Abstract—Machine-type communication (MTC) is the key technology to support data transfer among devices (sensors and actuators). Cellular communication technologies are developed mainly for “human-type” communications, while enabling MTC with cellular networks not only improves the connectivity, accessibility, and availability of an MTC network but also has the potential to further drive down the operation cost. However, cellular MTC poses some unique challenges due to a huge mismatch between the cellular user equipment and the MTC device, caused mainly by the physical limitations, deployment environment and density, and application behavior of MTC devices. One of the most challenging issues is to provide an efficient way for an MTC device to access the network. We address the issues in the existing random access scheme in a cellular system (e.g., LTE), and propose an effective spectrum concept enabling a power and spectrally optimized design specifically-tailored for MTC.

Index Terms – Machine-to-machine communications, Internet of Things, cellular communications, LTE.

I. INTRODUCTION

Machine-to-machine (M2M) or machine-type communication (MTC) technology is for automated data transmission and measurement between mechanical or electronic devices, with applications in remotely controlled and managed systems (e.g., utilities, building automation, security, manufacturing), smart systems (e.g., intelligent homes, grids, electronic medical systems, cars, transport and logistics), and telemetry and telematics. MTC represents the baseline communications that enable the interactions between devices and applications in the Internet to form the so-called Internet of Things (IoT) [1]. The connectivity for devices, machines, vehicles, buildings and many other “things” is becoming crucial to maintaining competitive positioning in any given market, and has become a strategic priority for cities, industry and enterprises in leading sectors.

The key component of an MTC system is the field-deployed devices with embedded sensors of wireless access to the core network. MTC thus has a great potential to become an important revenue stream for connectivity providers, i.e., the wireless network operators. There are several industry groups...
currently developing new wireless access technologies dedicated to MTC. It is evident that it is more
cost-effective for operators to take advantage of the well-developed and tested radio access technologies,
and the well-established networks, such as the cellular systems, Wi-Fi, Bluetooth, and ZigBee, to form a
unified, standard end-to-end MTC architecture to serve various MTC markets. Among these
technologies, Wi-Fi, Bluetooth or ZigBee provide short-range local wireless coverage on unlicensed
spectrum that allows limited transmit power, and is regulated by duty cycle and listen-before-talk (LBT)
restrictions, meaning there is no guarantee of service availability, coverage, or capacity, and more power
consumption on LBT and collision/retransmissions. These factors present limitations to certain IoT
applications and use cases. On the other hand, cellular networks operating on licensed spectrum provide
greater range and protected reference signals, resulting in wide-area time synchronization which
substantially improves MTC efficiency, while the asynchronous nature of other systems (e.g., Bluetooth
and ZigBee) leads to inefficiency and scaling issues. Therefore, the cellular network is gaining
momentum in becoming the most competitive and promising radio access technology for low-cost
connectivity due to its global coverage, supported by the most sophisticated network, highest spectral
efficiency, reliability, and mobility. It is natural to extend the cellular service to IoT using the existing
ellular infrastructure including cell sites and transceivers. These unique advantages clearly define the
future role of the cellular network in expending IoT/MTC markets [1]-[9].

However, extending today’s cellular services (e.g., the 4G LTE [10]) to IoT poses its own challenges
that cannot be overlooked [7]-[9], mainly due to the large discrepancy (in transceiver capabilities and
applications) between the MTC device and the LTE user equipment (UE). First, most MTC devices are
characterized by low operational power consumption (critical for non-rechargeable batteries), infrequent
low rate transmissions (e.g., a few transmissions per day and several Kbytes per transmission for an
automated water meter), and latency-tolerance (e.g., on the order of minute or 10s of minutes). Second,
low-cost is another important aspect of MTC devices (so that they can be deployed on a mass scale and
even in a disposable manner), which may impair the transceiver performance and shrink the link budget.
These behaviors and characteristics of an MTC device are very different from the LTE device, e.g., the
smart phone for “human-type” communications (HTC) empowered by large-capacity (rechargeable)
batteries and costly hardware, which are typically characterized by high power, high performance, high
data rates, and high mobility. The natural challenge for LTE is to continue the evolution path towards
more efficient mobile broadband platforms supporting high-end devices while at the same time
providing a unified, reliable, ubiquitous, and cost-effective wireless connectivity for all IoT needs.
3GPP started the study on cellular MTC, i.e., the LTE-MTC, dating back as early as 2009 aiming to define the high-level 3GPP network improvements to support MTC, which is well-documented in [2], [3], [11]. Most recently, a new 3GPP work item, i.e., the enhanced LTE-MTC or LTE-eMTC, has been officially created to establish a new category of low-cost MTC devices for LTE networks [8], [9]. More constraints on the MTC device have been proposed to further reduce the cost and power consumption, such as reduced transmission power (e.g., from 23 dBm to 20 dBm for a potentially on-chip power amplifier), reduced peak rate (e.g., 1 Mbps, without MIMO or mobility), simplified hardware (e.g., a single RF chain and baseband processor, and half duplex operation which allows efficient RF implementations such as the elimination of a duplexer), and the narrowband operation (e.g., 1.08 MHz on both downlink and uplink). The reason that LTE-eMTC chooses 1.08 MHz (the bandwidth of 6 LTE resource blocks) as the minimum MTC bandwidth supported is that the existing LTE system acquisition channel and the random access channel (RACH) is 1.08 MHz in bandwidth (fixed and non-configurable).

The reduced capability significantly degrades the performance of MTC devices, resulting in coverage shrinkage. Yet there is a substantial market for the MTC use cases in which devices are deployed deep inside a building (e.g., the basement), which requires coverage enhancement over the current LTE cell footprint, imposing more stress on the already tight link budget. Depending on the actual environment, additional coverage up to 15 dB is typically required to extend the coverage to areas where MTC devices are potentially deployed. For ease of discussion, we divide the coverage extension levels into four different classes: Channel class (CC) 1 includes the MTC devices that are in the coverage extension level of 15 dB, corresponding to a maximum coupling loss of 140+15=155 dB, where the 140 dB is the maximum coupling loss for the traditional LTE coverage. Channel classes 2 to 4 corresponds to maximum coupling losses of 150, 145, and 140 dB, respectively.

