ISBN: 978-628-95207-8-1. ISSN: 2414-6390. Digital Object Identifier: 10.18687/LACCEI2024.1.1.695

DECT Evolution towards Meeting the Requirements for IMT-2020 in the Residential Environment

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Abstract– ***Energy efficiency and spectrum efficiency have been identified by "IMT for 2020 and beyond" (International Mobile Telecommunications) as two of the current wireless network capabilities that need substantial enhancement to satisfy the exponential growth of IoT and high data rate applications. "Digital Enhanced Cordless Telecommunications" (DECT) is the leading standard around the world for cordless telecommunications and it has the great advantage to operate on a "designated" license-free RF band (1880/1900 MHz in Europe). However, the original DECT has very low energy efficiency and very low spectral efficiency, and therefore, DECT is neither suitable for ultra-low energy applications nor for high data rate multimedia streaming applications. The "European Telecommunications Standards Institute" Technical Committee DECT (ETSI TC DECT) is working on these two aspects, and it has proposed a new set of "Technical Specifications" that enables DECT to support both ultra-low energy (DECT-ULE) and high data rate (DECT-2020 New Radio) application domains. In this paper, we introduce an energy consumption model for the DECT "Portable Part" (PP) that lets us analyze in detail the operation of a PP in the "standby mode". The model lets us show that the simple reduction on the requirement of how often the PP must monitor the "paging" beacon enables DECT for ultra-low energy applications. We then show that the use of the state-of-the-art multi-carrier "Orthogonal Frequency Division Multiplexing" (OFDM) modulation, and the spatial multiplexing "Multiple Input Multiple Output" (MIMO) antenna technique, enables DECT for high data rate multimedia streaming applications.***

Keywords-- IMT-2020, DECT-2020 New Radio, DECT-ULE, 3GPP LTE.

I. INTRODUCTION

IMT-2020 [1] establishes the vision for mobile telecommunications for 2020 and beyond based on the forecast that traffic volume and number of devices will continue to grow exponentially. IMT-2020 points out eight current network capabilities that should be enhanced to satisfy such demands: peak data rate, user experienced data rate, latency, mobility, connection density, energy efficiency, spectrum efficiency, and area traffic capacity. Spectrum efficiency has a direct impact on data rate (peak and user experienced), connection density, and area traffic capacity; and therefore, it is one of the most important capabilities to enhance. Energy efficiency is crucial in the case of battery-operated Internet of Things (IoT) devices since it has a direct impact on battery lifetime.

"Digital Enhanced Cordless Telecommunications" (DECT) [2] is the leading standard around the world for digital cordless telecommunications and it has the great advantage to operate on a "designated" license-free RF band (in Europe, from 1880 MHz to 1900 MHz). "Designated" meaning that no other technologies can be deployed in the DECT band, as it is the case, for the highly congested Industrial, Scientific and Medical (ISM) band, where WiFi, Bluetooth, Zigbee, and other technologies operate. In this paper, we show that, although DECT has evolved to support VoIP [3] and packet data services [4], DECT still has both low energy efficiency and low spectrum efficiency capabilities [5] compared to nowadays technologies such as Long Term Evolution (LTE) [6]. Therefore, the legacy DECT standard is not suited for ultra-low energy applications (ULE), or data-rate hungry applications, such as multimedia streaming. We call "DECT legacy" or simply "DECT" the standard variants of DECT defined in [2], [3] and [4].

Digital Object Identifier: (only for full papers, inserted by LACCEI).
ISSN, ISBN: (to be inserted by LACCEI).
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DECT targets use cases where mobility is not the most stringent requirement, such as the residential and industrial environments. A theoretical performance evaluation of DECT-ULE for monitoring and controlling wireless sensor networks (WSN) in industrial environments is published in [7]. In this paper, we concentrate on the residential environment use cases, such as "smart home" and "multimedia streaming".

We present first an analysis of the current DECT capabilities in terms of energy consumption and throughput capacity and stand out the enhancements that need to be implemented in DECT to meet the IMT-2020 objectives in the residential environment. We then describe how the European Telecommunications Standards Institute Technical Committee ETSI TC DECT is actively working on the one hand, on a new set of specifications for ultra low energy (DECT-ULE) [8], [9], and on the other hand, on a new radio specification, called DECT- 2020 New Radio [10], capable to support high data rates. Regarding energy consumption, we first introduce an energy consumption model for the DECT "Portable Part" (PP) that lets us study in detail the operation of a PP in the "standby mode". The model lets us show that the main reason for the low energy efficiency of the current DECT standard is the requirement on Portable Parts (PP) to continuously monitor the highly frequent "paging" events generated by the Fixed Part (FP). A simple reduction on the requirement of the frequency with which the PPs monitors the "paging" events from the FP can lead to an extension of the battery standing time from one week to almost two years.

Regarding spectrum efficiency, we show that the main reason for the low spectral efficiency with regard to current standards, is the use of the single-carrier modulation "Gaussian Minimum Shift Keying" (GMSK) [11]. We show that using the state-of-the-art multi-carrier modulation techniques, such as the

"Orthogonal Frequency Division Multiplexing" (OFDM) [12], and the spatial multiplexing antenna technique "Multiple Input Multiple Output" (MIMO) [13], can lead to significant improvements in spectral efficiency going from 0.384 (bit/s)/Hz of the legacy DECT standard to up to 56 (bit/s)/Hz with a 1024-QAM OFDM modulation and a 6x6 MIMO antenna system. With such a spectral efficiency, DECT can reach up to 1.12 Gbps of data rate, being therefore able to satisfy the current IMT-advanced [14] objective in terms of peak data rate, which is 1 Gbps. Since our main focus is the residential environment, it seems reasonable to assume that the 1.2 Gbps can be distributed among up to twelve user devices requiring up to 100 Mbps, and therefore DECT-2020-NR [10] will be able to satisfy the IMT-2020 [1] objective in terms of user experienced data rate, which is 100 Mbps. Notice that we cannot claim that DECT-2020-NR will satisfy the IMT-2020 objective in terms of peak data rate, which is 20 Gbps [1].

These two axes of performance enhancement of the current DECT standard show that DECT-ULE and DECT-2020-NR can satisfy IMT-2020 requirements for application domains such as "smart home" and "multimedia streaming".

The remaining of this paper is organized as follows. Section II reviews the vision and overall objectives of IMT-2020. Section III presents a brief overview of DECT. Sections IV and V analyze with detail DECT's evolution for ultra low energy and multimedia streaming application domains. Finally, Section VI draws our conclusions.

