Preliminary evaluation of NB-IOT technology and its capacity

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***Abstract*—The Internet of Things (IoT) addresses a huge set of possible application domains, requiring both short- and long-range communication technologies. For long distances, a number of proprietary and standard solutions for Low Power Wide Area Networks (LPWAN) are already available. Among them, NB-IOT is a candidate technology supported by many operators. This paper provides an estimation of the uplink performance, through a mathematical approach, in terms of network throughput. Finally, the optimization of a specific set of parameters, in order to provide the best performance, is discussed.**

I. INTRODUCTION

The Internet of Things (IoT) is emerging as a set of integrated technologies, new solutions and services, which are expected to change the way people live and produce (or benefit from) goods. The IoT paradigm, making all unmanned ”things” (daily objects, industry machines, sensors, robots, animals, etc.) connected to the Internet, addresses a very large set of application domains. Recently, the interest of industry towards applications requiring a very long range of transmission and low energy consumption, denoted as Low Power Wide Area Networks (LPWAN), grew significantly [1].

Some proprietary solutions, working on license-exempt spectrum bands, are already deployed in some regions: as an example Sigfox[1] operates both as a technology and a service provider for LPWAN; another big player is the LoRa Alliance[2], which produced a proprietary solution known as LoRaWAN working in the license-exempt band, available in many countries, close to 900 MHz. Meanwhile, the 3GPP is supporting three different LPWAN standards that will work on the licensed spectrum of mobile networks and will be commercially available by the end of 2017: Extended Coverage GSM (EC-GSM-IoT), LTE Machine Type Communications Category M1 (LTE-MTC Cat M1) and Narrowband IoT (NB-IOT). The latter technology has technical characteristics similar to LPWAN proprietary solutions, with the advantage of being a standard; many mobile network operators worldwide are supporting the development of NB-IOT, which might become a future reference IoT communication technology for several application domains. In the meanwhile, some network operators are pushing the LoRaWAN technology and supporting the developers’ community [2].

In this context, made of many evolving technologies, it can be expected that a single one will not be capable of addressing efficiently all the different IoT use cases. It is in the interest of big players, to identify the range of applications that make a specific technology suitable. This paper shows results of an ongoing project developed at the University of Bologna supported by Telecom Italia Mobile, both interested into defining the technical limits of NB-IOT and the opportunities it provides.

The scientific literature on NB-IOT is slowly expanding. Various surveys have been published since the definition of the standard, such as [3], [4] or [5]. In [6] the Authors focus on the estimation of NB-IOT coverage capability in different scenarios through simulations of the various physical channels. In [7] the Authors perform a study on a possible deployment in the city of London considering only a fraction of the base stations upgraded with the new technology. In [8] a detailed study of the capacity of a possible real case deployment in a rural area is conducted. After the coverage capability is assessed, considering realistic measurements on the territory, the capacity in terms of network average data rate is estimated. This estimation is accurate but limited to a specific scenario and application. Our intent is to provide a general overview of a NB-IOT system, the degrees of freedom represented by some configuration parameters, their impact on the system performance and to provide models which can be applied to a wider set of scenarios.

II. NB-IOT TECHNOLOGY

NB-IOT was designed having in mind the need for low deployment and hardware costs. This technology can be considered as a new LTE class of devices with a new physical layer but similar upper layers for an easy integration with the existing cellular network.

The minimum amount of radio resources that can be reserved for a NB-IOT system is a Physical Resource Block (PRB) which, according to the 3GPP standard, corresponds to a 180 kHz band.

The User Equipment (UE) and the evolved Node B (eNB) exchange information using the new physical channels described in detail in Sections II-A and II-B. A combination of UDP and IP, two well known and simple protocols, are used in NB-IOT; they introduce only a 28 bytes overhead.

Resources are assigned to the UEs according to a scheduling algorithm that runs with period T_S usually equal to the Transmission Time Interval (TTI). In [4] the Authors suggest

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[1] Sigfox, http://www.sigfox.com/en/

[2] LoRa alliance, https://www.lora-alliance.org/.

to use a TTI equal to 640 ms, differently from LTE which commonly uses 40 ms.