Extending cellular services to IoT faces yet another important challenge. That is, there is a huge mismatch between the massive amount of IoT devices and the capacity of the current LTE network due to the scarce LTE spectrum that has already been overwhelmed by HTC. New spectrum must be exploited in order to meet the mass IoT market needs. Recently, more and more GSM spectra are being re-farmed for new wireless services. The GSM spectrum is divided into 200-kHz frequency bands. They are designated by the International Telecommunications Union (ITU) for the operation of GSM mobile services, and mostly are located in the frequency range from 380 MHz to 920 MHz depending on region. The frequencies of these bands are ideal for low power and low rate MTC applications. These hundreds
of small chunks of licensed spectrum are becoming available to wireless connectivity operators. However, the current LTE (including the LTE-eMTC) cannot take advantage of these bands since the minimum operating bandwidth of LTE is $1.4$ (1.08 excluding the guard bands) MHz as noted earlier.

Clearly, LTE must continue its evolution in order to meet the challenges imposed by emerging applications and markets by taking advantage of the available small bands. The focus of this article is thus on the design of a new random access physical layer signaling structure to enable the power- and spectrally-efficient operation of MTC in the bands that are narrower than 1.08 MHz, particularly the 200-kHz bands, where a legacy LTE (including LTE-eMTC) system fails to work.

In Section II, we briefly review the LTE random access scheme. Section III first provides a battery consumption analysis of an MTC device, addresses the limitations of LTE random access when applied to MTC, and then proposes a new random access design that is power- and spectrum-optimized for MTC, henceforth referred to as the narrowband LTE MTC or simply LTE-$n$MTC. Section IV provides an MTC link budget analysis, and presents simulation results for verification of the proposed design. Section V concludes this paper.

II. LTE RANDOM ACCESS

An MTC device wakes up in response to the event of data arrival as a result of, e.g., reporting a meter reading from the device’s upper application layer. Due to the random nature of this type of event, a random access mechanism must be employed in order to gain access to the cellular network. In this section, we briefly review the LTE random access scheme.

Fig. 1 shows typical operations performed by a device in response to an uplink data transfer request. Upon waking up, the device obtains a cell ID from the cell selection protocol, which is usually the ID of the most recently used cell. The device performs a system acquisition by searching for the downlink synchronization signals of the cell. If found, the device synchronizes its local timing and frequency to the synchronization signals which includes a one-way propagation delay in timing. As soon as the timing and frequency are acquired, the device locates the downlink broadcast channel and decodes the system information, e.g., the uplink random access resource configuration. If the synchronization signals of the cell are not found, the device goes back to the cell selection procedure and looks for the next candidate cell listed in the preferred roaming list (PRL) provided by the operator.

Since in sleep, all resources (via which the device communicates with the network access point or the base station) are released back to the network, the device needs to request resources from the network
upon waking up from the sleep in order to re-establish a communication link with the network. This is accomplished by a random access mechanism. Fig. 2 (a) shows the LTE random access signal flow which is initiated by a preamble transmitted by the device on the resources (specified in the system information) reserved particularly for the random access purpose. The random nature of this type of signaling comes from the unscheduled use of the network resources due to the fact that the network access point or base station has no knowledge of when or by whom the signal will be sent. Therefore no resource can be reserved for a particular device in advance. Hence, the transmission of the signal has to be on a set of shared or common resources and done in a contentious manner.

An LTE random access preamble is a Zadoff-Chu (ZC) sequence-based CDMA (code division multiple access) signal that is time-frequency spread over the entire uplink random access resources (referred to as the Physical Random Access Channel or PRACH in LTE terminology) occupying 1.08 MHz of the total system bandwidth shared among all devices [12]-[14]. The ZC sequence can be mathematically represented as

\[ x_\mu[n] = e^{-j \frac{2\pi \mu(n+1)}{N_{ZC}}} , \quad n = 0,1,\ldots,N_{ZC} - 1 \]  

where \( \mu \) is the ZC sequence root, \( N_{ZC} \) is the length of the ZC sequence. As depicted in Fig. 3, the waveforms with different ZC sequences transmitted by multiple devices are multiplexed in the same random access preamble resource in a CDMA manner. The length of the cyclic prefix (CP), \( T_{CP} \), is
selected to be sufficiently long to accommodate the round-trip propagation delay (e.g., $T_{cp} = 35 \, \mu s$ for a cell size of 5 km); and the guard time is used to prevent the random access signal from protruding into the following orthogonal frequency division multiplexing (OFDM) symbol as a result of the propagation delay.

Before the preamble can be transmitted, a device estimates the path loss via the downlink signals. The device then randomly selects a preamble from a pool of 64 waveforms, and transmits it on the uplink random access resources (or PRACH) that is 1.08 MHz in bandwidth (fixed and non-configurable) at the power just enough to compensate for the path loss to minimize the near-far effect. Since the transmission timing is obtained from the downlink synchronization signals, the arrival time at the network access point or base station contains a round-trip (i.e., downlink plus uplink) propagation delay. The base station constantly detects the presence of any of the 64 preambles on the random access resources within a search window that is large enough to accommodate the largest round-trip delay (determined by the cell size). If detected, the random access response message is transmitted on the downlink traffic channel (or PDSCH in LTE terminology). The random access response message

![Diagram](image-url)
contains the detected preamble index, and its associated information including the 11-bit time advance command, the 16-bit temporary identifier for further communications between this device and the base station, and the uplink data channel (PUSCH) resource configuration (20 bits) for the device to transmit the subsequent contention resolution message on. Note that the temporary identifier is not valid until the device wins the contention. The value of the time advance equals the round-trip propagation delay of the detected device, \( t_{\Delta} \) (estimated from the preamble), for use by the device to advance its transmission time (by \( t_{\Delta} \)) to compensate for the round-trip propagation delay. The signals from different devices are then time-aligned at the base station receiver such that a smaller CP can be used on the uplink traffic channel (i.e., PUSCH) to absorb just the multipath spread.

On the device side, once the preamble is sent, it monitors the corresponding random access response messages on PDSCH. A failure to receive the response from the base station can be the result of insufficient transmit power and/or a miss of detection by the base station. The device then restarts the same procedure with increased preamble power. If the decoded message contains the preamble index that the device has used, the device advances its timing (indicated in this message), and transmits the contention resolution message on the specified PUSCH resources (the first \textit{scheduled} transmission on uplink). The contention resolution is necessary since it is possible that more than one devices have used the same preamble waveform (i.e., a collision), and the device has not yet had confirmation that the response is intended for it rather than another device.