II. IMT-2020 OVERVIEW

The present section is mostly based on ITU Std. M.2083-0 [1] and all figures are reproduced from there with some highlights from us.

IMT-2020 [1] defines the framework and overall objectives of the International Mobile Telecommunications for 2020 and beyond. Anticipating that users should be able to access services anywhere, anytime, IMT-2020 recommends that IMT-2020 interwork with other radio systems such as Radio Local Area Networks (RLANs). One of the worldwide well established RLANs is DECT [2].

A. *Use Cases*

IMT-2020 is envisaged to support diverse use cases and applications that include [1]:

- **Enhanced Mobile Broadband:** This use case addresses human-centric scenarios for mobile access to multimedia content, services, and data.
- **Massive Machine Type Communications:** This use case is characterized by a very large number of connected devices typically transmitting a relatively low volume of non-delay sensitive data. The devices are required to be low cost and have a very long battery life.
- **Ultra-Reliable and Low Latency Communications:** This use case has stringent requirements for capabilities such as throughput, latency, and availability. Some examples include wireless control of industrial manufacturing or production processes, remote medical surgery, distribution automation in a smart grid, transportation safety, etc.

Additional use cases are expected to emerge which are currently not foreseen. Fig. 1 illustrates some examples of envisioned use cases by IMT-2020. We mark with red circles those use cases that will be covered by DECT-ULE [8], [9] and DECT-2020 in the residential environment [10].

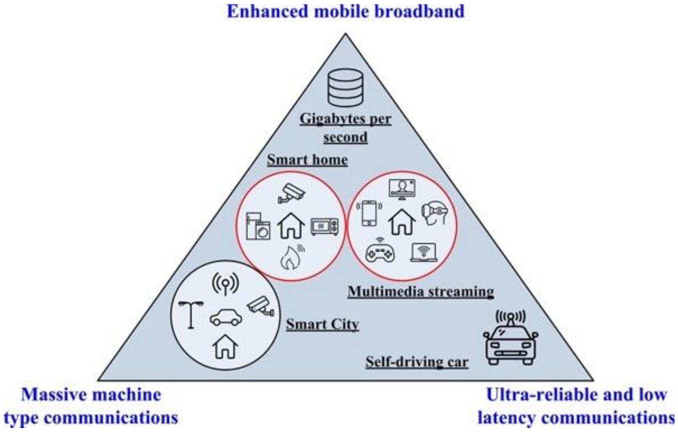

Fig. 1 ITU-R IMT-2020 scenarios [1].

B. *Key Capabilities*

IMT-2020 is expected to provide far more enhanced capabilities than the current IMT-2000-Advanced capabilities defined in [14], [15]. A set of eight parameters are considered to be key capabilities of IMT-2020: peak data rate, user experienced data rate, latency, mobility, connection density, energy efficiency, spectrum efficiency, and area traffic capacity. Fig. 2 shows the expected enhancement of the key capabilities from IMT-2000-Advanced [14] to IMT-2020. We highlight with red ellipses the "Energy Efficiency" and "Spectrum Efficiency" key capabilities that are the main scope of this paper.

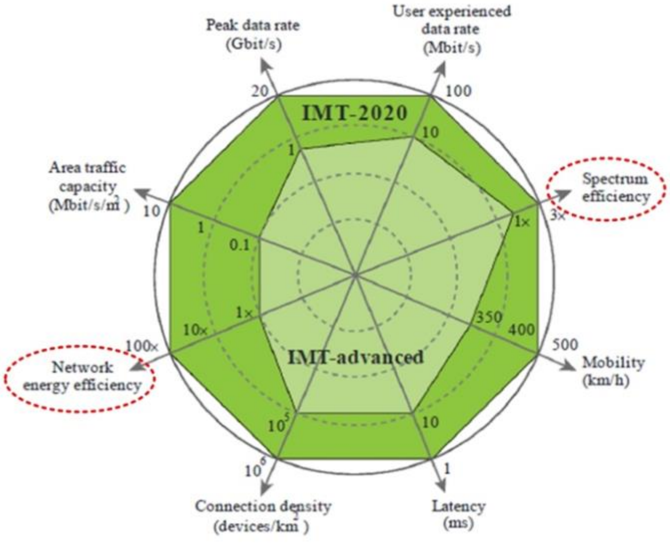

Fig. 2 Enhancements to Networks Key Capabilities from IMT-Advanced to IMT-2020 [1].

It is worth highlighting: the 10 times increase in user experienced data rate (from 10 Mbps to 100 Mbps), the 100 times increase in network energy efficiency, the 10 times reduction in latency (from 10 ms to 1 ms), and the 10 times increase in connection density (from 10^5 to 10^6 devices/km^2).

While all key capabilities may be important to some extent for all use cases, the relevance of some of them may be significantly different, depending on the use-cases scenarios. In the enhanced mobile broadband use case, user experienced data rate, area traffic capacity, peak data rate, mobility, energy efficiency and spectrum efficiency all have high importance, but mobility and the user experienced data rate would not have equal importance simultaneously in all scenarios. For example, in the residential environment, a higher user experienced data rate, but a lower mobility would be required than in the wide area coverage scenario. In the massive machine type communications use case, the following key capabilities are required: support for a huge number of low bit rate, zero/very low mobility, devices that may transmit only occasionally; and minimum data rate in virtually all circumstances [16]. A low-cost device with long operational lifetime is vital for this use case [1], but high bit rates are not crucial.

III. DECT OVERVIEW

DECT is the leading standard around the world for digital cordless telecommunications and is described in a series of standards issued by ETSI [2]. The initial DECT standard was further developed into the New Generation DECT (NG-DECT) standard [3], with primary target on VoIP applications, keeping backwards compatibility with all previous developments. A packet data service also was standardized by DECT in DECT Packet Radio Service (DPRS) [4]. The use of the DECT band is being re-engineered for new services. ETSI's work on DECT-ULE [8] shows that the DECT technology is being reoriented towards new application domains, such as: home automation, home security and climate control.

A residential DECT system is a short-range cordless communication system organized in a simple star topology as (Fig. 3). The Fixed Part (FP) is typically the gateway connected to the WAN by xDSL or fiber. In many cases, there are only one or two Portable Parts (PP; telephone handsets) wirelessly connected to the FP. The cell coverage for indoor environments starts at 50 m for conditions such as offices with metallic partition walls and goes up to 200 m for open-plan conditions.

