

Beyond LoRa and NB-IoT: Proposals for Future LPWA Systems

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I. EPHYL project context

II. Tailoring Index-Modulation for uplink IoT

III. Enhancing Coverage in Narrow Band-IoT Using Machine Learning

EPHYL: Enhanced PHY for Cellular Low power communication IoT



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□ 3 years project from Oct. 2016 to Dec. 2019

□ Partners

- Sequans, CEA-LETI, Centrale-Supélec, ISEP, and INRIA

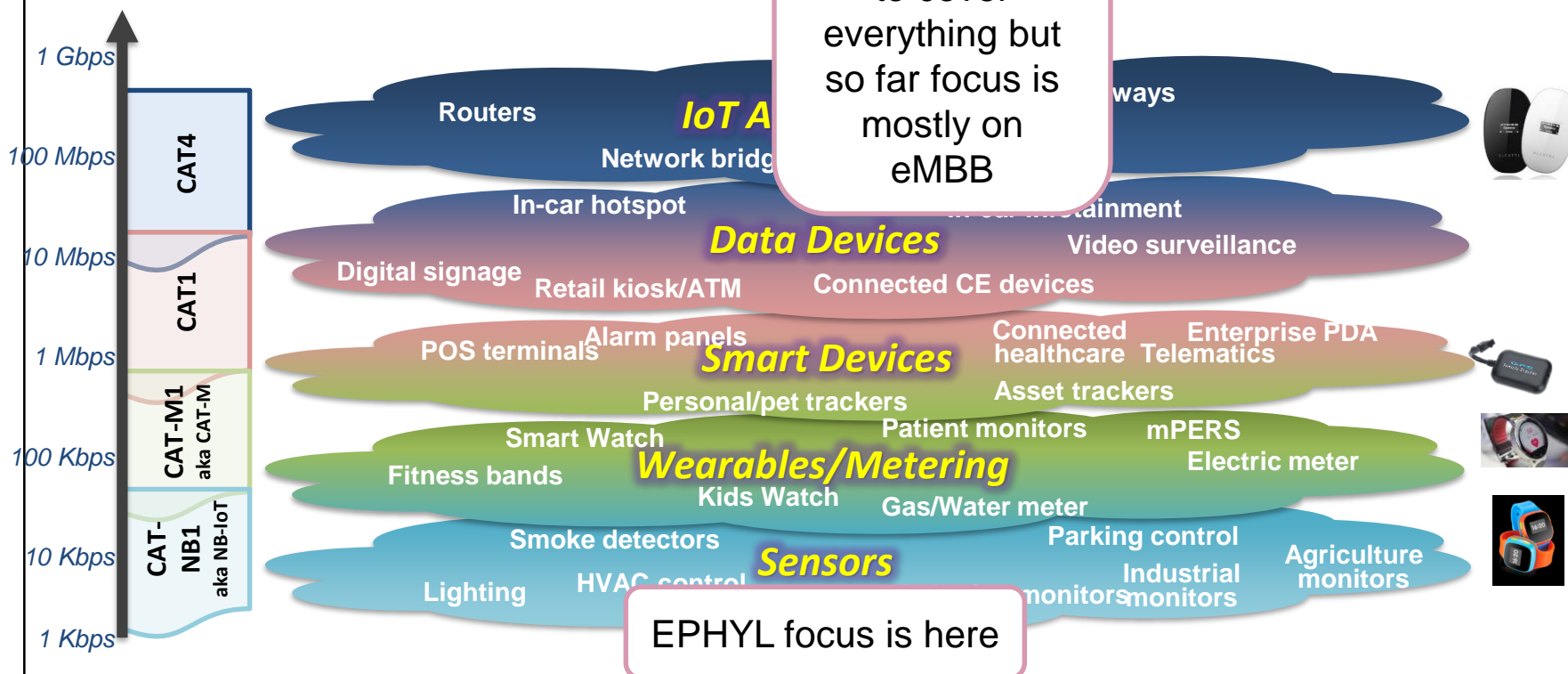


EPHYL
IoT waveforms

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Many types of IoT

5G is supposed to cover everything but so far focus is mostly on eMBB



Project Objectives

The overall objective of the project EPHYL is to investigate future LPWA technologies with the aim to improve coverage, data rate and connectivity while keeping similar level of complexity and power consumption at the node for the access.

New waveforms enablers will be investigated and trialed in order to increase the efficiency of future systems and to provide efficient and fair access to the radio resource.

