Recent Advancements in M2M Communications in 4G Networks and Evolution Towards 5G

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***Abstract*—Machine-to-Machine (M2M) communications is considered to be one of the key enablers for the provisioning of advanced applications and services such as smart cities and hospitals, automated vehicular and industrial device operation. Currently, in LTE-Advanced systems, the main focus has been on supporting massive deployment of low cost devices, with enhanced radio access network coverage. In this work, we present the recent MTC enhancements being studied for Rel-12 and Rel-13 LTE systems. Detailed performance analysis based on LTE system settings are also presented. The LTE capacity evaluations performed based on devices per physical resource block indicate that significantly large number of devices can already be supported in an LTE system, based on the assumptions used, with minimal system overhead. We also present an overview of some of the key scenarios, requirements and use cases currently being considered for M2M communication in fifth generation systems. The performance requirements currently being considered for massive, and ultra-reliable M2M communication is also discussed.**

I. Introduction

Machine-to-Machine (M2M) communications involve machines communicating with each other and exchanging information with remote servers, possibly over a cellular network infrastructure. Such technologies are considered as key enablers for next generation smart cities and homes, automated factories and other integrated commercial environments. The main aim of such communication techniques is to enable smart city solutions, for e.g. with intelligent metering, infrastructure management, city automation, and automated health management systems. There are also public safety applications for surveillance and security currently being studied as well. The possible issues and different approaches for provisioning such applications using cellular infrastructure as the backbone is studied in [1].

While there are several advantages that could be obtained as a result of M2M communications, and by minimizing human interactions for tasks that can be automated, there are several key issues acd challenges that needs to be addressed as well. One of the key issue is the access method for devices engaging in M2M communication to the infrastructure. There are several possible solutions for this, for e.g. by using wired access (optical, cable, DSL, etc.), or wireless local area networks (WLAN, Bluetooth, etc.) or using wide area cellular network infrastructure (General Packet Radio Service (GPRS), 3G, Long Term Evolution-Advanced (LTE-A), WiMAX, etc.) [1], [2]. In this work, we mainly consider the issues related to the deployment of M2M devices or Machine Type Communication (MTC) using 3rd Generation Partnership Project (3GPP) LTE-A network infrastructure, as well as the possible evolution towards Fifth Generation (5G) systems.

From a physical layer perspective, the work done in [1], [2] considers the random access procedure with dense deployment of MTC devices as one of the key challenges to be addressed, especially taking into account the possible performance degradation for normal devices. Some of the other key issues considered include Quality of Service (QoS) provisioning, efficient group management of MTC devices, apart from Physical Random Access Channel (PRACH) overload control and opportunistic random access, and a reinforcement learning-based evolved Node B (eNB) selection is also proposed in [1]. The work done in [2] evaluates the possible impacts of massive MTC deployments on traditional traffic, and some open issues such as priority case definition and group management, dynamic resource allocation and resource reservation for MTC devices in LTE-A.

Group mobility management mechanism in an MTC environment with large-scale deployment of MTC devices based on the grouping of devices with similar mobility patterns is proposed in [3]. A location database is considered for estimating the similarities in mobility patterns, with a leader device managing the mobility of devices, enabling better handling of congestion due to signaling. The application of cross-domain M2M data combining using a semantic-based approach for provisioning new data services is studied in [4], which indicates the wide range of service provisioning possibilities with the wide adoption of such technologies. An overview of the recent trends, and various standardization activities currently ongoing for M2M and Internet of Things (IoT) is presented in [5]. Some of the forums considered in the work include 3GPP, BroadBand Forum (BBF) and oneM2M.