In this paper, we call "DECT legacy" (for short "DECT") to all DECT standard variants prior to DECT-ULE [8]. For backwards compatibility all variants of the DECT standard including the most recent ones, such as DECT-ULE [8], and those in preparation, such as DECT-2020 New Radio [10], keep the same structure of the Physical Layer as DECT [3], [4].

A. DECT Spectrum Management

In Europe, the most common radio frequency spectrum allocated to DECT is in the band 1880/1900 MHz [17]. However, countries outside Europe have allocated the 1900/1920 and 1910/1930 MHz bands to DECT-similar services. In this paper, we will concentrate our analysis in the 1880/1900 MHz band.

The 1880/1900 MHz band is divided into ten RF channels with center frequency Fc given by:

$$F_c = F_0 - c \times 1.728 \text{ MHz} \tag{1}$$

where, F_0 = 1897.344 MHz and c = 0, 1, …, 9, as is shown in Fig. 4.

The modulation method used is the Gaussian Minimum Shift Keying (GMSK) with a bandwidth times bit-period (BT) product of nominally 0.5 and a peak carrier deviation δf = 288 kHz. A binary "1" is encoded with a peak frequency deviation of (+δf), giving a transmit frequency of (F_c + δf). A binary "0" is encoded with a peak frequency deviation of (−δf), giving a transmit frequency of (F_c − δf) [17].

B. DECT Time-Frame

DECT has two operational modes, the Frequency Division Duplex (FDD) mode that requires a pair of available resource spectrum, one assigned exclusively to the uplink and one to the downlink, and a Time Division Duplex (TDD) mode operating in unpaired spectrum. In the following, we consider the TDD mode.

Each radio channel is structured into 10-ms frames capable of carrying 12 digital telephone conversations. The 10-ms time frame is divided into 24 slots (TSLOT = 416.7μs), with two slots allocated to each telephone call, each slot conveying 480 bits for each communication direction, as is shown in Fig. 5.

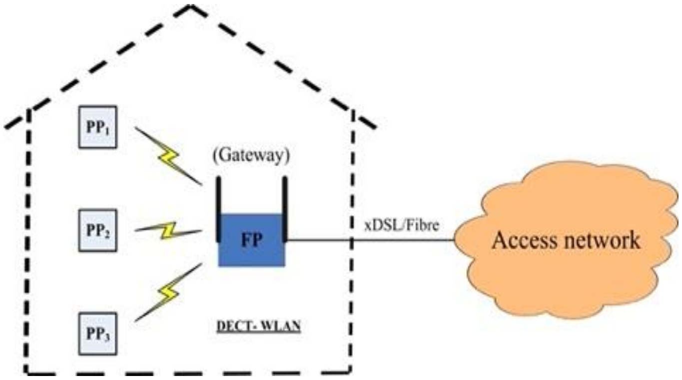

Fig. 3 DECT Star Topology.

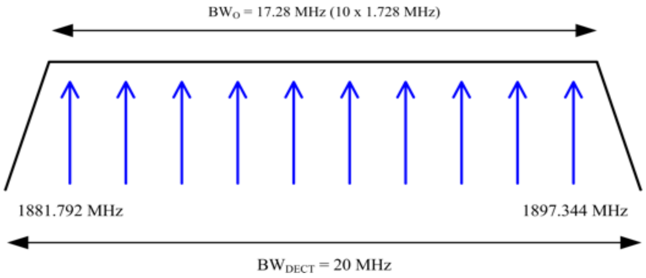

Fig. 4 Distribution of the ten RF channels inside the DECT spectrum.

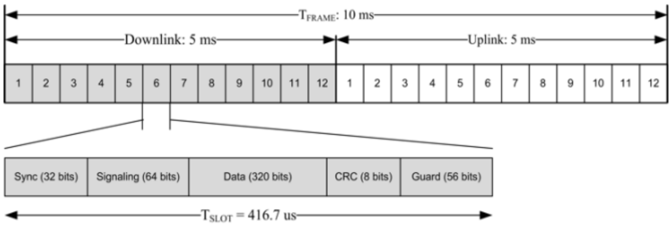

Fig. 5 DECT time-frame structure.

C. *DECT Time-Frequency Grid*

Given the organization of the time and frequency resources, DECT can carry up to 120 simultaneous digital telephone conversations in the coverage area of the FP. Each conversation occupies a duplex channel that carries: a two-way digital voice channel, a two-way digital signaling channel, and a two-way synchronization channel (See Fig. 5).

The DECT radio resource is represented by a grid with two dimensions: carrier frequency and time (Fig. 6). The blue and green units in Fig. 6 represent two on-going FP«--»PP communications. The red unit represents a “Beacon” unit whose function is explained in the following section.

D. *DECT Beacon Function*

A DECT base station (FP) continuously broadcasts a “Beacon”, in every frame, so that the DECT handsets (PP) can lock-on to, as is described in Section 5.7 of [18]. The beacon transmission can be part of an active communications link between the FP and a PP (“Traffic Bearer”) or a “Dummy Bearer” transmission. The FP “Beacon” carries information concerning: FP identity, FP capabilities, FP synchronization information, DECT channels status, and PP “paging” information for an incoming call set-up, as is shown in Fig. 7. The “Beacon” is a part of the “signaling” field shown in Fig. 5.

For letting the FP set up the link with the PPs using the least interfered available channels, the FP continuously scans and measures the RF signal strength of all DECT channels (frequency-carrier/time-slot pairs) and establishes an ordered list of the corresponding “Received Strength Signal Indicators” (RSSI). A low RSSI represents a free and non-interfered channel, while a high RSSI represents a busy or interfered channel. Based on this list, the FP continuously applies on its side a “Dynamic Channel Selection and Allocation” algorithm.

PPs must also scan periodically (once every 30 seconds according to Section 11.4.2 of the standard [18]) all DECT channels and establish a similar RSSI list. Two situations are possible: 1) a FP with which the PP is associated, transmits a “Beacon Function” containing a “Paging” message for the PP; in this case, the PP must lock onto the corresponding DECT channel and continue with the set up communications procedure, 2) the PP wishes to initiate a communication with one of the FPs to which it has access rights; in this case, the “Beacon Function” from the FP contains information about the status of the channel (free or occupied), the PP analyzes this information and locks onto the FP having the strongest RSSI, as mandated by the DECT standard [18].

