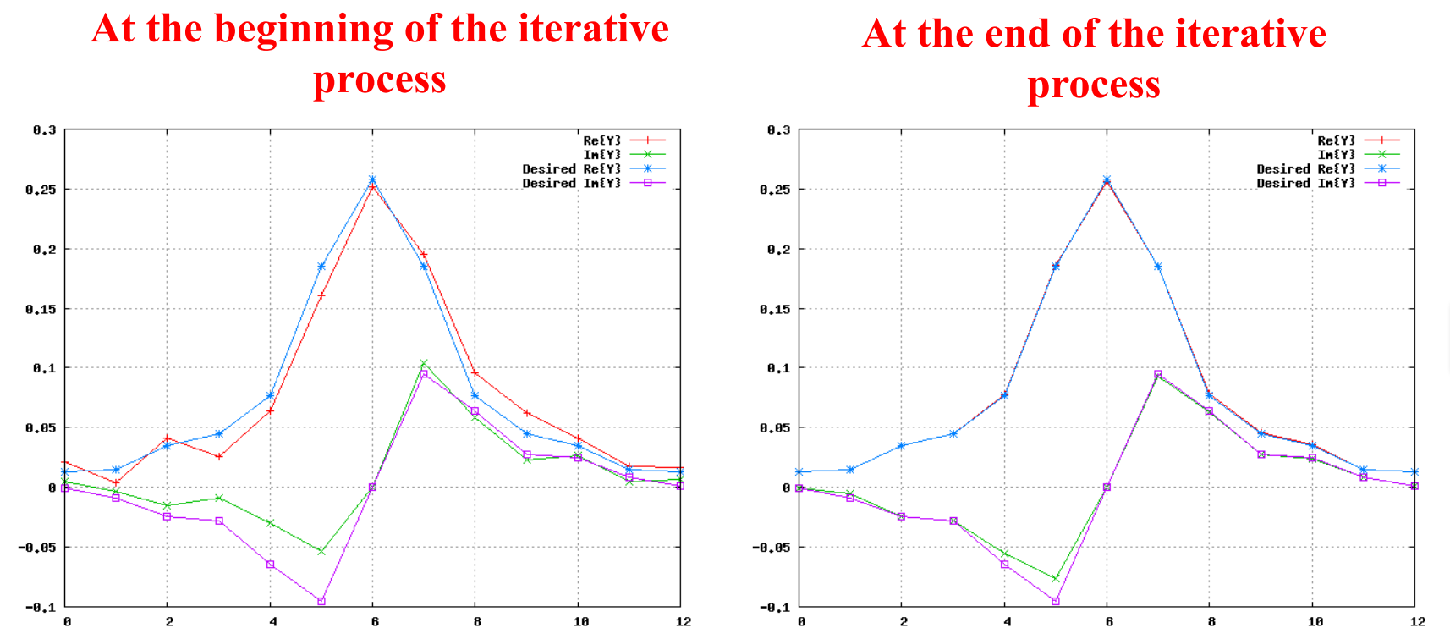
Why SIW? They combine most of the advantages of planar printed circuits (compactness, light weight, easiness to fabricate, flexibility, and low cost) and of metallic waveguides (low losses, complete shielding, power handling). Moreover, SIW structures allow the integration of active circuits, passive components and radiating elements on the same substrate [13].

Antenna Requirements: the antenna has to generate a cosecant squared pattern in the vertical plane that covers almost 30°, so it can provide a uniform incident power density for any user position in the coverage area.



Two base station antennas have been designed with different half power beam width on the horizontal plane, 60° and 33°, respectively.