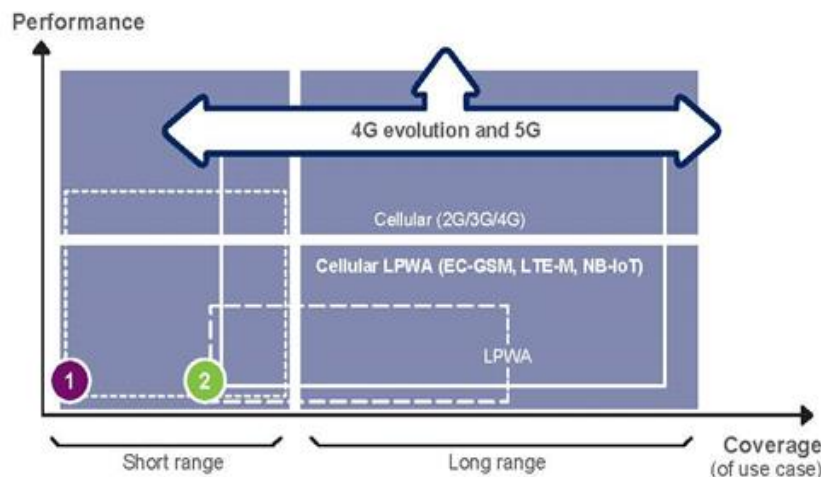


II. Tailoring Index-Modulation for uplink IoT

Internet-of-Things

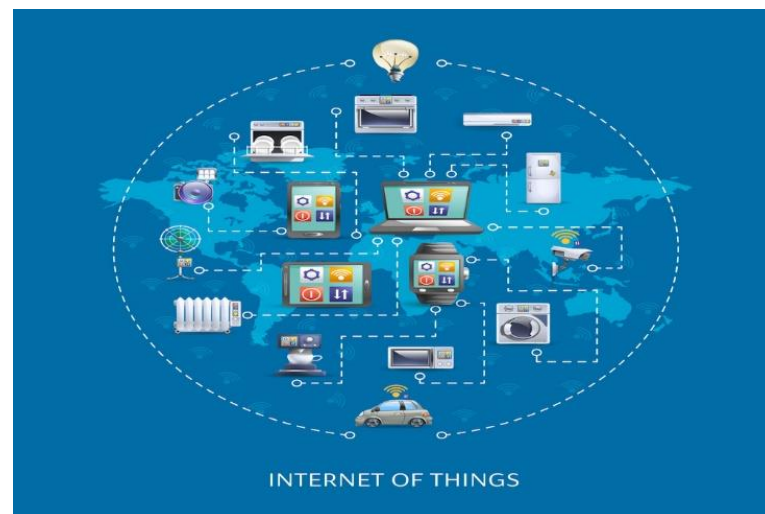


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Technologies addressing different IoT technologies
Source: Ericsson white paper 2016.

- 1 Unlicensed spectrum (Wi-Fi, Bluetooth, Zigbee etc.)
- 2 Unlicensed spectrum (SIGFOX, LoRa etc.)



Source: PYMNTS.com/ March 2017.

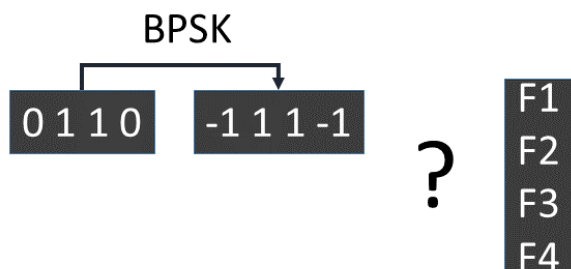
One of the most challenging requirement of countless range of IoT applications, is to achieve energy efficiency high enough to offer ten years of battery lifetime for end devices.

Unlike traditional cellular technologies, LPWA offers sets of features to low power devices at the expense of low data rates.

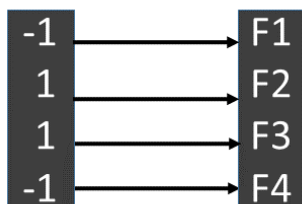
Indexed modulation (IM)

IM principle

- IM technique consists of selecting a set of sub-carriers for each symbol, the selected sub-carriers will carry on the input data symbols while the rest of the sub-carriers are turned off.
- Additional information is coded through the choice of sub-carriers indices in a given symbol.

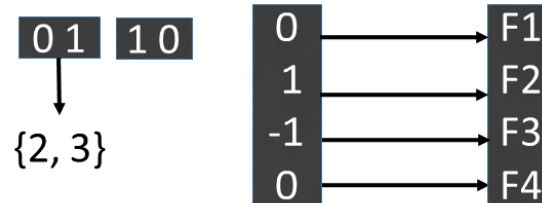


Conventional modulation



Index modulation

Bits	Index set
0 0	{1, 2}
0 1	{2, 3}
1 0	{3, 4}
1 1	{1, 4}



SC-FDMA with IM

Parameters:

U : the total number of users,

m_u : bits to transmit which are introduced to the index modulation block.

G_u : is the number of groups within an SC-FDMA-IM block

n_u : is the number of sub-carriers in each group,

k_u : is the number of active sub-carriers in each group

$m_u = G_u(m_1^u + m_2^u)$: input information bits is mapped to a SC-FDMA-IM symbol associated to a user u

$m_2^u = k_u \log_2(\mathcal{M})$ is the number of bits mapped to \mathcal{M} -ary constellation

m_1^u : is the number of bits to be mapped to an index set of active sub-carriers,

