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In Depth Performance Evaluation of LTE-M for M2M Communications

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***Abstract*— The Internet of Things (IoT) represents the next wave in networking and communication which will bring by 2020 tens of billions of Machine-to-Machine (M2M) devices connected through the internet. Hence, this rapid increase in Machine Type Communications (MTC) poses a challenge on cellular operators to support M2M communications without hindering the existing Quality of Service for already established Human-to-Human (H2H) communications. LTE-M is one of the candidates to support M2M communications in Long Term Evolution (LTE) cellular networks. In this paper, we appraise and present an in depth performance evaluation of LTE-M based on cross-layer network metrics. Compared with LTE Category 0 previously released by 3GPP for MTC, simulation results show that LTE-M offers additional advantages to meet M2M communication needs in terms of wider coverage, lower throughput, and a larger number of machines connected through LTE network. However, we show that LTE-M is not yet up to the level to meet future applications requirements regarding a near-zero latency and an advanced Quality of Service (QoS) for this massive number of connected Machine Type devices (MTDs).**

Keywords*— *Internet of Things (IoT) ; Machine-to-machine (M2M) ; Machine Type Communications (MTC) ; Long Term Evolution (LTE) ; Performance evaluation ; LTE-M ; Machine Type Devices (MTDs)

I. INTRODUCTION

In the era of Big Data and the Internet of Things (IoT), the growing demand in Machine-to-Machine (M2M) applications affect directly mobile networks and share an important part of mobile traffic. This massive number of connected devices will reach 25 billion connected devices by 2020 as forecasted by many analysis [1]. Unfortunately, current mobile networks are not capable yet to meet M2M communication needs. This urged researchers to push efforts towards new network architectures and capacity enhancements. Higher throughput and capacity than Long Term Evolution (LTE) and LTE advanced (LTE-A) cellular networks are offered while

M2M refers to a communication paradigm that enable machines to communicate with each other without the manual assistance of humans. M2M applications are widely used in vehicle tracking, user and home security, banking, remote monitoring and smart grid. Machine-type communications (MTC) can be achieved through a centralized or a peer-to-peer model. However, the need to manage and connect this large number of machines for longer distance made the Long-Term-Evolution (LTE) and the Long-Term-Evolution-Advanced (LTE-A) cellular networks as candidates to integrate MTC.

At first, LTE as a platform was not optimized yet to support low data rate requirements for M2M in devices such as sensors, smart meters etc. LTE supports high data rates and the transfer of large amount of data with a reduced latency. While current research is ongoing for achieving higher LTE throughput based on carrier aggregation, other research direction is ongoing towards achieving lower throughput with low cost and power in order to meet MTC needs based on LTE platform.

EXALTED Project [2] firstly introduced LTE-MTC, also called LTE-M, as a new scalable end-to-end network architecture to expand LTE for machine devices and support secure, energy-efficient and cost-effective M2M communications for low-end devices. MTC devices will be connected through an LTE-M backbone integrated in LTE network without hindering mobile network performance.

Starting the last quarter of 2014, 3GPP in its release 12 [3] presented an evolution of LTE in 3GPP Radio Access Network (RAN) by focusing on extended coverage and low cost enhancements. The first new user equipment (UE) category “Cat-0” for LTE-MTC was also introduced by 3GPP in this release which provide reduced complexity, power consumption, low data rates and delay tolerant transmissions during a M2M communication. In its Release 13, 3GPP completed on optimizing LTE architecture, safety features, latency reduction and indoor positioning to support MTC and released two new categories for LTE-based Machine Type devices (MTDs): LTE Cat. 1.4 MHz and Cat. 200 KHz [4].

On the road of optimization of LTE for IoT, we aim in this work to conduct an in depth performance study of LTE-M protocol based on cross-layer modified parameters (coverage distance through physical layer, scheduling algorithms at the MAC layer, payload size at the application layer level) and measured network metrics (throughput, end-to-end delay and jitter, packet loss ratio) then we analyze and compare the results to LTE Cat-0 in congestion and non-congestion scenarios carried out through the LTE module of NS3 simulator. Hence, the main contribution of this paper is to highlight LTE-M advantages over previous 3GPP LTE releases for MTC and to show what should be enhanced in LTE-M to reach 5G applications demands in terms of higher capacity, lowest latency and the ability to satisfy the highest level of QoS.

