Coverage Enhancement Techniques for Machine-to-Machine Communications over LTE

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Abstract

The tremendous growth of machine to machine (M2M) applications has been a great attractor to cellular network operators to provide machine type communication services. One of the important challenges for cellular systems supporting M2M terminals is coverage. This is because terminals can be located in spaces in buildings and structures suffering from significant penetration losses. Since these terminals are also often stationary, they are permanently without cellular coverage. To address this critical issue, the third generation partnership project (3GPP) and in particular its radio access network technical specification group (RAN TSG) have commenced work on coverage enhancement (CE) for long term evolution (LTE) systems in June 2013. This article reviews the CE objectives defined for LTE machine type communication and presents CE methods for LTE downlink and uplink channels discussed in this group. The presented methods achieve CE in a spectrally efficient manner and without notably affecting performance for legacy (non M2M) devices.

Index Terms

Coverage Enhancement; Machine Type Communications; Long Term Evolution

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I. Introduction

Recent advances in the provision of reliable and ubiquitous cellular communications have paved the way for a new era in wireless communications that will see massive communication between automated devices over wireless links. This concept, commonly referred to as machine to machine (M2M) communications, is an enabling technology for a large variety of application domains, including electricity management (smart grids), healthcare, transportation and logistics, and home and industry automation. As a result, M2M communications is one of the fastest growing technologies in the field of telecommunications. The GSM Association forecasts that the number of M2M cellular connections reaches about a quarter of a billion in 2014. Furthermore, according to ABI research from January 2014, the (projected) numbers of annual shipments of wireless modules for cellular M2M communications will increase from about 40 million in 2011 to about 185 million in 2019. This demonstrates the strong incentive for *cellular* wireless technology providers to participate in this market. The latest cellular communication standards developed by the third generation partnership project (3GPP) are long term evolution (LTE) and LTE advanced (LTE A). Many cellular network operators are migrating from GSM, UMTS/HSPA, and other legacy standards to LTE. LTE provides a flexible communication architecture designed to enable communication at a lower cost per bit and to accommodate the continuous growth in wireless cellular demand, both in the number of connections and in the required data rate [1]. There is an obvious advantage for operators if the expanding LTE infrastructure will also support M2M applications (and eventually the Internet of Things (IoT)).

Wireless devices for M2M communication generally serve applications whose quality of service requirements are different from those handled by conventional (human operated) LTE user equipment (UE). For example, many M2M applications require transmitting only infrequent and short messages and are often more delay tolerant compared to the human to human (H2H) and human to machine (H2M) applications. In this context, requirements on peak data rates can often be relaxed. We expect that the market for wireless modules supporting only these lower rates (< 1Mbps) will grow notably faster than the total cellular M2M market.

Against this background, the 3GPP standardization process has recognized the need for extending the LTE standard to better support M2M applications and to meet the pecific requirements of machine type communication (MTC) devices. In particular, 3GPP has started to add MTC specific optimization into LTE A starting from Release Ten (Rel 10) of the standard in 2010 [2]. Several new MTC related work items have been studied for Rel 12 [3]. These include the introduction of a new UE category, the so called category 0 (CAT0), equipped with a single antenna, half duplexing frequency division duplex (HD FDD), and lower ransport lock sizes in rder o educe cost [4].

Table 1 shows some of the properties of the new CAT0 UE in comparison to legacy LTE UE categories 1 to 5, which are dominantly used in current LTE network deployments. We observe that CAT0 UEs have reduced peak rates and diversity/MIMO capabilities for the benefit of low cost design. The associated estimated cost savings are of the order of 50% compared to CAT1 devices [3]. Further cost savings in terms of reduced bandwidth, maximum transmit power and support for downlink transmission modes are investigated in ecently pened 3GPP work item for Rel 13 [5].

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Table 1: Comparison of some features for LTE UE categories 1-5 and LTE MTC UEs (category 0 (CAT0) devices). DL=downlink, UL=uplink.

