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Multiple Access for 5G – A New Look on NOMA

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ACKNOWLEDGMENT

This presentation is based on joint work with:

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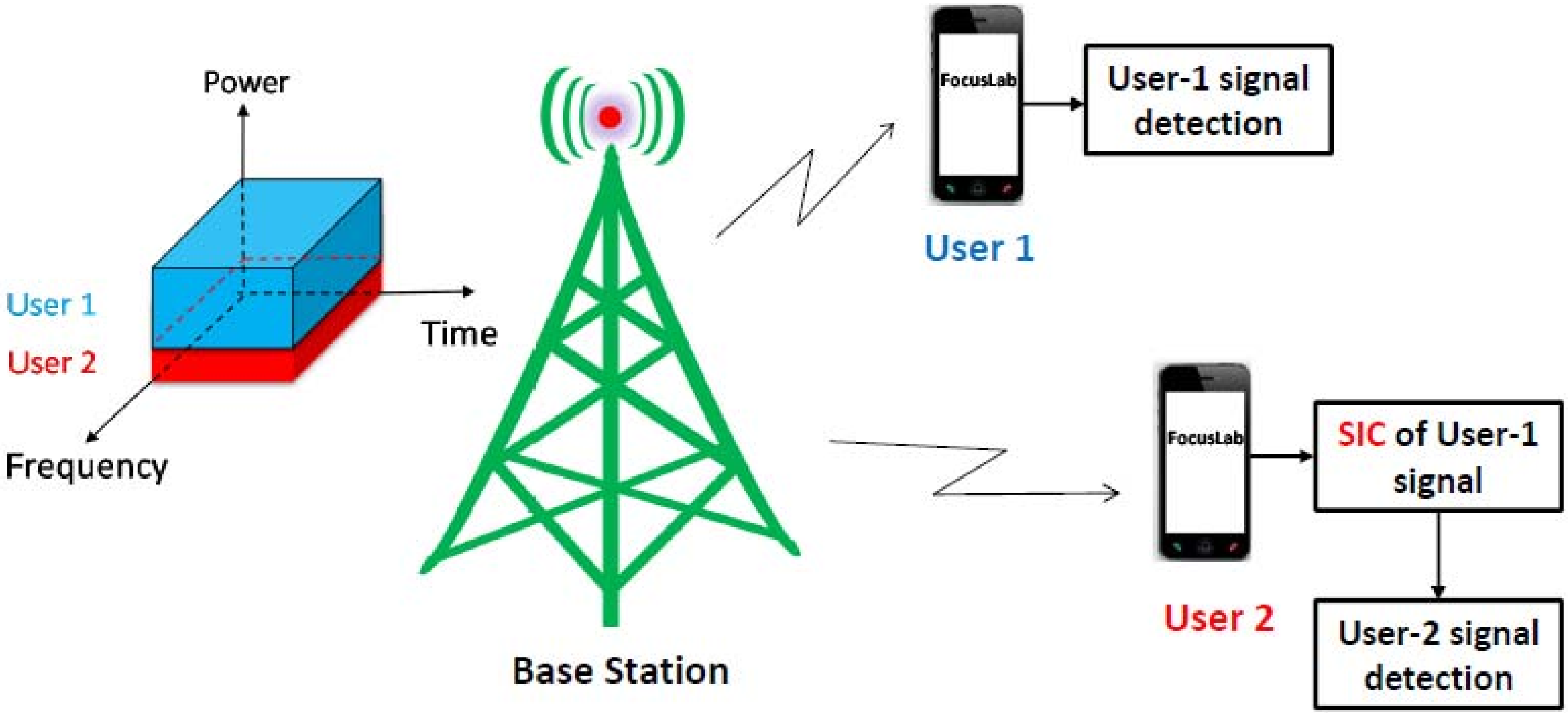
A HISTORICAL REVIEW

- ❑ In 2G cellular networks, the global standard GSM used TDMA, and IS-95 adopted CDMA.
- ❑ 3G networks were based on Wideband CDMA (WCDMA).
- ❑ Multicarrier transmission (OFDM) was introduced in WiFi, WiMAX, and 3GPP LTE.
- ❑ For multiple access, WiFi continued to use TDMA, WiMAX adopted OFDMA, and LTE used OFDMA on the downlink and Single-Carrier FDMA on the uplink.
- ❑ All of these multiple access techniques are orthogonal and avoid interference between user signals. Of course, perfect synchronization is required on the uplink.

MULTIPLE ACCESS FOR 5G

- Future 5G cellular targets three different types of services:
  1. Enhanced Mobile Broadband (eMBB)
  2. Massive Machine-Type Communications (mMTC)
  3. Ultra-Reliable and Low Latency Communications (URLLC)
- The 3GPP has adopted OFDMA for eMBB and URLLC traffics, but no decision has been made yet for mMTC.
- Information theory states that orthogonal multiple access (OMA) is not optimal in general and promises significant gains using non-orthogonal multiple access (NOMA).
- Based on this, a lot of research has been reported over the past few years on NOMA, and various schemes were proposed for 5G standardization. NOMA stands today as a serious candidate for mMTC services.

NOMA DOWNLINK



Power

User 1

User 2

Time

Frequency

Base Station

FocusLab

User-1 signal detection

User 1

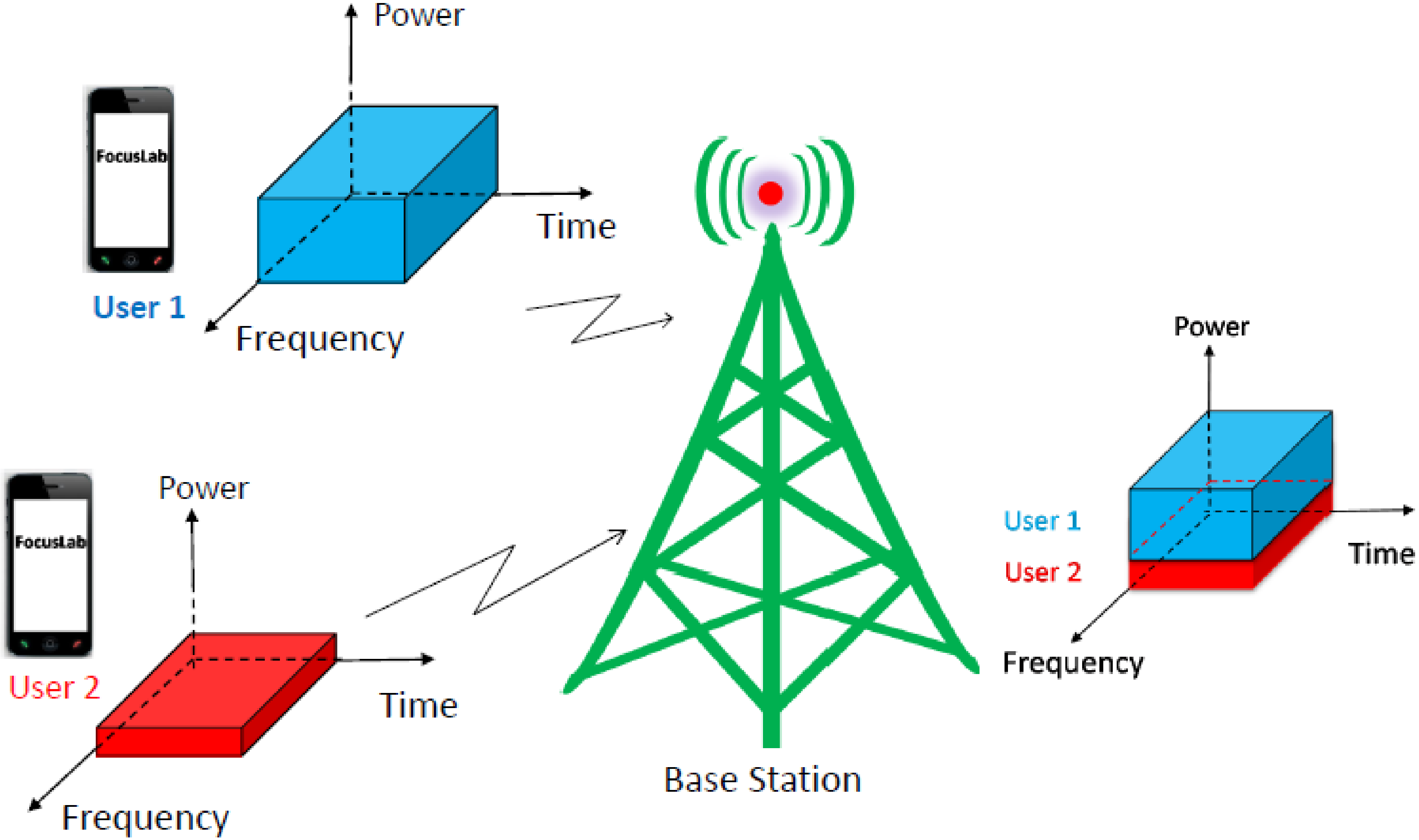
FocusLab

SIC of User-1 signal

User-2 signal detection

User 2

NOMA UPLINK


Power
FocusLab
Time
User 1
Frequency
Power
FocusLab
User 2
Time
Frequency
Base Station
Power
User 1
User 2
Time
Frequency