E. DECT Spectral Efficiency

As mentioned in Section III-A, DECT uses GMSK modulation with a gaussian pulse having a BT product of 0.5, and a maximum frequency deviation from the carrier equal to $\delta f = 288$ kHz [17]. Since in GMSK modulation the bit rate (BR) is equal to two times the frequency difference between the higher and lower frequencies ($BR_{GMSK} = 4\ \delta f$) [11], the DECT “Cell Throughput Capacity” ($DECT_{CTC}$) is computed by (2).

$$\mathrm{DECT_{CTC}} = 10\ \text{Sub-band} \times \left(\frac{4\times\delta f}{\text{Sub-band}}\right) \times (1-OH) \quad (2)$$

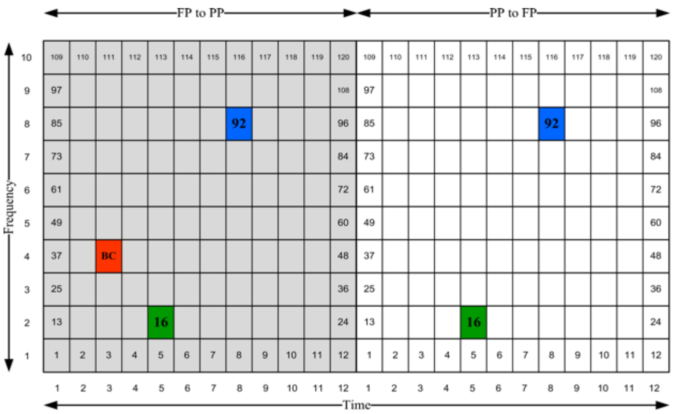

Fig. 6 DECT Time-Frequency Resource Grid.

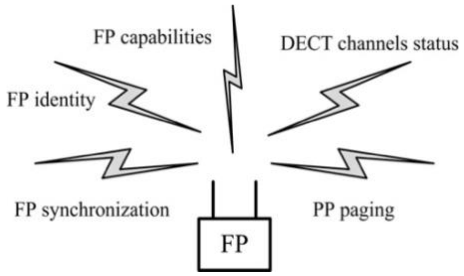

Fig. 7 DECT Beacon

where, OH is the overhead due to the error control (CRC), signaling and synchronization channels, and guard time embedded in each conversation together with the digital voice (data) channel (See Fig. 5) and is given by (3).

$$OH = \frac{\text{full channel - data channel}}{\text{full channel}} = \frac{160\ \text{bits}}{480\ \text{bits}} = \frac{1}{3} \quad (3)$$

Replacing OH in (2), we get (4) that let us conclude that $DECT_{CTC}$ is equal to 7.68 Mbps.

$$\mathrm{DECT_{CTC}} = 10 \times 4 \times 288\ [\text{kbps}] \times \left(1-\frac{1}{3}\right) = 7.68\,\text{Mbps} \quad (4)$$

Given that $DECT_{CTC}$ is 7.68 Mbps and that the DECT “Cell Bandwidth” is 20 MHz, the DECT “Cell Spectral Efficiency” is 0.384 (bit/s)/Hz.

IV. DECT EVOLUTION FOR ULTRA LOW ENERGY

In this section, we present the modifications that have been introduced into the current DECT technology to render it more energy consumption efficient and satisfying ultra-low energy consumption requirements of battery-operated IoT devices.

We first introduce an energy consumption model for the DECT devices that will let us quantitatively analyze the energy consumption profile of DECT devices. We then apply the energy consumption model to a current DECT PP product [19], and finally, we show the modifications that the ETSI DECT Ultra Low Energy (ULE) standardization [8], [9] proposes to substantially extend the battery lifetime of the DECT-ULE devices.

A. Energy Consumption Model

Fig. 8 shows a simple energy consumption model that we propose and that will let us estimate the lifetime of the battery pack powering a DECT PP. The PP operates in one of three modes (states): 1) Hibernation mode (e_0), 2) Paging mode (e_1), and 3) Transaction mode (e_2).

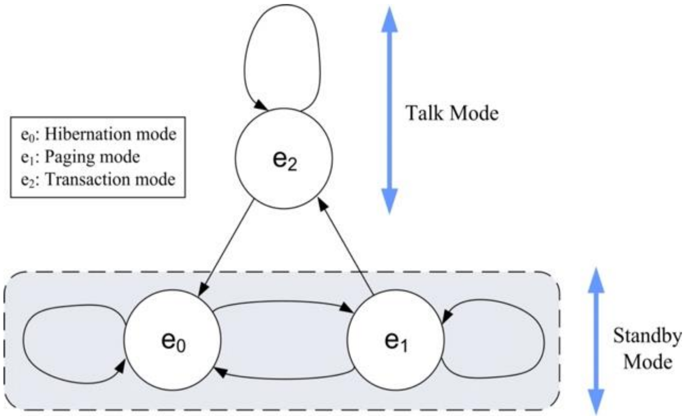

Fig. 8 DECT Energy Consumption Model.

In the Hibernation mode, the PP shuts down all operating functions except the one required to monitor a low power local timer. The PP enters the Hibernation mode between two consecutive paging scans (Paging mode) or after a talk (Transaction mode) is finished.

In the Paging mode, the PP scans the DECT RF channels for a beacon message from the FP indicating that there is a call for the PP. Therefore, the energy consumption is dominated by the RF receive circuitry.

In the Transaction mode, the PP either receives or transmits its data subject to the maximum RF power constraints of the DECT specification. This mode is dominated by the energy consumption of the power amplifier [20].

For simplicity, in the following analysis, we consider that the time unit is the duration of a DECT time frame, i.e., 10 ms.

Let:

- e_0 be the energy consumed by the PP while in the “Hibernation mode”,
- e_1 be the energy consumed by the PP while in the “Paging mode”,
- e_2 be the energy consumed by the PP while in the “Transaction mode”, and
- E be the energy stored in a set of one or more batteries used to power the PP.

The energy E is consumed by the PP and is given by (5).

$$E = (e_0 \times n_0 + e_1 \times n_1 + e_2 \times n_2) \times T_{std} \tag{5}$$

where:

- T_{std} is the standing time (lifetime) that the PP takes to completely consume the energy stored in the set of batteries that power the PP, given in hours.
- n_0 is the number of 10 ms time frames that the PP stays in the “Hibernation mode” per hour.
- n_1 is the number of paging scans per hour that the PP performs in the “Paging mode”. We consider that a paging scan takes place during one 10 ms time frame.
- n_2 is the number of 10 ms time frames that the PP stays in the “Transaction mode” per hour.

DECT equipment manufacturers usually specify the energy characteristics of their products in terms of the battery standing time assuming the PP is continuously in a “Talk mode” or in a “Standby mode”.