$K_u = k_u G_u$: is the total number of active sub-carriers

$N_u = n_u G_u$: the total number of the allocated sub-carriers for a user u

SC-FDMA with IM

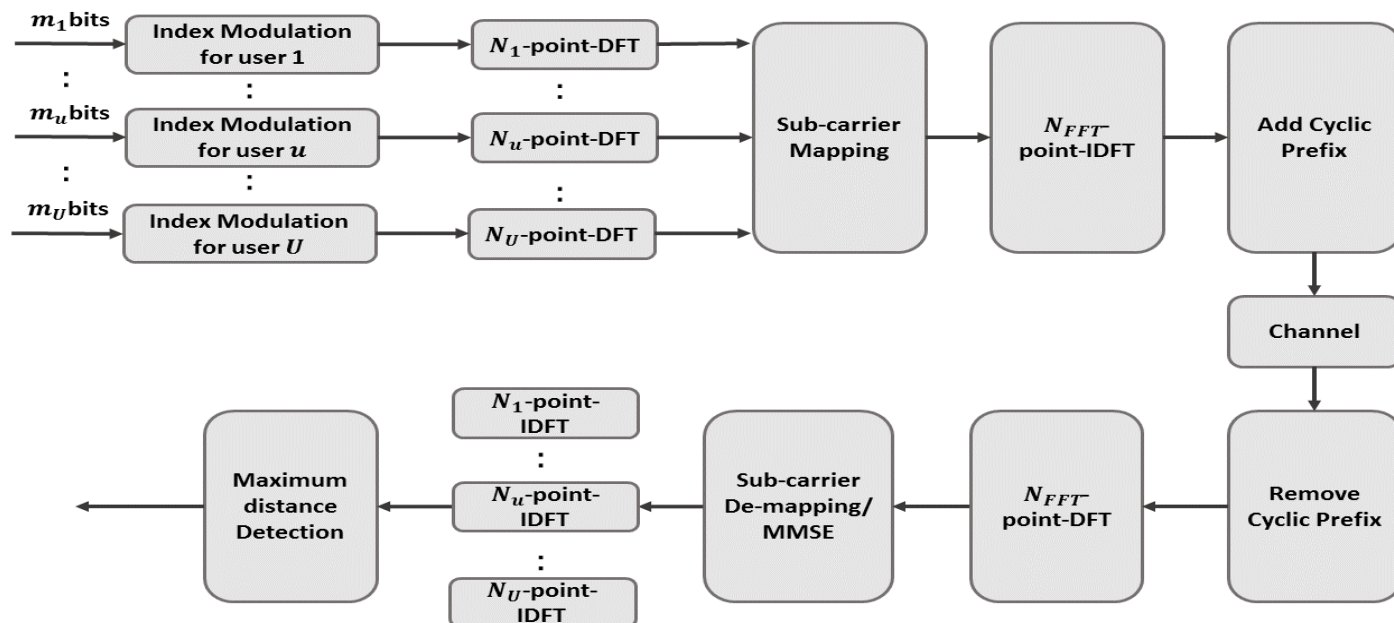


Figure: SC-FDMA-IM transceiver.

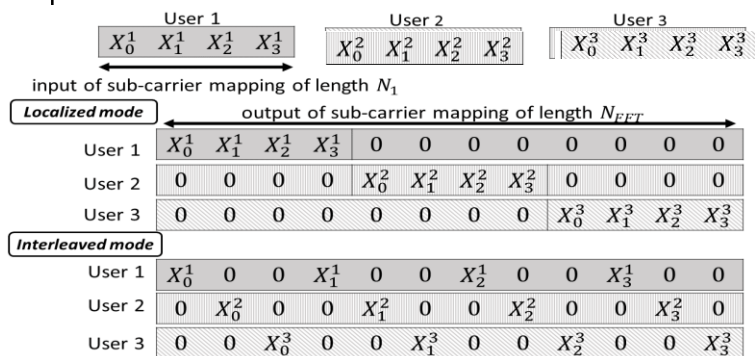


Figure: SC-FDMA-IM access modes. Example when number of users is equal to $U = 3$ and $N_{FFT} = 12$.

Spectral efficiency



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$$\xi(\text{bits/s/Hz}) = \frac{B^r(\text{bits/s})}{W(\text{Hz})}.$$

$$B_u^r = \frac{G_u}{T + T_{cp}} \left(\left\lfloor \log_2 \left(\frac{n_u}{k_u} \right) \right\rfloor + k_u \log_2(\mathcal{M}) \right).$$

$$\begin{aligned} \xi_{\text{IM}} &= \frac{\sum_{u=1}^U B_u^r}{\sum_{u=1}^U W_u} \\ &= \frac{\sum_{u=1}^U G_u \left(\left\lfloor \log_2 \left(\frac{n_u}{k_u} \right) \right\rfloor + k_u \log_2(\mathcal{M}) \right)}{(T + T_{cp}) \Delta F \sum_{u=1}^U N_u} \end{aligned}$$

For each group of sub-carriers, only $\text{round}(\alpha n_u)$ are active out of n_u ,

$$\rho(U) = \frac{G_U \left(\left\lfloor \log_2 \left(\frac{n_U}{k_U} \right) \right\rfloor + k_U \log_2(\mathcal{M}) \right)}{n G_U \log_2(\sqrt{\mathcal{M}})} - 1.$$

Spectral efficiency increase for different numbers of users: $\rho = \frac{\xi_{\text{IM}} - \xi_0}{\xi_0}$,
where ξ_0 is the spectral efficiency of the benchmark classical SC-FDMA.

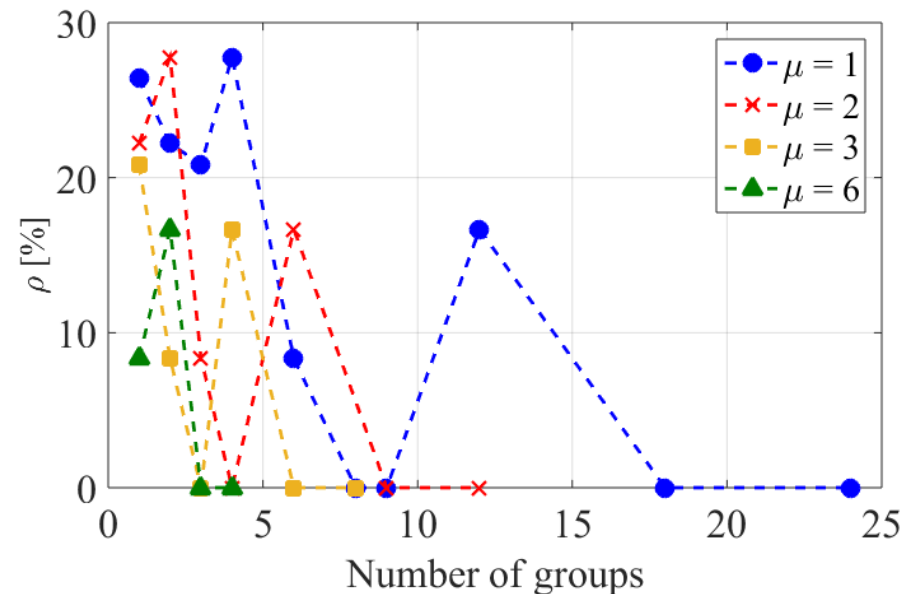


Figure: Spectral efficiency increase of different numbers of users for different numbers of groups.