BASIC PRINCIPLE OF NOMA

- Consider a 2-user uplink channel, where User 1 has a strong power $\boldsymbol{P_1}$ and User 2 has a weak power $\boldsymbol{P_2}$.
- The receiver can detect the User-1 signal in the presence of interference from the User-2 signal. Then, it can subtract the detected User-1 signal from the received signal to detect the weaker User-2 signal without interference.
- Assuming an AWGN channel of bandwidth W = 1 Hz, the User-1 capacity in bits per channel use (bpcu) is:

$$R_1 = log_2\left(1 + \frac{P_1}{P_2 + N_0}\right)$$

- And the User-2 capacity is:

$$R_2 = log_2\left(1 + \frac{P_2}{N_0}\right)$$

BASIC PRINCIPLE OF NOMA (CONT'D)

- Consequently, the total capacity is:

$$R = R_1 + R_2 = log_2\left(1 + \frac{P_1}{P_2 + N_0}\right) + log_2\left(1 + \frac{P_2}{N_0}\right)$$

- A simple manipulation gives:

$$R = log_2\left(\left(1 + \frac{P_1}{P_2 + N_0}\right)\left(1 + \frac{P_2}{N_0}\right)\right) = log_2\left(1 + \frac{P}{N_0}\right)$$

- Here, $P = P_1 + P_2$ is the total power. This shows that the capacity of the multi-user channel is identical to that of the single-user channel with the same total power.
- Consider now an OFDMA system with 2 users and write $P_1 = \alpha P$, $P_2 = (1 - \alpha)P$, $W_1 = \alpha W$, and $W_2 = (1 - \alpha)W$, with $0 \leq \alpha \leq 1$. In other words, the power is uniformly distributed over the N carriers composing the OFDMA signal.

BASIC PRINCIPLE OF NOMA (CONT'D)

- The capacity equations for the two users are:

$$R_1 = \alpha log_2\left(1 + \frac{P_1}{W_1 N_0}\right) = \alpha log_2\left(1 + \frac{P}{N_0}\right)$$

$$R_2 = (1-\alpha) log_2\left(1 + \frac{P_2}{W_2 N_0}\right) = (1-\alpha) log_2\left(1 + \frac{P}{N_0}\right)$$

- The total capacity $R = R_1 + R_2$ is identical to the NOMA capacity in this case.
- The difference appears when the two user signals have different attenuations. Assume now that User-2 signal is attenuated by 6 dB. The OFDMA capacity becomes:

$$R_{OFDMA} = \alpha log_2\left(1 + \frac{P}{N_0}\right) + (1-\alpha) log_2\left(1 + \frac{P/4}{N_0}\right)$$

BASIC PRINCIPLE OF NOMA (CONT'D)

- And the NOMA capacity becomes:

$$R_{NOMA} = log_2\left(1 + \frac{\alpha P}{(1-\alpha)\,P/4 + N_0}\right) + log_2\left(1 + \frac{(1-\alpha)\,P/4}{N_0}\right)$$

$$= log_2\left(1 + \frac{(1+3\alpha)P}{4N_0}\right)$$

- To compare these capacities, assume $\alpha = 0.8$ and $P/N_0 = 15$ so that the single-user capacity is 4 bpcu. In this case, $R_{OFDMA} = 3.65$ and $R_{NOMA} = 3.78$, i.e., NOMA increases capacity by 3.5%.
- The advantage of NOMA increases when the parameter α is reduced or the user-2 signal is further attenuated.
- But NOMA requires a successive interference cancellation (SIC) receiver, which will have problems if there is no strong imbalance between the two signals.

PRACTICAL CONSIDERATIONS

- ☐ The powers received from the two users sharing the same band and time interval must be significantly different to ensure that the receiver will work properly.
- ☐ For the uplink, this involves "pairing" of users in the resource allocation process in order to have a user with a strong signal paired with a user having a weak signal.
- ☐ As for the downlink, the two signals originate from the same point and travel on the same path. Their attenuations being the same, the base station must transmit different power levels to the two users paired. This means that the two users will have different data rates and/or performance levels.

NOMA IN THE RECENT LITERATURE

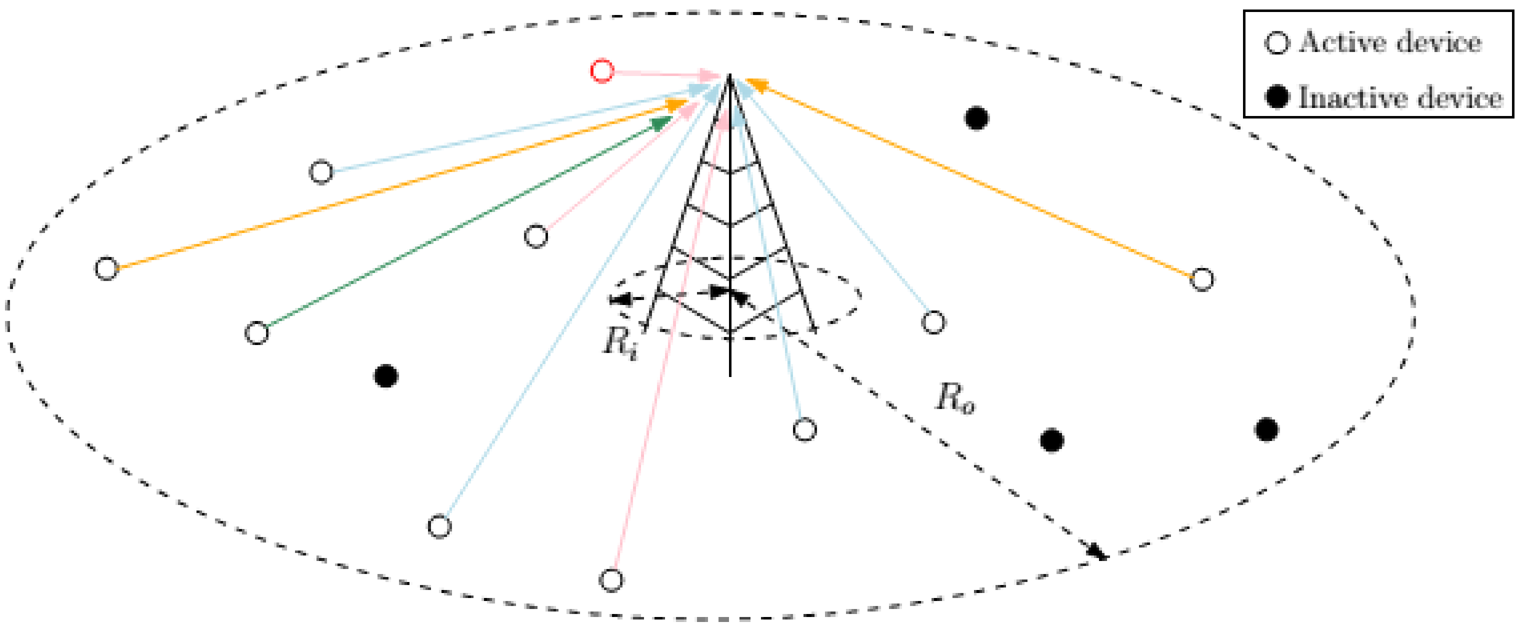
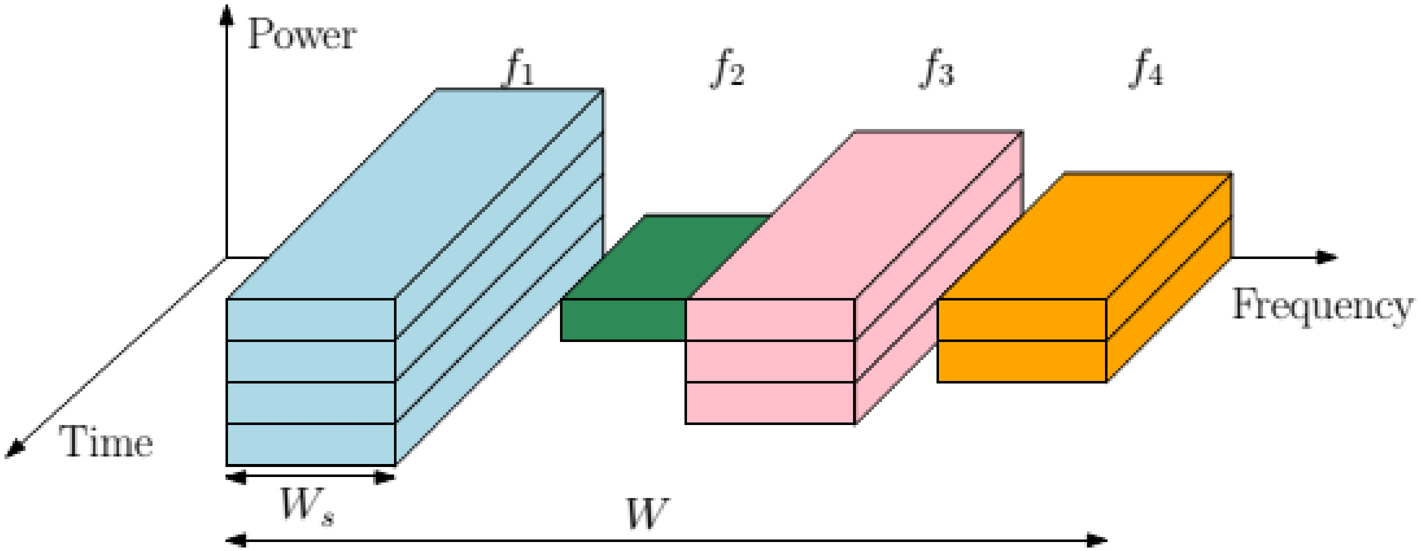