The “Talk mode” corresponds to the definition of our “Transaction mode”. Therefore, $n_0 = n_1 = 0$, and (5) becomes:

$$E = e_2 \times n_2 \times T_t \tag{6}$$

where, T_t is the time that the PP takes to completely discharge the pack of batteries, that power the PP, while in the “Talk mode”.

The “Standby mode” corresponds to the case where the PP continuously switches back and forth between our definitions of “Paging mode” and “Hibernation mode”, and it never enters the “Transaction mode”. See the greyed block in Fig. 8.

In the “Standby mode”, n_2 in (5) is zero. Therefore, E is given by the following equation:

$$E = (e_0 \times n_0 + e_1 \times n_1) \times T_s \tag{7}$$

where, T_s is the time that the PP takes to completely discharge the pack of batteries that power the PP, while in the “Standby mode”.

B. Battery Capacity and Energy Consumption

For a battery-operated electronic device, one of the most important characteristics is the battery lifetime. The battery lifetime is a function of the electric charge stored in the battery and the rate at which an electronic device drains the current from the battery.

It is common practice to specify the battery charge capacity in terms of Ampere-hours (Ah), having dimensions of electric current multiplied by time, equal to the charge transferred by a steady current of 1 A flowing for 1 hour. Ampere-hours is not an SI (International System of Units) electric charge unit. The SI unit of electric charge is the Coulomb (C) which is the electric charge transported by a constant current of one Ampere in one second (1C = 1A . 1s).

In this paper, we stick to the SI; therefore, we convert the Ah specification into an equivalent electric charge SI unit.

In general, the amount of electric charge transferred from the battery to the electronic device in a time interval from t_1 to t_2 is given by (8):

$$Q = \int_{t_1}^{t_2} i(t)dt \tag{8}$$

where, $i(t)$ is the instantaneous current drained by the electronic device.

Therefore, 1 Ah is equal to 3600 C. The electric charge capacity of smaller batteries is usually specified in mAh. 1 mAh = 10^{-3} Ah = 3.6 C.

The energy consumed by an electronic device in a time interval from t_1 to t_2 is given by (9):

$$E = \int_{t_1}^{t_2} v(t)i(t)dt \tag{9}$$

where, v(t) is the instantaneous voltage, and i(t) is the instantaneous current drained by the electronic device.

In general, the battery voltage varies during discharge, but an average or nominal value may be used to approximate the energy calculation by (10):

$$\hat{E} = V \times I \times t \tag{10}$$

The SI unit of energy is the Joule, which can be expressed as: (1J = 1V.1A.1s). A Joule can also be expressed in terms of the electric charge Q in Coulombs and the voltage V in Volts (1J = 1C.1V).

Notice that multiplying the nominal battery voltage V by the battery capacity in Ah gives an estimate of how much energy in terms of watt-hours the battery contains.

C. Example of Energy Consumption of a Current DECT PP

For illustration purposes, let us analyze in detail the energy consumption of the "Thomson CONECTO 300" handset [19]. This DECT handset has the following specifications:

- Battery standing time of 4 hours in the "Talk mode".
- Battery standing time of 168 hours in the "Standby mode".
- Handset powered by a set of 4 rechargeable 1.2 V NiMH batteries with 600 mAh charge capacity.

Therefore, the 600 mAh of electric charge of a 1.2 V NiMH battery correspond to 2160 C (600 x 3.6 C), and the energy "E" stored in the four 1.2 V NiMH batteries is: E= 10368 J (4 x 1.2 V x 2160 C). See Section IV-B.

Let us continue with the computation of e_0. Thomson's CONECTO 300 datasheet does not specify the amount of current (I_0) that is drained by the handset when it is in the "Hibernation mode", as defined in our model, but it is reasonable to assume that a PP in such a sleep mode drains 10µA of current. Indeed, the datasheet of a current DECT-ULE chip specifies that the chip alone drains 1 µA in a similar "Hibernation mode" [21].

Therefore, e_0 can be computed with (11):

$$e_0 = V \times I_0 \times t_0 \tag{11}$$

where, V is the voltage of the battery pack (4.8 V) and t_0 is the duration of a DECT frame as previously mentioned (10 ms). Therefore, e_0 = 0.48 µJ.

The number of 10 ms time frames contained in one hour (n_0) can be computed as:

$$n_0 = \frac{\frac{3600\ s}{1\ h}}{0.01\ s} = \frac{360000}{h} \tag{12}$$

The number of "paging" events that take place in one hour is n_1. The DECT specification [18] states that the paging interval must be 30s (T209: max time between updates of channel list.). Therefore, n_1 can be computed as:

$$n_1 = \frac{\frac{3600\ s}{1\ h}}{30\ s} = \frac{120}{h} \tag{13}$$

With all this, we are ready to compute the energy e1 consumed during a "Paging mode" event, using (14), derived from (7).

$$e_1 = \frac{\frac{E}{T_s} - e_0 \times n_0}{n_1} \tag{14}$$

Knowing that E = 10368 J, T_s = 168 h, e_0 = 0.48 µJ, n_0=360000/h, and n_1 = 120/h, we can compute e_1 using (14). We obtain e_1 = 0.514 J.

In the following, let us do a similar analysis for the "Talk mode" of the "Thomson CONECTO 300" handset. The energy e_2 consumed by the PP during one 10 ms time frame in the "Transaction mode" can be computed using (15) that is derived from (6).

$$e_2 = \frac{E}{n_2 \times T_t} \tag{15}$$

where, n_2 is the number of 10 ms time frames contained in 1 h, and therefore $n_2 = n_0$ = 360000/h. Knowing that E = 10368 J, and T_t = 4 h, we obtain e_2 = 7.2 mJ.

Table I summarizes the different components of the energy consumption of the "Thomson CONECTO 300" handset [19].

TABLE I
ENERGY CONSUMPTION OF THOMSON HANDSET.

E	T_t	T_s
10.368×10^3 [J] 4.8 V @ 600 mAh	4 [hours]	168 [hours]
e_0	e_1	e_2
0.48×10^{-6} [J]	0.514 [J]	7.2×10^{-3} [J]
e_1/e_0	e_2/e_0	e_1/e_2
1.0684×10^6	15×10^3	71.23

The first two rows of Table I correspond to the energy performance data published by the manufacturer in its datasheet, the remaining rows are computed with our energy consumption model. Interesting values to remark are the ratios e_i/e_j:

- e_1/e_0 is equal to 1.07 x 10^6, which means that the energy consumed by the PP during one 10 ms time frame in the "Paging mode" is more than one million times the energy consumed by the PP during one 10 ms time frame in the "Hibernation mode",
- e_2/e_0 is equal to 15000, which means that the energy consumed by the PP during one 10 ms time frame in the "Transaction mode" is 15 thousand times the energy consumed by the PP during one 10 ms time frame in the "Hibernation mode", and
- e_1/e_2 is equal to 71.23, which means that the energy consumed by the PP during one 10 ms time frame in the "Paging mode" is more than 70 times the energy consumed by the PP during one 10 ms time frame in the "Transaction mode".