M2M traffic characterization based on traffic trace collection from an actual cellular network is done in [6]. The network performance based on round trip time and packet loss ratio is also presented for M2M traffic, and compared with that of smartphones and other commercial applications. In this work, we present the LTE enhancements studied in 3GPP, addressing some key issues such as overload control, reducing device cost while enable ultra-long battery life, improving coverage, etc. The design targets currently set in 3GPP for such enhancements mainly consider GSM EDGE Radio Access Network (GERAN) as a baseline for evaluations [12]. There is significant interest from network operators on this topic, due to the perceived due to the potential of provisioning new and innovative services for the end users. This is the main motivation behind active research and standardization currently ongoing for this topic. The performance evaluations are also done based on the LTE capacity for different M2M device types, and the overhead caused to the system in general, rather than analyzing the M2M traffic characteristics alone, as done in [6]. Also the various delay requirements and packet loss metrics of the M2M traffic is considered to be outside the scope of this work.

Currently, significant amount of research is ongoing for finding potential system enhancements that would be required for handling the increase in data rate requirements for 5G cellular systems. The coexistence of human-centric and machine type communications is anticipated to lead to a diverse set of communication characteristics in such systems [7]. Various scenarios and requirements for 5G systems currently being studied, and the vision of the METIS project is presented in [7]. The support for massive MTC type device deployment, sustaining a minimal data rate, with possibly low latency requirements, is considered in [8] as a potentially disruptive technology leading to architectural and component design changes in 5G systems.

The work done in [9] proposes new physical layer technology components for 5G such as unified frame structure, multicarrier waveform design, etc., enabling transmissions with low latency. A flexible OpenAirInterface platform is presented in [10], which takes new approaches and technologies currently being considered for 5G systems such as cloud RAN, application of software defined networking principles, massive multi-antenna techniques, full-duplex communication, etc. Performance evaluations based on massive MTC deployments is also considered in the work. One of the key application requirement considered in the system design was the provisioning of IoT with dense deployment of MTC devices. In this work, we also look at the new and diverse set of requirements and scenarios currently being considered for 5G systems, and the drivers behind such enhancements.

The rest of the paper is structured as follows: Section II gives an overview of the LTE enhancements for M2M currently being studied. Section III discusses the performance analysis using the proposed enhancements. The possible 5G scenarios, requirements and enhancements for M2M communication is presented in Section IV. Section V gives a summary of the paper.

II. LTE Enhancements for M2M

LTE radio access network enhancements for M2M communications have been studied by 3GPP in [11]-[14]. These enhancements address the issues of overload control, network support for M2M devices, device cost reduction, power saving for ultra-long battery life, signaling overhead, and coverage enhancement. Illustrative coverage and capacity analysis for M2M on LTE have been provided in [15]-[17]. Based on the studies done in [12]-[14], 3GPP have standardized or is in the process of standardizing the features shown in Table I

The features listed in Table I ensure that LTE can meet M2M requirements of low-cost devices, ubiquitous coverage, and ultra-long battery life. To support coexistence of human and machine traffic, service differentiation of the different traffic types can be handled by various techniques. They include, for example, time-controlled access of M2M devices including access grant time and forbidden time interval, and limiting services to M2M devices if their behavior is not aligned with M2M features. Scheduling prioritization (e.g., through modifying the scheduling metric based on UE category), and semi-persistent scheduling to lower overhead can also be used. Using these techniques, the network is able to minimize the impact from machine traffic to human traffic.

Table I. LTE Features For M2M Services

LTE Release	Feature
Rel-11 (2012)	• UE power preference indication • RAN overload control
Rel-12 (2014)	• Low-cost UE category (Cat-0) • Power saving mode for UE • UE assistance information for eNB parameter tuning
Rel-13 (expected 2016)	• Low-cost UE category • Coverage enhancement • Power saving enhancement

A. *Low-Cost Devices*

One key requirement for supporting M2M in LTE is the availability of low cost devices. Typical LTE devices have been designed to provide broadband services. For example, the least capable LTE device, called Category-1 device, has 2 receive antennas, RF bandwidth of 20 MHz, and can support data rates of at least 10 Mbps in the downlink and 5 Mbps in the uplink. This makes them overdesigned for low-rate and delay-tolerant M2M services. In Rel-12, low-cost M2M devices with reduced capabilities have been introduced. This new device category (called Category-0 device) have the following reduced capabilities –

- One receive (Rx) antenna and associated receiver chain.
- Reduced peak data rates of 1 Mbps in downlink and uplink.
- Optional half-duplex FDD operation.