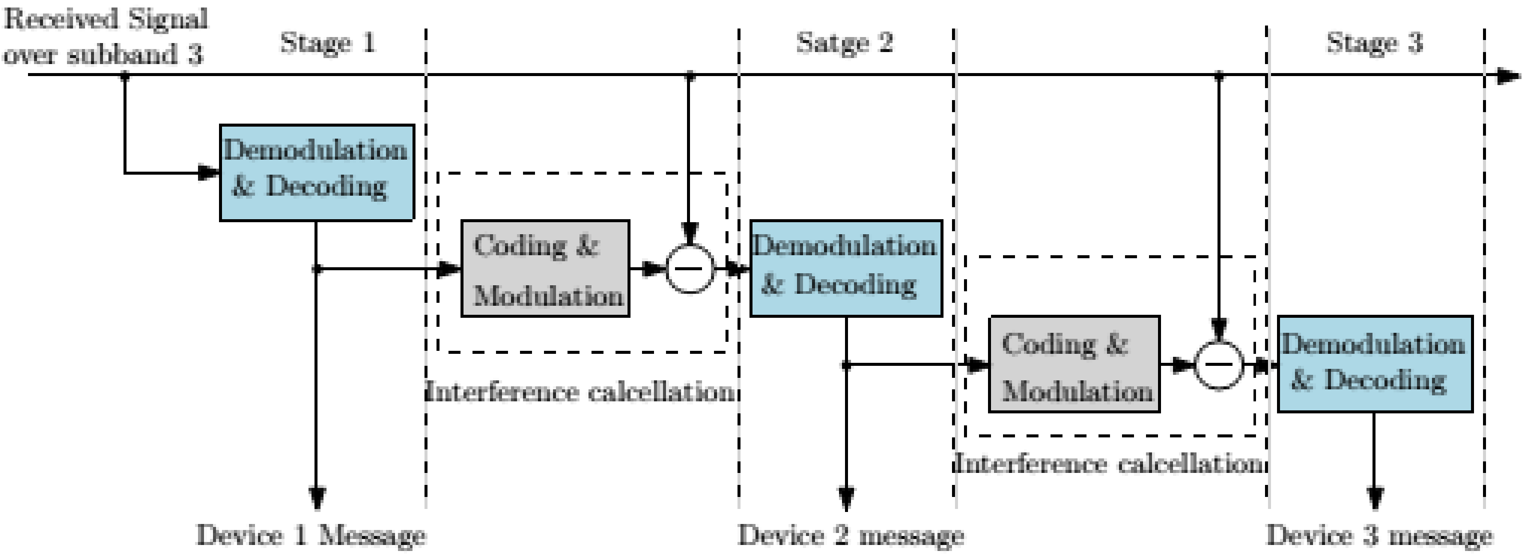
Illustration of a Multiband Uplink NOMA with different devices randomly selecting a subband.

NOMA IN THE LITERATURE (CONT'D)



Stacking of the transmitted signals in 4 subbands

NOMA IN THE LITERATURE (CONT'D)



Successive interference cancellation (SIC) in Subband 3

CHALLENGES FOR THE RECEIVER

- This receiver has 3 stages, because 3 signals are transmitted in the same subband. The first stage detects the message of Device 1 assuming that the power received from this device is significantly higher than the powers of the other two.
- Of course, performance of this detector stage will be far from performance of detection on interference-free channels. Stage 2 will detect the message of Device 2 after cancelling (most of) the interference from Device 1, and the third stage will detect the message of Device 3 after cancelling (most of) the interference from Device 1 and Device 2.
- Obviously, a large power imbalance is needed between devices to achieve acceptable performance. But due to interference, performance of this NOMA scheme cannot get very close to that of interference-free transmission.

SUMMARY OF NOMA TODAY

- The recent NOMA literature has been heavily focused on information theoretical arguments and concepts like degrees of freedom, capacity regions, and achievable rates, and practical problems have not been sufficiently addressed.
- The SIC receiver universally adopted in the NOMA literature may be optimum from information theoretic standpoint, but in practice it cannot give performance close to that of interference-free transmission unless the power imbalance between the superposed user signals is extremely high.
- The signal-to-noise ratio (SNR) degradation goes to 0 only if the interfering signal power goes to 0, in which case the concept of NOMA vanishes!

HOW MUCH SNR DEGRADATION?

- ☐ The main objective in practice is to achieve the error performance of interference-free transmission.

- ☐ The bit error rate (BER) in the presence of AWGN noise and interference is of the form:

  $$BER \cong K.erfc\left({}^{\lambda P_1}\big/_{(P_2+\sigma_n^2)}\right)$$

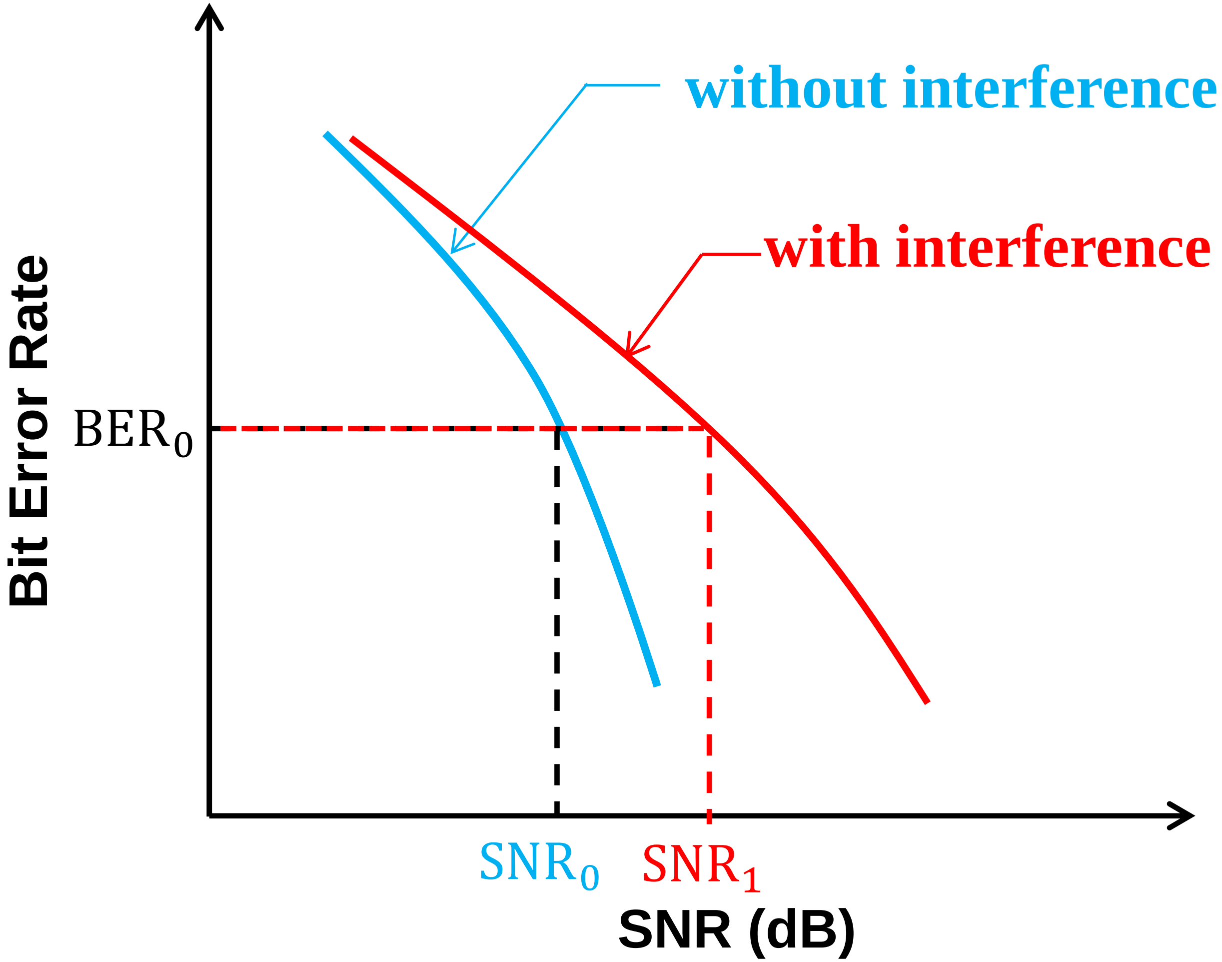
  where K and λ are modulation-dependent parameters, $\boldsymbol{P_1}$ is the power of the strong signal to be detected, $\boldsymbol{\sigma_n^2}$ is the noise power, and $\boldsymbol{P_2}$ is the power of the interfering signal.