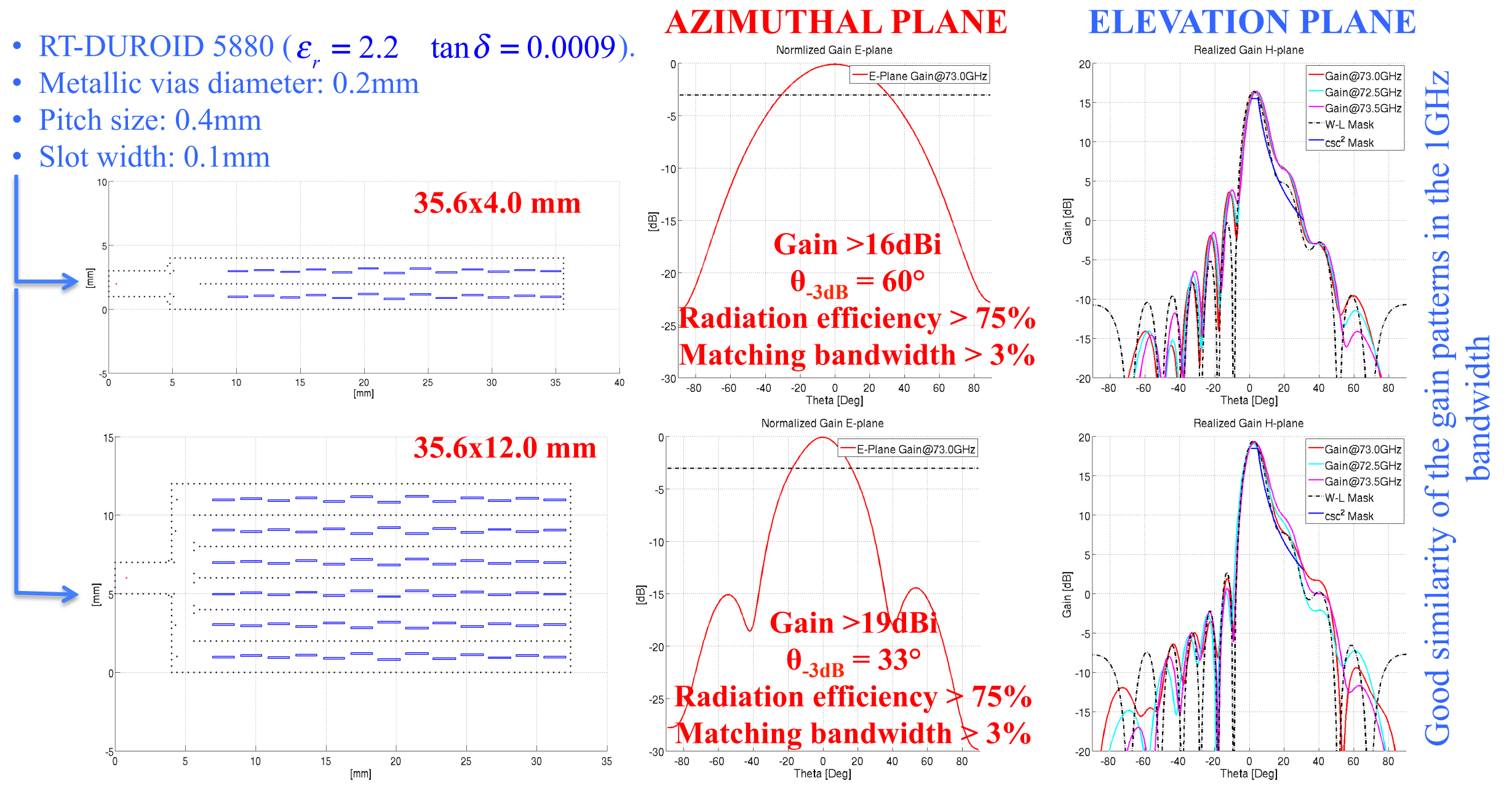
For the array radiation pattern synthesis, an **alternate projection method** has been used forcing that the coefficients of the Schelkunoff polynomial are symmetrical complex conjugate. Thus, it allows applying the classical method in [14]. To take into account the mutual coupling between the array elements, an iterative method, that makes use of a full wave analysis of the entire structure, has been applied to determine the optimal length and position of each slot.