A. Physical Uplink Shared Channel

Most of the uplink radio resources are used by the Narrowband Physical Uplink Shared Channel (NPUSCH), where the UEs transmit their data free from interference from other users thanks to the scheduling mechanism.

As in LTE, the PRB can be divided into 12 subcarriers spaced by $\Delta f = 15$ kHz, but to improve the coverage a spacing of $\Delta f = 3.75$ kHz can also be selected, for a total of 48 subcarriers per PRB. The reduced bandwidth improves the receiver sensitivity as the same amount of energy is overlapped with a smaller amount of noise; ultimately the transmission range is improved considerably at the expense of the bitrate and energy consumption as the transmission occupies the channel for a longer amount of time.

The time axis numerology is inherited from LTE, 10 ms frames are divided into 10 subframes or 20 time slots, each of them containing $N^{UL}_{symb} = 7$ SC-FDMA symbols. Each combination of subcarrier and SC-FDMA symbol is called Resource Element (RE), which can encode either 1 or 2 bits depending on the modulation used.

Although in LTE a whole PRB could be assigned as a resource to a user, in NB-IOT the minimum allocable Resource Unit (RU), is smaller. Different sizes are allowed in order to accommodate efficiently a much larger number of users; every RU, in general, is composed of N^{RU}_{sc} subcarriers and N^{UL}_{slots} time slots.

Table 10.1.2.3-1 of the standard document [9] reports the allowed sizes.

The REs present in the time-frequency domain are not dedicated entirely to user data, some of them are reference symbols for synchronism purposes. The actual number of useful REs in a RU (N^{RU}_{RE}) to be considered is reported in Table A.16.1-1 of [10] and can be either 96 or 144.

In order to further improve coverage, blind retransmissions can be used. As defined in [9], the parameter M^{NPUSCH}_{rep} represents how many times the radio resources assigned to a particular upstream should be repeated immediately; in other words, if the packet to be transmitted requires N_{RU} RUs, the eNB will reserve $N_{RU} \times M^{NPUSCH}_{rep}$ consecutive RUs for the transmission.

B. Physical Random Access Channel

The remaining part of the time-frequency plane is dedicated to the Narrowband Physical Random Access Channel (NPRACH) which is used to perform the Random Access Procedure.

For this physical channel the spacing between different subcarriers is 3.75 kHz. Among the 48 subcarriers available in the PRB, only N_{sc} are dedicated to the Random Access Procedure.

The Random Access Procedure is triggered by different events, in particular when the application requires the transmission of a packet to the network. First a signal called *preamble* is transmitted to notify the eNB the intention to transmit, then an handshake between the two devices let the UE get a temporary address. During this procedure potential collisions between preambles transmitted by different devices are solved; among all the colliding devices, only to one the transmission is granted by the eNB.

The preamble is composed by several Symbol Groups, signals which occupy a single subcarrier for different amounts of time depending on the size of the cell. A UE that wants to initiate a Random Access Procedure has to select a random subcarrier on which to transmit the first symbol group, then it has to perform frequency hopping, according to a pseudo-random sequence, until four symbol groups are transmitted. Once a preamble is sent, similarly to the NPUSCH, it is possible to perform repetitions in order to enhance the coverage; therefore M^{NPRACH}_{rep} preambles are sent in total, each of them containing symbol groups which continue following the frequency hopping sequence.

The pseudo-random sequence is defined in a way that if two UEs in the same cell choose the same initial subcarrier, their preambles would overlap entirely until the end of the NPRACH, whereas if the initial subcarriers were chosen differently, no overlap would occur. As a consequence, the NPRACH is constituted by N_{sc} orthogonal resources.

As represented in Figure 1, the NPRACH is scheduled cyclically with a period of N^{NPRACH}_{period} ms, while the NPUSCH occupies the remaining time intervals. The length of a NPRACH occurrence is constant, therefore increasing the period implies to reserve more resources to the NPUSCH and viceversa.

