An Overview of 3GPP Enhancements on Machine to Machine Communications

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The authors present an overview of several features included in 3GPP to accommodate the needs of M2M communications, including changes in the physical layer such as enhanced machine type communications, and new MAC and higher-layer procedures provided by extended discontinuous reception.

Abstract

The broad connection of devices to the Internet, known as the IoT or M2M, requires low-cost power-efficient global connectivity services. New physical layer solutions, MAC procedures, and network architectures are needed to evolve the current LTE cellular systems to meet the demands of IoT services. Several steps have been taken under the 3GPP to accomplish these objectives and are included in the upcoming 3GPP LTE standards release (3GPP Release 13). In this tutorial article, we present an overview of several features included in 3GPP to accommodate the needs of M2M communications, including changes in the physical layer such as enhanced machine type communications, and new MAC and higher-layer procedures provided by extended discontinuous reception. We also briefly discuss the narrowband IoT, which is in the development stage with a target completion date of June 2016.

Introduction

In a largely connected world, the amount of devices that access the Internet is increasing year by year. During the last decade, the increase in mobile traffic has mainly been caused by the global adoption of smartphones and the corresponding applications, which have caused the cellular networks to move from voice-centered to data-centered services. These applications require high data rate, global access to the Internet, and seamless mobility, which have been the main driver of cellular standards in the past.

In many cases, the development of *smart* devices and services, such as smart grid, smart cities, sensor networks, wearable devices, connected homes, and connected cars, pose a new set of requirements not currently supported or optimized by Long Term Evolution (LTE) cellular systems, which has the primary focus of mobile broadband (MBB) communications. The support of machine-to-machine (M2M) communications is one of the major requirements for next-generation networks [1]. Some of the key requirements of M2M communications are listed below.

Cost Reduction: In the current smartphone market, the price of the communication unit (e.g., the cellular modem) is only a small part of the overall device, which makes cost reduction much less important than other aspects, such as high peak data rate and spectral efficiency. For M2M, the cost of the communication unit has to be drastically reduced to be integrated within other types of devices, such as wearable devices (e.g., activity trackers, heart rate sensors), utility meters (water, gas, or electric), alarms, and other types of sensors. Various cost reduction techniques have been considered by the Third Generation Partnership Project (3GPP), including reduced computational complexity (e.g., reducing the bandwidth of the device or the supported transmission modes), reduced data rate, single antenna support, and half duplex operations.

Reduced Power Consumption: In many metering or sensor network applications, it is desirable to deploy battery operated devices targeting years of operation. For example, a utility company may want to collect metering information from their clients by installing a cellular modem in the metering device and having this information transmitted to a central server periodically with a duty cycle of several hours or days. Once deployed, it is expected to operate these devices over many years without the need to change batteries or redeployment. Similarly, it is critical to reduce power consumption for wearable and other tracking devices.

Enhanced Coverage: Many devices targeting M2M applications may experience poor signal reception conditions. For example, metering or alarm devices may be deployed in basements or concrete structures, which significantly increases the path loss between the transmitter and receiver. In order to reach these kinds of devices, M2M communications may require a 15–20 dB coverage enhancement with respect to regular cellular services.

There are several proprietary technologies in the so-called low-power wide-area (LPWA) family targeting Internet of Things (IoT) applications with extremely low throughput and operating in unlicensed spectrum [2]. In 3GPP, there has been an effort to enable IoT services by standardized solutions in cellular networks and to reuse the existing infrastructure as much as possible. LTE Release 12 introduced some initial features to meet the requirements driven by IoT applica-

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tions. A new user equipment (UE) category (Category 0) [3] with reduced peak data rate, half duplex operation with relaxed RF requirements, and a single receive antenna was defined to reduce the baseband and RF complexity of the UE. From the higher-layer perspective, power saving mode (PSM) [4] was adopted to allow a UE to drastically reduce power consumption for applications with delay-tolerant mobile-originated (MO) traffic in order to achieve years of battery life. In Release 13, additional improvements were introduced to drive down the cost and power consumption further. In this article we provide a high-level overview of the physical layer enhancements introduced in enhanced machine-type communications (eMTC), and the medium access control (MAC) and higher-layer improvements brought by extended discontinuous reception (eDRX). In addition, we also briefly summarize the work on the narrowband IoT (NB-IoT), which started in September 2015 with a target completion date of June 2016.

The remainder of this article is structured as follows. The next section describes the set of physical layer features introduced under eMTC. Then we briefly summarize high-level features of NB-IoT. Following that we present the higher-layer changes to support reduced power consumption under eDRX. The final section presents the conclusions.

Enhanced Machine-Type Communications

eMTC introduces a set of physical layer features aiming to reduce the cost and power consumption of UEs and extending coverage, while at the same time reusing most of the LTE physical layer procedures [5]. An eMTC UE can be deployed in any LTE evolved Node B (eNB) configured to support eMTC and can be served together with other LTE UEs by the same eNB. This allows eMTC deployment with the existing infrastructure just by applying a software update. The main features introduced by eMTC are as follows.