The contention resolution message contains a 40-bit “contention resolution key” (e.g., the device’s unique identification within the network). If the base station successfully decodes the message, a
contention resolution response that mirrors the received contention resolution message is transmitted, and addressed to the device with the same contention resolution key. A failure to receive the message from the base station can be the result of collision; and the device has to restart the procedure from the beginning.

We see that the LTE as well as LTE-eMTC random access involves a sequence of message exchanges between a device and the network. This presents excessive overhead for MTC considering the MTC application data per wakeup are typically small, which is not surprising since the LTE random access is not optimized for MTC but for human-type communications. It is now clear that there are two major issues in the random access of LTE-eMTC for applications in MTC: (1) excessive overhead that may incur unnecessary battery and resource consumption; and (2) non-scalable preamble bandwidth (fixed 1.08 MHz) that prevents its deployment in narrower band such as the 200 kHz GSM bands.

III. RANDOM ACCESS IN LTE-nMTC

In this section, we propose a solution to the issues present in the LTE-eMTC. The new design is specifically optimized for LTE MTC operating on narrow bands, henceforth referred to as “LTE-nMTC”.

A. Battery Consumption Analysis

A device’s battery life is crucial to most MTC applications, and is therefore the key to cellular MTC, and hence the main focus of the optimization.

Depending on the type of an MTC device, the typical capacity of the battery ranges from 500 mAh (e.g., for a smart watch) to 5000 mAh (e.g., for a metering device). The required battery life for MTC ranges from days (e.g., for smart watches) to years (e.g., for metering).

During reception, the current drawn from a battery is mainly by baseband processing $I_{0}$, i.e.,

$$I_{rx} \approx I_{0},$$

whereas during transmission, the total current drawn is by the signal transmission plus baseband processing. It can be approximated as

$$I_{tx} \approx I_{0} + \frac{P/\eta}{V},$$

where $P$ is the transmit power, $V$ the battery voltage (e.g., 3 V), and $\eta$ the power amplifier efficiency ranging from 10% to 40%. A typical value of $I_{0}$ is on the order of 150 mA. Assuming the
maximum transmit power of the device is 20 dBm, $I_o = 150$ mA, and $\eta = 30\%$, the total current drawn is 150 mA during reception, and 260 mA during transmission, which is much greater than the current pulled from the battery when the device is in deep sleep (on the order of a few micro-Amps).

The battery consumption per random access is thus

$$C = t_{Tx} I_{Tx} + t_{Rx} I_{Rx},$$

where $t_{Tx}$ and $t_{Rx}$ are the total transmit and receive time during a random access process, respectively. The actual values of $t_{Tx}$ and $t_{Rx}$ depend on the random access design. Nevertheless, it is clear that the device’s “air time” has a profound effect on the battery life, and its optimization is vital to most MTC applications.

In the following subsection, we propose a power optimized random access design for MTC. We first simplify the random access procedure, and then optimize the random access channel resource configuration in the sense of minimal air time and maximal overall spectral efficiency.

B. Simplified Random Access Signaling

The preamble in LTE random access does not contain any kind of device identifier, causing ambiguities among accessing devices. This necessitates contention resolution message exchanges between the device and the base station. For most MTC applications, only a small amount of application data needs to be exchanged between the device and the network per access. The overhead of this access method becomes significant, and may become a bottleneck in terms of battery life, considering that signaling takes much longer time to close the MTC link than in the legacy LTE due to the reduced capability of an MTC device and the need for coverage extension (we will see more detailed discussions in this regard in Section IV). Simplification of the random access procedure can potentially save device power as a result of the elimination of the preamble and the contention resolution from the random access procedure.

The primary purpose of the preamble in the legacy LTE random access is 1) to indicate to the base station the presence of an accessing device, and 2) to provide the base station a means of measuring the uplink timing offset (i.e., the round-trip propagation delay) of the device. The handshakes that follow the preamble are for the base station to provide the access device with a unique and shortened identifier within the cell for the subsequent data communications between the base station and the device. These two goals are accomplished by a single special OFDM signal in the following design.
As illustrated in Fig. 4, the proposed random access channel occupies \( s \) subcarriers out of a total of \( S \) subcarriers, thereby constituting a total of \( N_{\text{RACH}} = \frac{S}{s} \) random access channels. The random access signal, transmitted on one of the random access channels by a device, consists of \( N_{\text{OFDM}} \) special OFDM symbols. Each OFDM symbol is equipped with an extended CP (longer than the traffic channel CP, e.g., \( T_{\text{CP}} = 35 \mu s \) for a cell size of 5 km) for absorbing not only the multipath spread but also the round-trip propagation delay to enable decoding of the access request message \( M \) carried by the random access signal from a device without the knowledge of the arrival timing of each individual random access signal. It is to be noted that the use of a longer CP increases the overhead of an OFDM symbol. Nevertheless, this effect can be compensated by using a longer OFDM symbol (i.e., smaller subcarrier spacing) as will be seen later.

The message \( M \) contains a 10-bit access ID, 4-bit resource request, and 10-bit CRC, resulting in a
message that has $|\mathcal{M}|=24$ information bits. This message is channel-coded (tail-biting-convolutional coding), QPSK modulated, and cell-specifically scrambled to produce a sequence of modulation symbols, which are further mapped onto the resource elements of the random access channel that is randomly selected by the device from a pool of $N_{\text{RACH}}$ channels (cf. Fig. 4). The access ID is also randomly selected by the device from a pool of $2^\alpha$ access IDs. Like the temporary identifier in LTE, the access ID is used for the identification of a device in the current access within the current cell. Here the 4-bit uplink resource request is used to indicate the volume of the uplink data for uplink resource allocation. The difference between Fig. 4 and Fig. 3 is that the random access channels used by devices are frequency-division-multiplexed (FDM) rather than code-division-multiplexed (CDM). Each channel only occupies a fraction of the bandwidth instead of the entire bandwidth. We will see the advantage of FDM over CDM in MTC later.

As shown in Fig. 4, using the base station timing, the base station extracts the $N_{\text{OFDM}}$ OFDM symbols without the need for the knowledge of the arrival time of each individual device, $\Delta t_u > 0$, \( u \in \{1, 2, \ldots, N\} \) (where $N$ is the number of access devices in the current random access occasion) due to the use of the extended CP, and then tries to decode the $N_{\text{RACH}}$ potential messages on the $N_{\text{RACH}}$ random access channels. For notational simplification, we drop the device index, $u$, without causing confusion.