Energy efficiency



To save energy in SC-FDMA-IM, we will activate the lowest possible number of active sub-carriers while maintaining the same spectral efficiency than classical SC-FDMA and a low implementation complexity.

The energy efficiency increase

$$(G_U, n_U, k_U) \in \begin{cases} (18, 4, 1) & \text{if } U = 1 \\ (9, 4, 1) & \text{if } U = 2 \\ (6, 4, 1) & \text{if } U = 3 \\ (3, 4, 1) & \text{if } U = 6 \end{cases} \rightarrow \mathcal{R}(U) = \frac{UG_U(k_U \log_2(\mathcal{M}) - n_U \log_2(\sqrt{\mathcal{M}}))}{Un_U G_U \log_2(\sqrt{\mathcal{M}})} = -50\%.$$



The introduction of index modulation reduces the energy consumption by 50% which is a significant improvement, especially for low-power wide-area networks.

Performance Analysis

Table: Parameter settings for SC-FDMA-IM

Parameters	Definition	Value for NB-IoT	Value for LTE-M
N_{FFT}	IFFT/FFT size	72	256
ΔF	Inter-carrier spacing	3.75 kHz	15 kHz
T	Duration of block of symbols	$\frac{1}{\Delta F}$	
T_{cp}	Duration of cyclic prefix	$T/8$	
RB	Resource Block	12 sub-carriers	
\mathcal{M}	\mathcal{M} -QAM Constellation	4 for SC-FDMA-IM and 2 for SC-FDMA	
r	Roll-off of the root raised cosine filter	0.3	
L	Upsampling coefficient	4	
ν	Number of path for Rayleigh channel	8	
N_{iter}	Number of iterations	10^6 for PAPR and BER simulations	

Table: Look-up table for IM.

Incoming bits m_1	Associated index set
00	1
01	2
10	3
11	4

$U = 6$ (1 RB is assigned to each user), in LTE-M, the user occupies 6 RB, $(n, k) = (4, 1)$, for signal recovery, a minimum mean square error (MMSE) equalization is employed along with a minimum distance detector.

PAPR Performance Analysis



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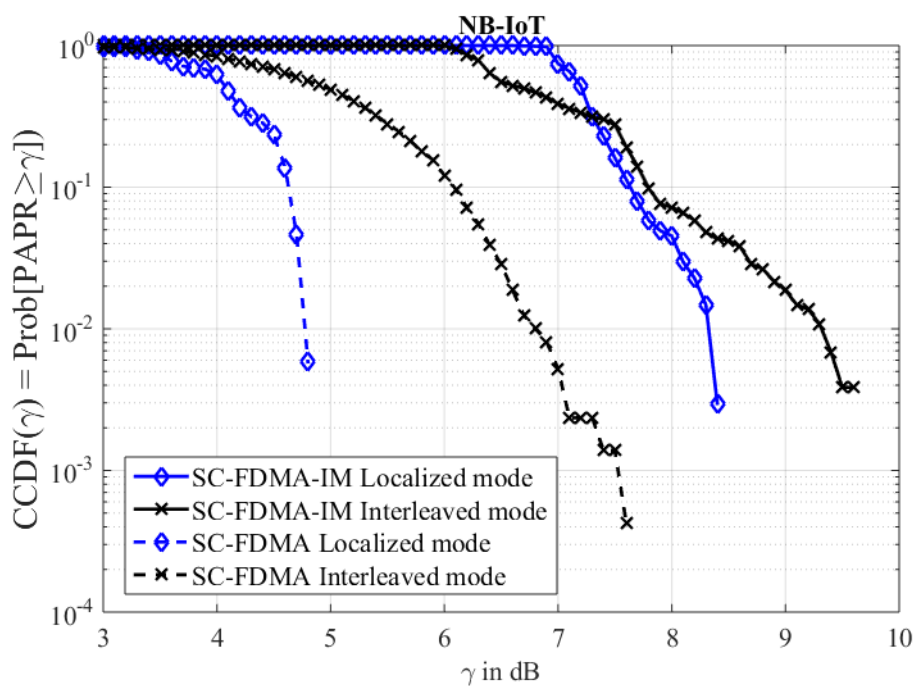


Figure: PAPR performance for SC-FDMA-IM in NB-IoT scenario.