The rest of the paper is structured as follows: Section II relates our work to other performance evaluation studies and presents the main contribution of our work. Section III gives an overview of M2M communications and other infrastructure technologies which may support the IoT. Section IV presents the simulation methodology, network parameters and explains the simulated scenarios. Simulation results and the performance analysis of LTE-M are discussed in Section V. Section VI present our future work and gives the conclusion of the paper.

II. RELATED WORKS

Many research studies evaluated the performance of cellular networks in supporting M2M communications. A performance evaluation of LTE QoS has been studied in [5] by varying payload sizes and a solution is proposed to increase throughput in uplink with packet aggregation performed on the IoT gateway. However, M2M low-throughput in the order of Kbps was not considered in this simulation. Authors in [6] also proposed a cross-layer aggregation solution based on data buffering and clustering of nearby users. LTE-M is introduced as a possible solution to improve transmission efficiency without being considered in the performance comparison. The paper concludes that by buffering and clustering, packets overhead are minimized which increases the number of users served by a single cell. In [7] an LTE integrated service based on overhead minimization is suggested to improve energy efficiency and increase the number of MTDs supported by a single eNodeB. Authors evaluated LTE for M2M on a bandwidth of 10 MHz without considering the 1.4 MHz bandwidth adapted by LTE-M for M2M communications. Costantino, Luca, et al. have proposed in [8] a hybrid architecture for IoT where M2M devices are connected to an IoT gateway and evaluated the impact of M2M traffic in terms of network performance on traditional communications between UEs. On the MAC layer, Zain, Aini Syuhada Md, et al. compared in [9] the performance of different scheduling algorithms for VoIP traffic in LTE-A networks. 1.4 MHz and 20 MHz bandwidth were both simulated only in downlink without taking mobility into consideration. Also downlink throughput is evaluated in [10] at MAC-layer level with NS3 Simulator. The paper proposed a new modelling framework which improves error correction and achieve high communication reliability by adopting a combination of link adaptation and error correction schemes. Authors in [11] evaluated the performance of Channel-Aware MTC (CAT) based on LTE resource allocation measurements of a real LTE deployment and introduced a new measurement methodology which quantifies the resource requirements of LTE Uplink for different channel conditions in terms of delay and data rate and reduces the effect of MTC on H2H services. However, to the best of our knowledge this is the first attempt where LTE-M as a protocol is evaluated based on cross-layer network parameters and compared to other MTC technology in the same LTE uplink scenario. Our work combines the theoretical studies of MTC in cellular networks with the practical work through the LTE module of NS3 simulator. We focus on the in depth performance evaluation of LTE-M in uplink with single and multi-nodes scenarios while taking into consideration random distributions of devices and mobility.

III. LTE-M IN M2M ENVIRONMENT

A. M2M communications

The major challenge in mobile communications is to maintain a high data rate network connectivity as well as ensuring high scalability, low delay and good security. However, M2M communications is distinguished by a massive number of low-cost, low data rate and low-powered devices. Various standard organizations such as 3GPP, ETSI, IEEE, and telecommunications industry association (TIA), are active in supporting M2M features and defining network architectures for M2M communications [12]. In addition, many technologies such as SigFox and LoRa [13] mainly targeted for M2M are now presented as candidates to support IoT networks: SigFox is an open standard technology for IoT and characterized by a low power, low bandwidth and an extremely low throughput. LoRa which stands for Long Range Radio, is a wireless technology which will fulfill to develop smart city using sensors and automated products/applications. LoRa offers a larger bandwidth, good security and data streaming and better throughput and provide less low-power devices than SigFox. LoRa and SigFox both operate on low-power wide-area networks (LPWAN) and are not adapted to support long distance communications between machines. However, LPWANs network technologies are able neither to offer coverage everywhere, nor to guarantee highly reliable coordinated control of the network. Therefore, integrating MTC services into the existing cellular networks is proposed as a solution due to cellular networks capability to deal with the challenge of ubiquitous and transparent coverage. Furthermore, the wide-area mobile network access paradigm offers a number of other advantages over LPWANs such as higher efficiency, robustness and security [14]. This explains the release of LTE-M and Narrowband LTE-M also called as NB LTE-M by 3GPP to integrate machine-type communications into cellular networks. The biggest advantage of LTE-M is that it operates on an already existing LTE infrastructure. LTE base stations only need to be upgraded to support LTE-M features for IoT. Thus, it is easier for the operators to maintain older base stations instead of building new ones.