In the current scheme, the presence of an access device is detected by a successful decoding of an access request message as indicated by a CRC check, whereas in current LTE it relies on the detection of the preamble waveform based on a threshold. Since the threshold is a function of the level of instantaneous interference from other accessing devices (which is hard to be accurately estimated), the detection is inefficient due to the use of an overly-high threshold in order to keep the rate of false detection manageable. A low detection probability of the preamble means more preamble transmissions for an access device, and hence more power consumptions. In this sense, the current scheme has a clear advantage owing to the more reliable CRC check.

When a device’s access request message $\mathcal{M}$ is detected on one of the $N_{\text{RACH}}$ random access channels as a result of a successful decoding of $\mathcal{M}$ (i.e., CRC checks), an uplink resource assignment for uplink data uploading is sent through the downlink control channel (i.e., PDCCH) addressed to the device with the access ID indicated in $\mathcal{M}$ for data transmission. Fig. 2 (b) draws the simplified call
flow, compared to the one in Fig. 2 (a).

Although decoding of the access request message itself does not require the timing information due to the protection of the extended CP in the current design, the round-trip propagation delay of the detected device, $\Delta t$, still remains unknown and needs to be estimated from the detected access request signal by the base station. The estimated delay is then attached to the uplink resource assignment message [cf. Fig. 2 (b)] so that the device can advance its transmission time (by $\Delta t$) to compensate for the round-trip propagation delay in the subsequent uplink transmissions on the traffic channels (including data and control channels). A smaller CP can then be used only to accommodate the multipath spread in the subsequent uplink data transmissions on the traffic channel. The propagation delay estimation using the access request signal is described in Subsection D.

A collision happens whenever more than one device happen to select the same random access channel with a probability of

$$p_{ch} = 1 - \left( \frac{N_{RACH} - 1}{N_{RACH}} \right)^{N-1} = 1 - \left( 1 - \frac{1}{N_{RACH}} \right)^{N-1}. \quad (5)$$

In the legacy LTE random access, the temporary device identifier is assigned by the base station, while in the current design, it (the MTC device’s access ID) is randomly chosen by the device itself. A collision happens when more than one device choose the same access ID. The corresponding probability is

$$p_{id} = 1 - \left( 1 - \frac{1}{N_{ID}} \right)^{N-1}, \quad (6)$$

where $N_{ID} = 2^{16}$ is the number of available IDs for selection. The total collision probability is then

$$p_c = 1 - (1 - p_{ch})(1 - p_{id}). \quad (7)$$

Since the number of available access IDs ($N_{ID}$) is, by design, to be much greater than the number of random access channels ($N_{RACH}$), $p_{ch} \gg p_{id}$. Therefore, $p_c \approx p_{ch}$. That is, the collision is dominated by the access channel collision whose probability is in reverse proportion to the number of random access channels. The consequence of the channel collision is most likely a failure to decode the message by the base station. The device then will not receive the resource assignment from the base station. Another round of random access attempt at the next random access opportunity is necessary, thereby resulting in increased total transmission time.

Reducing the collision probability requires an increase in the number of random access channels
However, for a given total random access bandwidth of \( W \), a larger \( N_{\text{RACH}} \) means a smaller bandwidth (\( w = W/N_{\text{RACH}} \)) per random access channel, a lower data rate that each channel supports, and a longer transmission time for a device. The following question then arises: Given a bandwidth of \( W \), what is the resource configuration scheme for random access channels (i.e., the bandwidth of a random access channel) that minimizes the overall access request message transmission time? To answer this question, we need the concept of “effective bandwidth”.

C. Effective Bandwidth and Optimal Resource Configuration

The SNR of an OFDM resource element (RE, i.e., a subcarrier over the duration of an OFDM symbol \( T \)) of the random access channel is

\[
\rho_{\text{RE}} = \frac{TP/s}{\alpha \zeta N_0} = \frac{1}{s} \cdot \frac{TP}{\alpha \zeta N_0}
\]

as a result of matched-filtering through DFT, where \( T = \frac{S}{W} \) is the duration of an OFDM symbol, \( \zeta \) is the noise figure of the receiver, \( N_0 \) is the noise power spectral density (i.e., -174dBm/Hz), and \( \alpha \) is the coupling loss whose value depends on the MTC channel class of the device: \( \alpha = 155, 150, 145, \) and \( 140 \) dB for channel classes 1, 2, 3, and 4, respectively. The total number of REs per OFDM symbol is \( s \) per channel. The corresponding maximum data rate (bits/OFDM symbol) is

\[
r = s \cdot \log(1 + \rho_{\text{RE}}) = s \cdot \log \left(1 + \frac{1}{s} \cdot \frac{TP}{\alpha \zeta N_0}\right),
\]

and the maximum data rate in bits/sec is

\[
r = s \cdot \log \left(1 + \frac{1}{s} \cdot \frac{TP}{\alpha \zeta N_0}\right) \frac{1}{(T + T_{CP})}
\approx \frac{s}{S} W \cdot \log \left(1 + \left(\frac{s}{W}\right)^{-1} \cdot \frac{P}{\alpha \zeta N_0}\right),
\]

(10)

Taking into account the imperfection of a realistic system, Equation (10) becomes

\[
r(w, \alpha) = w \cdot \log \left(1 + w^{-1} \cdot \frac{\beta P}{\alpha \zeta N_0}\right),
\]

(11)

where \( \beta \) is included to reflect the deficit in performance between a realistic system and the theoretical
limit. In general, the larger the $w$ is (or the larger the transmission bandwidth is), the higher the transmission rate, and the shorter the transmission time of the access request message $M$. That is,

$$\tau(w, \alpha, |M|) = \frac{|M|}{r(w, \alpha)} = \frac{|M|}{w \log \left(1 + \frac{\beta P}{\alpha \zeta N_0}\right)}.$$  \hspace{1cm} (12)

In fact, when $w \to \infty$,

$$\tau(\infty, \alpha, |M|) = \lim_{w \to \infty} \tau(w, \alpha, |M|) = \frac{|M| \ln 2}{\beta P},$$  \hspace{1cm} (13)

which is the minimum transmission time for message $M$, i.e.,

$$\tau(w, \alpha, |M|) > \tau(\infty, \alpha, |M|), \ \forall w < \infty.$$  \hspace{1cm} (14)

given $\alpha$ or the channel class.