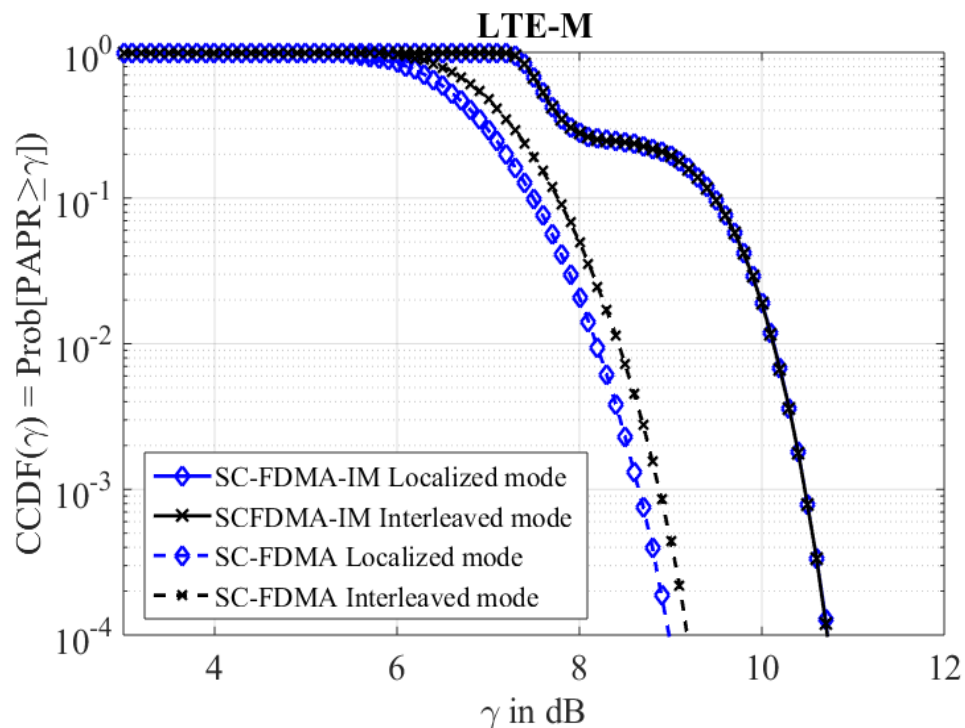


Figure: PAPR performance for SC-FDMA-IM in LTE-M scenario..

BER Performance Analysis



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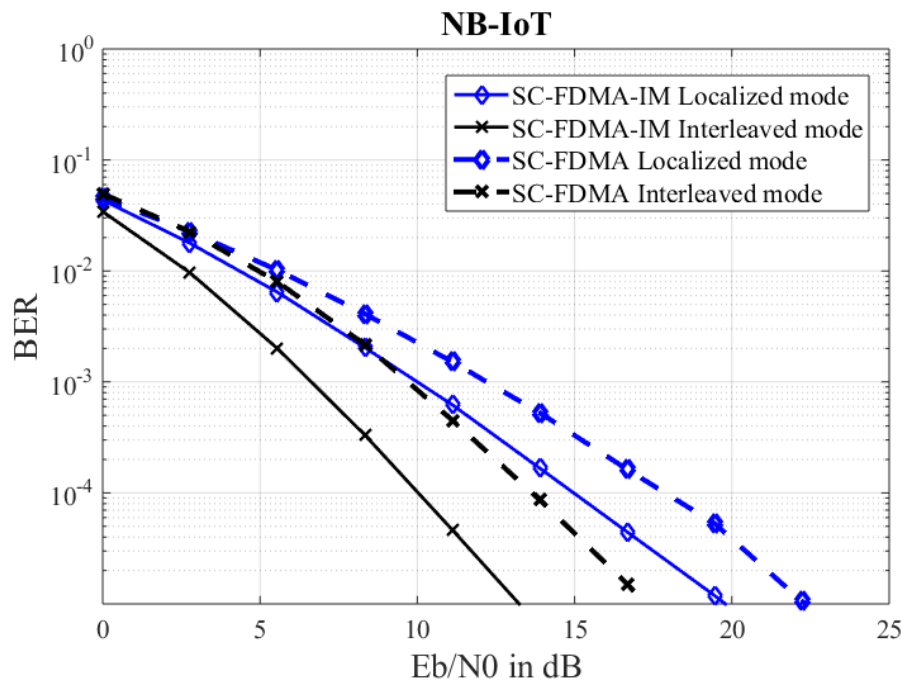


Figure: BER performance for SC-FDMA-IM in NB-IoT scenario.

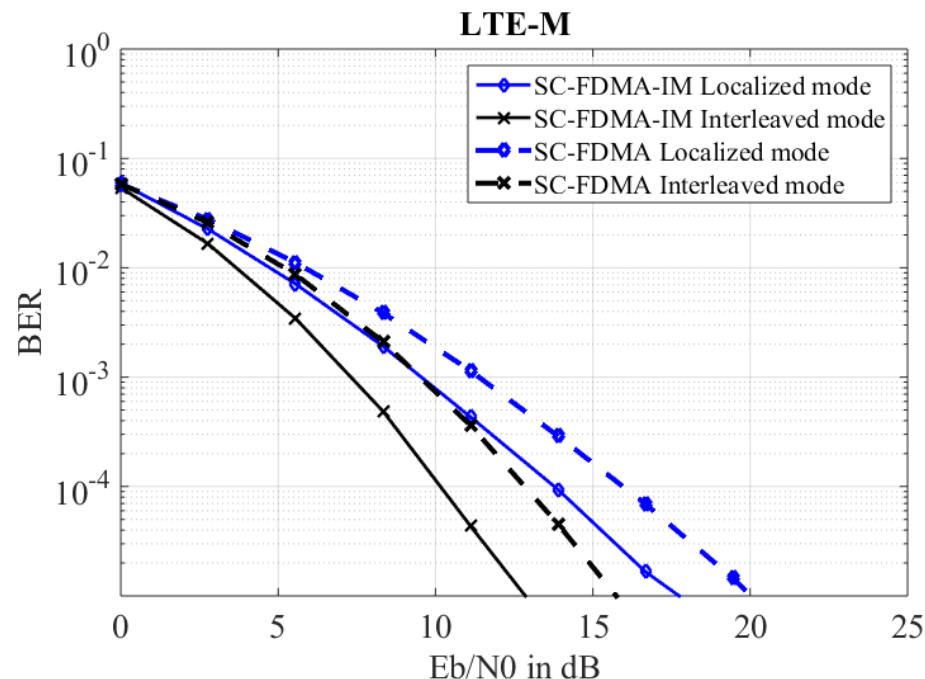


Figure: BER performance for SC-FDMA-IM in LTE-M scenario.