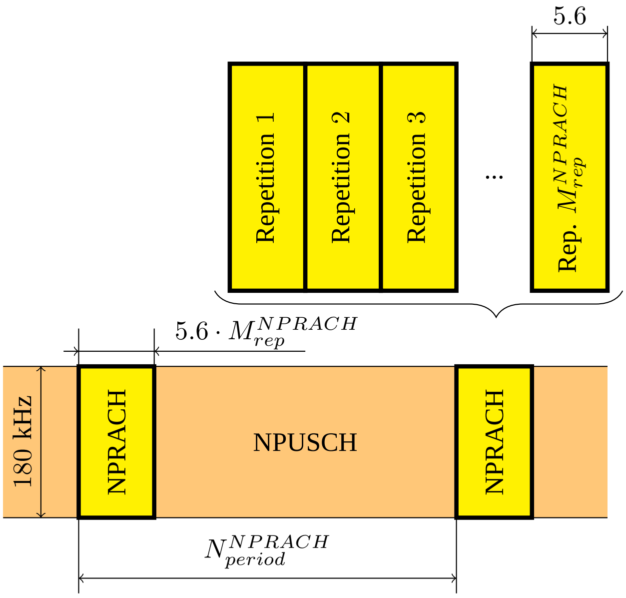

Fig. 1. NPRACH and NPUSCH scheduling (quotes are in ms).

III. SYSTEM LEVEL ANALYSIS

A. Performance metrics

The scenario considered in this paper is an area where N UEs are deployed and connected to a network composed of a single eNB.

Every UE is implementing a given use case defined by λ, the average number of packet transmitted per unit of time by a single device, and P_L, the payload size of a packet in bytes.

We define the network throughput (T) as the amount of application layer information sent by the UEs that the network receives and processes per unit of time. The throughput is limited by the characteristics of the physical channels, so its maximum value (T_{max}) is an indication of the maximum capacity of the network in a given configuration.

B. Assumptions

In this paper we define a series of assumptions on the network functioning, which allows us to develop a simple mathematical model to provide a performance estimation close to reality.

We assume perfect orthogonality among the radio resources in the NPUSCH and a perfect coverage, therefore the only cause of packet transmission failure is a collision during the Random Access Procedure. Notice that with the term collision we intend the case of multiple UEs choosing the same initial subcarrier for the frequency hopping sequence which are not distinguishable by the eNB which, therefore, will grant the resources only to one of them.

We assume to use format 0 preamble, which implies a preamble length of 5.6 ms, and to have only a single coverage class, therefore all the subcarriers in the NPRACH are available to initiate the Random Access Procedure and $N_{sc} = 48$.

Taking into account these assumptions, it is possible to derive an expression for the success probability of the Random Access Procedure (P_s^{RAP}) given N_U concurrent users accessing the same NPRACH occurrence. The procedure succeeds if the UE of interest is chosen by the eNB instead of one of the other C UEs which started the hopping sequence from the same initial subcarrier. This probability can be formulated as

$$p_S^{RAP} = \sum_{c=0}^{N_U} Pr\left\{\text{success}|C=c\right\} Pr\left\{C=c\right\} \tag{1}$$

The success probability conditioned to having other c concurrent users is $Pr\left\{\text{success}|C=c\right\} = \frac{1}{1+c}$, while the probability for this particular case to happen is

$$Pr\left\{C=c\right\} = \binom{N_U}{c}\left(\frac{1}{N_{sc}}\right)^c\left(1-\frac{1}{N_{sc}}\right)^{N_U-c} \tag{2}$$

Finally, the success probability of the Random Access Procedure can be expressed as

$$P_s^{RAP} = \sum_{c=0}^{N_U} \frac{1}{1+c}\binom{N_U}{c}\left(\frac{1}{N_{sc}}\right)^{N_U}\left(N_{sc}-1\right)^{N_U-c} \tag{3}$$

Notice that when the number of users is very high, approximately one user per subcarrier succeeds, therefore the following statement is true

$$\forall N_U >> N_{sc} \Rightarrow P_s^{RAP} \simeq \frac{N_{sc}}{N_U} \tag{4}$$

Using this last approximation, it is possible to derive an expression for the maximum system throughput considering only the limits of the NPRACH.

$$T_{max}^{NPRACH} = \frac{8P_L N_{sc}}{N_{period}^{NPRACH}} \tag{5}$$

We assume $\Delta f = 15kHz$, a perfect scheduling algorithm and a resource allocation pattern which allows to have a RU scheduled every ms. A pattern that complies to this description utilizes two RU composed by 3 subcarriers and 8 time slots, and two RU composed by 6 subcarriers and 4 time slots. All four resources contain $N_{RE}^{RU} = 144$ REs.