D. DECT modifications for Ultra Low Energy

There are several IoT applications where the frequency of the paging events is not required to be as frequent as one paging event every 30 s as it is specified by the present DECT standard for the cordless telecommunications application. Therefore, in the following, we show how we can substantially increase the battery standing time by simply reducing the number of paging events per hour (n_1) when the DECT PP operates in the “Standby mode”.

From (7), we obtain the following equation:

$$T_s = \frac{E}{e_0 \times n_0 + e_1 \times n_1} \tag{16}$$

Recall that for the “Thomson CONECTO 300”: E = 10368 J, e_0 = 0.48 µJ, e_1 = 0.541 J, and n_0 = 360000/h. Fig. 9 shows the variation of the battery standing time as a function of the number of paging events per hour (n_1).

It is worth noticing that by reducing the number of paging events down to one every hour, the battery standing time can be extended up to 1.7 years from 7 days that is obtained when the paging events frequency is of one every 30s. The principle of reducing the frequency of the paging events for reducing energy consumption on the DECT PP side is applied by ETSI TC DECT in a couple of “Technical Specifications”, named “Home Automation Network (HAN), Phases 1 and 2” [8], [9]. These specifications are intended to cover “Machine to Machine Communications” based on the principles of “Ultra Low Energy”. DECT-ULE provides bi-directional radio communication with medium range, data protection, and Ultra Low Energy consumption between different types of Portable Devices and Radio Fixed Parts. DECT-ULE Phase 1 is intended primarily, but not necessarily, for Home Automation scenarios.

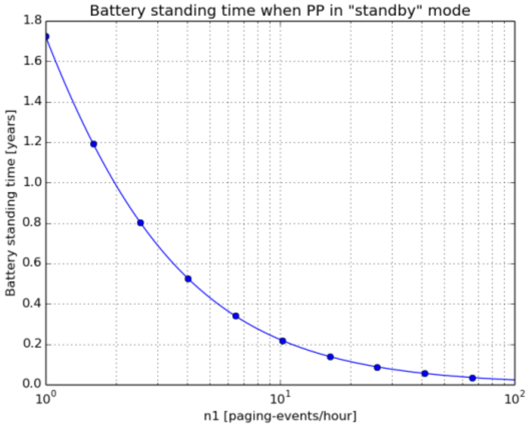

Fig. 9 Battery Standing Time as a Function of Paging Events per Hour.

Three types of PP devices are part of DECT-ULE phase 1 [8]:

- **Fast Actuator type PP:** Devices optimized for fast response times (both ways) and significant FP to PP traffic. Typical applications are, for instance, electricity control elements. These devices must periodically listen the paging channel following the configured paging cycle. Fast actuators are normally line powered.
- **Slow Actuator type PP**: Devices optimized for medium response times and significant FP to PP traffic. Typical applications are, for instance, thermostats and related control elements. These devices are not required to continuously listen for paging messages, they are assumed to listen only from time to time, asynchronously, according to a wake-up timer, whose value and tolerance are known by the FP, but not the listening time. Slow actuators are normally battery powered.
- **Sensor type PP**: Devices characterized by long sleep times, and strong energy savings requirements. The traffic is dominated by the PP to FP direction. Sensors are typically battery powered and are still able to provide fast response times from PP to FP. Typical applications are, for instance, command elements in electricity control, smoke detectors and motion detectors. Two sub-types of sensors are considered: 1) those that listen to the paging channel with a very slow or ultra slow paging cycle (Type I_a), and 2) those that, in normal conditions, do not listen to any paging channel (Type I_b).

In order to support these new paging capabilities, DECT-ULE specifies new paging channels for ULE over an “Extended Dummy Bearer” (beacon). These new paging channels support a wide range of modes from fast to ultra- slow paging, as is shown in Table II, and many devices. The granularity of the paging cycle parameter is of one TDMA frame (10 ms).

With regard to DECT-ULE Phase 1 [8], DECT-ULE Phase 2 [9] adds support for: 1) hybrid PP devices, i.e., devices that utilize ULE and non-ULE services, such as voice, from the FP, and 2) downlink broadcast, which is the capability for the FP to transmit ULE messages to multiple PP devices.

TABLE II
DECT-ULE PAGING CYCLES.

	Paging Cycle	Power
Fast Actuator	10 ms - 160 ms	Line
Slow Actuator	160 ms - 10 min	Battery
Sensor Type I_a	160 ms - 60 min	Battery
Sensor Type I_b	Infinite ms	Battery

Examples of the applications that can be built with DECT-ULE Phase 2 are: 1) medical pendant alarms, intercoms, and other M2M devices with voice capability, and 2) lighting control using the downlink broadcast feature.

V. DECT EVOLUTION FOR MULTIMEDIA STREAMING

Multimedia streaming requires large amounts of bit rate that the present DECT technology cannot provide, as it was shown in Section III. However, we showed in [5], that LTE, with the state-of-the-art multi-carrier OFDM modulation and a 4 x 4 MIMO spatial multiplexing system, would be capable to provide up to 300 Mbps (with 64- QAM) using the 20 MHz of bandwidth of the present DECT band.

There are two ways to increase the bit rate of a communications channel: 1) augmenting the cell spectral efficiency, and 2) augmenting the bandwidth of the RF spectrum of the band. ETSI TC DECT and the DECT Forum industry body are currently developing a new set of DECT standards with these two guidelines in mind. This requires major changes to the current DECT radio interface, specially to the MAC and Physical (PHL) layers [10]. This new radio interface is called "DECT-2020 New Radio" (DECT-2020, for short in this paper), and it will be capable to meet the IMT-2020 requirements [1], in terms of user experienced data rate and spectral efficiency.

A. DECT-2020 Spectrum Management

Due to the requirement of efficient sharing of the DECT band (1880/1900 MHz) with legacy DECT, DECT-2020 uses the same basic carrier and spectrum structure. The bandwidth of the basic carrier is BWBC = 1.728 MHz. DECT-2020 uses OFDM modulation with a sub-carrier separation of 27 kHz. In other words, a DECT-2020 basic carrier is composed of 64 sub-carriers of BWSC = 27 kHz. DECT-2020 also foresees the use of half-carriers with a bandwidth of BWHC = 0.864 MHz.