Narrowband Operation: The support of a wideband RF front-end and higher sampling frequencies increase the cost and power consumption of a UE. An eMTC UE follows narrowband operation for the transmission and reception of physical channels and signals, and the maximum channel bandwidth is reduced to 1.08 MHz, or 6 LTE resource blocks (RBs). This bandwidth is selected to allow the eMTC UE to follow the same cell search and random access procedures as legacy UEs, which use the channels and signals that occupy six RBs: the primary synchronization signal (PSS), the secondary synchronization signal (SSS), the physical broadcast channel (PBCH), and the physical random access channel (PRACH). The eMTC UE can be served by a cell with much larger bandwidth (e.g., 10 MHz), but the physical channels and signals transmitted or received by the eMTC UE are always contained in 1.08 MHz. A new frequency unit, called a narrowband, was defined in LTE Release 13 to accommodate this operation. A narrowband is a predefined set of six contiguous RBs in which an eMTC UE can operate. In the case of a 10 MHz channel (50 RBs), for example, 8 non-overlapping narrowbands are defined in the specification. Most of the channels of Release 12 LTE can be reused just by constraining the resource allocation to be within a narrowband. This narrowband operation is shown in Fig. 1a.

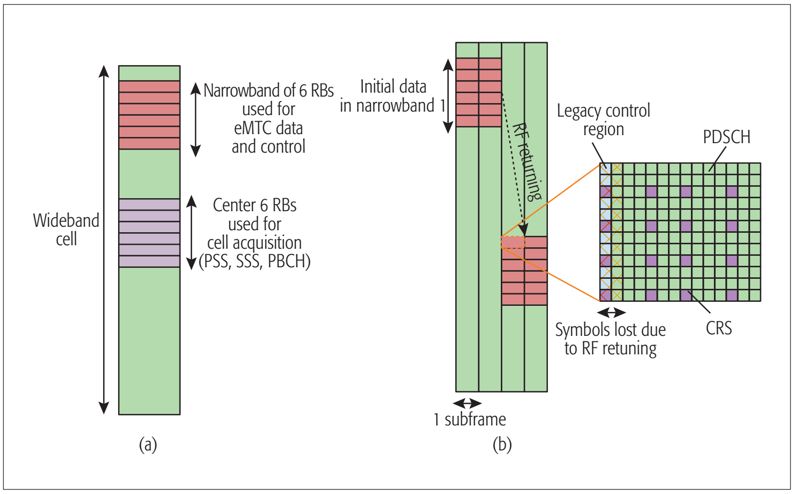


Figure 1. a) Narrowband operation; b) repetition with RF retuning.

Low Cost and Simplified Operation: Many features introduced for Category 0 UEs are maintained for eMTC UEs, such as a single receive antenna, reduced soft buffer size, reduced peak data rate (1 Mb/s), and half duplex operation with relaxed switching time. New features are introduced to further reduce the cost of eMTC UEs, such as reduced transmission mode support (only transmission modes 1, 2, 6, and 9 are supported), reduced number of blind decodings for control channel, no simultaneous reception (a UE is not required to decode unicast and broadcast data simultaneously), and the aforementioned narrowband operation.

Transmission of Downlink Control Information: The legacy physical downlink control channel (PDCCH) is wideband and uses the first orthogonal frequency-division multiplexing (OFDM) symbols in a subframe, that is, control and data are multiplexed in the time domain within the same subframe. A similar structure is adopted for other control channels like the physical control format indicator channel (PCFICH) and physical hybrid automatic repeat request (HARQ) indicator channel (PHICH). A narrowband UE is not able to monitor these channels, so their functionality is replaced by new mechanisms introduced in Release 13 eMTC:

- New control channel: Instead of the legacy control channel (PDCCH), a new control channel called MPDCCH is introduced. This new control channel spans up to six RBs in the frequency domain and one subframe in the time domain. The MPDCCH is similar to enhanced PDCCH (EPDCCH), with the additional support of common search space for paging and random access.
- Handling legacy control region: In legacy LTE, the size of the control region (in number of OFDM symbols) is indicated in the PCFICH and can potentially change every subframe. In eMTC this information is semi-statically signaled in the system information block (SIB), so eMTC devices do not need to decode PCFICH.

Two modes of operation are introduced to support coverage enhancement (CE). CE Mode A is defined for small coverage enhancements, for which full mobility and channel state information (CSI) feedback are supported; CE Mode B is defined for UE in extremely poor coverage conditions, for which no CSI feedback and limited mobility are supported.