B. LTE-M overview

Many cellular operators and companies such as Nokia [15], Ericsson [16] and Qualcomm [17] introduced LTE-M as a potential technology to optimize LTE for the IoT. However, EXALTED [2] was the first project of the European Union's Seventh Framework Program (FP7) to present LTE-M as a new system that extends LTE specifications for M2M communications and supports future wireless communication systems in terms of extended coverage, lower cost, better security, energy efficiency and the ability to support a larger number of connected devices.

The proposed network architecture in EXALTED integrates LTE-M in the LTE cellular network (Figure 1). In this architecture, LTE mobile phones and LTE-M devices communicate via the same LTE/LTE-M network. Each M2M device can either communicate with other devices as a standalone device, connect directly to the application server over the LTE-M network, or can form a capillary network with other M2M devices of the same type and connect with the server via a M2M gateway. The M2M gateway run the same application and functionalities as other M2M devices.

However, it is considered as the most important element of this architecture. The M2M gateway performs protocol translation and data aggregation before transmitting messages to the application server via a specific LTE-M interface. While maintaining the same Evolved Packet Core (EPC) for LTE network, the network access to LTE-M Devices and M2M Gateways is provided by LTE-M Base Stations (LTE-M eNodeB). Not all Machine-type devices support LTE-M technology, those devices are addressed as Non-LTE-M devices. LTE-M devices support the LTE-M protocol stack. Thus, there's no need for a protocol translation and all data are directly forwarded to the application server. However, in the case of Non-LTE-M devices, protocol translation from the capillary network to the LTE-M protocol stack is mandatory through the M2M gateway which is also responsible of data extraction and re-encapsulation at the destination side.

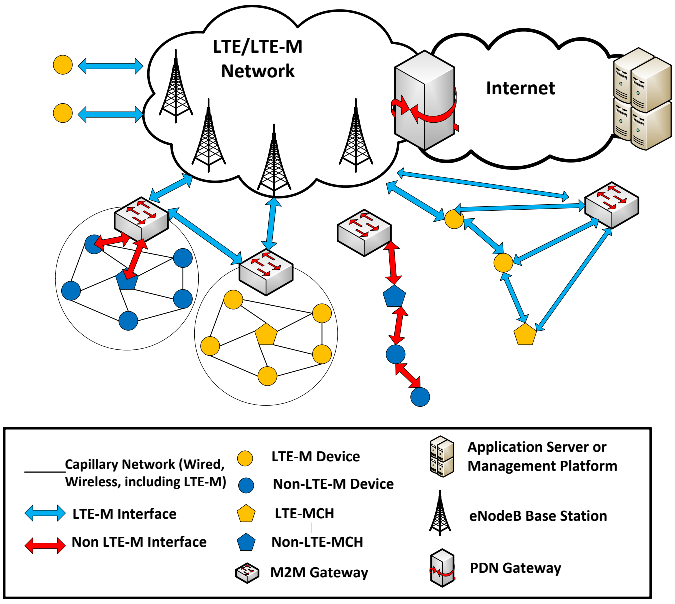

Fig. 1. LTE/LTE-M Network Architecture

In their latest releases, 3GPP worked on continuous advancements in M2M communications over LTE and LTE-A networks. In 2008, 3GPP released LTE Category 4 and Category 1 which differ in terms of downlink and uplink data rate while maintaining the same 20 MHz bandwidth as shown in Table 1 below.