Fig. 5 plots (12) relative to $\tau(\infty, \alpha, |M|)$, i.e.,

$$\Delta \tau(w, \alpha) = \frac{\tau(w, \alpha, |M|) - \tau(\infty, \alpha, |M|)}{\tau(\infty, \alpha, |M|)} = \frac{\tau(w, \alpha, |M|)}{\tau(\infty, \alpha, |M|)} - 1$$  \hspace{1cm} (15)

for devices belonging to the four channel classes, which represents the extra transmission time incurred due to the use of a finite transmission bandwidth $w$. Note that the normalized transmission time in (15) is no longer a function of the message size $|M|$.
Although \( \Delta \tau(w, \alpha > 0 \ (\forall w, \alpha) \), it is observed that there exists an effective bandwidth \( w^\star \) for every channel class such that once exceeded, the effect of the transmission bandwidth on the reduction of the transmission time diminishes. That is, for \( w > w^\star \), the device becomes more power-limited rather than bandwidth-limited, meaning that allocating more bandwidth provides limited help in reducing the transmission time. If we define the effective bandwidth as the \( w^\star \), at which \( \Delta \tau(w^\star, \alpha) \) equals, e.g., 10\%, the \( w^\star \) for channel classes 4, 3, 2, and 1 are then 94, 30, 9, and 3 kHz, respectively. They are summarized in Table 1. The lower the channel class is, the less sensitive it is to bandwidth. Clearly, devices belonging to the class whose bandwidth is less than the effective bandwidth are therefore bandwidth-limited, and those whose bandwidth is greater than the effective bandwidth are power-limited. The effective bandwidth therefore provides a good balance between the transmission time and the spectral efficiency (or the total number of FDM channels that a given \( W \) supports). Since the effective bandwidth of a low channel class is less than that of a high channel class, more FDM channels are available for a low channel class for a given total bandwidth.

Based on this effective bandwidth concept, the subcarrier spacing of 15 kHz for legacy LTE data channels is too large for MTC, and a finer granularity is needed. The subcarrier spacing is thus reduced by a factor of 5, i.e., 3 kHz in the new design to match the smallest effective bandwidth (CC1). The reduction of subcarrier spacing has the following implications: (1) Five times as many FDM channels for CC1 devices; (2) The OFDM symbol in time domain is elongated by a factor of 5, which increases OFDM symbol energy by 7 dB; and (3) The data channel CP length can also be increased by five times, i.e., \( \frac{5 \mu s \times 5 = 25 \mu s}{25 \mu s + (3 kHz)^{-1}} \approx 7\% \) as in the legacy LTE, \( \frac{5 \mu s}{5 \mu s + (15 kHz)^{-1}} \approx 7\% \) [11]. Longer CP allows for not only larger multipath spread but also more tolerance to timing errors which relaxes the uplink timing requirement. This is beneficial since timing estimation is less accurate under narrow band than wideband due to the reduced time resolution under

| Channel Class \( \alpha \) | 4 (140dB) | 3 (145 dB) | 2 (150 dB) | 1 (155 dB) |
|-----------------------------|------------|------------|-------------|-------------|
| Effective bandwidth \( w^\star (\alpha) \) (kHz) | 94 | 30 | 9 | 3 |
| Transmission time \( \Delta \tau(w^\star, \alpha) \) (%) | | | | 10 |
the narrow band as will be seen in subsection D. However, narrower subcarrier spacing also means more vulnerability to frequency offsets due to frequency tracking errors and/or Doppler spread although much lower mobility (hence lower Doppler effects) in MTC applications than HTC is expected.

Note that $\tau(w, \alpha, |\mathcal{M}|)$ or $\Delta \tau(w, \alpha)$ represents the transmission time for a non-contention based transmission in a collision-free environment as for the data transmissions on the traffic channels. In the case of random access on the random access channels, the transmission is unscheduled or contentious. The actual transmission time is hence $\Delta \tau(w, \alpha)$ plus the re-transmissions in the case of collisions whose probability is directly related to the number of random access channels, $N_{\text{RACH}} = \frac{W}{w}$, as given in (5),

$$p_c(w, N) = 1 - \left(1 - \frac{1}{N_{\text{RACH}}} \right)^{N-1} = 1 - \left(1 - \frac{w}{W} \right)^{N-1},$$ (16)
given the number of accessing devices $N$ in the current random access opportunity. Therefore, the total transmission time is also a function of the collision probability, and can be derived as follows:

$$\tau_c(w, \alpha, N, |\mathcal{M}|) = \lim_{K \to \infty} \sum_{i=1}^K (1 - p_c(w, N)) p_c^{i-1}(w, N) \left( i \cdot \tau(w, \alpha, |\mathcal{M}|) \right)$$

$$= \tau(w, \alpha, |\mathcal{M}|) \lim_{K \to \infty} (1 - p_c(w, N)) \sum_{i=1}^K i \cdot p_c^{i-1}(w, N)$$

$$= \tau(w, \alpha, |\mathcal{M}|) \lim_{K \to \infty} \left( \frac{1 - p_c^K(w, N)}{1 - p_c(w, N)} - K \cdot p_c^K(w, N) \right)$$

$$= \tau(w, \alpha, |\mathcal{M}|) \lim_{K \to \infty} \frac{1 - p_c^K(w, N)}{1 - p_c(w, N)}$$

$$= \tau(w, \alpha, |\mathcal{M}|) \frac{1 - p_c(w, N)}{1 - p_c(w, N)}.$$ (17)

Clearly, $\tau_c(w, \alpha, N, |\mathcal{M}|) > \tau(w, \alpha, |\mathcal{M}|)$ due to the fact that $0 < p_c(w, N) < 1$ in the contention-based random access.

Ultimately, we look for the $w$ that minimizes (17). Alternatively, we search for the $w$ that minimizes the extra time or penalty introduced by the contention among $N$ accessing devices. That is,

$$w^*(\alpha, N) = \arg \min_{w \in w^*(\alpha)} \Delta \tau_c(w, \alpha, N),$$ (18)

where

$$\Delta \tau_c(w, \alpha, N) = \frac{\tau_c(w, \alpha, N, |\mathcal{M}|)}{\tau(w^*, \alpha, |\mathcal{M}|)} - 1.$$ (19)
The optimal random access channel bandwidth in (18) is a function of the number of contending devices $N$ per random access opportunity.