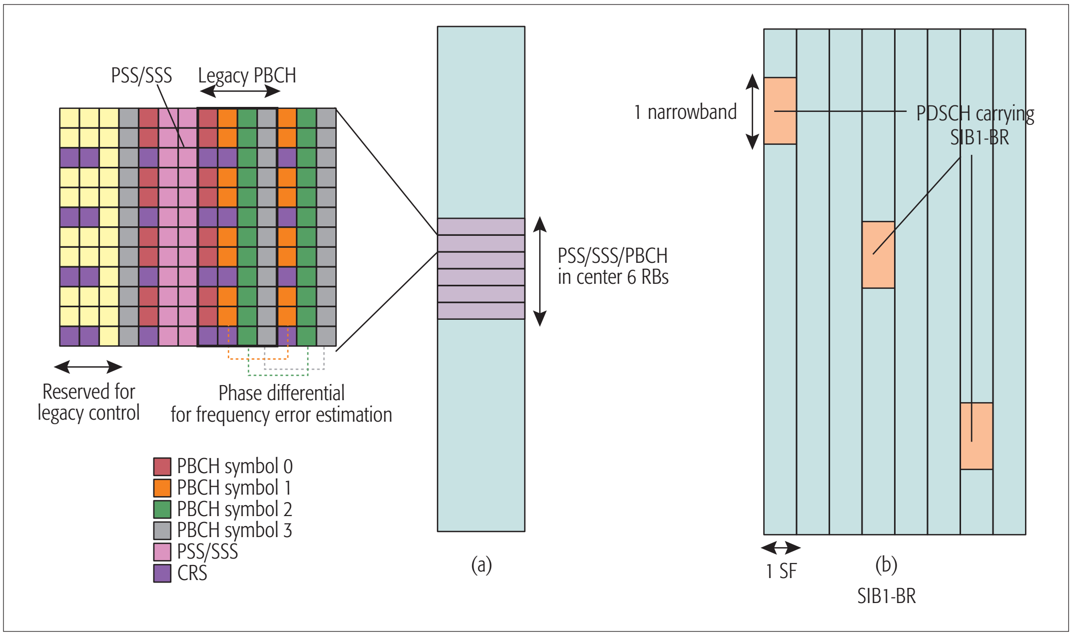


Figure 2. a) Cell search; b) system information acquisition.

• HARQ feedback for uplink transmissions: In legacy LTE this information is contained in PHICH, and retransmissions can be non-adaptive (use the same resources as the previous transmission) and are synchronous (the timing of retransmissions is fixed). In eMTC, there is no support of the PHICH, and retransmissions are adaptive, asynchronous, and based on new scheduling assignment received in an MPDCCH.

Extended Coverage: The presence of devices in extreme coverage conditions (e.g., a meter in a basement) requires the UEs to operate with much lower signal-to-noise ratio (SNR). eMTC targets 15 dB coverage enhancement with respect to Release 12 LTE, which results in 155.7 dB maximum coupling loss between transmitter and receiver. This enhanced coverage is obtained by repeating in time almost every channel beyond one subframe (1 ms) to accumulate enough energy to decode [6]. This feature is similar to uplink transmission time interval (TTI) bundling introduced in Release 8 to improve the uplink coverage for voice over IP (VoIP). The TTI bundling length, which can span 4 subframes (TTI of 4 ms) in Release 8, is extended up to 2048 subframes for the data channels in Release 13 eMTC. The following channels support repetition in eMTC: the physical downlink shared channel (PDSCH), physical uplink shared channel (PUSCH), MPDCCH, PRACH, physical uplink control channel (PUCCH), and PBCH. Two modes of operation are introduced to support coverage enhancement (CE). CE mode A is defined for small coverage enhancements, for which full mobility and channel state information (CSI) feedback are supported; CE mode B is defined for UE in extremely poor coverage conditions, for which no CSI feedback and limited mobility are supported.

Frequency Diversity by RF Retuning: Due to the narrowband RF, single antenna, and limited mobility, eMTC UEs experience limited frequency, spatial, and time diversity. In order to reduce the effect of fading and outages, frequency hopping is introduced among different narrowbands by RF retuning. This hopping is applied to the different uplink and downlink physical channels when repetition is enabled. For example, if 32 subframes are used for transmission of PDSCH, the 16 first subframes may be transmitted over the first narrowband; then the RF front-end is retuned to a different narrowband, and the remaining 16 subframes are transmitted over the second narrowband. With the assumption of a single local oscillator (LO) in the device, up to two OFDM symbols are assumed for this retuning. This narrowband operation is depicted in Fig. 1b for PDSCH repetition, where the first two OFDM symbols in the subframe after retuning are lost. Since these symbols are used for legacy control channels, the impact is limited to the loss of cell-specific reference signals (CRS) in this symbol.

In the following section we present the changes in UE operation with these new features. More precisely, we first present the new procedure for cell acquisition/initial random access and further details on data communications.

Cell Search and Initial Access

For cell search and initial access, eMTC UEs use the same signals and channels as a legacy LTE UE. The UE searches for the PSS/SSS in the center 6 RBs to obtain the cell ID, subframe timing information, duplexing mode (time-division, TDD, or frequency-division, FDD), and cyclic prefix (CP) length. There are no enhancements to PSS/SSS with the assumption that the eNB can power boost these signals to decrease the search time and power consumption of eMTC UEs in poor coverage conditions. The next step is to decode PBCH, which carries the master information block (MIB). The legacy PBCH is transmitted in the second slot of subframe 0, and for eMTC this channel is repeated in the first slot of subframe 0 and in another subframe (subframe 9 for FDD and subframe 5 for TDD). The PBCH repetition is performed by repeating the exact same constellation points in different OFDM symbols so that they can be used for initial frequency error estimation even before attempting PBCH decoding. In Fig. 2a we show the repetition pattern for subframe 0 in FDD, normal CP, and how the repeated symbols can be used for frequency error estimation. The information in the MIB is shared between eMTC UE and legacy UE, with system bandwidth, system frame number, and number of CRS antenna ports signaled to both types of UEs.