	Release 8	**Release 8**
	Cat. 4	***Cat. 1***
Downlink peak rate	150 Mbps	10 Mbps
Uplink peak rate	50 Mbps	5 Mbps
Number of antennas	2	2
Duplex mode	Full duplex	Full duplex
UE receive bandwidth	20 MHz	20 MHz
UE transmit power	23 dBm	23 dBm

Table 1. LTE Network Parameters

In 2014, MTC were addressed by 3GPP in its Release 12 and introduced LTE Cat-M adapted for M2M communications. Cat-M follows Cat-1 as the second generation of LTE chipsets meant for IoT applications. Cat-1 is appropriate for IoT applications that may need to send images or video streaming. However, LTE Cat-1 can be described as a low-performance LTE technology more than an MTC adapted category. This is why 3GPP proposed next Cat-0 as the first technology for machines (Cat-M) which supports lower features in terms of cost, throughput, number of antennas and includes power saving mode enhancements for user equipment (UE). IoT devices such as sensors and smart meters tend to have much smaller data messages to send and do not need high speed or large bandwidth. In many applications, the data message can be less than 1 Byte. Hence, in its Release 13, 3GPP introduced LTE-M and NB-LTE-M as the two newest technologies to support low-throughput M2M communications.

Unlike Release 12 for Cat.0 where modifications were more on the UE's side only, Release 13 includes modifications on both UE and eNodeB sides. Table 2 illustrates the parameters of the latest three releases of LTE Category M which stands for machines. In comparison with LTE Cat-0, LTE-M only monitor 6 Resource Blocks (RBs) per subframe and thus operates on a smaller bandwidth. Moreover, with NB-LTE-M, more modifications in terms of protocol are needed because NB-LTE-M supports only 1 RB for system bandwidth and offers the lowest throughput between all LTE Categories.

	Release 8	**Release 13**	**Release 13**
	Cat. 0	***Cat. 1.4 MHz***	***Cat. 200 kHz***
Downlink peak rate	1 Mbps	1 Mbps	200 kbps
Uplink peak rate	1 Mbps	1 Mbps	144 kbps
Number of antennas	1	1	1
Duplex mode	Half duplex	Half duplex	Half duplex
UE receive bandwidth	20 MHz	1.4 MHz	20 MHz
UE transmit power	23 dBm	20 dBm	23 dBm

Table 2. LTE Cat. M Network Parameters

IV. Simulation Methodology and Parameters

In this section, we present the simulation methodology based on which the performance comparative study between LTE Cat.0 and LTE-M will be conducted.

A. Simulation Methodology and Tracing

In this work, we used the LENA LTE module (ns-2.35 Release) of the open source NS3 network simulator [18]. The reason for choosing NS3 is because of its strong tracing architecture compared to other network simulators. NS3 provides a callback tracing system based on multiple trace sources associated by a specific object and identified by a name. The programmer has the ability to follow specific simulation events by creating his own tracing functions in C++. NS3 also offer the opportunity to store multiple layers outputs events in a text file and to trace packet transmit/receive events via packet capture (PCAP) files. However in our work, all network performance results are inspected using FlowMonitor which is a network monitoring framework for NS3, offering an easier way to analyze flow metrics such as throughput, delay, jitter and packet loss ratio. For a detailed description of this monitoring framework we refer the reader to [19] and references within.

B. Simulated Scenarios and network parameters

The ratio of data traffic transmitted by the massive number of M2M devices in the future is larger in uplink than in downlink [20]. Thus, we focus in this study on the LTE uplink traffic only and we compare and evaluate LTE Cat-0 and LTE-M performance based on throughput, delay, jitter and packet loss ratio in single-node and multi-nodes scenarios. Figure 2 illustrates the first example MTC scenario where a single M2M device is uploading data traffic with a maximum rate of 1 Mbps.

The LTE network will allow data traffic from the eNodeB to be routed to the remote host through the Evolved Packet Core (EPC) which contains the PGW (Packet Gateway) and the SGW (Serving Gateway) and handles the management and signaling functions of LTE. The application installed on the M2M device is a UDP-based On-Off application with a default payload size of 1000 Bytes. Thus, with a null value for the off-time application, 1 packet per second is sent constantly.