- ☐ Suppose that we want to achieve a bit error rate BER_0 and the SNR value required to achieve this BER value in the absence of interference is **SNR_0 = $\boldsymbol{P_1/\sigma_n^2}$.**

HOW MUCH SNR DEGRADATION?

- In the presence of an interference power $\boldsymbol{P_2}$, the desired BER will be reached if $\boldsymbol{P_1/\sigma_n^2 = P_1/(P_2 + \sigma_{n'}^2)}$.
- **SNR$_1$ =**$\boldsymbol{P_1/\sigma_{n'}^2}$ represents the SNR value in the presence of interference that is needed to achieve the desired BER, and **SNR$_1$ - SNR$_0$** represents the SNR degradation at this BER value.
- The SNR degradation is a function of the interference level and it increases with decreasing BER values. In fact, the SNR degradation becomes infinite when the interference power exceeds some critical value.
- In NOMA, SNR degradation is a function of the power imbalance between the superposed user signals. A very strong power imbalance is needed in order to have a small SNR degradation, and in this case the users will not have the same quality of service (QoS).

ILLUSTRATION



QUESTION: HOW OLD IS NOMA?

- ☐ The current interest in NOMA is closely related to the start of 5G standardization. Virtually all papers published on the subject appeared in the past 5 years or so. For instance:

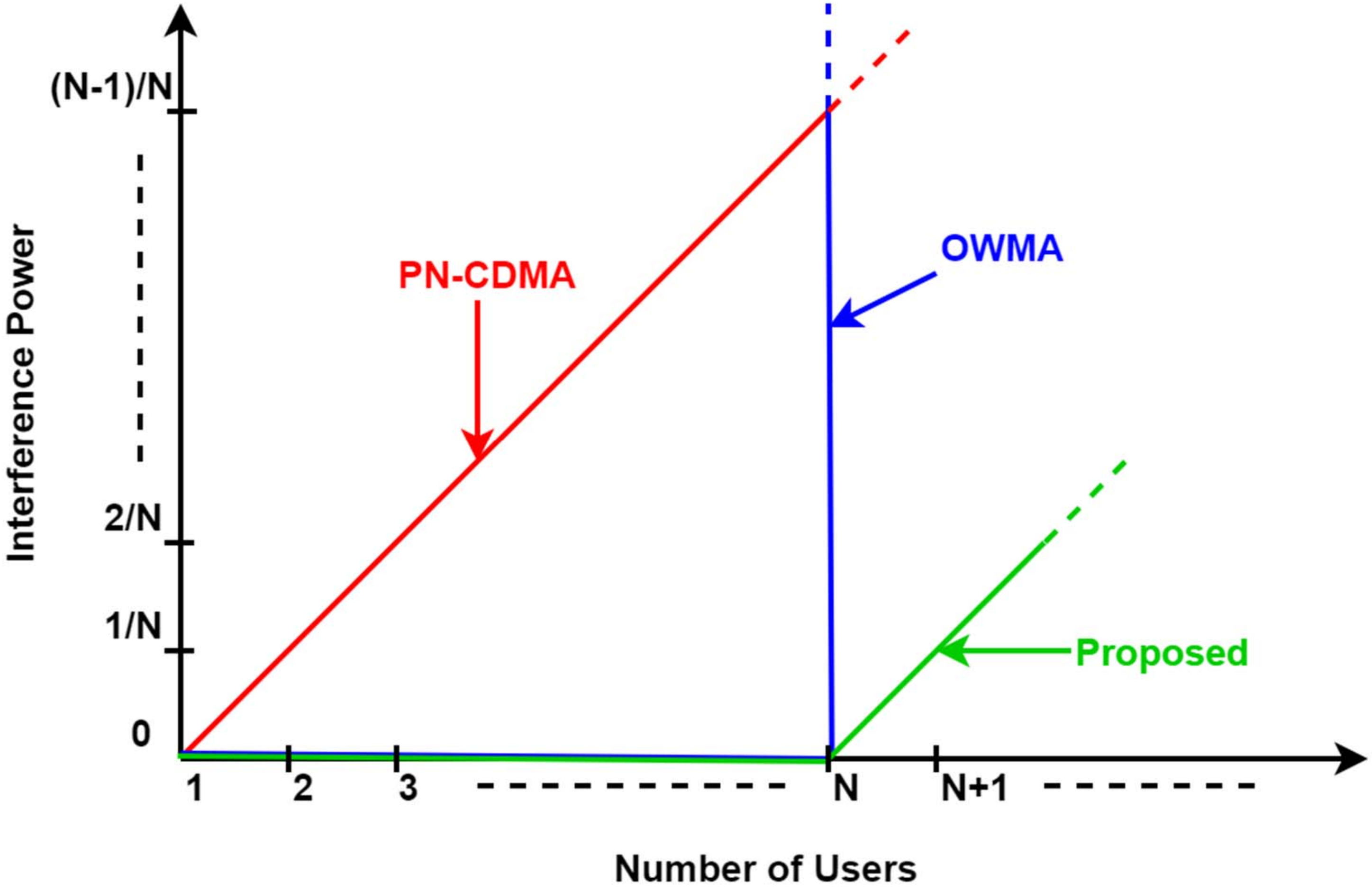
1. Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, “Non-Orthogonal Multiple Access (NOMA) for Cellular Future Radio Access,” Proc. *VTC 2013 Spring*, June 2013.
2. Z. Ding, Z. Yang, P. Fan, and H. V. Poor, “On the Performance of Non-Orthogonal Multiple Access in 5G Systems with Randomly Deployed Users,” *IEEE Signal Processing Letters*, vol. 21, no. 12, December 2014.
3. L. Dai, B. Wang, Y. Yuan, S. Han, C.-L. I, and Z. Wang, “Non-Orthogonal Multiple Access for 5G: Solutions, Challenges, Opportunities, and Future Research Trends,” *IEEE Communications Magazine*, vol. 53, no. 9, Sept. 2015.
4. M. Shirvanimoghaddam, M. Dohler, and S. J. Johnson, “Massive Non-Orthogonal Multiple Access for Cellular IoT: Potentials and Limitations,” *IEEE Comm. Magazine*, vol. 55, no. 9, Sept. 2017.

REVEALING ITS FOUNDATION

❑ Interestingly, recent NOMA authors seem unaware that the foundation of NOMA can be traced back to the year 2000 when a series of papers introduced the concept of multiple access using two sets of orthogonal signal waveforms.

1. H. Sari, F. Vanhaverbeke, and M. Moeneclaey, "Multiple Access Using Two Sets of Orthogonal Signal Waveforms," IEEE Comm. Letters, vol. 4, no. 1, January 2000.
2. H. Sari, F. Vanhaverbeke, and M. Moeneclaey, "Extending the Capacity of Multiple Access Channels," IEEE Comm. Magazine, vol. 38, no. 1, January 2000.
3. H. Sari, F. Vanhaverbeke, and M. Moeneclaey, "Channel Overloading in Multiuser and Single-User Communications," Proc. PIMRC 2000, September 2000.
4. F. Vanhaverbeke, M. Moeneclaey, and H. Sari "Turbo Multiple Access: Channel Overloading Using Two Sets of Orthogonal Signal Waveforms and Iterative Interference Cancellation," Proc. the 2nd Int. Symposium on Turbo Codes & Related Topics, September 2000, Brest, France.