- Marwa Chafii, Faouzi Bader, and Jacques Palicot, "**SC-FDMA with Index Modulation for M2M and IoT Uplink Applications**", at the Proc. of the IEEE Wireless Communications and Networking Conference [IEEE WCNC'2018], Barcelona-Spain. April 2018.
- Julio Manco-Vasquez, Marwa Chafii, and Faouzi Bader, "**Tailoring Index-Modulation for uplink IoT and M2M Networks**", in the Proc. of the IEEE Wireless Communications and Networking Conference (IEEE WCNC'2019), Marrakech, Morocco, April 2019.

III. Enhancing Coverage in Narrow Band-IoT Using Machine Learning

NB-IoT Challenges

Coverage enhancements

Threes coverage classes are allowed by a serving cell to an NB-IoT end device:

- CE level 0: normal coverage with MCL 144 dB and 15 kHz sub-carrier spacing
- CE level 1: robust coverage with MCL 154 dB and 15 kHz sub-carrier spacing
- CE level 2: extreme coverage with MCL 161 dB and 3.75 kHz sub-carrier spacing

Depending on the coverage level, the serving cell indicates to the UE to repeat the transmission {1, 2, 4, 8, 16, 32, 64, 128} times, using the same transmission power on each repetition. Combining the different retransmissions allows a coverage extension.

NB-IoT Challenges

Energy consumption

There are mainly two energy efficient techniques that have been designed in NB-IoT in order to minimize the power consumption in end devices and increase their battery life:

- Idle mode extended discontinuous reception (I-eDRX): This mode allows a discontinuous reception for maximum of 3 hours.
- Power saving mode (PSM): This energy saving mode allows unconnected state for up to 13 days, where UE enters to a deep sleep.

Unlike in I-eDRX, UE is unreachable while remains registered in the network. This mode save more energy than the idle mode.

Dynamic Spectrum Access



- ❑ The spectrum learning process can be modelled as a multi-armed bandit (MAB) framework.

Concept related to the MAB framework :

Reward: reward $r_t(k)$ in our scenario takes two values 0 or 1. After sensing the channel with the best probability of availability and the best probability of good coverage is updated.

Exploitation and exploration dilemma: It refers to a trade-off between the exploitation of the channel with highest reward, and exploring the other channels in order to get more information about their payoffs.

Regret: It means the loss represented by the difference between the expected reward associated to the suboptimal channel learned by the end device, and the ideal reward associated to the optimal channel. The regret of a policy π is:

$$R_t^\pi = t \cdot \underset{\substack{\downarrow \\ \text{reward of the optimal channel.}}}{\mu^*} - \sum_{l=0}^{t-1} r_l,$$

Let $\mu_k = E[d_k]$ the mean reward of the k^{th} channel.



$$E[R_t^\pi] = \sum_{k=1}^K (\mu^* - \mu_k) E[T_k(t)],$$

Expected cumulative regret

UCB in dynamic spectrum access

Parameters:

Upper confidence bound index $B_k(t)$ is computed at each instant t and for each channel k , and gives an estimation of the expected reward of a channel k . The UCB index is expressed as:

$$B_k(t) = \bar{X}_k(t) + A_k(t),$$

$$\text{such that } \bar{X}_k(t) = \frac{1}{T_k(t)} \sum_{l=0}^{t-1} r_l(k) \mathbb{1}_{\{a_l=k\}}$$

$$A_k(t) = \sqrt{\frac{\alpha \ln t}{T_k(t)}},$$

\bar{X}_k is the sample mean of the channel k reward

A_k is an upper confidence bias

α is an exploration coefficient for channel availability and coverage

$$a_t = \arg \max_k (B_k(t)).$$

Simulation results

NB-IoT supports the following deployment modes:

- In-band mode where NB-IoT is deployed within the LTE bandwidth, and occupies one or multiple physical resource blocks (180 kHz).
- Guard-band mode where NB-IoT operates within the guard-band of an LTE carrier
- Stand-alone mode where NB-IoT can either occupies one or more GSM carrier (200 kHz), or it can be deployed in an adjacent band to LTE.



LTE bandwidth	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
LTE PRB indices for NB-IoT	2, 12	2, 7, 17, 22	4, 9, 14, 19, 30, 35, 40, 45	2, 7, 12, 17, 22, 27, 32, 42, 47, 52, 57, 62, 67, 72	4, 9, 14, 19, 24, 29, 34, 39, 44, 55, 60, 65, 70, 75, 80, 85, 90, 95



Table I: LTE PRB indices allowed synchronization in for NB-IoT in-band deployment.

UCB Definitions

μ_{vac}^k : the expected mean reward associated to the vacancy of the PRBs k

μ_{cov}^k : the expected mean reward related to the coverage level of the PRBs k

Without loss of generality, we assume $\mu_{vac}^1 \leq \mu_{vac}^2 \dots \mu_{vac}^{14}$

$\mu_{vac}^1 = 10\%$ means that channel 1 is available 10% of the time.

$\mu_{cov}^1 = 50\%$ means channel 1 has a probability of 50% to be in a good coverage when it is free

PRB index	Channel index	μ_{vac}^k [%]	μ_{cov}^k	μ_{rep}^k	$\mu_{vac,cov}^k = \mu_{vac}^k \cdot \mu_{cov}^k$	$\mu_{vac,rep}^k = \mu_{vac}^k \cdot \mu_{rep}^k$
2	1	10	1	1/4	0.1	0.02
7	2	20	1/3	1/64	0.06	0.003
12	3	25	1/2	1/8	0.12	0.031
17	4	30	1/2	1/16	0.15	0.018
22	5	35	1/3	1/64	0.11	0.005
27	6	40	1/2	1/16	0.2	0.025
32	7	45	1/2	1/4	0.22	0.112
42	8	50	1/3	1/64	0.16	0.007
47	9	55	1	1/2	0.55	0.275
52	10	60	1/3	1/128	0.2	0.004
57	11	65	1/2	1/8	0.32	0.081
62	12	70	1/3	1/64	0.23	0.01
67	13	80	1	1/2	0.8	0.4
72	14	90	1/3	1/128	0.3	0.007

Table II: NB-IoT channel parameters for an LTE Bandwidth of 15 MHz when in-band mode is deployed.