Additionally, five reserved bits in the MIB are used in eMTC to convey scheduling information about a new system information block for bandwidth reduced devices(SIB1-BR), including time and frequency location, and transport block size. SIB-BR is transmitted over PDSCH directly, without any control channel associated with it. SIB-BR remains unchanged for 512 radio frames (5120 ms) to allow a large number of subframes to be combined. In Fig. 2b we show an example of transmission of SIB-BR over the wideband LTE channel.

SIB-BR carries the basic information needed by the UE to access the system, including valid downlink and uplink subframes, maximum support of coverage enhancement, and scheduling information for other SIBs. After decoding all the necessary SIBs, the UE is able to access the cell by starting a random access procedure.

For random access, the signaling of different PRACH resources and different coverage enhancement levels is supported. This provides some control of the near-far effect for a PRACH by grouping together UEs that experience similar path loss. Up to four different PRACH resources can be signaled, each one with a reference signal received power (RSRP) threshold. The UE estimates the RSRP using the downlink CRS, and based on the measurement result selects one of the resources for random access. Each of these four resources has an associated number of repetitions for a PRACH and number of repetitions for the random access response (RAR). Thus, UE in bad coverage would need a larger number of repetitions to be successfully detected by the eNB and need to receive the RAR with the corresponding number of repetitions to meet their coverage level. The search spaces for RAR and contention resolution messages are also defined in the system information, separately for each coverage level. Note that the PRACH waveform used in eMTC is the same as in legacy LTE (i.e., based on OFDM and Zadoff-Chu sequences). Further enhancements to the PRACH waveform (e.g., [7]) may be considered in future releases if needed.

After the random access procedure is successfully completed, the UE can establish aradio resource control (RRC) connection with the eNB. The UE can be configured to be in either CE mode A or CE mode B with a UE-specific search space to receive uplink and downlink data assignments.

Data Communications

Once the RRC connection is established, the UE blindly decodes the MPDCCH in the configured search space to obtain uplink and downlink data assignments. MPDCCH is a new control channel introduced in Release 13 based on the Release 11 EPDCCH channel. An MPDCCH can be repeated in the time domain and can also use frequency hopping to improve the performance in fading channels. Unlike a legacy PDCCH, an MPDCCH uses all the available OFDM symbols in a subframe to transmit the downlink control information (DCI), so time-domain multiplexing between control and data in the same subframe is not possible. Instead, a cross-subframe scheduling rule is followed in eMTC: An MPDCCH with a last repetition in subframe N schedules a PDSCH assignment in subframe $N + 2$. DCI carried by the MPDCCH provides information on how many times the MPDCCH is repeated so that the UE knows when PDSCH transmission starts. The PDSCH assignment can be in a different narrowband, so the UE might need to retune before decoding it. For uplink data transmission, scheduling follows the same timing as legacy LTE, where an MPDCCH ending in subframe N schedules a PUSCH transmission starting in subframe $N + 4$.

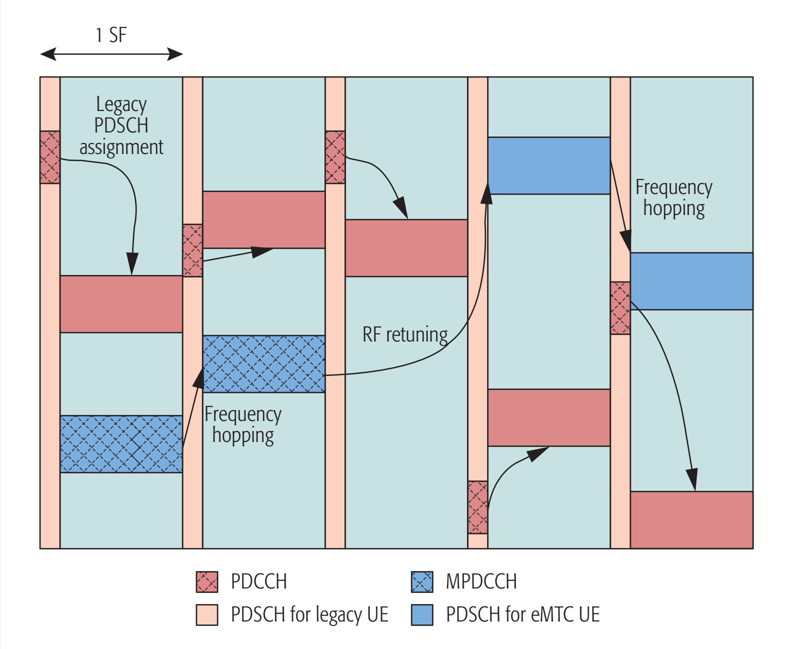


Figure 3. Scheduling timing for eMTC and legacy LTE PDSCH.

In Fig. 3 the difference in scheduling between eMTC UEs and legacy UEs is shown: legacy assignments are scheduled using the PDCCH, which uses the first OFDM symbols in each subframe. The PDSCH is scheduled in the same subframe in which the PDCCH is received. The eMTC PDSCH is cross-subframe scheduled, and a subframe is introduced between the MPDCCH and PDSCH to allow for MPDCCH decoding and RF retuning. As shown in the figure, the eNB scheduler can multiplex regular UE and eMTC UE in the same subframe just by assigning different resources and avoiding collision of the MPDCCH with the legacy PDSCH. Also, eMTC control and data channels can be repeated for a large number of subframes to be decodable in extreme coverage conditions, with a maximum number of repetitions of 256 subframes for the MPDCCH and 2048 subframes for the PDSCH.