Fig. 7 plots the time penalty, $\min_{w \in w^f(\alpha)} \Delta r_c(w, \alpha, N)$ in (18), as a function of $N$, which is a monotonically increasing function of $N$, for different channel classes. At an, e.g., 10% penalty, the devices that can be supported is $N = 7$ for CC1 ($\alpha = 155$ dB), and 3 for CC2 ($\alpha = 150$ dB), whereas for CC3 ($\alpha = 145$ dB) and CC4 ($\alpha = 140$ dB) $N$ dwindles down to less than two. On the other hand, in order for all high channel classes to support the same number of devices as CC1, i.e., $N = 7$, they have to live with much higher penalties, i.e., $\min_{w \in w^f(\alpha)} \Delta r_c(w^f(\alpha), \alpha, N) \gg 10\%$ ($\alpha = 150, 145,$ and $140$ dB).

This phenomenon can be better explained using Fig. 6, where we observe that for CC1 ($\alpha = 155$ dB) and at $N = 7$, the optimal bandwidth equals the effective bandwidth, i.e., $\frac{w^e(\alpha)}{w^f(\alpha)} = 1$. The 10% performance penalty is thus purely attributable to collisions. Whereas for higher channel classes to support $N = 7$, each random access channel of these classes has to settle with an optimal bandwidth $w^e(\alpha)$ that is much smaller than the effective bandwidth $w^f(\alpha)$, i.e., $\frac{w^e(\alpha)}{w^f(\alpha)} \ll 1$ ($\alpha = 150, 145,$ and $140$ dB) as shown in Fig. 6, in order to make room for a sufficient number of FDM channels, $\frac{W}{w^e}$. The
resultant bandwidth deficit (i.e., \( \frac{w^{\text{opt}}(\alpha)}{w(\alpha)} < 1 \)) gives rise to high performance penalty, \( \Delta \tau_c(w^{\text{opt}}, \alpha, N) \gg 1 \).

A solution to maintaining the collision at a reasonable low probability (corresponding to, e.g., 10% penalty) for high channel classes without incurring high bandwidth deficit penalty is to add more random access channels in a time division multiplexing (TDM) fashion. The collision probability with \( L \) chunks of TDM random access resources per random access occasion (cf. Fig. 8) is

\[
  p_c(w, N, L) = 1 - \left(1 - \frac{w}{LW}\right)^{N-1},
\]

where \( L \) is the multiplicity of the TDM random access resources in time domain. Clearly, (20) is less than (16) for \( L > 1 \). Nevertheless, \( L - 1 \) more TDM resources are needed to compensate for the shortage in bandwidth.

Referring back to Fig. 7 (dotted lines), we show the values of \( L \) needed for high channel classes, i.e., \( L_2 = 3, L_3 = 12, \) and \( L_4 = 36, \) such that \( N = 7 \) can be supported without incurring the bandwidth deficit penalty, i.e., \( \frac{w^{\text{opt}}(\alpha)}{w(\alpha)} \approx 1 \) for \( \alpha = 150, 145, \) and 140 dB. That is, the penalty due to contention is below 10% as long as the number of contending devices is less than 7 (cf. Fig. 6). In the following
discussion, $N$ is hence assumed to be 7 unless otherwise specified. The implication of $N$ on the overall random access capacity will be discussed in Section IV (D).

The optimal channel configurations are summarized in Table 2. Table 3 is for $W = 1.08$ MHz to show the bandwidth scalability of the design. We observe that the confliction between the channel bandwidth and the total number of channels is less severe under a wider bandwidth ($W = 1.08$ MHz), in which less deficit exists between $w^{++}$ and $w^-$, thereby, less performance loss attributable to the bandwidth deficit.

Fig. 8 is a block diagram illustrating the random access channel configuration for $W = 180$ kHz, where the number of subcarriers is chosen to be $S = 60$ which results in a subcarrier spacing of 3 kHz that matches the optimal bandwidth $w^{++}$ (cf. Table 2) by design. The CP overhead for an OFDM symbol is 

$$\frac{35\mu s}{35\mu s + (3\text{kHz})} \approx 9\%.$$  

D. Timing Estimation

As mentioned in Section III (B), the use of a preamble is mainly for the purpose of indicating the presence of an access device, and providing a means for measuring uplink timing (round-trip propagation delay) at the base station. Based on the arrival timing measurement from the preamble, the base station instructs the device to advance its uplink timing to compensate for the round-trip propagation delay such that the uplink signals from different devices are time-aligned at the base station.
A smaller CP can then be used to absorb the *multi-path delay* as well as timing errors for the subsequent uplink transmissions on the traffic channels. In the current simplified random access design, the presence of an access device is indicated by the successful decoding of its access request message, and the necessity for the knowledge of propagation delay is negated by using a larger CP (e.g., 35 $\mu$s ). However, the time of arrival estimation for each access device still remains necessary for subsequent uplink data transmissions on the traffic channel with a smaller CP (e.g., 25 $\mu$s ).

Once the access request message on a random access channel has been correctly decoded (i.e., the CRC checks), the access signal can then be effectively used as the “preamble” for device timing estimation after the message (known) are removed from the modulation symbols. Since the time offset between the arrival time and the base station timing (due to round-trip propagation delay), $\Delta t$, of a random access signal causes phase-ramping in the received signal in the frequency domain at a rate proportional to the time offset, the time offset can be estimated from the phase difference between two modulation symbols, $y_i$ and $y_j$, on different subcarriers.

Since the carrier frequency offset $\Delta f$ between the MTC device and the base station, i.e., the residual frequency synchronization error from the system acquisition causes a similar phase ramping effect on the received baseband signal but in the time domain, we have

$$y_j^*y_i^* = \left(he^{j2\pi\left(-q_iT^{-1}\Delta t + (T + T\tau_r)\Delta f\right)} + v_j\right)^* \left(he^{j2\pi\left(-q_jT^{-1}\Delta t + (T + T\tau_r)\Delta f\right)} + v_i\right)^*$$

$$= |h|^2 e^{j2\pi\left((q_j - q_i)T^{-1}\Delta t + (T + T\tau_r)\Delta f\right)} + h^*e^{-j2\pi\left(-q_jT^{-1}\Delta t + (T + T\tau_r)\Delta f\right)}v_j + v_i^*v_j^*$$

where $h$ is the channel gain, $q_i$ and $q_j$ are the indices of subcarriers which are occupied by symbol $y_i$ and $y_j$, $\Delta q \triangleq q_i - q_j$ is the separation (in subcarriers) between the two modulation symbols, $T^{-1} = \frac{W}{S}$ is the subcarrier spacing of the OFDM symbol, $v_i$ is the zero-mean Gaussian noise with variance $\sigma^2$, and $E\{v_i^*v_j^*\} = 0, \forall j \neq i$, and

$$u_{i,j} \triangleq he^{j2\pi\left(-q_iT^{-1}\Delta t + (T + T\tau_r)\Delta f\right)}v_i^* + h^*e^{-j2\pi\left(-q_jT^{-1}\Delta t + (T + T\tau_r)\Delta f\right)}v_j + v_i^*v_j^*.$$  