For simplicity we assume the reference channel A16-5 is used as defined in annex A.16 of [10]: QPSK modulation ($l = 2$ bit per symbol), an effective channel coding rate of $R_C = 0.56$ and an overhead due to upper layers of 28 bytes for UDP/IP and 24 bits for Transport Block CRC.

For each application upstream consisting in P_L bytes of data, the number of RU being requested by the UE is calculated as

$$N_{RU} = \left\lceil \frac{8(P_L+28)+24}{lR_C N_{RE}^{RU}} \right\rceil \tag{6}$$

The actual number of RUs allocated for the transmission is $N_{RU} \times M_{rep}^{NPUSCH}$ as mentioned in Section II-A.

Under these assumptions, the maximum throughput in kbps achievable, considering only the NPUSCH, is

$$\begin{aligned} T_{max}^{NPUSCH} = & \frac{8P_L}{N_{RU} M_{rep}^{NPUSCH} N_{period}^{NPRACH}} \times \\ & \times \left\lfloor N_{period}^{NPRACH} - 5.6 \cdot M_{rep}^{NPRACH} \right\rfloor \end{aligned} \tag{7}$$

In the end, the whole system is limited by the channel with the smallest capacity; therefore the maximum network throughput is defined as $T_{max} = \min\{T_{max}^{NPUSCH}, T_{max}^{NPRACH}\}$.

C. Optimal configuration of the network

NB-IOT has a considerable complexity; in order to plan an appropriate deployment and get an optimal performance, it is important to understand the degrees of freedom involved.

We already mentioned how the uplink channel is limited by the capacity of the NPRACH and NPUSCH combined, a configuration of the parameters such that one channel is saturated while the other one is under-used has to be avoided.

Equation 7 shows how the throughput of the NPUSCH depends on the NPRACH periodicity. In particular as the periodicity increases, the throughput increases and reach asymptotically a certain value. On the other hand the throughput of the NPRACH, expressed in Equation 5 has an opposite behavior. Therefore the network throughput can be maximized

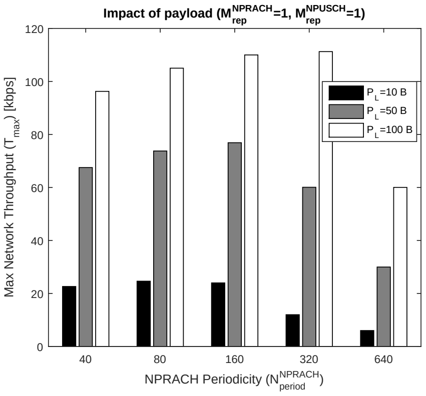

Fig. 2. Network Throughput as function of payload size and NPRACH periodicity.

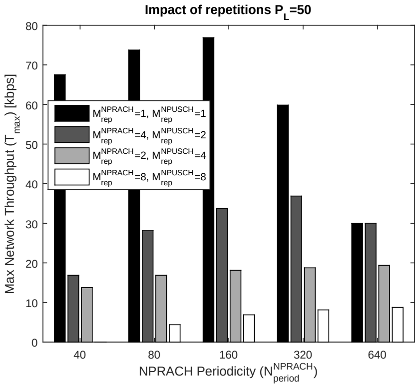

Fig. 3. Network Throughput as function of the number of repetitions in the two channels and NPRACH periodicity.

by selecting a proper value of N_{period}^{NPRACH}. We express the resulting throughput as $\hat{T}_{max}$.

There are two other parameters which have a considerable impact on the performance of the network: M_{rep}^{NPUSCH} and M_{rep}^{NPRACH}. As the devices lose coverage, they may decide to change coverage class and use a different number of blind repetitions in the two channels. In this way the budget link is improved due to the introduction of a processing gain at the expense of the throughput.