Downlink HARQ feedback is realized by a similar mechanism as legacy LTE: a PDSCH

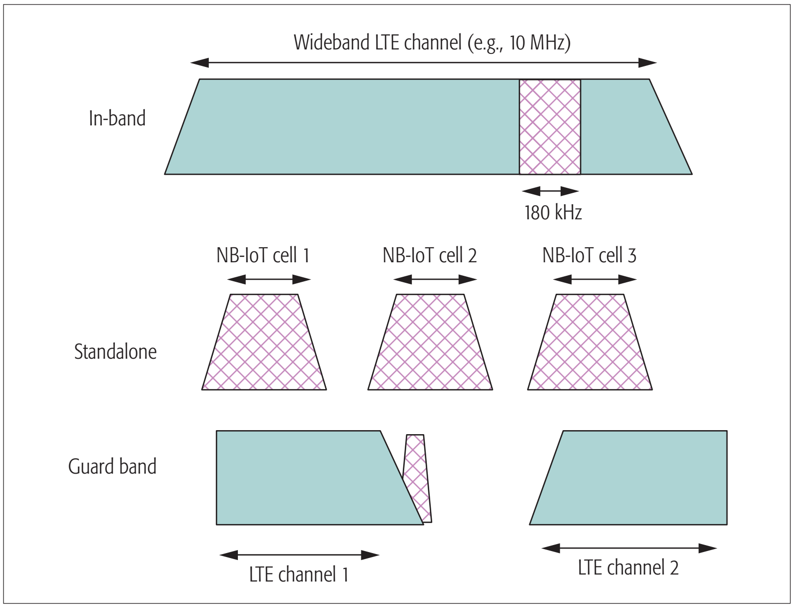


Figure 4. Different deployment modes of NB-IoT.

transmission ending in subframe N triggers a PUCCH transmission starting in subframe $N + 4$. Uplink HARQ is different from Release 12 LTE, as the time between retransmissions of the same HARQ process is no longer constant due to the dynamic bundling operation (bundling of a PUSCH can change in every assignment, whereas Release 8 TTI bundling is semi-statically configured by RRC signaling). HARQ retransmissions are directly triggered by receiving a new assignment over the MPDCCH. In this sense, the uplink operation in eMTC is asynchronous, following a similar procedure as downlink HARQ in previous LTE releases.

In general, eMTC introduces a wide range of features to enable cost savings and enhanced coverage while keeping great commonality with LTE, such as the reuse of most uplink and downlink physical channels. In the next section we briefly describe another technology introduced in 3GPP Release 13, which allows further bandwidth reduction to 180 kHz.

Narrowband Internet of Things

Similar to eMTC in reducing complexity and increasing coverage of cellular services, a separate work item, NB-IoT, was introduced in 3GPP for late inclusion in Release 13. Since the target completion date is June 2016, here we only provide a brief summary of what has been agreed so far for NB-IoT.

NB-IoT further decreases the bandwidth requirements compared to eMTC to 180 kHz. This narrowband bandwidth allows the device complexity to be further reduced at the expense of decreased peak data rate (around 50 kb/s for uplink and 30 kb/s for downlink). Furthermore, NB-IoT UEs only support limited mobility procedures. Thus, NB-IoT targets use cases with reduced mobility and very low data rate (e.g., metering devices) with the possibility of reusing GSM or LTE spectrum, while eMTC can cover applications with higher data rate and mobility requirements (e.g., wearables). For Release 13, both TDD and FDD are supported by eMTC, while only FDD is supported by NB-IoT (compatible with future TDD inclusion).

Unlike eMTC, which is always operated within an LTE spectrum, NB-IoT is designed to support three different deployment scenarios.

In-Band Operation: Similar to eMTC, NB-IoT can be deployed within an LTE wideband system. In this case, the narrowband comprises 1 resource block (180 kHz). For in-band operation the transmit power at the eNB is shared between wideband LTE and NB-IoT.

Standalone Operation: NB-IoT can also be deployed in a standalone 200 kHz of spectrum, for example, by *refarming* one or more GSM carriers. In standalone operation all the transmit power at the base station can be used for NB-IoT, thus increasing the coverage of these cells with respect to in-band deployment.

Guard-Band Operation: In this case, an NB-IoT cell is co-located with an LTE cell (e.g., they are served by the same eNB), but the NB-IoT channel is placed in a guard band of an LTE channel. In guard-band operation, the NB-IoT downlink can share the same power amplifier (PA) as the LTE channel, thus effectively also sharing the transmitted power.

In Fig. 4 we show a diagram of the different deployment modes of NB-IoT.

Due to the reduced bandwidth of NB-IoT, new physical channels are introduced for synchronization, broadcast information, and random access, as well as new downlink reference signals for channel estimation, tracking, and demodulation. The main NB-IoT features and differences in respect to eMTC are as follows.

Acquisition Process: eMTC and legacy LTE share the same cell search process, which includes detecting legacy PSS/SSS/PBCH. NB-IoT introduces a new set of broadcast channels and synchronization signals that use a bandwidth of 180 kHz.