It can be shown that $E\{u_{i,j}\} = 0$. Therefore,

$$E\{y_j^*y_i^*\} = |h|^2 e^{j2\pi\left(\Delta qT^{-1}\Delta t + (T + T\tau_r)\Delta f\right)}.$$  

(23)
Fig. 9 illustrates how an access request signal is mapped onto the physical random access channels to facilitate the time offset estimation, where we have groups of modulation symbols of a random access signal hopping between two physical random access channels to create a separation of $\Delta q \neq 0$ subcarriers between two groups of modulation symbols.

To estimate the time offset, the frequency offset in (23) is first obtained using the modulation symbols within a group that are on the same subcarrier, for which $\Delta q = 0$ [15],

$$\Delta f = \frac{1}{2\pi(T + T_{cp})} \arctan E\{y\_l, y\_l^\star\},$$

conditioned on

$$2\pi(T + T_{cp})|\Delta f| < \pi.$$  \hspace{1cm} (25)

Specifically, an estimate of (24) is

$$\hat{\Delta f} = \frac{1}{2\pi(T + T_{cp})} \arctan \sum_{n=0}^{N_{sym}/l-1} \sum_{k=0}^{l-2} y\_n\_l+k, y\_n\_l+k^\star,$$

where $l$ is the number of modulation symbols in one group.

After the temporal phase ramping is removed using the result from (26), the time offset is then obtained from the modulation symbols that are on separate subcarriers (i.e., $\Delta q > 0$), i.e.,
\[ \Delta t = \frac{1}{2\pi T^{-1}} \arctan E \{ y, y'_{rel} \}, \quad (27) \]

as long as
\[ 2\pi \Delta q T^{-1} \Delta t < 2\pi. \quad (28) \]

An estimate of (27) is
\[ \Delta t = \frac{1}{2\pi T^{-1}} \Delta q \sum_{n=0}^{N_{\text{norm}}/2^l-1} \left( \sum_{k=0}^{l-1} y'_{2(n+k)} \right) \left( \sum_{k=0}^{l-1} y'_{(2n+1)+k} \right)^*, \quad (29) \]

where \( y' \) is the signal after removing the time-domain phase ramp caused by frequency offset. Clearly, the larger \( \Delta q \) is, the less the estimation error. From (28), the maximum value of \( \Delta q \) depends on the largest time offset \( \Delta t \) which is the maximum round-trip propagation delay, a function of the cell size. For instance, the maximum value of \( \Delta q \) is 9 for a 5 km radius cell at a subcarrier spacing of 3 kHz.

IV. LINK BUDGET ANALYSIS AND SIMULATION RESULTS

Simulations have been carried out to examine the performance of LTE-nMTC random access design developed in the previous section, under the typical MTC environment (EPA 1 Hz [4]). The operating bandwidth of an MTC device is 180 kHz, with subcarrier spacing of 3 kHz and a CP length of 35 \( \mu \)s for random access channels, and 25 \( \mu \)s for traffic channels.

A. Link Budget Analysis

Before the simulation, the link budget for each channel class needs to be analyzed so that the operating SNR for each channel class can be determined.

Assuming the transmit power allocated to the signal is \( p \) (dBm), and the coupling loss is \( \alpha \) (dB), the required receiver sensitivity is then \( p - \alpha \) (dBm). If the bandwidth that the signal occupies is \( w \) (dB-Hz), and the noise figure of the receiver is \( \zeta \) (dB), the noise power at the receiver is thus \( w + N_0 + \zeta \) (dBm), where \( N_0 \) (dBm/Hz) is the noise power spectral density (i.e., -174 dBm/Hz). The corresponding signal SNR at the receiver is

\[ \Gamma = (p - \alpha) - (w + N_0 + \zeta) \]  

For the uplink, the transmit power \( P_{ul} \) is solely dedicated to the device itself. In this case, the
transmit power is fully allocated to the uplink signal, i.e., $p = P_{UL}$. The corresponding signal SNR at the receiver becomes

$$\Gamma_{UL} = (P_{UL} - \alpha) - (w + N_0 + \zeta_{UL}).$$

(31)

For LTE-nMTC random access channels, $w = w^{\text{LTE}}(\alpha)$, $\alpha = 155$, 150, 145, and 140 dB.

As for the downlink, the transmitter (base station) power is assumed to be evenly allocated over the entire system bandwidth for a fully loaded system. The allocated power to the signal is thus $p = P_{DL} + w - \Pi$ (dBm), where $P_{DL}$ (dBm) is the total transmit power for the system bandwidth of $\Pi$ (dB-Hz). The corresponding receive SNR therefore is

$$\Gamma_{DL} = (P_{DL} - \Pi) - \alpha - N_0 - \zeta_{DL} \text{ (dB)}.$$

(32)

where $P_{DL} - \Pi$ (dBm/Hz) is the downlink transmit power spectral density. Unlike the uplink, the downlink SNR is not a function of $w$, the bandwidth that the signal occupies.

Taking the uplink as an example, and assuming that an MTC device has a maximum transmit power of 20 dBm, the required receiver sensitivity is thus $P_{UL} - \alpha = 20 \text{dBm} - \alpha \text{dB}$. If we further assume that the noise figure of a base station receiver is $\zeta_{UL} = 5$ dB, the corresponding signal SNR received at the base station, according to (31), is

$$\Gamma(\alpha, w) = (20 \text{dBm} - \alpha \text{dB}) - (w \text{dB-Hz} + (-174 \text{dBm/Hz}) + 5 \text{dB})$$

$$= 189 \text{dBm} - (\alpha + w) \text{dB}.$$ (33)

For the LTE-nMTC access request signal, $w = w^{\text{LTE}}(\alpha)$, i.e., channel class dependent. Referring to Table 2, $\alpha + w^{\text{LTE}}(\alpha) \approx 189 \text{dB}$ for $\alpha = 155$, 150, 145, and 140 dB, yielding $\Gamma = 0$ dB for all channel classes.