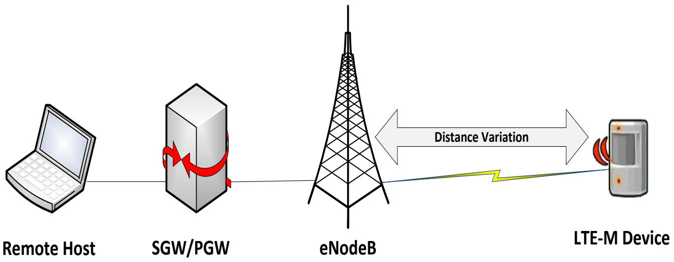

Fig. 2. Simulation Scenario

For this simulation, we considered Friis Free-space [21] as propagation path loss model between the transmitter and the receiver Isotropic antennas. Authors are aware that the use of Friis path loss model and Isotropic antennas in this simulation will not lead to realistic results. However, the objective of such utilization is to ideally evaluate the difference between LTE-M and LTE Cat-0 under similar conditions. This way, it will be clearer to detect and analyze performance metrics differences. At the eNodeB level, multiple scheduling algorithms can be implemented such as Proportional Fair (PF), Maximum Throughput (MT), Round Robin (RR) and many others. For single nodes simulations we kept the default PF algorithm which offers a balance between maximizing throughput while at the same time allowing all users at least a minimal level of service. However for multiple nodes simulation, a comparative study will be made between MT, RR and PF schedulers in multi-nodes scenario.

For a specific comparative study between both technologies, similar parameters were considered. On the application level, we kept the same packet payload size and data rate for both technologies. As standardized by 3GPP, a single Isotropic antenna for input and output (SISO) is configured. In addition, eNB transmission power, Noise Figure, path loss model and PF scheduling algorithm are all also kept as constants at the Physical and MAC layers. However, LTE-M and LTE Cat-0 operates on different frequency bandwidth. LTE Cat-0 operates on a 20 MHz bandwidth for uplink (i.e. 100 RBs per subframe) higher than LTE-M which works on a 1.4 MHz bandwidth (i.e. 6 RBs per subframe) and thus has a larger number of RBs allocated for devices.

By reason of considering LTE module for this simulation, single carrier FDMA (SC-FDMA) is the selected scheme for the uplink which is characterized by its enhanced power efficiency and offers a longer battery life for M2M devices. However, as mentioned in [22], the use of Generalized Frequency Division Multiple Access (GFDMA) [23][24] is required for multiplexing instead of SC-FDMA in order to reduce the bandwidth to a single RB like in the case of the NB LTE-M. Unfortunately, GFDMA is not implemented yet in NS3 Simulator which also does not support 1 RB configuration. Therefore, NB-LTE-M cannot be simulated in this paper and thus compared to LTE-M and LTE Cat-0. All previous simulation parameters are summarized in Table 3 below except otherwise mentioned.

Network Parameters	Values	
	LTE Cat 0	LTE Cat 1.4
Propagation loss model	Friis Free-space	Friis Free-space
eNB Tx Power	20 dBm	20 dBm
eNB Noise Figure	5 dB	5dB
Uplink Bandwidth	20 MHz	1.4 MHz
Resource Block Number	100	6
Uplink EARFCN	18100	18100
Downlink EARFCN	100	100
Antenna Model	Isotropic	Isotropic
MIMO Format	SISO	SISO
UE Tx Power	23 dBm	20 dBm
UE Noise Figure	9 dB	9 dB
Maximum Application Bitrate	1 Mbps	1 Mbps
Payload Size	1000 B	1000 B
Simulation Duration	20 s	20 s

Table 3. Simulation Parameters

In the following scenarios, we will first study the performance degradation for both technologies in terms of throughput and coverage when the distance between the M2M device and the eNodeB increases. Other than distance, many meters variation were also considered such as increasing the number of nodes, modifying payload size and scheduling algorithms. All scenarios and simulation results are presented and analyzed in the next section.

V. Results And Analysis

In this section, single and multi-nodes simulation scenarios are considered for LTE-M and LTE Cat-0 performance evaluation. After that, we analyze the results based on FlowMonitor network metrics.