Uplink Waveform: The uplink waveform of NB-IoT takes the single-carrier frequency-division multiple access (SC-FDMA) LTE uplink as a baseline, but adds some modifications on top to be more efficient in extreme coverage cases and also support lower-complexity UEs. The first change is that the minimum resource allocation is reduced from one RB to one subcarrier, thus leading to a single-tone modulation uplink transmission. In this single-tone modulation, the time-domain waveform during a symbol duration is a constant envelope sinusoid, which allows more efficient PA usage. Also, the narrower bandwidth of the uplink signals enables the multiplexing of a larger amount of UE in the same bandwidth. This increased level of multiplexing of UEs is especially useful in the case where these UEs are power limited and therefore do not benefit from being allocated a larger amount of bandwidth. Moreover, two different subcarrier spacings are allowed in NB-IoT uplink: 15 kHz (the same as legacy LTE) and 3.75 kHz (4 times lower than legacy LTE). The 3.75 kHz spacing allows for additional protection against timing errors due to the longer CP.

Downlink Transmission Schemes: A single transmission scheme based on space frequency block coding (SFBC) is supported for all physical

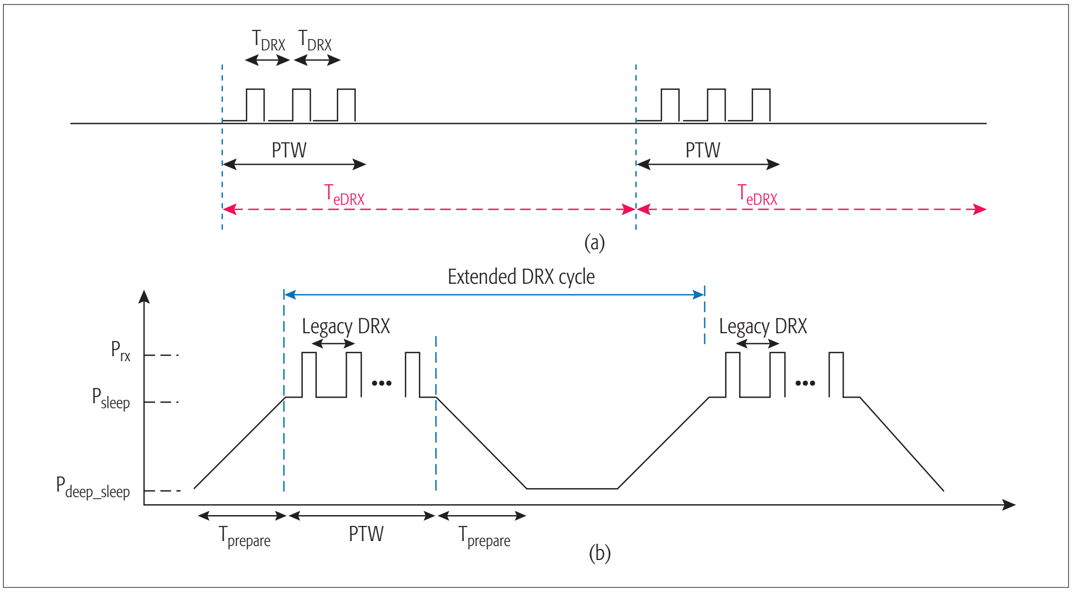


Figure 5. eDRX cycle in idle mode and resulting UE power levels.

Both eMTC and NB-IoT introduce changes in the physical layer that enable reduced device complexity and enhanced coverage, which are two of the main features required by M2M services. Although this reduced complexity also reduces the power consumption of UEs, additional modifications in the higher layer procedures are introduced to further increase the battery life of eMTC and NB-IoT UEs.

downlink channels, unlike eMTC, which supports both precoder and SFBC-based transmission schemes. One of the major changes in NB-IoT is the introduction of a new control channel based on SFBC that spans the entire subframe. A new downlink reference signal is introduced for demodulation and time/frequency tracking. Additionally, legacy LTE CRS can be used to enhance channel estimation when NB-IoT is deployed in-band.

Random Access: Unlike legacy LTE, which uses a PRACH based on Zadoff-Chu sequences, NB-IoT uses a PRACH based on single-tone transmission with hopping. A single-tone signal is used to increase the multiplexing capacity of PRACH while using a constant envelope signal, and the hopped transmission allows the eNB to estimate the round-trip delay to issue a timing advance command.

Both eMTC and NB-IoT introduce changes in the physical layer that enable reduced device complexity and enhanced coverage, which are two of the main features required by M2M services. Although this reduced complexity also reduces the power consumption of UEs, additional modifications in the higher-layer procedures are introduced to further increase the battery life of eMTC and NB-IoT UEs, which we describe next.