At the beginning of the iterative process
At the end of the iterative process

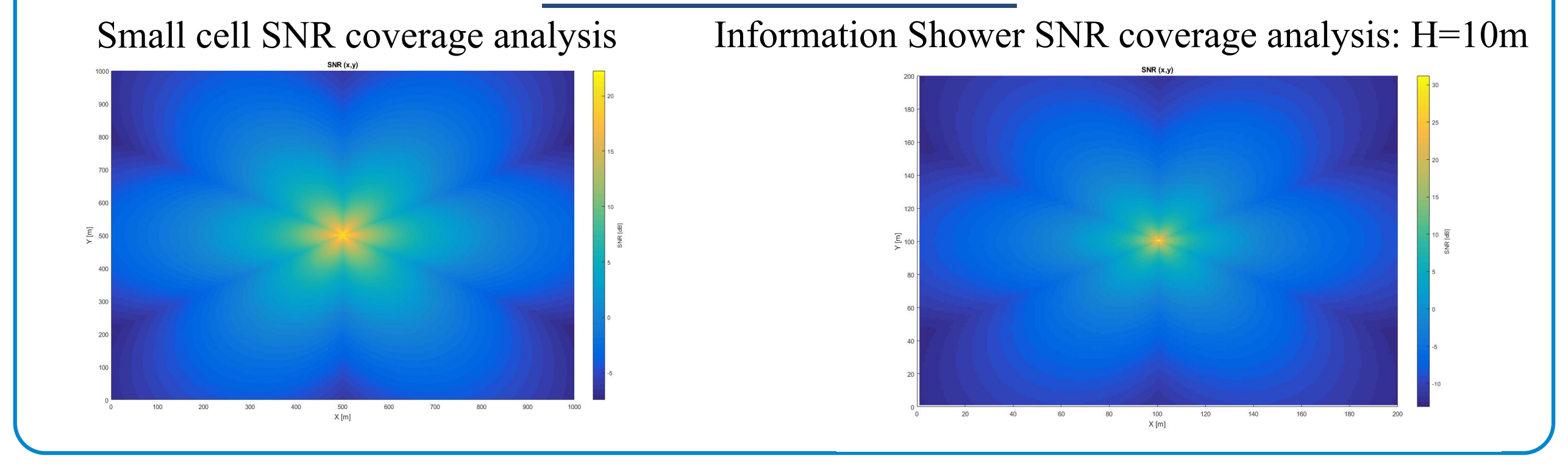
The length and position of each slot correspond to the final values of the normalized conduptance and susceptance

Slot Number	1	2	3	4	5	6	7	8	9	10	11	12	13
Length [mm]	1.5947	1.5945	1.6250	1.6211	1.6301	1.6184	1.5875	1.5459	1.5051	1.5103	1.4874	1.5128	1.5306
Offset [mm]	0.3305	0.5196	0.7889	1.0197	1.2519	1.6309	1.8702	1.8412	1.2405	1.0222	0.8231	0.4787	0.3150

- RT-DUROID 5880 ($\varepsilon_r = 2.2 \quad \tan\delta = 0.0009$).
- Metallic vias diameter: 0.2mm
- Pitch size: 0.4mm
- Slot width: 0.1mm