<table>
<tr><th colspan="2">Category</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>0</th></tr>
<tr><td rowspan="2">Peak rate Mbps</td><td>DL</td><td>10</td><td>50</td><td>100</td><td>150</td><td>300</td><td>1</td></tr>
<tr><td>UL</td><td>5</td><td>25</td><td>50</td><td>50</td><td>75</td><td>1</td></tr>
<tr><td colspan="8">Capability for physical layer functionalities</td></tr>
<tr><td colspan="2">RF bandwidth</td><td colspan="5">20 MHz</td><td>20 MHz</td></tr>
<tr><td rowspan="2">Modulation</td><td>DL</td><td colspan="5">QPSK, 16QAM, 64 QAM</td><td>All</td></tr>
<tr><td>UL</td><td colspan="4">QPSK, 16QAM</td><td>QPSK, 16QAM, 64QAM</td><td>QPSK, 16QAM</td></tr>
<tr><td colspan="8">Multi-antenna</td></tr>
<tr><td colspan="2">2 Rx diversity</td><td colspan="5">Assumed in performance requirements</td><td>Not supported</td></tr>
<tr><td colspan="2">2x2 MIMO</td><td>Not supported</td><td colspan="4">Mandatory</td><td>Not supported</td></tr>
<tr><td colspan="2">4x4 MIMO</td><td colspan="4">Not supported</td><td>Mandatory</td><td>Not supported</td></tr>
</table>

For a number of M2M applications, such as remote operation of vending machines, remote metering, or remote maintenance and control, MTC UEs can be installed inside buildings or structures with large penetration losses [6]. Furthermore, since these UEs are not mobile, they have no possibility of improving link quality. Hence, permanent coverage holes can occur. This critical shortcoming can only be overcome by *coverage enhancement* methods. In response to this, a coverage enhancement work item for MTC UEs was approved in the 3GPP radio access network technical specification group (RAN TSG) in June 2013 [4]. Initially, the aim was to complete this work item for Rel 12, but due to time limitations it was postponed and reopened in September 2014 for inclusion in Rel 13.

In this article, we review the coverage enhancement (CE) targets specified for MTC LTE and present CE techniques that can provide cellular connectivity in adverse propagation conditions and are considered for inclusion in the MTC standardization. For the former we first briefly describe the LTE resource structure and the coverage in its uplink (UL) and downlink (DL) channels in Section II. Then we choose three different LTE channels and explain the possible solutions for coverage enhancement in Sections III, IV and V. These include novel methods that can provide flexible CE under different network conditions. They do not require modifications of legacy LTE UEs and have little effect on their performance (e.g. by way of limitations to resource scheduling). They also attempt to retain overall cell spectral efficiency, which is important from a cost per bit perspective for mobile network operators. Focussing on CE for MTC LTE, this article is complementary to the discussion of CE for LTE advanced presented recently in [7].

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II. Overview of Coverage in Uplink and Downlink LTE Channels

In this section, we first briefly review LTE physical uplink and downlink channels and present a summary of the current coverage in these channels. This sets the stage for the coverage enhancement methods presented thereafter.

a) LTE Channels

In LTE, data is mapped to orthogonal radio resources in the time frequency plane. The atomic data unit, known as a resource element (RE), has the symbol duration of 66.7 microseconds, which corresponds to a subcarrier bandwidth of 15 kHz. For a normal cyclic prefix length, a grid of 7×12 REs in the time frequency domain is known as an LTE physical resource block (PRB). A PRB pair forms the basic unit commonly used in the LTE standard for scheduling and resource allocation. Taking guard bands and cyclic prefix into account, a PRB occupies around 200 kHz over half a millisecond, which is also the duration of an LTE time slot. One LTE sub frame consists of two time slots (1 ms), and 10 consecutive sub frames form a radio frame.

In both of the UL and DL directions, there are different physical channels, which are transmitted in specific REs of the time and frequency radio resources. The physical DL and UL shared channels (PDSCH and PUSCH) are dedicated to data exchange between the LTE base station (eNodeB) and the UEs. The size of the medium access control protocol data unit is called the transport block size (TBS), and the time taken for its transmission is referred to as the data transmission time interval (TTI). The TTI is equal to the duration of one sub frame. The data channels are complemented by a number of control channels, including the physical DL control channel (PDCCH) for allocating PRBs to PDSCH and PUSCH, the physical UL control channel (PUCCH) for transmitting UE resource requests and link quality information, the physical broadcast channel (PBCH) in the DL, which broadcasts the information required at a UE for joining a cell, and the UL physical random access channel (PRACH), which is used for contention based random access for requesting a resource allocation from the eNodeB.

b) Coverage Requirements

Maximum coupling loss (MCL) is a measure for coverage in LTE channels. It is defined as the difference between maximum transmission power in the channel and its corresponding receiver sensitivity [8]. A higher MCL value indicates a smaller required signal to noise ratio (SNR) for a target (often 1%) block error rate (BLER), which translates into a better coverage for that channel.