Three different options of channel bandwidth have been considered:

- **Full-carrier Channel**: The transmission bandwidth is equal to the basic DECT-2020 channel with 1.728 MHz (BW_{BC}). However, to guarantee compatibility with other DECT-2020 and DECT transmitters, not all the sub-carriers carry data. The four sub-carriers on each edge of the basic channel are null sub-carriers. Therefore, the occupied bandwidth (BW_O) is equal to 1.512 MHz (56x27 kHz). Fig. 10 shows the DECT-2020 spectrum organization of this Full-Carrier channel.
- **Multiple-carrier Channel:** The transmission bandwidth is equal to N_C 1.728 MHz, where $N_C \in \{2, 4, 8, 12, 16\}$. A proper number of zero (null) sub- carriers are inserted to produce a suitable occupied bandwidth. $N_C = 16$ corresponds to the maximum possible number of carriers, where $BW_{MC} = 27.648$ MHz and $BW_O = 20.736$ MHz that fits exactly in the legacy full DECT band.
- **Half-carrier Channel:** The transmission bandwidth is equal to one half the basic DECT channel, i.e., $BW_{HC} = 0.864$ MHz and $BW_O = 0.648$ MHz.

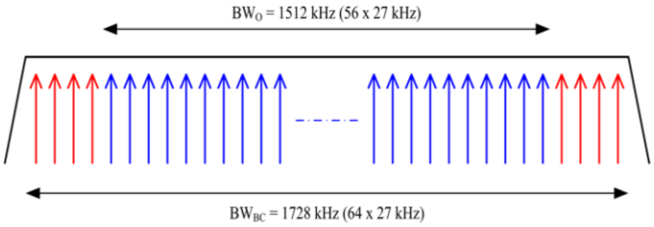

Fig. 10 DECT-2020 Full Carrier OFDM Symbol.

1) DECT-2020 Time Frame: The DECT-2020-time frame and time slot are equal to those of the legacy DECT, i.e., $T_{FRAME} = 10$ ms, and $T_{SLOT} = T_{FRAME}/24 = 416.7$ µs. However, DECT-2020 FP and PP devices communicate using packets of OFDM symbols. The nominal duration of a DECT-2020 OFDM symbol is $T_{SYM} = T_{SLOT}/10 = 41.67$ µs. Therefore, the time structure of a DECT-2020 frame is the one shown in Fig. 11.

In addition to the legacy DECT full slots, DECT-2020 foresees the use of half slots, i.e., $T_{HSLOT} = T_{FRAME}/48 = 208.33$ µs.

In order to support low-latency scenarios, DECT-2020 can also operate with 30 slots/frame ($T_{SLOT} = 333.3$ µs), or with 40 slots/frame ($T_{SLOT} = 250$ µs), or in a frameless mode.

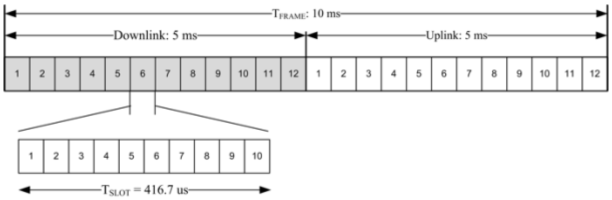

Fig. 11 DECT-2020 Time Frame Structure.

2) DECT-2020 Time Frequency Grid: Similar to what we did for legacy DECT, we can conveniently represent the DECT-2020 management of the time-frequency resource with a two-dimensional grid. For example, the structure of the time-frequency grid for the basic "Full-Carrier" channel is shown in Fig. 12.

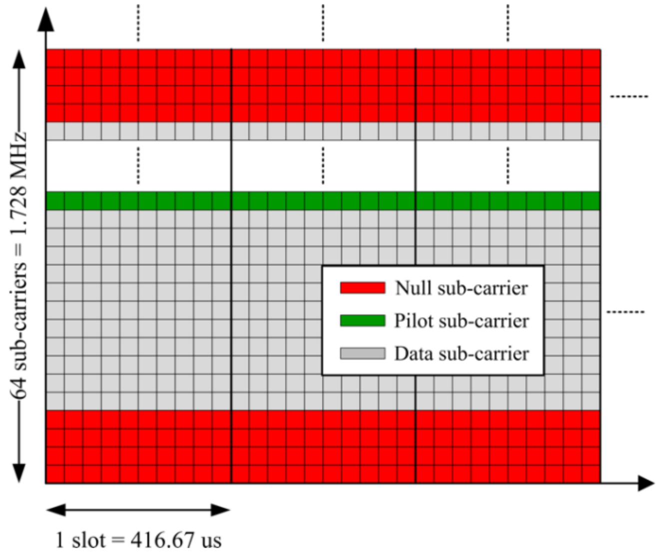

Fig. 12 DECT-2020 Time-Frequency Grid for Full Carrier Channel.

On the frequency dimension, there are 64 sub-carriers of 27 kHz of bandwidth each constituted of: 8 null sub-carriers, 52 data sub-carriers and 4 pilot sub-carriers. The pilot sub-carriers are used to monitor the quality of the RF bands.

On the time dimension, the 416.67 µs slot is constituted of ten 41.67 µs OFDM symbols.

As mentioned previously, DECT-2020 FP and PP devices communicate using packets of OFDM symbols. The packet duration is variable; however, the packet transmissions always start on a slot boundary.

The FP maintains a Time/Frequency Map (TFM) for communication with the PP clients. A given FP«--»PP communication follows the same TFM, except for certain slots specifically allocated for contention-based access. The TFM can change dynamically, based on MAC layer commands.

3) DECT 2020 Performance: The “Cell Throughput Capacity” of DECT-2020 can be computed with (17):

$$DECT\text{-}2020_{CTC} = \frac{N_{SD} \times N_{BPSC} \times R}{T_{SYM}} \qquad (17)$$

where:

- N_{SD} is the number of sub-carriers that carry user data.
- N_{BPSC} is the number of bits per sub-carrier, which is a function of the modulation used.
- R is the code rate. DECT-2020 uses FEC, and therefore, some of the bits in the user packets are redundant. R is the fraction of bits that carry non- redundant user data.
- T_{SYM} is the OFDM symbol duration (41.67 µs).

N_{SD} in (17) is given by (18).

$$N_{SD} = N_{SC} - N_{SP} - N_{SN} \qquad (18)$$

where: N_{SC} is the total number of sub-carriers, N_{SP} is the number of pilot sub-carriers, and N_{SN} is the number of “null” sub-carriers in the DECT-2020 channel.