For Rel-13, a new device category with even lower complexity will be defined. Based on Rel-12 Category-0 device, this new device will have further reduced capabilities as follows –

- Reduced device RF bandwidth of 1.4 MHz in downlink and uplink.
- Reduced maximum transmit power to allow for an integrated Power Amplifier (PA) implementation – e.g. 20 dBm compared to 23 dBm for the baseline LTE device.

Table II provides a comparison of the different LTE FDD device categories. The modem complexity relative to Category-1 device is also provided in the table. Complexity reduction can be used to estimate the reduction in the bill-of-materials (BoM) cost of the modem. Using Category-1 device as the baseline, reducing the device RF bandwidth to 1.4 MHz provides a cost reduction of approximately 39 %. Together with peak rate reduction to 1 Mbps and a single RF antenna, the complexity reduction is approximately 59%. Half-duplex operations provides another 7 – 10 % complexity reduction, while maximum power reduction will provide 2 – 7 % cost reduction (assuming integrated PA). All together, the techniques can provide 68 - 76 % reduction in BoM cost of the modem. Thus, the modem cost of the Rel-13 low-cost device is expected to be approximately 25 % of the Category-1 modem.

TABLE II. LTE FDD DEVICE COMPARISON

Device Capability	Rel-8 Cat-4	Rel-8 Cat-1	Rel-12 Cat-0	Rel-13 Low-cost
Downlink peak rate	150 Mbps	10 Mbps	1 Mbps	1 Mbps
Uplink peak rate	50 Mbps	5 Mbps	1 Mbps	1 Mbps
Max No of downlink spatial layers	2	1	1	1
Number of device RF receiver chains	2	2	1	1
Duplex mode	Full Duplex	Full Duplex	Half (Optional)	Half (Optional)
Device bandwidth	20 MHz	20 MHz	20 MHz	1.4 MHz
Max Tx power	23 dBm	23 dBm	23 dBm	~20 dBm
Modem complexity relative to Cat-1	125%	100%	50%	25%

B. Coverage Enhancement

LTE coverage using Category-1 device has been studied in [12] with the Maximum Coupling Loss (MCL) for FDD and TDD systems shown in Table III. For FDD, the MCL is 140.7 dB while for TDD, the MCL is 146.7 dB. The reason the MCL is higher for TDD is due to the user of 8 Tx - 8 Rx antennas at the eNB compared to 2 Tx - 2 Rx antennas for FDD.

TABLE III. LTE COVERAGE - MCL IN DECIBEL.

LTE	PUCCH	PRACH	PUSCH	PDCCH	PBCH	PDSCH
FDD 2Tx-2Rx	147.2	141.7	140.7	146.1	149.0	145.4
TDD 8Tx-8Rx	149.4	146.7	147.4	146.9	149.0	148.1

In LTE Rel-13, coverage enhancement will be specified to target MCL of 155.7 dB, corresponding to 15 dB enhancement from the FDD MCL shown in Table III. This will provide increased cell coverage area as well as the ability to support devices in location with high penetration loss (e.g. smart meters installed in the basement).

However, Rel-13 low-complexity devices will have smaller coverage due to reduced capacities, namely

- 1 Rx antenna will lead to approximately 4 dB degradation in performance of the downlink channels. This is due to lack of receiver combining and diversity gain.
- Reduced maximum transmit power will lead to a corresponding degradation in coverage of the uplink channels.
- Reduced UE bandwidth of 1.4 MHz in downlink and uplink can lead to degradation in performance due to lack of diversity gain. It has been estimated that this results in approximately 1 – 3 dB loss in performance.