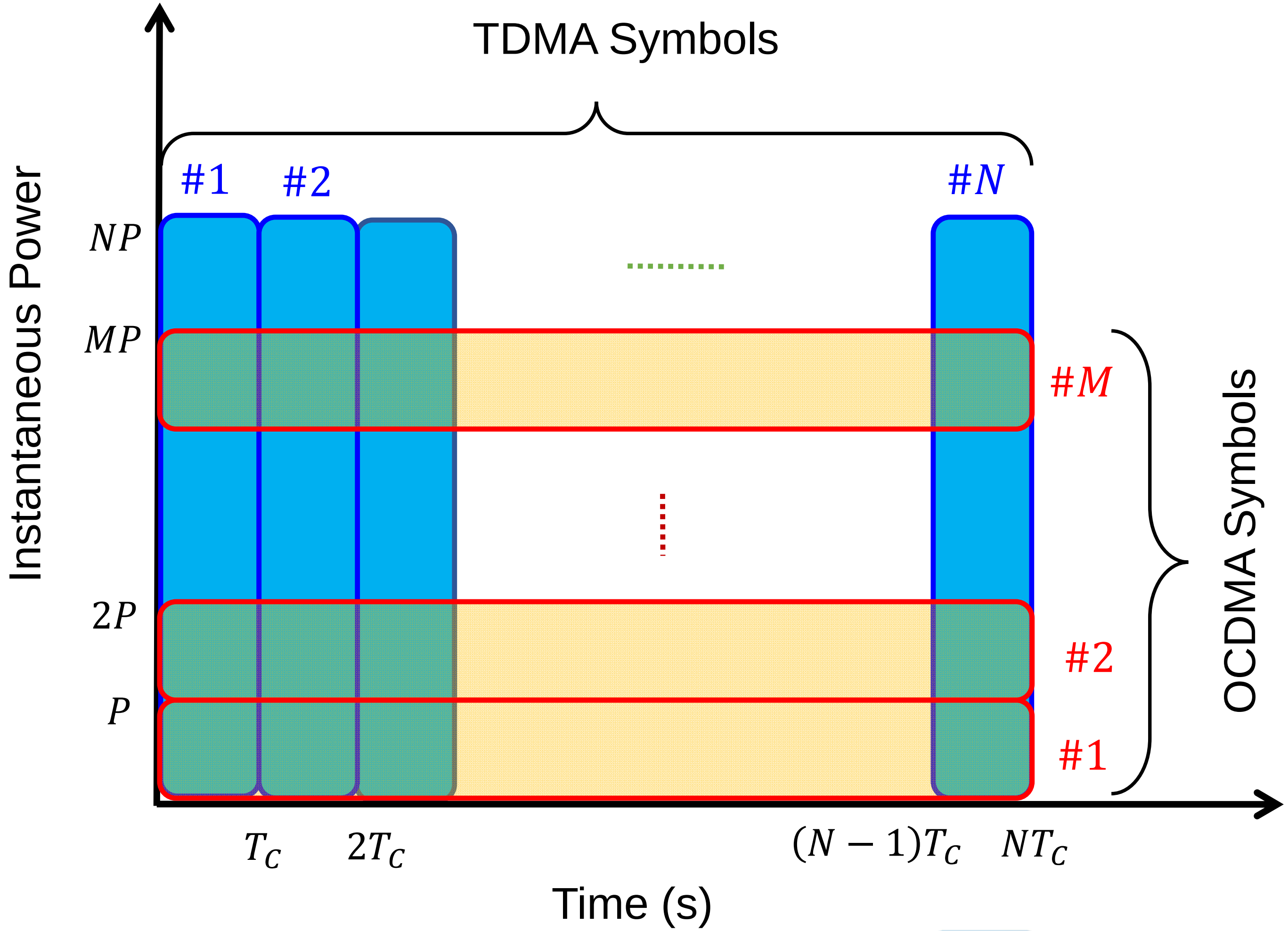
BASIC OBSERVATION MADE IN 2000



TARGETING THE BEST

- The question was whether we can devise a multiple access scheme that combines the respective virtues of Orthogonal Waveform Multiple Access (OWMA) and Pseudo-Noise Code-Division Multiple Access (PN-CDMA) while avoiding their shortcomings.
- In other words, the objective was to accommodate without any interference N users on a channel whose bandwidth is N times the bandwidth which would be required by the individual users if they tranmitted alone, and at the same time break the hard limit of N users that is specific to OWMA.
- This question led to the use of two sets of orthogonal signal waveforms together with an iterative detector to cancel the interference between users whose resources are from different signal sets.

COMBINING TDMA AND OCDMA



COMBINED TDMA/OCDMA

- Consider the superposition of a TDMA signal with N users and an OCDMA signal with M users, where $\mathrm{M} < N$.
- There is no interference between TDMA users and no interference between OCDMA users. But all TDMA users interfere with all OCDMA users, and vice versa.
- The TDMA symbols are denoted $\{a_n, n = 1, 2, \dots, N\}$, where $a_n$is assigned to user #*n*. The OCDMA symbols are denoted $\{b_m, m = 1, 2, \dots, M\}$, where $b_m$is assigned to OCDMA user #*m*.
- The OCDMA symbols are spread using Walsh-Hadamard sequences $W_m = \left(w_{m,1}, w_{m,2}, \dots\dots, w_{m,N}\right)$, $m = 1,2, \dots\dots, M$.
- The transmitted signal is of the form: $x_n = a_n + \frac{1}{\sqrt{N}} \sum_{m=1}^{M} w_{m,n} b_m$ for $n = 1, 2, \dots, N$.

COMBINED TDMA/OCDMA (CONT'D)

- The received signal is $r_n = x_n + u_n$ for $n = 1, 2, \ldots, N$. Provided that M is not too large, this signal can be sent to a threshold detector to make preliminary decisions on the transmitted TDMA symbols.
- These decisions can be subtracted from the received signal to form:

$$y_n = a_n - \hat{a}_n + \frac{1}{\sqrt{N}} \sum_{m=1}^{M} w_{m,n} b_m + u_n$$

- Assuming $\hat{a}_n = a_n$, this equation simplifies to:

$$y_n = \frac{1}{\sqrt{N}} \sum_{m=1}^{M} w_{m,n} b_m + u_n$$

- The interference from TDMA symbols disappears and then we only have OCDMA symbols with additive noise.

COMBINED TDMA/OCDMA (CONT'D)

- The next operation of the receiver is to perform signal despreading and make decisions on the OCDMA symbols. Signal despreading consists of:

$$z_k = \frac{1}{\sqrt{N}} \sum_{n=1}^{N} w_{k,n} y_n = \frac{1}{\sqrt{N}} \sum_{n=1}^{N} w_{k,n} \left(\frac{1}{\sqrt{N}} \sum_{m=1}^{M} w_{m,n} b_m + u_n \right)$$

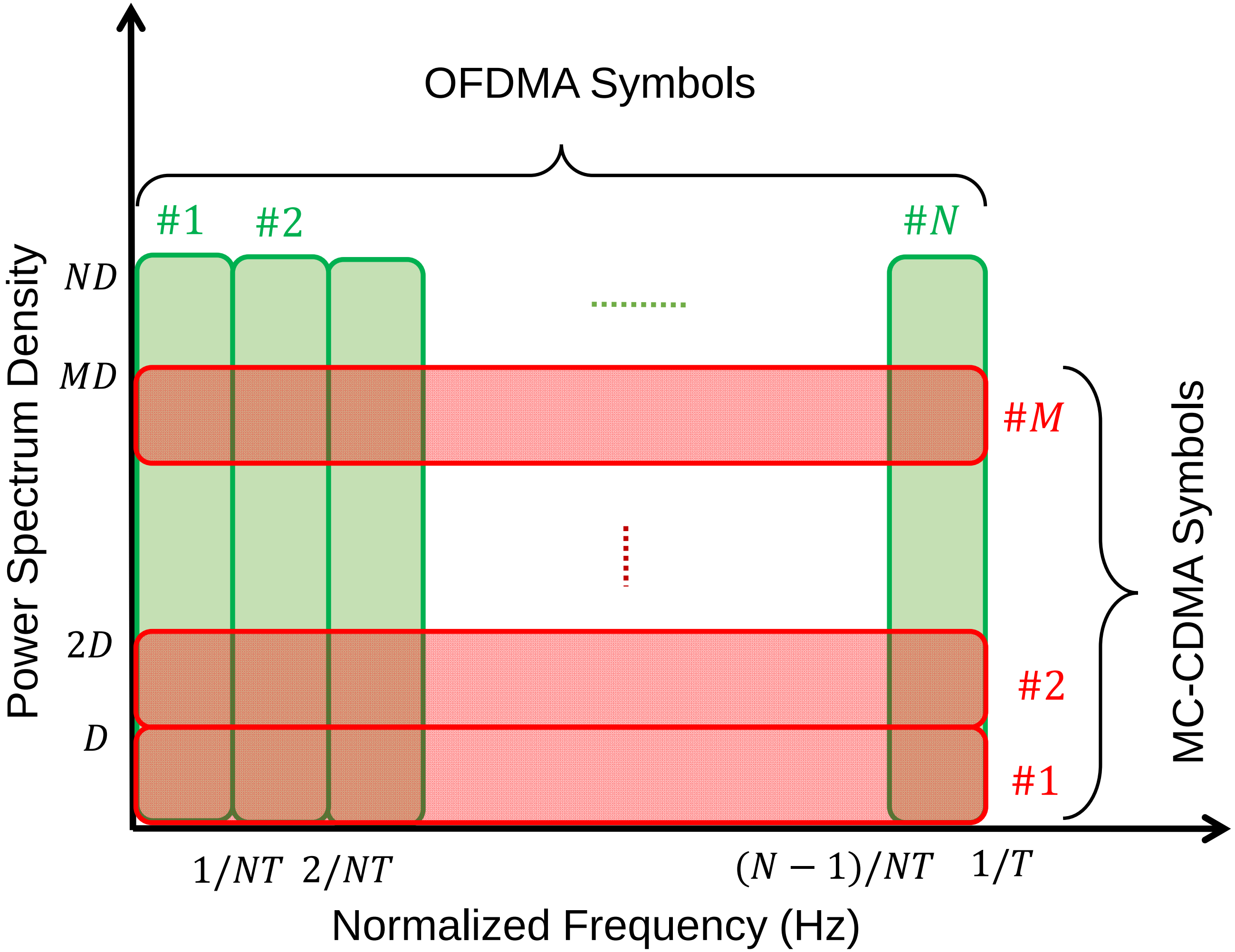
$$= b_k + \frac{1}{\sqrt{N}} \sum_{n=1}^{N} w_{k,n} u_n$$

- First-iteration decisions on OCDMA symbols are made by passing these samples to a threshold detector.
- When the first-iteration decisions are also available for OCDMA symbols, their interference on TDMA symbols can be cancelled and the second iteration proceeds in the same manner…

A NOMA PROPOSAL FOR mMTC in 5G

- Since OFDMA has been the basic multiple access technique in 4G and has also been selected as the baseline for 5G, it is natural to consider the frequency-domain version of the NOMA scheme based on TDMA/OCDMA.
- Consider an OFDMA with N carriers and assume that each carrier is assigned to a separate user. This scheme can accommodate N users providing one QAM symbol to each of them during every OFDM symbol period.
- We superpose to the OFDMA signal a set of MC-CDMA signals carrying information for a second set of users.
- All equations presented earlier remain the same except that now n with $1 \leq n \leq N$ designates the carrier index and x_n designates the signal transmitted on the nth carrier.