UCB Scenarios



UCB(vac) means that the policy consider only the vacancy distributions μ_{vac}^k and assumes that the different channels have the same coverage properties.

UCB(vac,cov) takes into account both the vacancy and the coverage criteria. The policy is then based on the distribution $\mu_{vac,cov}^k$, which is inversely related to the coverage level.

UCB^k(vac,rep) considers the number of required repetitions rather than the coverage level along with the availability of the channel. $\mu_{vac,rep}^k$ is then the mean reward distribution considered in this case, which is inversely related to the number of repetitions.

UCB(vac, \overline{cov}) in this scenario, the channels do not have the same coverage quality but follow the distributions μ_{cov}^k . However, the end device does not take the coverage criterion in the calculation of the UCB index, its calculation is based only on the vacancy distributions μ_{vac}^k .

Performance Analysis

The exploration coefficient α is set to 1.5 for all the studied scenarios.

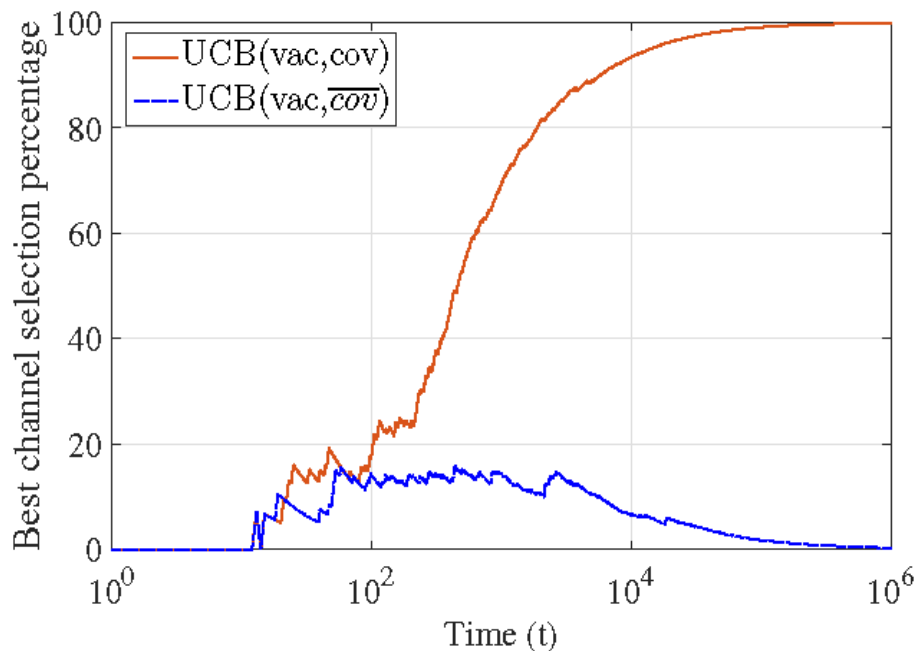


Figure 1: Impact of considering coverage on best channel selection percentage.