Table IV lists the required coverage enhancement amounts for different channels to reach 155.7 dB MCL for different device categories. Note that a maximum transmit power of 20 dBm is used for Rel-13 low-cost devices.

TABLE IV. REQUIRED COVERAGE ENHANCEMENT

Device	PUCCH	PRACH	PUSCH	PDSCH	PBCH	EPDCCH	PSS/SSS
Category-1	8.5	14.0	15.0	10.3	6.7	9.6	6.4
Category-0	8.5	14.0	15.0	14.3	10.7	10.4	10.4
Rel-13 Low-cost	11.5	17.0	18.0	16.9	10.7	10.4	10.4

Table V lists potential coverage enhancement techniques and applicable channels. Some techniques such as relaxing the performance requirements, multiple decoding attempts, and multi-subframe channel estimations do not require specification changes other than to redefine the appropriate performance requirements. Other techniques such as repetition/subframe bundling, overhead reduction, and increasing reference signal density will require standard changes.

Note that coverage enhancement will be scalable and configurable, with the aim to minimize the amount of reception and transmission time for each device. A mechanism to identify coverage range will be needed so that the device can be configured for appropriate coverage enhancement amount.

C. Device Power Saving

Two important features have been introduced in LTE to help reduce power consumption – power preference indication and power saving mode. Power preference indication allows the device to indicate to the network that it prefers a low-power consumption mode of operation. The network may then configure radio resource parameters appropriately such as reduced measurements and longer sleep time to minimize device power consumption. In Rel-12, a power saving mode was introduced. In this state, the UE remains registered to but not reachable by the network for mobile terminating traffic. The UE can be viewed to be in the power-off or sleep mode, and will wake up only when there is data to send or after timer expiration. This mode is intended for UEs with infrequent mobile-originated data transmission. It is well suited for M2M services with timed transmissions such as remote sensing and smart grid.

In Rel-13, additional power saving techniques will be considered for both normal and enhanced coverage modes. Some of the techniques being considered include reducing system acquisition time, half duplex operation, reducing control channel overhead, reducing measurements and measurement reports, configurable coverage enhancement, and relaxing requirements.

TABLE V. POTENTIAL COVERAGE ENHANCEMENT TECHNIQUES

Technique	PUCCH	PRACH	PUSCH	EPDCCH	PBCH	PDSCH	PSS/SSS
Repetition/subframe bundling	x	x	x	x	x	x	
PSD Boosting	x	x	x	x	x	x	x
Relaxed Requirement		x					x
Overhead reduction				x			
HARQ retransmission			x			x	
Multi-subframe channel estimation	x		x	x	x	x	
Multiple decoding attempts					x		
Increased reference signal density			x			x	

D. *Network Control and Tuning*

To prevent system overload by M2M traffic, Extended Access Barring (EAB) was introduced in Rel-11. This feature allows only M2M devices with mobile originated traffic that have been configured for EAB to be barred from accessing the cell when it is congested.

In Rel-13, M2M device can also send assistance information about its traffic type/pattern. This assistance information will help the network configure radio resource parameters appropriately. For example, for device with infrequent data transmission, the eNB can configure the inactive timer to enable fast connection release.

III. PERFORMANCE ANALYSIS

In this section, we present LTE capacity results for some M2M services. The analysis will consider M2M deployment in two simulated system deployments – urban and suburban macro-cell deployment. The inter-site distance is 500m and 1732 m for urban and suburban scenarios, respectively. The macro-cell system simulation scenario is of a traditional 57-cell system setup (19 sites, each with 3 sectors) with wrap-around. Devices are randomly placed within each cell as shown in Fig. 1. Relevant simulation parameters are listed in Table VII.