That is, the operating SNRs for the access request signal are the same for all channel classes as listed in Table 4.

The link budget for the LTE-eMTC random access signals can be analyzed similarly, except that, unlike in LTE-nMTC where the signal bandwidth is individually optimized for each channel class,
channel bandwidth $w$ for LTE-eMTC random access signals are channel classes independent. The operating SNRs are therefore different for different channel classes. For the downlink, the base station transmit power is 46 dBm for a 10 MHz total system bandwidth, and the noise figure of the device is 9 dB. The corresponding signal operating SNRs are listed in Table 4.

B. Simulation Results

Fig. 10 shows the link performance of the LTE-nMTC access request signal for various channel classes. The transmission time intervals (TTIs) for the LTE-nMTC access request signal to close the various channel class links are summarized in Table 5. The TTIs for LTE-eMTC random access signals are also listed in Table 5 for reference.

Table 5 Transmission time intervals (TTIs) of LTE-nMTC random access message for different channel classes. EPA channel with 1Hz Doppler; $S = 60$ subcarriers. The TTIs for LTE-eMTC random access signals at different random access stages (cf. Fig. 2) are also included for reference. $W = 180$ kHz for LTE-nMTC, and $W = 1.08$ MHz for LTE-eMTC.
Let’s consider channel class 1 as an example. After taking into account the collision and decoding error ($p_c = 1\%$), the average transmission time for LTE-nMTC is

$$T_{tx} = \frac{T_{tx}}{1-p_c} \approx 0.245\text{sec} \approx 0.27\text{sec},$$

where $T_{tx}$ is the TTI for LTE-nMTC channel class 1, and the 9% collision probability is obtained from (16). Hence, the battery consumption per random access according to (4) is

$$C_{LTE-nMTC} = t_{tx}I_{tx} = 0.27\text{sec} \times 260\text{mA} \approx 0.020\text{mAh}$$

or 0.0004% two AA battery capacity ($C_{AA} = 5000\text{mAh}$).

For LTE-eMTC, it is approximately (ignoring the collision, miss of preamble detection, and random access response and contention resolution decoding error)

$$C_{LTE-eMTC} = t_{tx}I_{tx} + t_{rx}I_{rs} = (T_{tx1} + T_{tx2} + T_{tx3})I_{tx} + (T_{rs1} + T_{rs2})I_{rs}
= (0.08 + 0.85 + 0.13)\text{sec} \times 260\text{mA} + (1.564 + 0.574)\text{sec} \times 150\text{mA}
\approx 0.166\text{mAh}$$

or 0.0033% two AA battery capacity. This is an 88% reduction in battery consumption for each random access.

Fig. 11 shows the power consumption comparison between LTE-nMTC and LTE-eMTC under different channel classes.

Longer air time not only means higher power consumption, it also means higher resource overhead.
The total time-frequency resources used is \(180\mathrm{kHz} \times 0.27\mathrm{sec} = 48,600\) for LTE-nMTC, whereas \(1210,680\) for LTE-eMTC. The reduction in resource usage for each random access is therefore around 96%.

Fig. 12 shows the timing estimation performance using the LTE-nMTC access request signal for different channel classes. We observe that the timing error is in the range of \(\pm 5\mu\text{s}\) (95 percentile) which consumes about \(10\mu\text{s}\) of the CP, leaving \(15\mu\text{s}\) for the multipath delay spread, which is sufficient for the traffic channels.

C. Support for Larger Cells

So far in the discussion, a CP size of \(35\ \mu\text{s}\) (corresponding to typical cell sizes of less than 5 km) is used for the random access channel to absorb the propagation delay. Due to the low duty cycle of the random access (e.g., 10%), the overall overhead of the random access channel CP is rather small even with a much larger CP. Therefore, very large cells can be supported with the current design. For instance, a CP of \(235\mu\text{s}\) (for a cell size of 35 km) can be supported with an overall overhead of \(\sim 4\%\).

D. Random Access Capacity

From the previous analysis, the number of devices per random access opportunity \(N\) of the current design for the bandwidth of \(W = 180\ \text{kHz}\) should be controlled below 7. For the random access duration of about 0.25s, the random access period is set to be 2.5 seconds to maintain a 10% overhead (cf. Fig. 8). Therefore, a total of \(60s/2.5s \times 7 = 168\) devices can be supported per minute, per band (of
width 180 kHz), and per cell. The random access capacity of a cell is thus 168 devices per band for the device wake up period of 1 minute, and 2,520, 5,040, and 10,080 devices for the periods of 15, 30, and 60 minutes, respectively. The control mechanism of the number of random access devices per random access occasion can be found in [16].

V. CONCLUSION

MTC communication is a key component of Internet of Things for connecting devices to the Internet. Cellular networks have the greatest potential to provide a reliable and global connectivity for MTC applications. One of the major challenges in cellular MTC is efficient random access, a process via which a device establishes a (wireless) communication link with the network. Its power and spectral efficiency is of particular importance to cellular MTC due to the MTC device’s battery limitation and scarce cellular spectrum. In this paper, we first review the legacy LTE random access mechanism and address its limitations when applied to MTC. Firstly, the bandwidth of the random access channel that is used for transmitting the random access preamble signal is fixed at 1.08 MHz, which prevents it from being deployed in a narrower bandwidth such as the 200 kHz re-farmed GSM bands, and hence hinders the application of legacy LTE (i.e., LTE-eMTC) to mass IoT markets due to the already-scarce LTE bands. Secondly, the random access procedure that is optimized for human-type communication patterns presents a significant overhead for machine-type data communication patterns that are typically characterized by infrequent small data bursts. We then present a power- and spectrum-optimized, and bandwidth-scalable random access design, tailored specifically for cellular MTC. Specifically, we simplify the random access process by replacing the legacy preamble CDMA signal with a special OFDM signal to negate the need for preamble, contention resolution, and the conventional threshold-based waveform detection. We introduce the concept of effective bandwidth, and use it to optimize the power and spectral efficiency of the random access signal under a contention-based signaling environment. Link budget and power consumption analyses show an over 88% reduction in battery consumption and 96% in resource usage, compared to the traditional LTE random access.

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