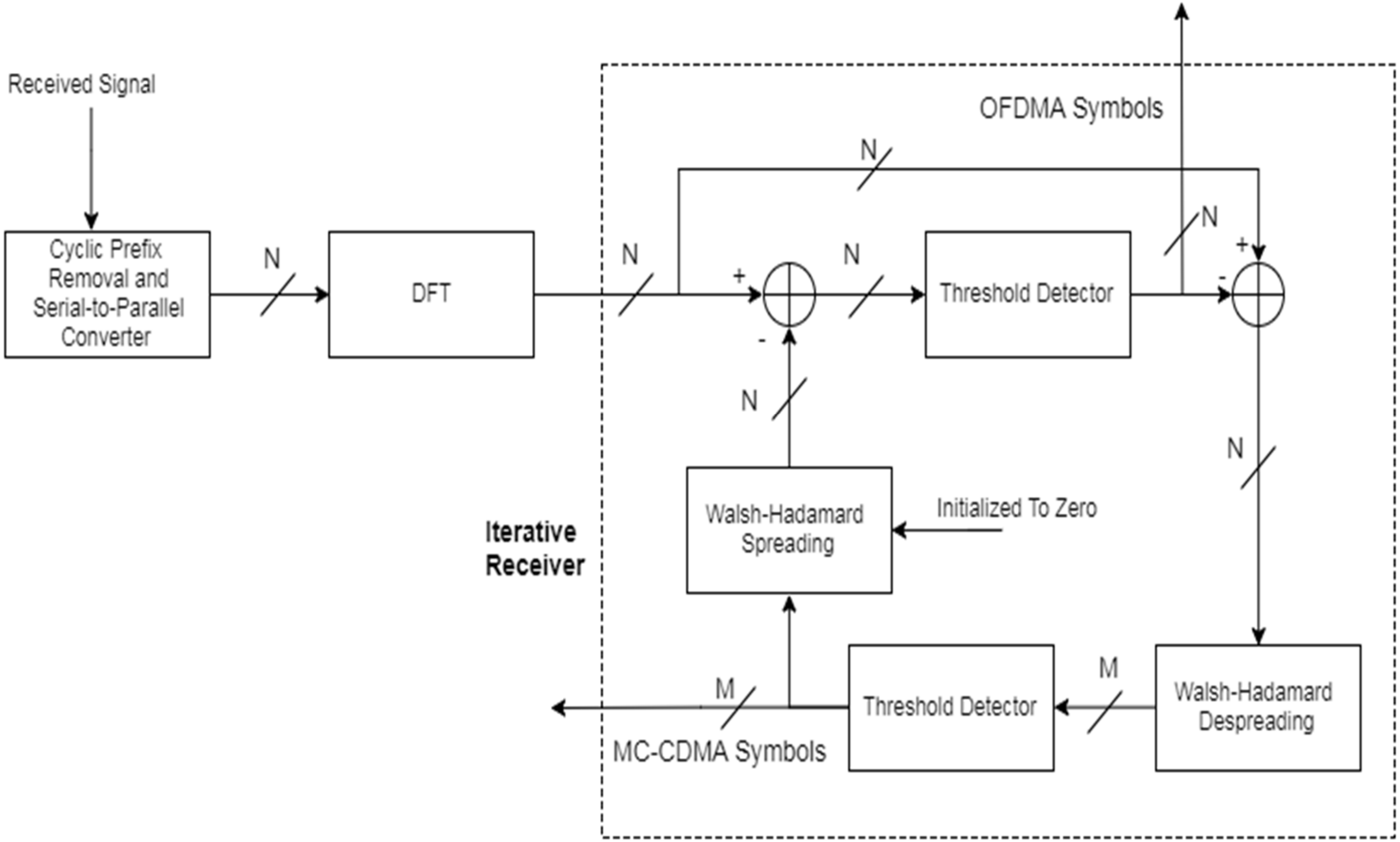
COMBINED OFDMA/MC-CDMA



BASIC CHARACTERISTICS

- Both OFDMA users and MC-CDMA users have the same average power and symbol energy, and they can have the same QoS.
- In other words, this early NOMA concept fully avoids the power imbalance requirement that is present in power-domain NOMA, which forms the basis of NOMA in recent literature.
- The power imbalance that is required for reliable detection is an inherent property of the signal design.
- OFDMA and MC-CDMA can be assigned to users with different profiles and service requirements.
- Since it uses OFDMA as the primary signal set and MC-CDMA as a secondary signal set, this NOMA technique can be viewed as a convenient extension of OFDMA rather than a purely competing technology.