COVERAGE ANALYSIS

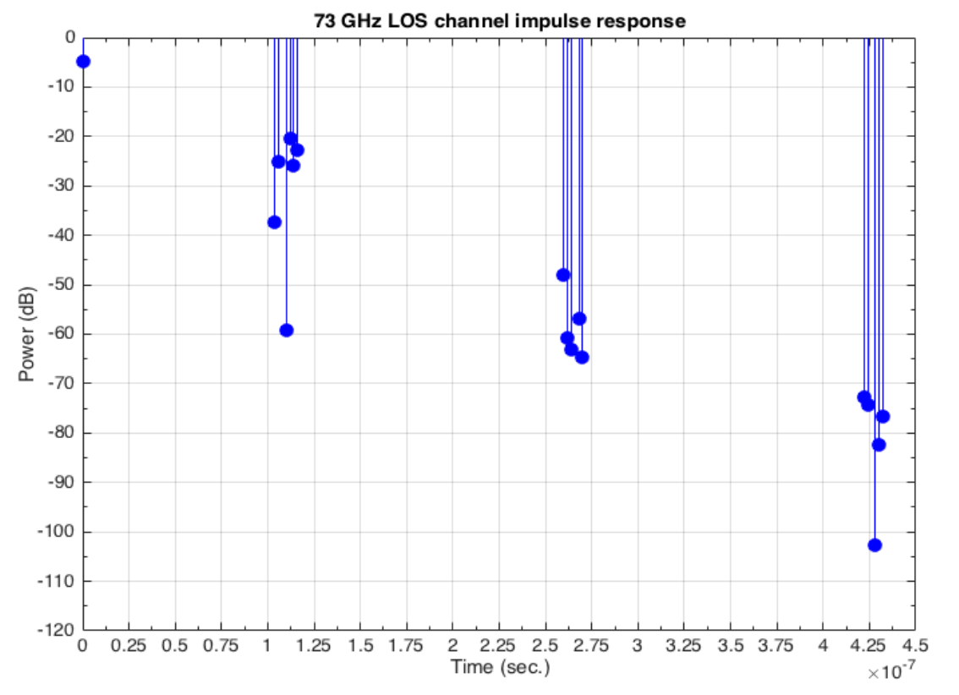

Small cell SNR coverage analysis
Information Shower SNR coverage analysis: H=10m

LINK PERFORMANCE ANALYSIS

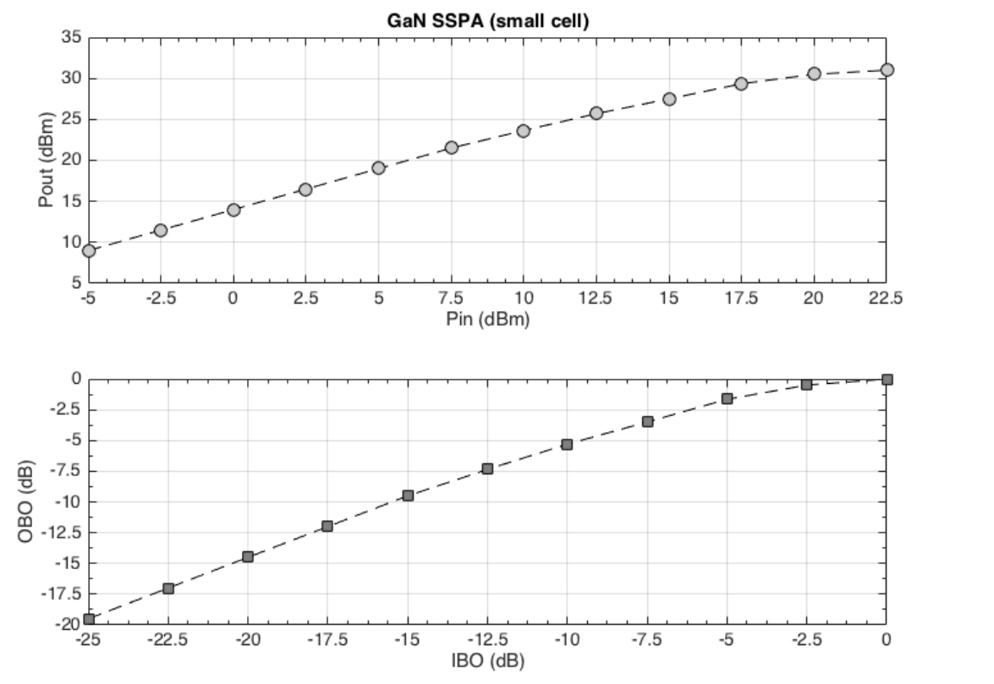
Simulation parameters:

	m	Modulation format	Modulation index	Trellis coding rate	N_{IFFT}	F_O
Conf. #1	1	4-QAM	0.7 rad.	1/2	1024	4
Conf. #2	2	16-QAM	1.0 rad.	3/4	1024	4
Conf. #3	3	64-QAM	1.0 rad.	5/6	1024	4

Channel modelling and nonlinear distortions:

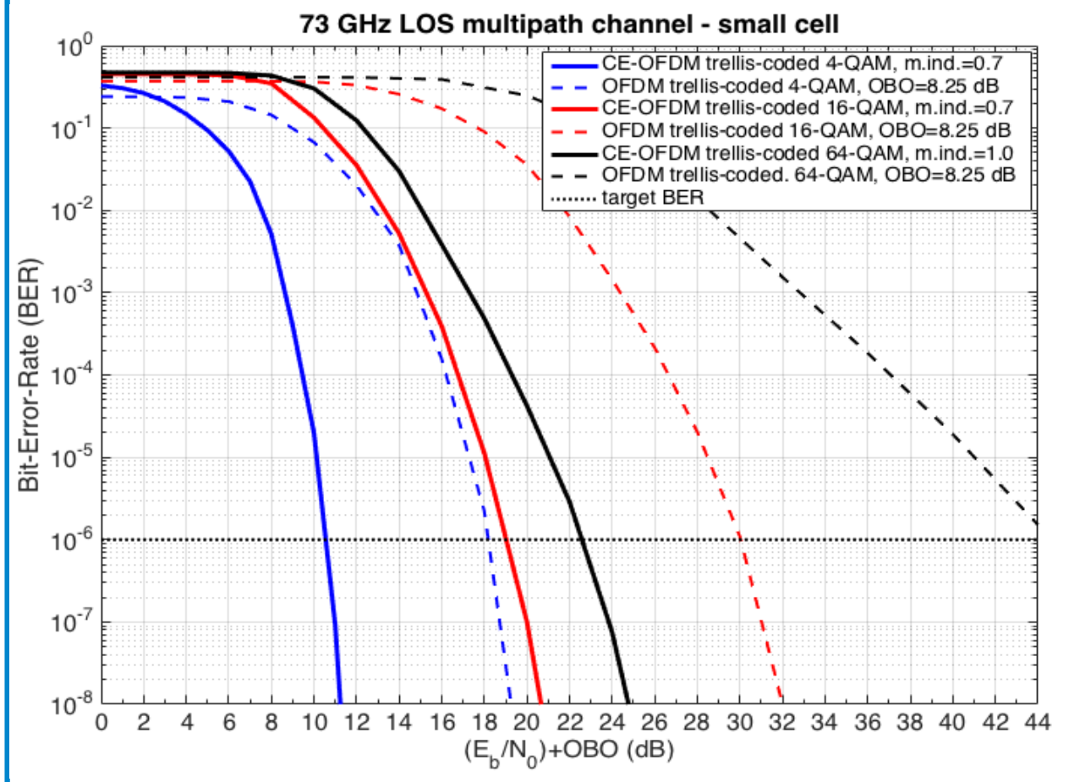


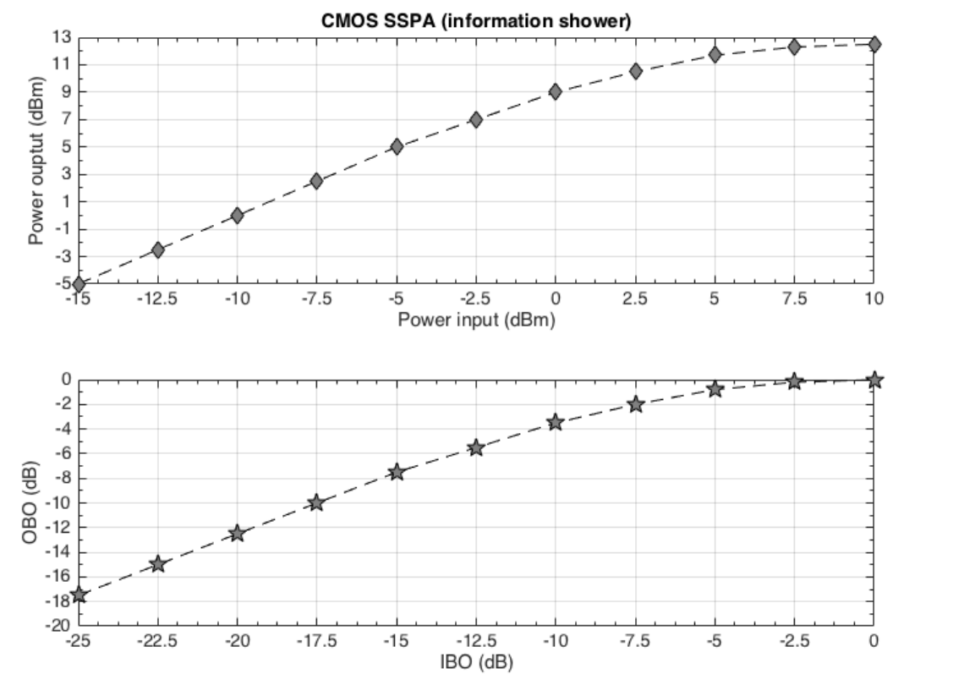
73 GHz clustered multipath channel (LOS) [16]