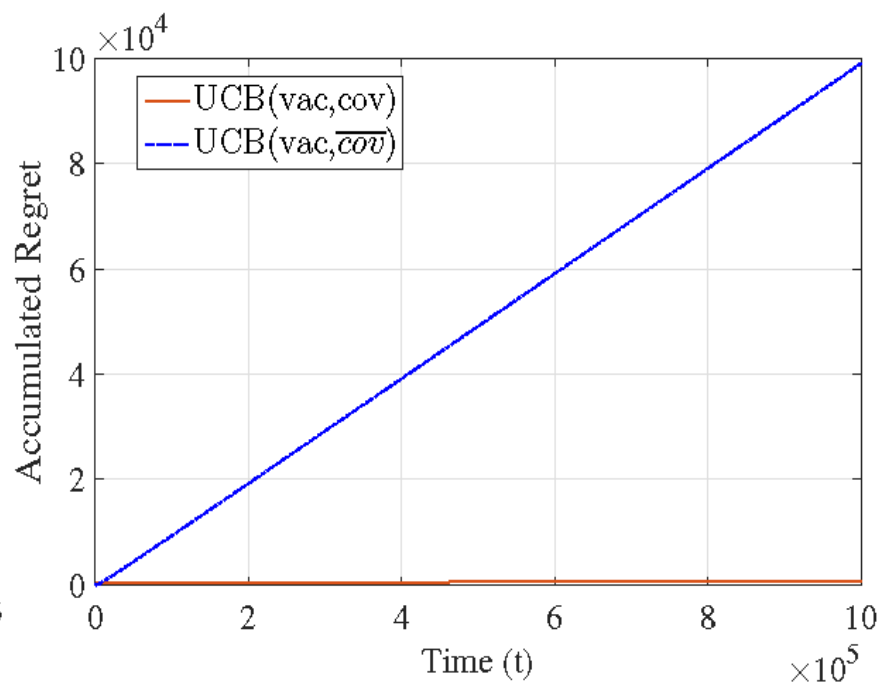


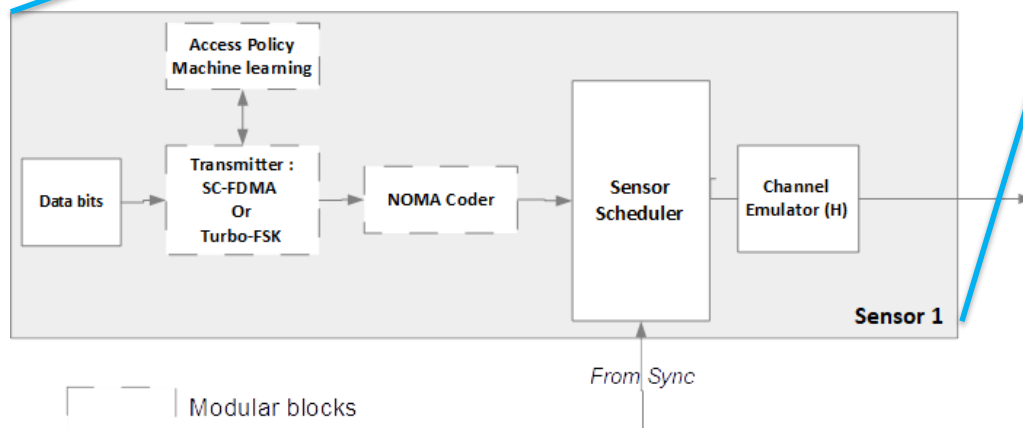
Figure 2: Impact of considering coverage on accumulated regret.

Prototyping and demonstration: FIT/CorteXLAB



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- Open environment
- We developed a framework to emulate LPWA that could be reused by the community



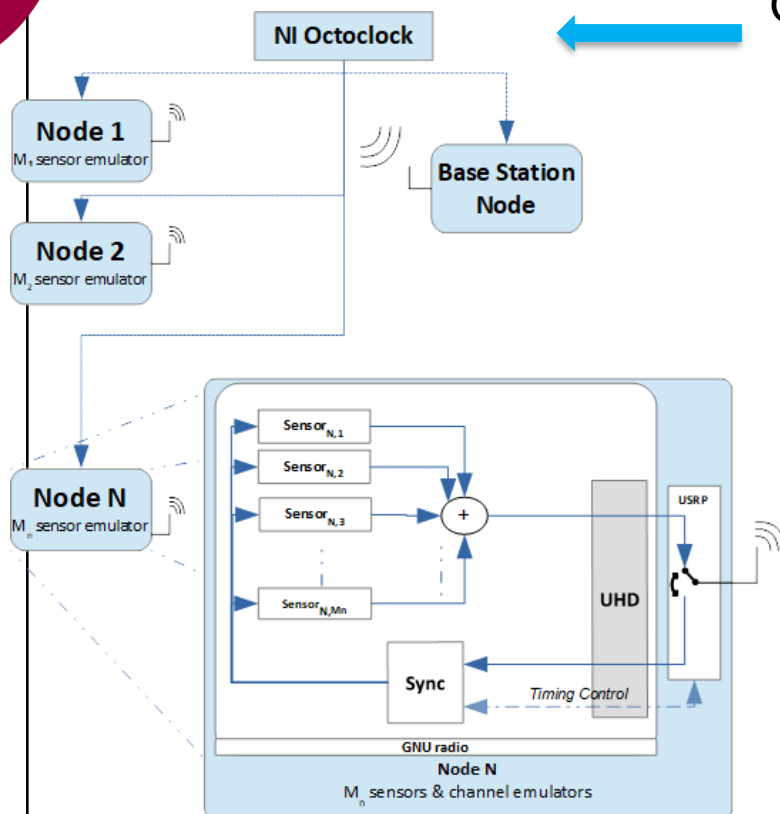
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Prototyping and demonstration

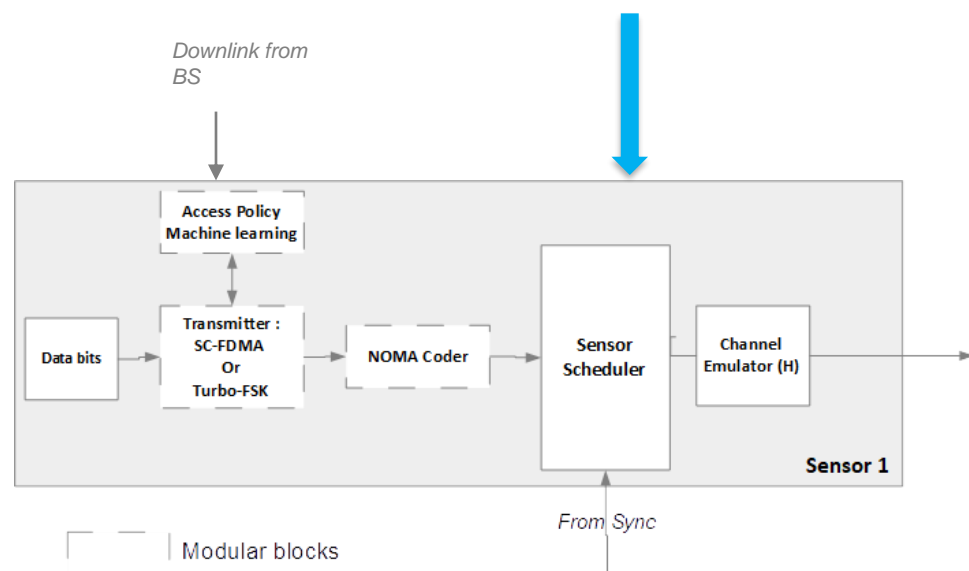


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Overall view of the network



Sensor architecture



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Conclusions

- ❑ LPWA is more and more important
- ❑ 3GPP has defined a set of solutions to cover all IoT needs, in particular cat-M and NB-IoT; Proprietary solutions (Lora, Sigfox) were proposed too
- ❑ EPHYL is focusing on waveforms and methods going beyond those solutions
- ❑ More efficient modulation and coding scheme for PHY
- ❑ Modern MAC, towards distributed but efficient access
- ❑ Proposals are being prototyped in FIT/CorteXLAB environment; most of development will be release as open source.

Thank you for your attention,

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