TABLE VI. LTE CAPACITY PER PRB FOR M2M SERVICES

Application		Average Transaction Time (Seconds)	Average Message Size (Bytes)	Capacity (devices per PRB)	
				Urban	Suburban
Smart Meter	UL	9000	2017	7.5e4	5.6e4
	DL	56000	25		
Health Sensor		60	128	5.3e3	4.0e3
Home Security		600	20	1.2e5	9.2e4

Table VI shows the number of M2M devices that can be supported per physical resource block (PRB) for several M2M services. Each PRB occupies 180 kHz bandwidth and there are 50 PRBs available in a 10MHz system.

From the table, it can be seen that the LTE capacity for M2M services is very high. In a suburban environment, the average number of homes in a cell has been estimated to be between 4,647 and 10,456. If each home is assumed to have 3 smart meters (water, gas, electricity), it can be seen from Table VI that less than one PRB (2 % overhead for a 10 MHz system) will be required to support smart meter service.

TABLE VII. SIMULATION PARAMETERS

Parameter	Macro-cell
Inter-site distance	500 m, 1732 m
Cellular Layout	Hexagonal grid, 19 cell sites, 3 sectors per site
System Bandwidth	10 MHz
M2M device Bandwidth	1.4 MHz
Penetration Loss	20 dB + potential 15 dB extra penetration loss
Carrier Frequency	2 GHz
Distance-dependent path loss	L=I + 37.6log10(.R), R in 4ilometres I=128.1 – 2GHz
Power Control Setting	Fraction power control with Ks=0 α = 0.8, Po=-84
Link Adaptation	On, MCS-based link adaptation
Channel model	Typical Urban (TU)
Channel Estimation	Non-ideal
Scheduling	Proportional fairness (α=1.0, β=0.7), frequency non-selective
Receiver	MMSE

IV. M2M COMMUNICATION IN 5G

It is predicted that in 2020 the total number of connected devices will roughly about 50 billion [7], almost double comparing to today's number. A significant portion of the increase is perceived to be due to the machine type of communications. Naturally, the development of 5G technologies would need to take this key factor into account, apart from the enhancements currently being proposed for LTE-A systems. International Telecommunication Union Radio-communication Standards Sector (ITU-R) is preparing its vision for the overall objectives for systems beyond 2020 [18], and based on the market, traffic and future spectrum requirements work done, M2M communications is considered to be a key element in future systems.

The possible evolution of Mobile BroadBand (MBB) from IMT-2000 and IMT-Advanced towards 2020 and beyond is as shown in Fig. 1 [19], based on the assumption that the traffic requirements would be increased by a thousand times over the next decade. Conventional MBB is expected to be replaced with extreme MBB (xMBB), which provides new services such as virtual and augmented reality, higher resolutions, 3D TV, improved quality of experience and smart content delivery. The new use cases to be considered in such systems include massive and ultra-reliable MTC.

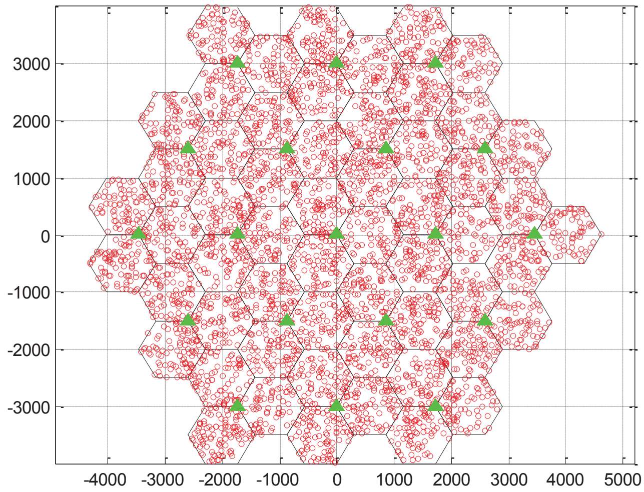
Fig. 1. Simulation scenario with 19 sites (57 cells).