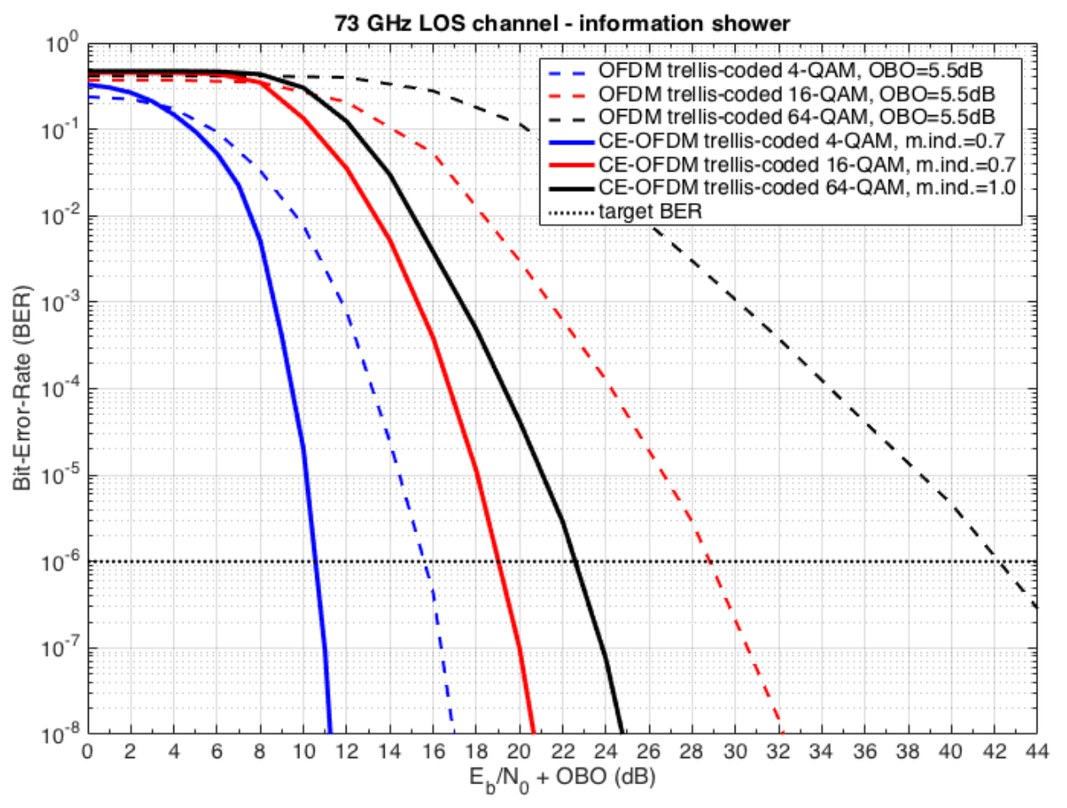
Nonlinear characteristic of GaN SSPA amplifier for small cell [17]

Simulation results:





Nonlinear characteristic of CMOS SSPA amplifier for information shower [18]



E_b/N_0 AND *SNR* VALUES REQUIRED TO ACHIEVE THE EXPECTED BER PERFORMANCE OF 10^{-6} IN THE SMALL CELL DOWNLINK AND IN THE INFORMATION SHOWER SCENARIOS

		CE-OFDM		OFDM	
		E_b/N_0	*SNR*	E_b/N_0	*SNR*
Trellis coded 4-QAM	Small cell	10.5 dB	1.5 dB	18 dB	18 dB
	Inf. shower	10.5 dB	1.5 dB	15.75 dB	15.7 dB
Trellis coded 16-QAM	Small cell	19 dB	14.7 dB	30 dB	34.8 dB
	Inf. shower	19 dB	14.7 dB	29 dB	33.8 dB
Trellis coded 64-QAM	Small cell	23 dB	21 dB	44.5 dB	51.5 dB
	Inf. shower	23 dB	21 dB	42.5 dB	49.5 dB

$$SNR_{TC-CEOFDM} = \left(E_b/N_0\right) + 10\log_{10}\left(mr_c/F_O\right) \quad [5]$$

$$SNR_{TC-OFDM} = \left(E_b/N_0\right) + 10\log_{10}\left(2mr_c\right)$$

CONCLUSION AND FUTURE WORK

In this paper, an mm-Wave communication system based on the use of trellis-coded Constant-Envelope OFDM (CE-OFDM) multicarrier technique is proposed for 5G communications. Its effectiveness for very high data-rate applications is proved by computer simulations in the small cell downlink and in the information shower scenarios. The trellis coded CE-OFDM can exploit frequency diversity more effectively than trellis-coded OFDM and allows an increased coverage and rate in mm-wave LOS multipath channels characterized by clustered fading and large shadow standard deviation.
Future works will deal with the adoption of the spectral pre-coding, that has been already proposed in [10] to reduce side-lobe power and, definitely, increasing spectral efficiency. The effects of non-ideal channel estimation and phase-noise should be also assessed in order to further prove the resilience of the proposed multicarrier scheme.

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