The 3GPP study item [8] focused on identifying the LTE channels with critical MCLs. For this, the study item considered medium data rata and VoIP applications. Table 2 summarizes the MCL of the above mentioned channels in LTE as reported in [3] and [8]. Since CAT0 UEs will be equipped with only one receive antenna as shown in Table 1, a 4 dB penalty has been applied to the MCL of downlink channels in Table 2. Furthermore, a target MCL of 155.7 dB has recently been agreed on for CAT0 UEs [9]. The resulting required CEs for the different channels are summarized in he st ow Table 2.

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Table 2: MCL for UL and DL LTE channels in FDD mode [3] [8]. eNodeB in 2 transmit and 2 receive antenna configuration. UE CAT1 with 1 transmit and 2 receive antennas, UE CAT0 with 1 transmit and 1 receive antenna.

MCL in dB	UL channels			DL channels		
	PUCCH	PRACH	PUSCH	PDCCH	PBCH	PDSCH
Category 1 UE	147.2	141.7	140.7	146.1	149.0	145.4
Category 0 UE	147.2	141.7	140.7	142.1	145.0	141.4
Target MCL	155.7	155.7	155.7	155.7	155.7	155.7
Required CE for CAT0 UE in dB	8.5	14.0	15.0	13.6	10.7	14.3

Solutions suggested to achieve CE include signal repetition and/or more efficient detection and decoding techniques, relaxed reception requirements, new channel and signal design, and power boosting [4]. In the remainder of this article we elaborate on such methods. Furthermore, since data usage for MTC UEs is far lower than for typical H2H devices, spectral efficiency for UE specific traffic is less of a concern compared to broadcast information, such as master information blocks (MIBs) and system information blocks (SIBs), which need to be continuously sent in LTE systems. Given this, we focus on CE techniques to improve the PBCH, which is dedicated for MIB transmission, and the SIB broadcasting, which is scheduled by PDCCH and sent via PDSCH. Another characteristic of MTC UEs is that they tend to send UL data much more often than DL data. Therefore, and since the PUSCH requires the largest coverage gain (see Table 2), we also focus on novel CE techniques to improve PUSCH.

We start with the PBCH in Section III and demonstrate the possibility of a 10.7 dB CE through novel decoder designs. In Section IV, we present CE for SIB broadcasting. Finally, a transmission strategy based on spreading and bundling of data is introduced in Section V in order to efficiently achieve a 15 dB CE in the PUSCH. These strategies generally exploit the relaxed MTC latency requirements by prolonging the decoding time and having the MTC UE waiting for more data. If stricter latency requirements apply, CE often leads to a reduced spectral efficiency. We note that the methods presented in this manuscript have been introduced to the RAN TSG by the authors in [10], [11] and [12]. At the time of writing of this article, the RAN TSG is considering these MTC CE techniques for possible inclusion in the Rel 13 of the LTE standard. They are collated here with the aim of providing timely information to researchers and scholars interested in LTE MTC coverage enhancement.

III. Coverage Enhancement Techniques for PBCH

Since re designing broadcasted channels, such as PBCH, would break backward compatibility with legacy UEs, broadcasted channels need to be supported by a network for a long time. At the same time, decoding PBCH is the pre requisite of a successful connection in low coverage. Hence, although the MCL

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value of PBCH is better than those for other channels in Table 2, a 10.7 dB CE still needs to be achieved as efficiently as possible.

a) PBCH Background

PBCH is transmitted in the first sub frame of each frame and has a TTI of 40 ms. The PBCH nominally transmits 14 bits of control information (the MIB). Via cyclic redundancy check (CRC) and tail biting rate 1/3 encoding and cyclic rate matching, codewords of 1920 bits are generated. These are divided into 4 redundancy versions (RVs), which are transmitted every 10 ms in sub frame #0 of a radio frame. The relative location of the RV within he 0 s TI ncodes another 2 bits of data, see [1] for details.