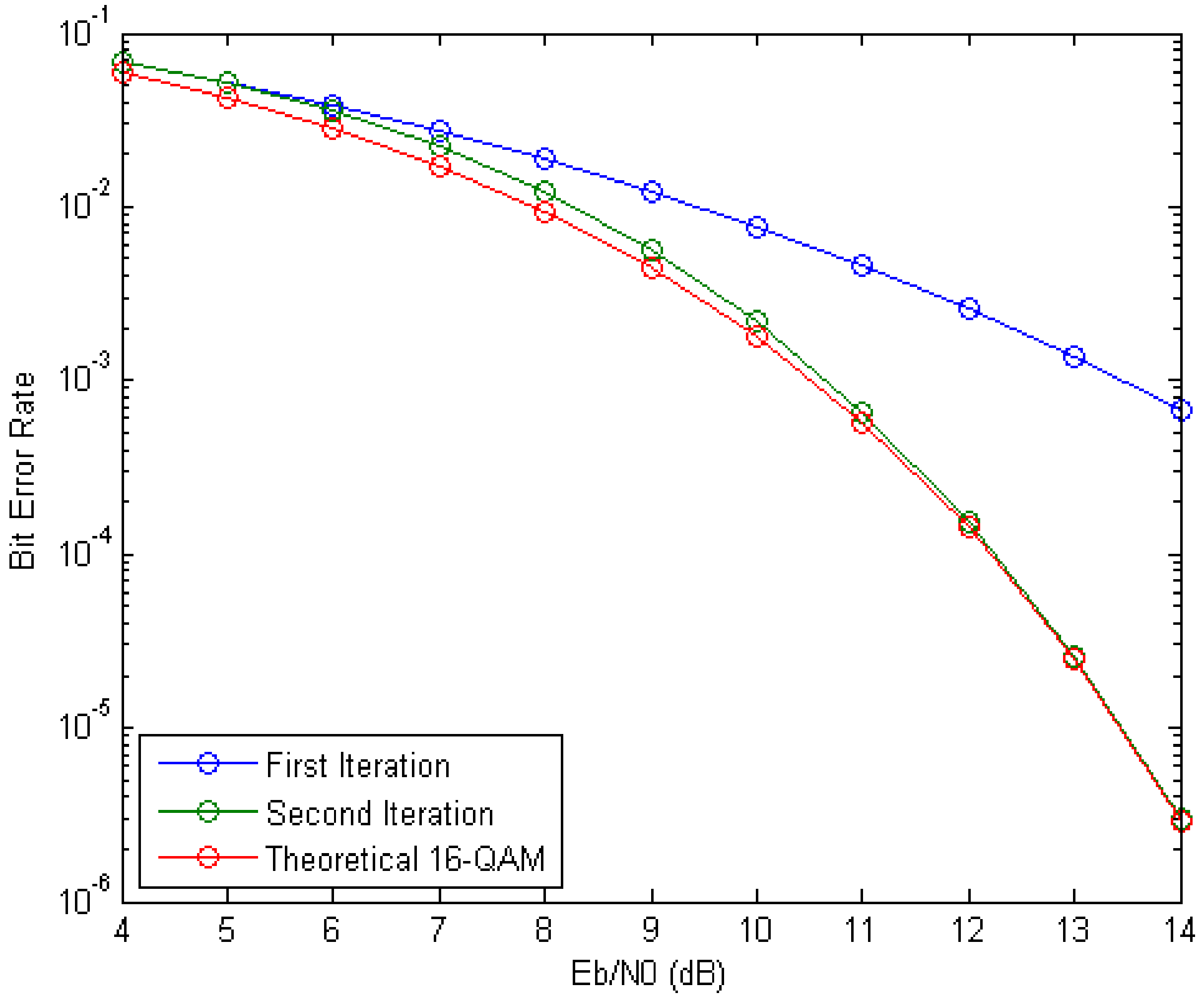
RECEIVER BLOCK DIAGRAM



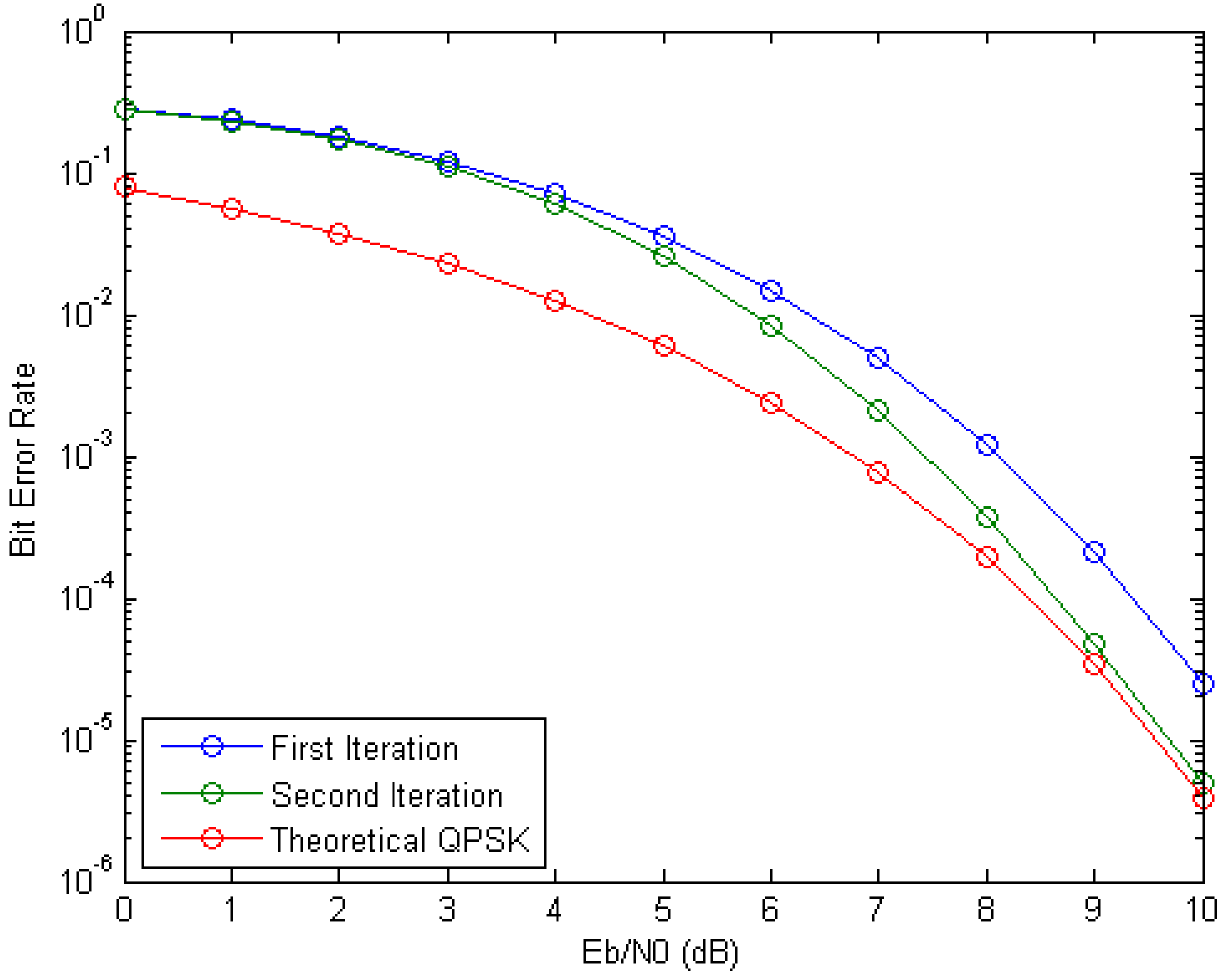
BER PERFORMANCE

- Performance of the NOMA scheme based on the combination of OFDMA with MC-CDMA was evaluated by means of computer simulations.
- The simulations were carried out over an AWGN channel using uncoded 16QAM modulation for OFDMA users and uncoded QPSK for MC-CDMA users.
- In the first set of simulations, the number of OFDMA users was N = 64, and the number of MC-CDMA users was M = 4.

BER FOR OFDMA USERS (N = 64, M = 4)



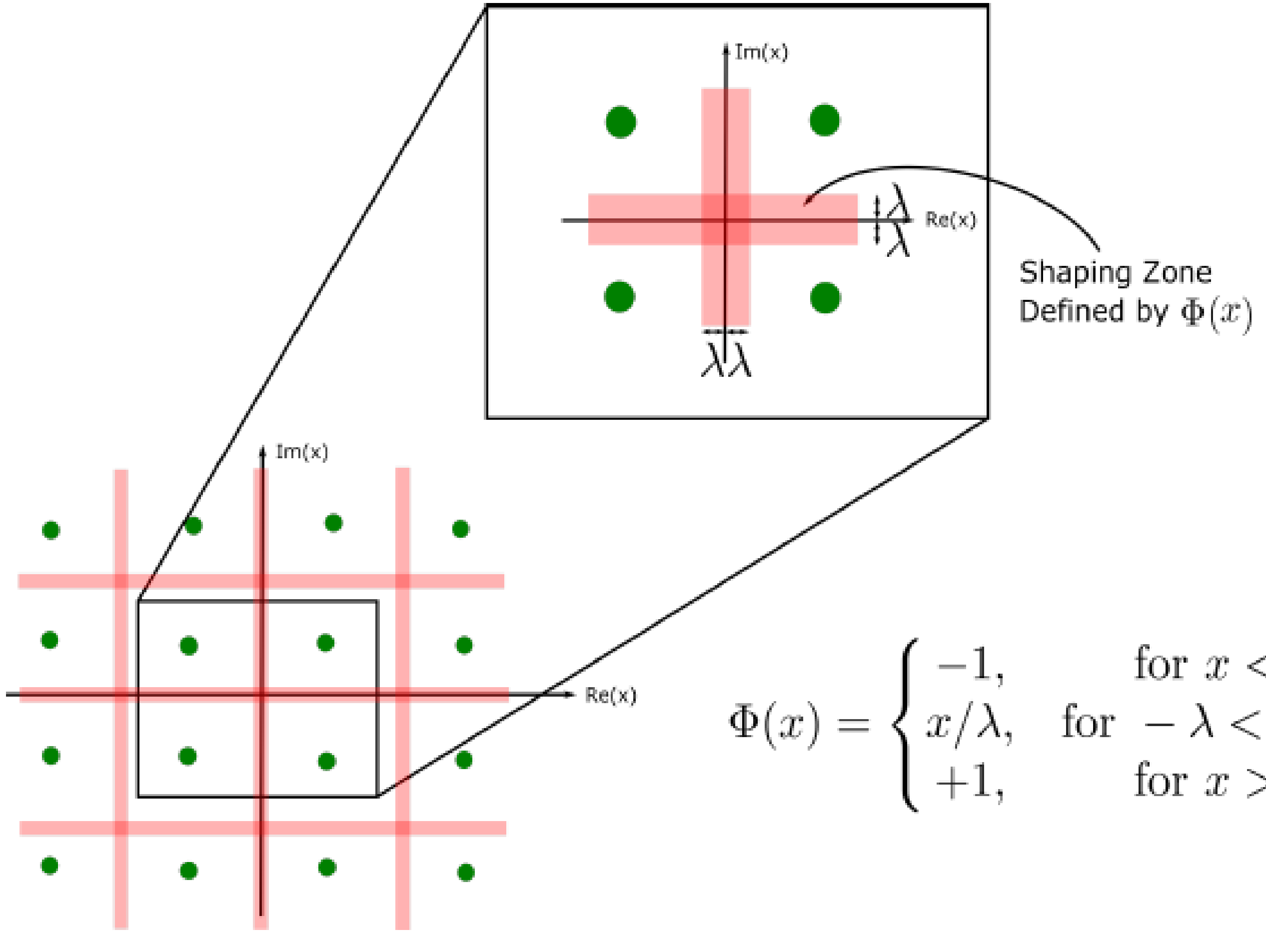
BER FOR MC-CDMA USERS (N = 64, M = 4)



DETECTION ISSUES

- In the above simulations, the number of MC-CDMA users is rather modest: The channel overloading factor with respect to OFDMA is only 6.25%.
- When the value of M reaches $\sqrt{N}$, the interference level leads to a closed eye diagram in the first detection stage and errors may occur even in the absence of noise.
- As M increases beyond this critical value, hard-decision detectors come to a performance limit, and soft-decision iterative interference cancellation becomes necessary to approach the performance of interference-free transmission.
- This issue will be illustrated using N = 256 and M = 44 corresponding a channel overloading factor of 17.2%.