Extended Discontinuous Reception

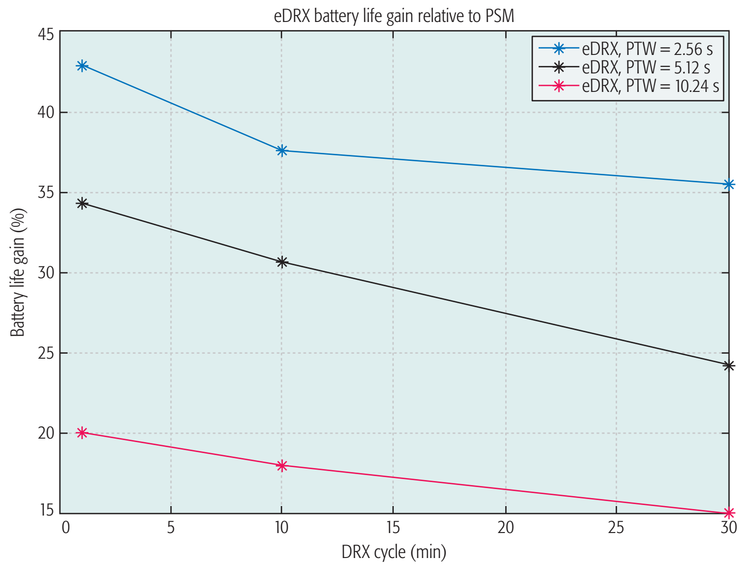
The main feature to reduce power consumption from the radio perspective is discontinuous reception (DRX). A UE configured with a DRX cycle can avoid monitoring the control channel continuously, enabling the UE to switch off parts of the circuitry to reduce power consumption. DRX is supported in Release 12 LTE with cycles up to 2.56 s. In order to efficiently support M2M communications with low duty cycle, however, the maximum DRX cycle should be increased to several minutes or even hours. A longer DRX-based mechanism for power savings enhancements has the following key advantages over PSM:

- DRX is well suited for unscheduled mobile terminated (MT) data with some requirement on delay tolerance; PSM, on the other hand, would require the UE to negotiate a periodic tracking area update (TAU) timer equal to (or slightly shorter than) the maximum allowed delay tolerance.
- A UE in DRX does not generate unnecessary signaling (resulting in power inefficiency) during periods of time when there is no data for the UE; in contrast, PSM performs TAU procedures at every TAU timer expiry, regardless of the data availability for the UE.

Extended DRX cycles are introduced in Release 13 for both idle and connected modes, thus enabling further UE power savings when the UE is not required to be reachable as frequently. For idle mode, the maximum possible DRX cycle length is extended to 43.69 min, while for connected mode the maximum DRX cycle is extended up to 10.24 s.

Since the system frame number (SFN) in LTE wraps around every 1024 radio frames (10.24 s), eDRX introduces Hyper-SFN (H-SFN) cycles to enable an extended common time reference to be used for paging coordination between the UE and the network. The H-SFN is broadcast by the cell and increments by one when the SFN wraps around (i.e., every 10.24 s). The maximum eDRX cycle corresponds to 256 hyper-frames.

A UE configured with an eDRX cycle in idle mode monitors the control channel for paging during a paging transmission window (PTW). The PTW is periodic with starting time defined by a paging hyper-frame (PH), which is based on a formula that is known by the mobility managing entity (MME), UE, and eNB as a function of the eDRX cycle and UE identity. During the PTW, the UE monitors paging according to the legacy DRX cycle (TDRX) for the duration of the PTW or until a paging message is received for the UE, whichever is earlier. The eDRX cycle and corresponding UE power consumption levels are illustrated in Fig. 5. Note that during the idle time outside of the PTW, the UE power



UE power consumption model parameters

Parameter	Value	Comments
P_{rx}	1 unit/ms	Power consumed for RX
P_{tx}	2 unit/ms	Power consumed for TX
P_{sleep}	0.01-0.02 unit/ms	Power consumed during legacy DRX sleep mode
P_{deep_sleep}	0.0002 unit/ms	Optimized sleep state
$T_{prepare}$	500 ms	Time to transition between deep sleep and sleep states
T_{eDRX}	1 min–30 min	Extended DRX cycle
T_{DRX}	2.56 s	Legacy DRX cycle

Figure 6. eDRX idle mode battery life savings gain relative to PSM.

(Pdeep_sleep) will typically be much lower than the sleep power within the PTW (Psleep). The transition to the deep-sleep state is not instantaneous and requires some preparation time for the UE to load or save the context into non-volatile memory. Hence, in order to take full advantage of power savings in deep-sleep state, the eDRX cycle (TeDRX) should be sufficiently long and the PTW as small as possible.

Figure 6 compares the battery consumption performance of devices configured with eDRX and PSM for various eDRX/TAU cycles based on the model parameters given below. The performance measure is provided as battery life gain (percent) that a device configured with eDRX can achieve over a device configured with PSM when eDRX/TAU cycles are on par. The devices are assumed to perform two MT transactions per day, and otherwise stay in deep sleep when not in PTW (if configured with eDRX) or performing TAU followed by an "active time" (if configured with PSM). It can be observed that significant power savings of up to 43 percent can be achieved when using eDRX, especially for a small PTW. When the eDRX cycle is increased, the delay tolerance also increases, and the gap between eDRX and PSM becomes smaller as expected.

Conclusions and Future Study

The support of M2M communication in cellular networks requires the introduction of new features to enable low cost, low power, and enhanced coverage. In Releases 12 and 13, several new features have been added to LTE, such as physical layer changes to reduce the UE complexity and increase coverage, and higher-layer procedures to reduce the power consumption of devices. In this article we have provided a high-level overview of the new features introduced in 3GPP Release 13: eMTC, NB-IoT, and eDRX.