Due to the mentioned legacy issues, changes in the structure of PBCH for CE would be impractical. In the following, we therefore present two UE based methods that achieve CE exploiting the existing PBCH structure [10].

b) Increase PBCH Decoding Attempts (IPDA) Method

The first CE method, which we refer to as the IPDA method, is to continue decoding of PBCH transmissions until decoding has been successful. This conceptually simple method does not require any modifications to the PBCH, but rather relaxes the BLER target and the UE acquisition time. Furthermore, and different from other CE approaches like PBCH repetition or power boosting [13], no additional spectrum or power resources are exhausted. However, IPDA can readily be combined with these methods. Finally, the IPDA method does not increase signal buffering or processing requirements of the UE. However, it significantly increases decoding latency. But this is often acceptable for MTC UEs and will be discussed later in the evaluation section.

c) Correlation Decoder (CD)

Our second method replaces the default PBCH *decoder*, consisting of de rate matching, tail biting and CRC decoding (see [1]), by a maximum likelihood (ML) decoder. ML decoding is achieved by correlating the PBCH received samples with all possible PBCH sequences. Hence, we refer to the method as correlation decoder (CD). The number of possible sequences is 3x4x12288, where the factors 3, 4 and 12288 are due to the possible 3 antenna configurations at the eNodeB, the 4 relative locations of the RV (2 bit information), and the fact that only 12288 of the 2^{14} 14 bit patterns are possible. The PBCH sequence with the highest correlation value is the ML estimate. However, to limit the possibility of false alarm, usually done through CRC decoding, the ratio of the likelihoods for the ML and the second best sequence is compared to a threshold. If the ratio is above the threshold, the ML estimate is used as the decoding result, otherwise a decoding failure is declared.

The CD approach can naturally be extended to cover multiple TTIs. Furthermore, decoding can be performed after de rate matching, when the PBCH sequence length becomes 120 samples for each TTI. This simplifies correlation to 120 additions per PBCH sequence.

d) Evaluation

Table 3 shows the CE simulation results for IPDA and CD methods for an extended pedestrian type A (EPA) channel with 1 Hz Doppler. For the simulations, we used the MATLAB LTE toolbox and the settings

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listed in [10]. For the IPDA case, we also consider its combination with intermittent duplication of the PBCH (as suggested in [14]) in order to reduce acquisition time. The table shows the acquisition times for different percentiles (99%, 90% and mean) and for different coverage gains, which are calculated based on a required 1% BLER for PBCH.

Table 3: CE achieved with IPDA and CD as function of the acquisition time. CD uses a fixed decoding window of *n* TTIs (*n=1,2,3,4*) and thus acquisition time is constant equal to *n* x 40 ms.

	Duplication Intermittency	Coverage Gain	Mean Acquisition Time (ms)	90% tile Acquisition Time (ms)	99% tile Acquisition Time (ms)
IPDA method	repetition sent every frame (100% more PBCH resources)	10.7 dB	65.1	120	600
		6.0 dB	43.5	80	240
		3.0 dB	41.0	80	120
	repetition sent every 2nd frame (50% more PBCH resources)	10.7 dB	77.3	120	720
		6.0 dB	46.0	80	280
		3.0 dB	41.7	80	120
	repetition sent every 4th frame (25% more PBCH resources)	10.7 dB	90.3	200	800
		6.0 dB	47.1	80	320
		3.0 dB	41.8	80	160
	no repetition	10.7 dB	105.8	240	1000
		6.0 dB	49.6	120	400
		3.0 dB	43.2	80	160
Correlation decoder	no repetition (1% BLER)	2.3 dB	40 (1 TTI)		
		4.5 dB	80 (2 TTIs)		
		7.5 dB	120 (3 TTIs)		
		12.5 dB	160 (4 TTIs)		

We observe that IPDA can provide enhanced coverage at the expense of acquisition time. Acquisition time can be reduced through intermittent duplication, which requires additional resources and thus increases unwanted overhead. However, the PBCH acquisition times drop sharply when less than the maximal CE of 10.7 dB is required. This means that only UEs in the deepest coverage holes will experience occasional lengthy acquisition times.

For the CD the table shows the CE for different correlation lengths and thus acquisition times (which are multiple of the 40 ms TTI). For an acquisition time of 160 ms and 1% BLER (i.e., 99% success rate), the CD method can provide an about 9.5 dB additional gain compared to the IPDA method without repetition. This is due to the fact that the CD is the optimal ML decoder. While the CD is more complex than IPDA, it can be made simpler by noting that during re acquisition some of the MIB values are known, which reduces the number of required correlations. Thus, MTC UEs may *implement both the IPDA method and the CD*, he ormer or nitial IB cquisition nd he atter or e acquisition of MIBs.