Both parameters affect only the capacity of the NPUSCH as expressed in Equation 7. In particular the impact of increasing M_{rep}^{NPRACH} is moderate because normally the increased length of the NPRACH would still be short with respect to the NPRACH period, therefore the number of RUs in the NPUSCH is reduced only by a small amount. On the other hand increasing M_{rep}^{NPUSCH} leads to a much more important proportional decrease of the throughput as this parameter is in the denominator of Equation 7.

IV. NUMERICAL RESULTS

Firstly we studied how the payload size affects the network throughput and the problem of the optimization of the NPRACH periodicity. Figure 2 shows how T_{max} varies for all the possible values of periodicity allowed, $N_{period}^{NPRACH} \in \{40, 80, 160, 320, 640\}$, and for three possible payload sizes which represent roughly the possible range of allowed values, 10, 50 and 100 bytes.

In general the throughput is greatly affected by the payload size because the overhead introduced by the UDP/IP protocol is comparable to the amount of useful data. $\hat{T}_{max}$ can vary from 25 to 111 kbps for this reason. The optimal value of periodicity increases from 80 to 320 as the payload size increases.

To study the dependence of the throughput with the repetitions we evaluate four scenarios defined by the pairs $\left(M_{rep}^{NPUSCH}, M_{rep}^{NPRACH}\right) \in \{(1,1), (2,4), (4,2), (8,8)\}$. We chose these values because the two parameters, most likely, would assume a similar value during the nominal functioning of the network as the coverage should be improved in both channels equally.

Figure 3 shows how T_{max} varies as the periodicity is set differently for the settings of repetitions considered. A payload of 50 bytes is assumed.

It is clear that an increase of the repetitions cause a dramatic drop of the performance, from $\hat{T}_{max} = 77$ kbps, in case only one repetition is used, to $\hat{T}_{max} = 9$ kbps, when 8 are used in both channels. In the intermediate cases the throughput varies considerably depending on which parameter is greater. As predicted, M_{rep}^{NPUSCH} has the biggest impact on the performance as the configuration $\left(M_{rep}^{NPUSCH}, M_{rep}^{NPRACH}\right) = (4, 2)$ produces a throughput which is half of the one produced by $\left(M_{rep}^{NPUSCH}, M_{rep}^{NPRACH}\right) = (2, 4)$.

When the number of repetitions is changed, the optimal value of NPRACH periodicity varies considerably, generally speaking it increases as M_{rep}^{NPUSCH} increases. In Table I we report the optimal values of N_{period}^{NPRACH} and the resulting throughput $\hat{T}_{max}$. In any case the configurations studied in this paper represent only a small subset of all the possible cases, in fact the repetitions can be set up to 128, value which would cause a proportional drop in the throughput.

By observing Figure 3 it is possible to see that for the two cases where the optimal periodicity is 640, the two series of bright bars, the maximum throughput is not actually reached. A better performance could be reached with a longer NPRACH period, but in order to do so, T_S should be increased as well, with a consequent worsening of the average latency which is strictly related to this parameter.

TABLE I
NETWORK THROUGHPUT FOR DIFFERENT NUMBER OF REPETITIONS.

M_{rep}^{NPUSCH}	M_{rep}^{NPRACH}	Optimal NPRACH Periodicity	$\hat{T}_{max}$ [kbps]
1	1	160	77
2	4	320	37
4	2	640	19
8	8	640	9

V. CONCLUSION

We defined a mathematical model approximating with good accuracy the NB-IOT technology. We used this model to estimate the performance of a network composed by a single cell maximizing the network throughput. We observed how the performance can be maximized by tuning the amount of radio resources divided among the two uplink physical channels and how the optimal solution changes with different settings of the network. Finally, we observed how the coverage affects the performance through the use of repetitions.

This study offers a preliminary overview of what could be expected from a NB-IOT network and what are the key optimization problems that need to be addressed. The results are quite promising as the throughput and size of a NB-IOT network in good coverage conditions appears to be hundreds of times higher than a similar network implemented with a proprietary technology such as LoRaWAN. Ultimately the most interesting question that is still open is how the repetitions would be set in a real case where the coverage is poor, and how much the performance would be worsen.

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