NSC in (18) is given by (19).

$$N_{SC} = \frac{N_C \times BW_{BC}}{BW_{SC}} \qquad (19)$$

where:

- N_C is the number of DECT basic carriers in the DECT-2020 channel.
- BW_{BC} is the bandwidth of the DECT basic channel (1.728 MHz).
- BW_{SC} is the bandwidth of a sub-carrier (27 kHz).

For computing the maximum “Cell Throughput Capacity” of DECT-2020, we consider the ideal case where the cell is occupied by one single user using the maximum multi-carrier channel and the most efficient modulation (1024-QAM).

In this case, $N_C = 16$. NSP, N_{SN}, and R are specified in [17], they are $N_{SN} = 56$, $N_{SP} = 32$, and R = 5/6. Therefore, from Equation 18, $N_{SD} = 936$. For 1024-QAM, $N_{BSPC} = 10$.

Replacing all these parameters in (17), we obtain DECT-2020_{CTC} equal to 187.2 Mbps.

The computation that we just presented, assumes a SISO antenna system. If a MIMO system is used, DECT-2020_{CTC} is ideally multiplied by the number of spatial streams (N_{SS}) corresponding to the MIMO system. Table III summarizes the “Cell Throughput Capacity” for different modulation types and MIMO systems. When spatial multiplexing is used, the maximum DECT transmission power (250 mW) is split among the different antennas.

Table III shows that DECT-2020 with MIMO 6x6, and 1024-QAM modulation attains 1.12 Gbps of throughput, and therefore, it is capable to meet the IMT-2020 objective of user experienced data rate [1].

Since the bandwidth of the DECT band is 20 MHz, we can compute the “Cell Spectral Efficiency” that is summarized in Table IV.

B. Additional Spectrum

In 1998, the European Parliament decided (Decision 128/1999/EC) the coordinated introduction of the Universal Mobile Telecommunications System (IMT- 2000/UMTS) in the European Community. The unpaired 2 GHz frequency bands, 1900/1920 MHz and 2010/2025 MHz were part of the assigned frequency bands. In 2012, CEPT (Conférence Européenne des Administrations des Postes et Télécommunications), which is the European regional organization dealing with postal and telecommunications issues, analysed the usage of these unpaired 2 GHz bands and concluded that they were mostly unused. The band 1900-1920 MHz, although licensed in many countries, remained largely unused, and the use of frequencies in the band 2010-2025 MHz had only been authorised in few countries [22]. Therefore, CEPT was mandated to assess and identify alternative uses of these unpaired 2 GHz frequency bands other than for the provision of mobile communications services through terrestrial cellular networks (as introduced by the IMT- 2000/UMTS Decision) as well as to develop less restrictive technical conditions for their deployment while ensuring co-existence with the electronic communications services in the paired 2 GHz spectrum [22].

TABLE III
DECT-2020 CELL THROUGHPUT CAPACITY [MBPS]

MIMO	Modulation			
	16QAM	64QAM	256QAM	1024QAM
1 X 1	67.39	112.32	149.76	187.20
2 X 2	134.80	224.60	299.50	374.40
4 X 4	269.60	449.30	599.00	748.80
6 X 6	404.40	673.90	898.60	1123.00

TABLE IV
DECT-2020 CELL SPECTRAL EFFICIENCY [BIT/S/HZ].

MIMO	Modulation			
	16QAM	64QAM	256QAM	1024QAM
1 X 1	3.37	5.62	7.49	9.36
2 X 2	6.74	11.23	14.98	18.72
4 X 4	13.48	22.46	29.95	37.44
6 X 6	20.22	33.70	44.93	56.16

One of the alternatives suggested by CEPT for the 1900/1920 MHz band is to make it available for DECT, so that a single continuous block of 40 MHz (1880/1920 MHz) is provided to DECT [22]. If this recommendation is adopted, DECT-2020 would double the theoretical maximum “Cell Throughput Capacity” that we presented in Section V-A3 (2.24 Gbps = 2 x 1.12 Gbps), and therefore, it would exceed the current ITU-Advanced objective, however it would not meet the ITU-2020 objective [1] which is 20 Gbps.

VI. CONCLUSIONS

Our main focus in this paper was the residential environment and especially the “Smart Home” and “Multimedia Streaming” application domains. This is the reason why we concentrated our study on the necessary enhancements to the current DECT standard regarding “energy efficiency” and “spectral efficiency”. We showed that the original DECT standard, that in Europe operates in the “designated” band from 1880 MHz to 1900 MHz, cannot satisfy the energy efficiency and spectrum efficiency requirements of nowadays IoT and multimedia streaming applications. The reasons are: in the first case, the DECT requirement on the PP to continuously (at least once every 30s) monitor the “paging” event generated by the FP which leads to an accelerated drain of the battery pack powering the PP; and in the second case, the low spectral efficiency due to the use of the single-carrier modulation GMSK.

With regard to energy efficiency, we presented an energy consumption model for the PP that let us show that the introduction of flexibility in the “paging” function so that the requirement on how often the PP must monitor the “paging” events is relaxed depending on the application, leads to an enormous enhancement of the energy efficiency. The lifetime of the batteries powering such an ultra low energy IoT device could be extended from a few weeks to several years.

With regard to spectral efficiency, we showed that the introduction of the state-of-the-art multi-carrier OFDM modulation and the use of a MIMO antenna system can lead to significant improvements in spectral efficiency going from 0.384 (bit/s)/Hz of the legacy DECT standard to up to 56.16 (bit/s)/Hz with a 1024-QAM OFDM modulation and a 6x6 MIMO antenna system. This enhancement on the spectral efficiency enables DECT the possibility of providing data rates of up to 1.12 Gbps, being therefore able to satisfy the current IMT-advanced [14] objective in terms of peak data rate, which is 1 Gbps. Since our main focus is the residential environment, it seems reasonable to assume that the 1.2 Gbps can be distributed among up to twelve user devices requiring up to 100 Mbps each, and therefore DECT would be able to satisfy the IMT-2020 [1] objective in terms of user experienced data rate, which is 100 Mbps.

Finally, we described how ETSI TC DECT is introducing these and other features in a new set of specifications: DECT-ULE [8], [9] to enable IoT applications, and DECT- 2020 New Radio [10] to enable high data rate applications, such as multimedia streaming.

The new DECT-2020 standard [10] will be capable to achieve at least a 100 times improvement in terms of battery life time, and up to a 100 times enhancement in the user experienced data rate with regard to the current DECT standard [2].

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