IV. SIB Coverage Enhancement Using Restrictive SIB Scheduling Method

Like the MIB sent on the PBCH, SIBs are also broadcast by the network and extra care must be taken in the broadcast design, because there will be no opportunity to improve it in the future without breaking backward compatibility. Although simple repetition for the PDCCH and PDSCH can be used to provide the required CE for SIBs, this would result in a spectrally inefficient implementation. In this section, we describe alternative methods, which we collectively refer to as Restrictive SIB Scheduling and which provide coverage gain in a spectrally efficient manner [11].

a) SIB Background

In the current Rel 12 there are 19 different SIBs which are broadcast. However, since CE is desired for mostly stationary UEs, many of the 19 SIBs do not need to be decoded. In fact, only SIB1, SIB2, and SIB14 need to be decoded by the UE when utilizing CE. If other SIBs are required, they could be sent via unicast methods. As SIB1 is the most important SIB, it is sent most frequently (every 20ms) and at a known sub frame (SF) (SF#5 of every other frame), and it must be decoded by the UE before the other SIBs.

Unlike MIBs, which have a dedicated physical channel (i.e., the PBCH), SIBs use the same physical channels as user plane data, i.e., PDCCH for scheduling and PDSCH for the data. We will discuss methods for CE for both channels in the following.

b) Combining-Legacy-SIBs-PDSCH Method

In the current LTE standard, different levels of coverage for the SIBs can be obtained by changing a SIB's coding rate or the number of repeats that are sent. Given there is a limited number of PRBs that can be used in an SF (e.g. only 6 in a 1.4 MHz system), repeating SIBs is an important method used today to extend the coverage. We note that all the repeats should be sent within the so called system information (SI) window. However, the information in SIB1, SIB2 and SIB14 are often static for long periods of times in normal operating conditions (e.g. the network is not in an emergency overload situation). Hence, to enhance coverage for the data portion of SIBs, i.e., the PDSCH, the UE could combine SIB repetitions beyond the SI window. Results in [11] show that for a 15 dB CE for SIB1, the 99% tile of the acquisition time is 2.4 seconds (corresponding to combining of 120 copies of SIB1). A similar number of copies would be expected for other SIBs. Since the other SIBs of interest (SIB2 and SIB14) are not sent as often, the acquisition time for those SIBs would typically be longer. In the context of MTC, we consider an extended acquisition time as generally more acceptable compared to increasing SIB transmission periodicity causing a loss in spectral efficiency. We also note that since the SIB message contains a CRC, the UE will stop decoding when it has correctly decoded the SIB. Thus, for the example above, acquisition time will often (i.e. 99% of the time) be shorter than 2.4 seconds.

c) PDCCH-less SIB Decoding Method

As mentioned above, the PDCCH is required to be decoded to obtain scheduling information. But lowering code rates for each PDCCH message is not sufficient to provide an up to 15 dB CE, because there are not enough PDCCH resources in an SF. Thus, the PDCCH message would have to be repeated across many SFs, which is spectrally inefficient. To avoid this, we first explore whether it would be possible to decode the mentioned SIBs without prior PDCCH decoding. Such a PDCCH less SIB decoding method would then require a different mechanism for the UE to acquire all the information contained within the PDCCH, so that the UE can skip PDCCH decoding. In particular, the UE needs (1) SIB transmission timing, (2) SIB PRB locations within the band, and (3) SIB coding rate.

SIB Transmission Timing: For SIB1, there is no problem because the SIB1 transmission timing is already known (e.g. every other SF#5). Thus, SIB1 could be used to also provide the precise transmission timing (i.e., more than the SI window already transmitted via SIB1) for SIB2 and SIB14. This would restrict the eNodeB's scheduler in that it may have to postpone a UE's DL transmission and the UE may experience additional latency. However, there is no decrease in spectral efficiency due to the scheduling restrictions.

SIB PRB locations within the band and coding rate: An intriguing solution is to provide the PRB location and coding rate within the 10 available spare bits of the MIB (legacy UEs will ignore these spare bits). Since the MIB has limited capacity only the SIB1 information needs to be in the MIB, and, similar to above, SIB1 can carry this information for SIB2 and SIB14 (legacy UEs will ignore these new information elements in the SIB1). Although this method still allows the PRB location and coding rate to be dynamic, the eNodeB loses some scheduling flexibility.

d) Combing-PDCCH Method

An alternate method to PDCCH less SIB decoding is to have the UE combine the copies of the PDCCH message already being sent to legacy UEs. For this to be feasible, the content of the PDCCH message must be static and the location of the PDCCH message within the PDCCH must be known a priori to the UE. For the content of the PDCCH message to be static, the PRB location and coding rate of the SIB must be static.