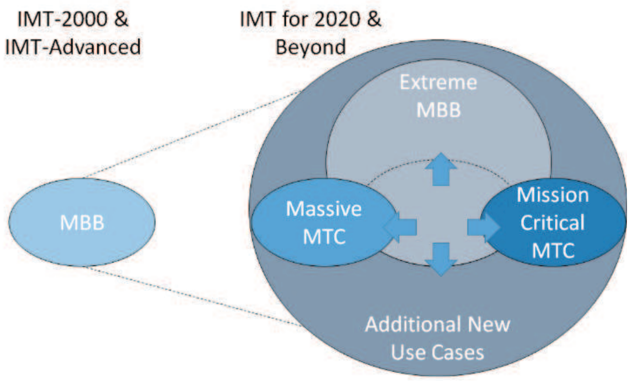

Fig. 2. Evolution of current MBB services towards beyond-2020 [19].

Due to the diverse set of MTC use cases and scenarios, two different flavors should be investigated in the future 5G system design: (1) low cost/low power consumption massive MTC (i.e. low category/massive MTC), and (2) mission critical MTC (i.e. high category/ultra-reliable MTC), where latency and reliability are key elements to be considered.

For low category/massive MTC, utility (e.g. electricity/gas/water) metering is one of the typical usage cases. Generally, these type of devices are characterized by low bit rate requirements, low cost and low power consumption (e.g. 10 years battery life with "AA" battery), but with a massive deployment. This can be seen as the next step of development, based on the current LTE MTC work.

For high category/mission critical MTC, automotive, industry automation and robot control are among the most important new areas which bring more stringent Quality of Service requirements in terms of latency, scalability and reliability as compared to traditional cellular services. Similarly, mission critical communications, which can help first responders work safer, smarter and faster in disasters and day-to-day incidents, have similar requirements as well.

Current wireless communication systems such as 2G, 3G, 4G (for e.g. LTE, LTE-A), or the IEEE ITS-G5 specification based on the 802.11p standard cannot satisfy the requirements of the most demanding automotive safety services. The QoS level to be provided with 5G system need to meet the requirements resulting from future highly automated driving and future industry Internet and go well beyond what can be achieved with any wireless communication technology today. The most important requirements currently for M2M communication in 5G systems currently being studied are [20]:

- Maximum allowable end-to-end latency, including jitter/retransmits less than 5ms.
- Reliability, for example packet loss rate 10^{-9} or 99.999%.

While the performance measurements and defining key performance indices of such requirements are challenging, one of the key consideration is the probability of avoidance of undesired events. For Massive Machine Communications (MMC), three different radio access types are also envisioned in [19] – direct access (MMC-D) to the access network, with accumulation/aggregation point (MMC-A) which accumulates the traffic locally and send it to the access point, and direct M2M communication (MMC-M) between MTC devices using for e.g. D2D communication. The performance requirements for such communication is assumed to be more relaxed with data delivery having higher delay constraints. The key consideration would be on providing efficient access and optimized scheduling for such devices.

V. Conclusions

Machine-to-Machine communication, with its capability of providing diverse set of applications and services, is considered to be a key technology enhancement for 4G LTE-Advanced systems, and is anticipated to maintain its dominance in 5G systems as well. In this work, we study in detail the various system enhancements currently proposed for LTE-Advanced systems, such as reducing the device cost, coverage enhancement, device power saving and network control and tuning. Detailed performance analysis using LTE system settings is also done, mainly to evaluate the LTE capacity for various MTC device types. Based on the evaluations done, it was shown that there would be less than 2 % overload for provisioning the considered MTC devices in a 10 MHz LTE system. Possible system enhancements, requirements and scenarios for M2M communication in 5G systems is also discussed, with further elaborations done on massive and ultra-reliable or mission-critical MTC anticipated in such systems. The performance requirements in terms of latency and reliability is also discussed further in this work.

Future directions for this work could include defining the requirements, and evaluating the performance of 5G systems with deployment of massive and ultra-reliable MTC devices. Evaluations based on more realistic traffic models for each of the MTC device / application type would also be an interesting area for further work.

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