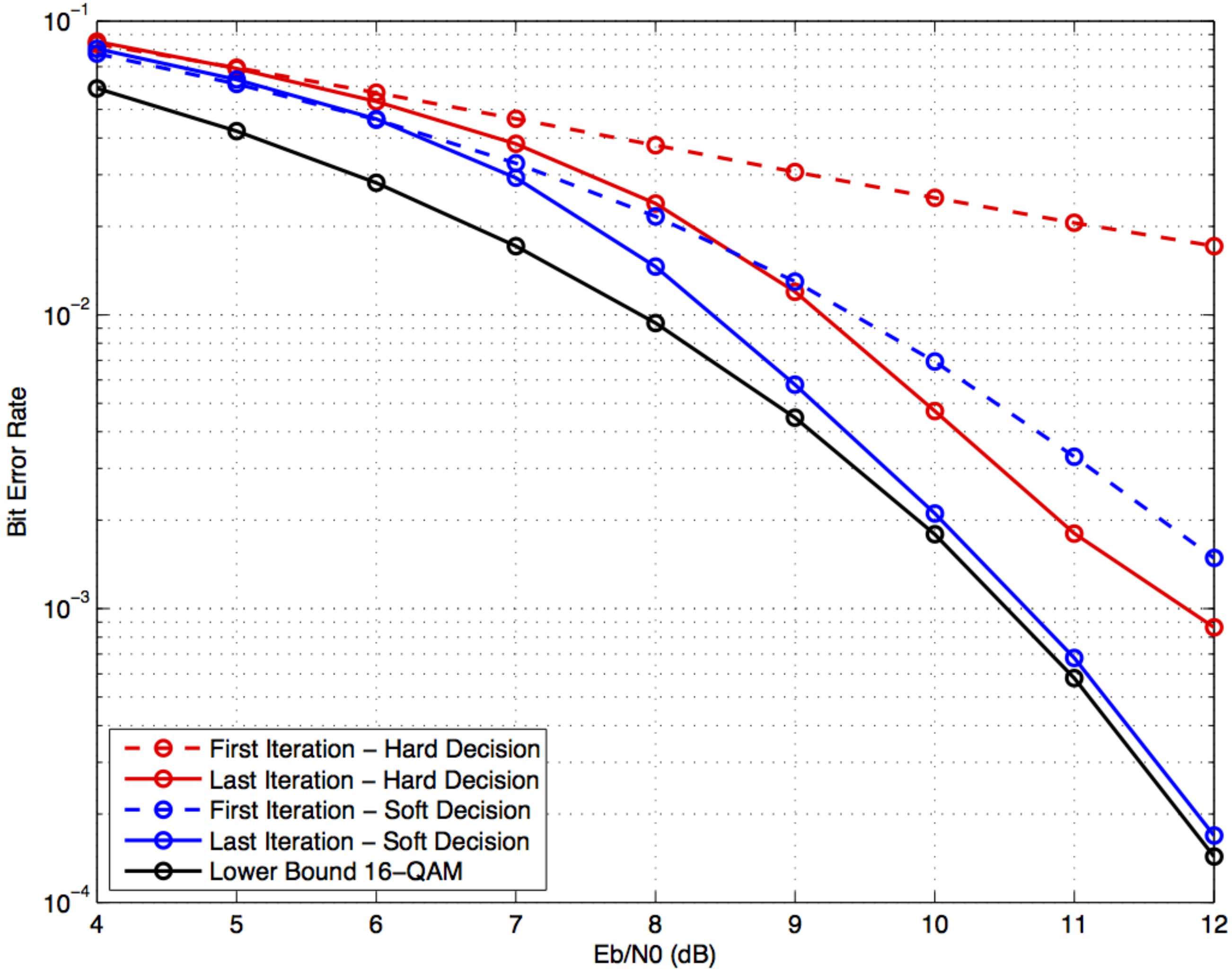
SHAPING OF THE SOFT-DECISION ZONES



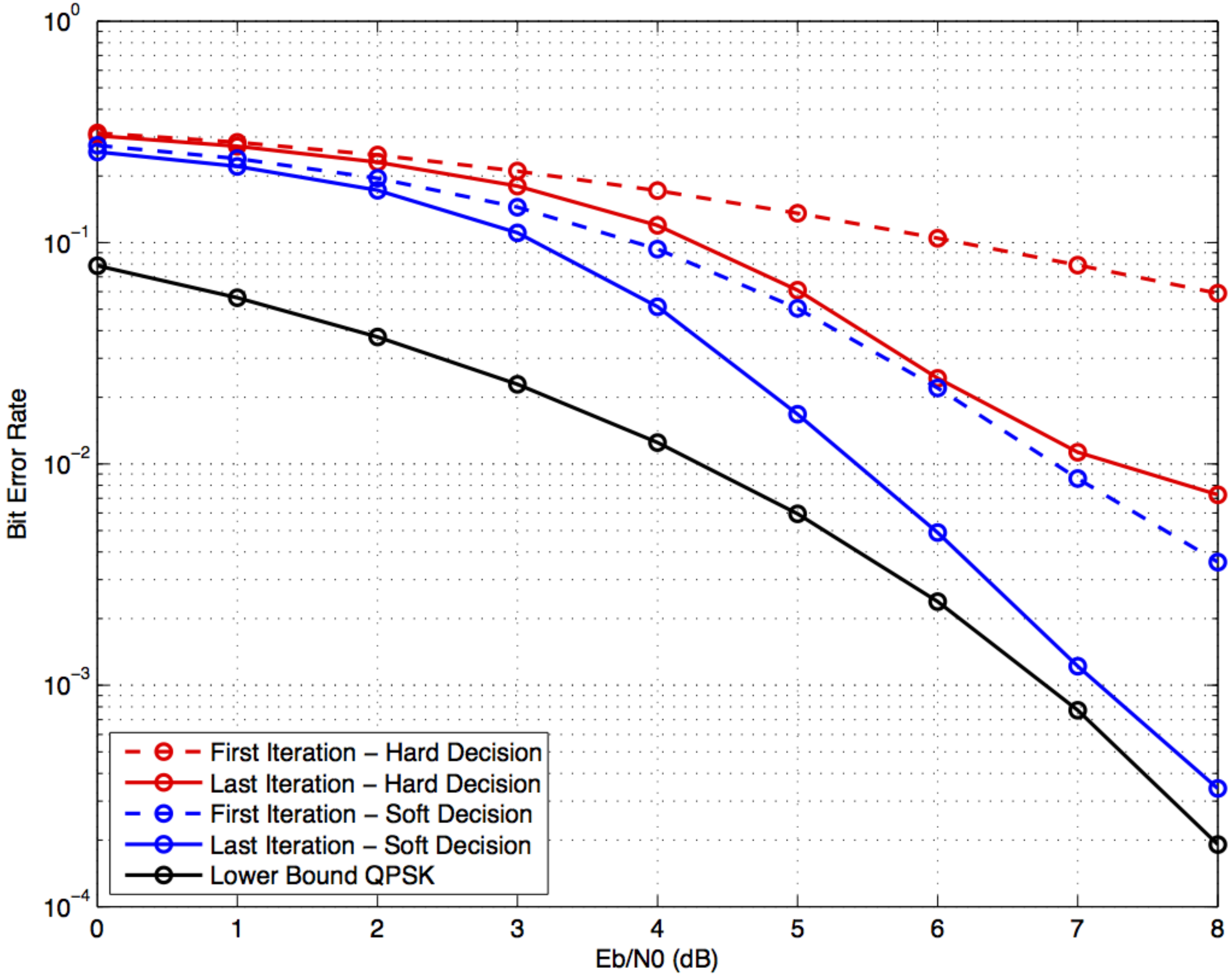
Shaping Zone
Defined by $\Phi(x)$

$$\Phi(x) = \begin{cases} -1, & \text{for } x < -\lambda \\ x/\lambda, & \text{for } -\lambda < x < +\lambda \\ +1, & \text{for } x > +\lambda \end{cases}$$

BER FOR OFDMA USERS (N = 256, M = 44)



BER FOR MC-CDMA USERS (N = 256, M = 44)



SUMMARY

- ☐ We first highlighted the fact the power imbalance required in power-domain NOMA places heavy constraints on resource allocation (for properly pairing users) and leads to uneven quality of service (QoS) figures.
- ☐ Next, we pointed out that although completely ignored in the recent literature, the foundation of NOMA actually goes back to the year 2000, when a series of papers introduced the concept of multiple access using two sets of orthogonal signal waveforms and iterative interference cancellation.
- ☐ Instead of pairing users and superposing their signals with the constraint of having a significant power imbalance, this early NOMA concept superposes the signals of two user groups and fully avoids the power imbalance requirement.

SUMMARY

- The instantaneous power imbalance that is required for the operation of the detector is an inherent property of the signal design in this scheme.
- Using this early concept, we have described a NOMA scheme which uses OFDMA as the primary signal set and MC-CDMA as the secondary signal set.
- This technique can be viewed as a natural extension of OFDMA to accommodate additional users. With the OFDMA already adopted by the 3GPP for eMBB and URLLC traffics in 5G, this scheme appears as an attractive solution to handle mMTC traffic by reusing the same radio resources.

TOPICS FOR FUTURE WORK

- Performance evaluation on fading channels.
- Inclusion of channel coding.
- Channel overload and performance tradeoffs using different types of detectors.
- Comparisons with other NOMA schemes.
- Study in the context of MIMO.
- Implementation issues, etc…

FURTHER READINGS

- H. Sari, A. Maatouk, E. Caliskan, M. Assaad, M. Koca, and G. Gui, "*On the Foundation of NOMA and its Application to 5G Cellular Networks*", Proc. WCNC 2018, April 2018, Barcelona, Spain.
- A. Maatouk, E. Caliskan, M. Koca, M. Assaad, G. Gui, and H. Sari "*Frequency-Domain NOMA with Two Sets of Orthogonal Signal Waveforms*", to appear in the IEEE Communications Letters.

THANK YOU

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