This method requires the UE to complete two steps: decode the PDCCH and then decode PDSCH. Thus this method would take longer to achieve SIB reception than the PDCCH less method given the same number of repetitions. Furthermore, if additional repetitions are sent to reduce the SIB acquisition time, the PDCCH and PDSCH portions would need to be repeated. Like the PDCCH less solution, this solution will be backward compatible since fixing the PDCCH and its contents will be transparent to legacy UEs.

V. TTI Bundling and CDMA for Coverage Enhancement in PUSCH

Many MTC UEs will have dominantly UL transmission. Furthermore, as shown in Table 2, the UL data channel, i.e., the PUSCH, requires the largest CE to meet the coverage target. Therefore, our final CE considerations concern the PUSCH.

a) PUSCH Background

Data transmitted over PUSCH is encoded with a rate 1/3 turbo encoder and then rate matched and arranged in four RVs, each of which matches the TBS (see [1]). Based on this, incremental redundancy

automatic repeat request (ARQ) can be performed after each TTI. That is, the receiver acknowledges the
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receipt of data, and in the case of a negative acknowledgement, the next RV of the current data will be transmitted. The default schedule for PUSCH transmission is to transmit one RV in one TTI, and to only transmit another RV if requested via negative acknowledgment (NACK). Reference [8] tackles the issue of CE for PUSCH through TTI bundling. In TTI bundling, all RVs are transmitted at once, without waiting or NACK. This leads to CE for delay limited application such as VoIP. The current LTE standard assumes a fixed bundling size of 4, but the current work in 3GPP for VoIP and medium data rates considers increasing the TTI bundle size to higher values to provide modest coverage gains.

Since M2M applications are often delay tolerant, we can think of combining bundling with repetition for CE. For example, increasing the bundling size from 4 to 8 means the UE would send each RV twice [15]. Furthermore, the bundling size could be adjusted dynamically, considering the UE's need for CE and its delay tolerance [15].

An alternative to repetition of data is the use of spreading. The advantage of spreading is that it enables multiple UEs to transmit concurrently, i.e., to perform code division multiple access (CDMA), which in turn improves system spectral efficiency. CDMA is already used in LTE, namely for PUCCH format 3 to provide multiple user access on the control channel [1].

In the following, we explain a method for simultaneous use of adaptive TTI bundling and spreading for MTC CE, and we present a signaling procedure for the flexible assignment of PUSCH resources to a variable number of UEs [12].

b) Flexible TTI Bundling with CDMA Support

Our method extends conventional LTE TTI bundling by adjusting the bundling size and the spreading factor used by UEs, according to the instantaneous cellular network conditions. These are defined through the number of "active" MTC UEs, i.e., UEs which ave ata o ransmit, their channel quality and thus instantaneous coverage, and the available PUSCH resources. The main advantage of using flexible bundling and spreading is that CE is achieved without overly compromising network spectral efficiency. Spreading is performed over REs at the same frequency, which simplifies despreading assuming the channel remains essentially constant over the spreading interval. Denoting the spreading length by N_S and performing bundling with bundling size N_B, the CE offered by the flexible TTI bundling and CDMA is about $10\log_{10}(N_B \times N_S)$ dB. The exact gain is somewhat larger when combining different RVs from the turbo code contained in TTI bundles. Figure 1 shows the structure of the code spread TTI bundling for PUSCH.

c) Protocol for flexible TTI bundling and CDMA

In order to successfully schedule the active MTC UEs to transmit in this scheme, the eNodeB should first adjust the values of N_S and N_B based on the number of active UEs and the required coverage gain, respectively. Then, it informs the MTC UE of the values of N_B and N_S and the assigned codes. To minimize the impact of this procedure on the current LTE standard, we note that some of the existing control flags in the PDCCH uplink grant are unlikely to be used in the MTC mode. Thus, they can be reused to inform the UE to obtain its TBS, bundling size, spreading length and code index. This would be done based on a