Future evolution of 3GPP standardization activities related to M2M technologies may include system capacity and user throughput improvements, congestion and overload control in connected mode, position location, as well as broadcast/multicast support.

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Biographies

Alberto Rico-Alvariño received his Ph.D. degree in electrical engineering from the Universidade de Vigo, Spain, in 2014. He joined Qualcomm Inc.'s (San Diego, California) Corporate R&D division in 2014 to work in standardization and development related to LTE-Advanced. He is actively involved in the standardization of eMTC and NB-IoT in LTE Release 13, among other topics.

Madhavan Vajapeyam received his B.S. degree in electrical engineering from the Universidade Federal da Paraiba, Campina Grande, Brazil, in 2000, and his M.S. and Ph.D. degrees in electrical engineering from the University of Southern California, Los Angeles, in 2002 and 2007, respectively. He joined the Corporate R&D division of Qualcomm in 2007, and has since been actively involved in the development and standardization of 3GPP LTE and LTE-Advanced technologies. His research interests include MAC and upper layer protocols for heterogeneous networks and machine-type communications.

Hao Xu received his B.S and M.S. from Moscow Power Engineering Institute and Technical University, Russia, in 1994 and 1996, respectively. He received his Ph.D. from Virginia Tech in 2000. During his Ph.D. research, he pioneered the millimeter-wave propagation research at 38 GHz and 60 GHz with Professor Theodore Rappaport. He received the IEEE Communications Society Steve Rice Award in 1999 with Dr. G. Durgin and Dr. T. Rappaport. From 2000 to 2003, he worked at Bell Labs' Wireless Communication Research Lab, where the first MIMO system (BLAST) was invented. His research led to one of the first outdoor MIMO channel capacity evaluations, and the joint 3GPP/3GPP2 spatial channel model (SCM). In 2003, he received the Bell-Labs President Gold Metal Award. Since 2003, he has being working at Qualcomm R&D, where his main research focus is on wireless communications system design. He has led various research and prototyping efforts, as well as 3GPP physical layer design topics. He is currently leading eMTC/NB-IoT research and standardization activities. He has numerous journal publications and patents, and also served a few years as an Associate Editor for *IEEE Transactions on Wireless Communications*.

Xiaofeng Wang received his B.S. degree in electronics from Wuhan University, China, in 1991, his M.E. degree in telecommunications engineering from Beijing University of Posts and Telecommunications, China, in 1994, and his Ph.D. degree from the University of Victoria, Canada, in 2002. Since 2000, he has worked in both industry and academia. He was with PMC-Sierra Inc. as a systems engineer from 2000 to 2002, with the Department of Electrical and

Computer Engineering, Concordia University, Montreal, Canada, as an assistant professor from 2002 to 2007, with Wavesat Inc., Montreal, Canada, as the lead of the system group from 2008 to 2010, and with PMC-Sierra Inc., as a DSP lead from 2011 and 2012. Since 2012, he has been with Qualcomm Technologies Inc. as a senior staff engineer. His research interests lie in communication theory and systems. Recently, he has been mostly involved in the development of several new communications standards such as IEEE 802.3bp 1000 BASE-T1 and 3GPP NB-IoT. He is a co-rapporteur of 3GPP NB-IoT work item.

YUFEI BLANKENSHIP received her Ph.D. degree in electrical engineering from Virginia Tech in 2000. From 2000 tp 2007, she was with Motorola Labs, working on physical layer standardization with an emphasis on channel coding. She is currently a standards researcher with Ericsson. For 3GPP LTE Release 13, her focus was in the areas of MTC and NB-IoT.

JOHAN BERGMAN received an M.S. degree in engineering physics from Chalmers University of Technology, Gteborg, Sweden in 1997. He joined Ericsson in 1997 to work on baseband algorithm design for WCDMA. Since 2005, he has worked on physical layer standardization and RAN system design for WCDMA/LTE. Currently he is involved in standardization of MTC and NB-IoT in LTE Release 13.

TUOMAS TIRRONEN is a senior researcher at Ericsson Research, which he joined in 2012 to do Internet of Things related research. He received his D.Sc. in communications engineering in 2010 from Aalto University. His current research interests in addition to IoT include 4G and 5G wireless access technologies, performance evaluation, and radio protocols and resources. He has been supporting standardization work for machine type communications in LTE Release 13.

EMRE A. YAVUZ received his B.Sc. and M.Sc. degrees in electrical and electronics engineering from METU, Ankara, Turkey in 1995 and 1998, respectively. He was a software engineer with Alcatel in Toronto developing safety-critical real-time microprocessor firmware for embedded command, control, and communication applications in automated train systems from 1999 to 2001. He received his Ph.D. degree in electrical and computer engineering from the University of British Columbia in Vancouver in 2007. He worked as a technical consultant from 2007 to 2009 prior to joining the School of Electrical Engineering at KTH, Stockholm, Sweden, as a postdoctoral fellow. He is now a researcher at Ericsson AB, Stockholm, working with L2/L3 standardization and RAN system design. He is currently involved in the standardization of machine type communication in LTE Release 13.