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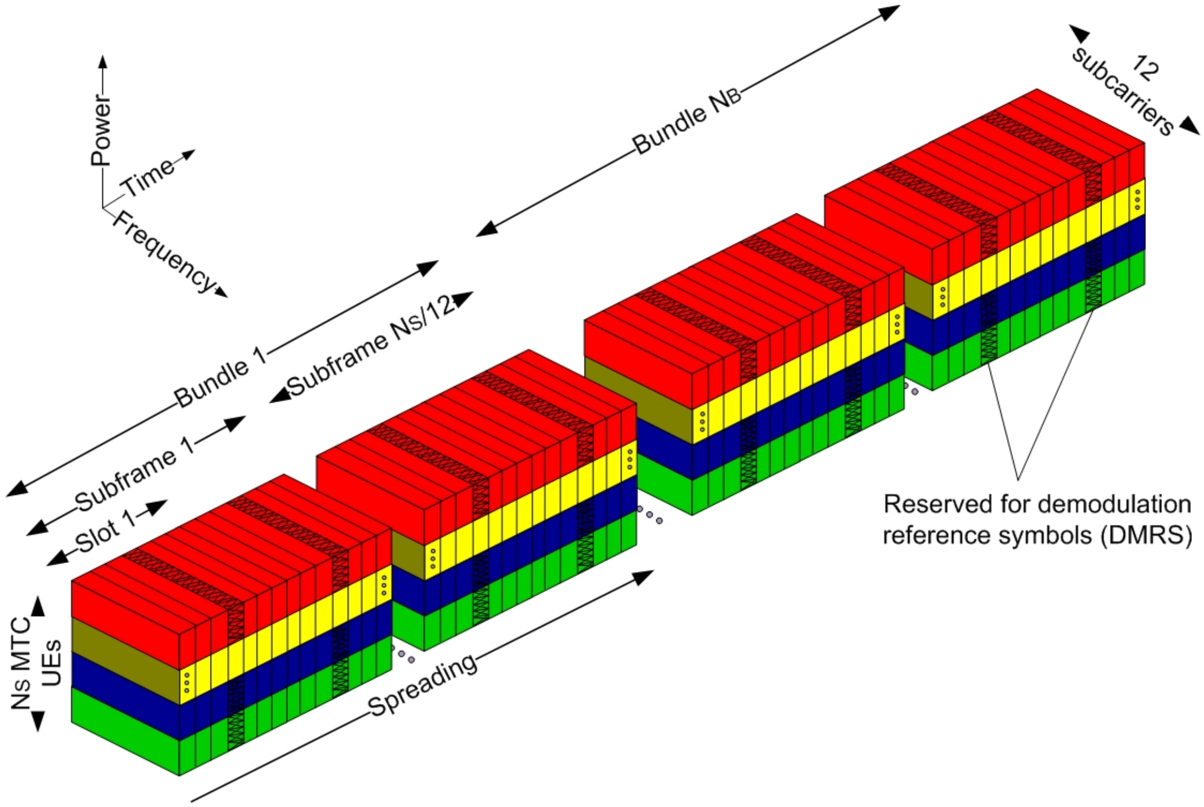

Figure 1: Structure of the bundling and spreading blocks for flexible TTI bundling and CDMA in PUSCH. Spreading with length N_S is performed over one or more consecutive sub-frames, which form a "spreading bundle". The spreading bundle is repeated N_B times. Calculation and assignment of N_B, N_S, and code index to MTC UEs is done by a scheduling protocol in the eNodeB.

configuration table for flexible TTI bundling and CDMA, which is a modified version of the TBS table used in legacy UEs. Using a modified TBS table, transmission with flexible TTI bundling and CDMA can be scheduled as follows.

1) When data is available for transmission, the MTC UE sends a scheduling request on the PUCCH.
2) The eNodeB waits for a predefined time, collecting requests of MTC UEs as in Step 1, and estimates their required coverage gain from the received channel quality index (CQI).
3) The eNodeB sets N_S to the closest spreading length that is available in the configuration table such that the current number of active MTC UEs can be accommodated.
4) The eNodeB chooses N_B based on the required coverage gain, $CE=10\log_{10}(N_B \times N_S)$ with N_S from Step 3.
5) Based on Steps 3 and 4 and available resources, eNodeB assigns resources to UEs. It sends a PDCCH DCI format 0 for PUSCH allocation and sets a flag to indicate that the modified TBS table needs to be used.

Waiting and collecting requests in Step 2 is done to utilize as much of the available CDMA codes as possible, which maximizes system spectral efficiency while providing CE through spreading for individual MTC UEs. Steps 3 and 4 can further be refined to account for MTC UEs in good coverage, which may not need the full spreading gain. For example, those UEs could be assigned shorter spreading sequences or multiple longer spreading sequences.

d) Performance Evaluation

According to the LTE coverage enhancement study [8], we evaluate the CE achieved with flexible bundling and CDMA by measuring the SNR required for a BLER of 2%. The first three columns of Table 4 show selected (N_S,N_B) combinations and the expected coverage gains compared to the case without bundling and spreading. We observe the CE due to spreading and bundling, which is proportional to N_B x N_S, reaches the required 15 dB (see Table 1) for various parameter combinations. Column 4 shows simulated coverage gains for the EPA channel with 1 Hz Doppler, assuming a TBS of 104 bits transmitted in one PRB (i.e., 180 kHz bandwidth) using QPSK and CDMA with orthogonal spreading sequences. The theoretical and simulated gains match well, where the latter include the effect of combining RVs in the Turbo decoder, which gives only another about 0.4 dB gain compared to pure repetition due to the already low code rate for only one RV. The last two columns of Table 4 show the spectral efficiency (over all MTC UEs) and data rate (per MTC UE). As can be seen, system spectral efficiency is affected by bundling but not by spreading, assuming that all spreading codes are used. Hence, no resources are wasted while benefitting from spreading gain and achieving the required CE. The amount of spreading that can be applied is however limited by the need for an essentially time invariant channel over N_S PRBs or extra reference symbols for channel estimation.

Table 4: Achieved coverage gain and spectral efficiency for flexible TTI bundling and spreading. Simulated CE, spectral efficiency and data rate for TBS=104 in one PRB using QPSK.

Spreading Length N_S	# of TTIs Bundled N_B	Theoretical CE (dB) $10\log_{10}(N_B \times N_S)$	Simulated CE (dB) (perfect channel estimation)	Spectral Efficiency over all MTC UEs bps/Hz	Data Rate per MTC UE (kbps)
1	1	0.0	0.0	0.578	104.0
2	6	10.8	11.2	0.097	8.7
6	2	10.8	10.7	0.290	8.7
22	2	16.4	16.4	0.289	2.4
12	9	20.3	20.6	0.067	1.0
1	66	18.2	18.6	0.009	1.6
66	1	18.2	18.1	0.578	1.6
1	72	18.6	19.0	0.008	1.4

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VI. CONCLUSION

This article has reviewed recent efforts presented in 3GPP to enhance coverage for LTE MTC. We have described methods for downlink broadcast and uplink data channels that are able to meet the CE targets specified or AT0 evices. An overview of the presented CE methods and their effects on the LTE system is provided in Table 5. They build on the existing LTE signal structures and are thus backward compatible, affect legacy and non MTC UEs as little as possible, and maintain high system spectral efficiency. The latter is particularly relevant for broadcast channels. The achieved CE generally comes at the cost of increased latency of transmission, which is a natural trade off for enhanced coverage and acceptable for many MTC applications. We believe that amendments to the LTE standard that support CE for low cost CAT0 UEs are very important to ensure that LTE will be competitive with alternative wireless access technologies, such as custom IoT wide area network protocols (e.g. Weightless™ and SigFox™), which claim to offer very low cost devices, high coverage, and very good battery life. Further M2M and IoT changes for LTE (e.g. to improve LTE battery life) are being discussed in 3GPP, and we expect to see them in eleases 13 and beyond.

Table 5: Summary of presented CE methods and their effects on the LTE system.

<table>
<tr><th>Channel</th><th>CE Method</th><th colspan="2">Pros (+) and Cons (–) to achieve CE</th></tr>
<tr><td rowspan="2">PBCH</td><td>IPDA</td><td rowspan="2">+ No changes to legacy broadcast channel
+ No changes to spectrum and power efficiency of system</td><td>+ No extra buffering or processing at UE
− Longer acquisition time</td></tr>
<tr><td>CD</td><td>− Increased processing at UE</td></tr>
<tr><td>PDSCH for SIB</td><td>SIB-PDSCH Combining</td><td rowspan="3">+ Fully compatible with legacy UEs
+ No changes to spectrum and power efficiency of system</td><td>− Longer acquisition time
− Need static SIB messages</td></tr>
<tr><td rowspan="2">PDCCH for SIB</td><td>PDCCH-less SIB decoding</td><td>− eNodeB scheduling restrictions
− Use spare bits of MIB</td></tr>
<tr><td>PDCCH Combining</td><td>− Longer acquisition time
− Need known PDCCH location and static SIB location and code rate</td></tr>
<tr><td>PUSCH</td><td>TTI Bundling with CDMA</td><td colspan="2">+ Better spectrum and power efficiency than repetition
− Loss in system spectrum efficiency if few UEs in poor coverage
− Boosting or repetition of reference symbols may be required</td></tr>
</table>

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