A. Single Node Scenario with Distance Variation

In the first experiment, we study the performance degradation of a single M2M device implementing both LTE Cat-0 and LTE-M with distance and compare results in terms of throughput, coverage, packet loss ratio, delay and jitter.

1) Throughput and Packet loss ratio with Distance

While the M2M device move away from the eNodeB we compare both technologies in terms of throughput and maximum coverage. By coverage we mean the maximum distance where a M2M device can still transmit data to the remote host. Both technologies differ in terms of M2M device maximum transmission power, frequency bandwidth, and the number of resource blocks per subframe. Throughput express the rate of successful received bits over LTE channel within simulation time and is calculated via FlowMonitor. The result is next divided by 1024 in order to express throughput in Kbps as shown in the following Eq.1 formula.

$$\text{Throughput (Kbps)} = \frac{\text{Recieved\_Bits}}{\text{Simulation\_Time(s)}*1024} \quad (1)$$

When the distance between the M2M device and the eNodeB reaches 12 KM, throughput start to decrease for both technologies as shown in Figure 3. However, the main difference between both cases is in the rapid decrease of throughput with LTE Cat.0 unlike LTE-M where throughput decreases slowly and reaches a broader distance. Moreover, in terms of coverage, the maximum distance where the device can still transmit data with LTE Cat.0 is 18 KM unlike LTE-M where a much better coverage is provided and the device can still transmit data even at a distance of 60 KM.

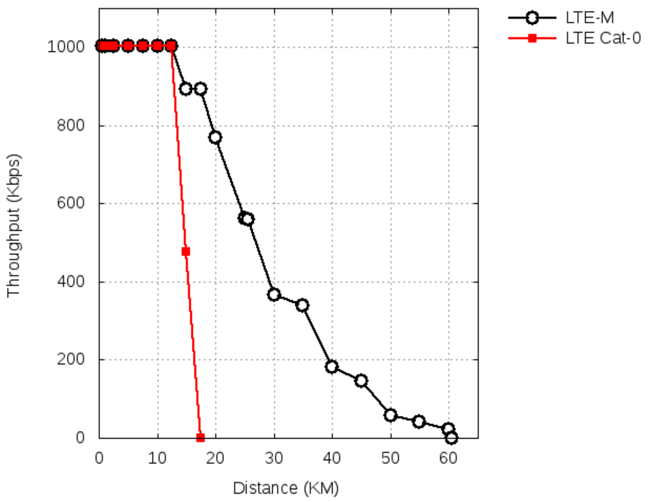

Fig. 3. Throughput variation with Distance

Although LTE Cat. 0 device has richer capabilities in this single node scenario, LTE-M device was still able to transmit data with a higher throughput and a longer distance. The result for this is due to power spectral density which represents the signal transmission power over frequency and is directly affected by the number of RBs per subframe. For this same power distributed over RBs, the power per block is higher with a bandwidth of 1.4 MHz which explains why LTE-M reaches a longer distance. In addition, based on Eq.2 below, RSRP which stands for the Reference Signal Received Power is inversely proportional to the number of RBs per subframe. Thus, based on this formula, decreasing the number of RBs will increase RSRP value.

$$\mathrm{RSRP} = \frac{\mathrm{RSRQ} * \mathrm{RSSI}}{\text{number of RBs}} \quad [25] \qquad (2)$$

RSSI stands for the Received Signal Strength Indicator which represents the received power from the serving cell including the interfering cells and noise power. In addition, RSRQ refers to the Reference Signal Received Quality and contributes in making a reliable handover or cell re-selection decision. Moreover, Signal to Noise Ratio in LTE is proportional to RSRP which also directly affects throughput and increase at its turn. In [26], the following Eq.3 has been proposed relating SNR to throughput where C is the throughput in Kbps, W is the bandwidth of one RB (i.e. 180 KHz), SNR is the signal to noise ratio and α value which vary between 0.1 to 1.

$$C = \beta . W . \log_2 (1+\alpha . snr) \quad [26] \qquad (3)$$

Compared to the previous result, packet loss ratio variation with distance is inversely proportional. At the same distance where throughput degradation is detected, we start to lose packets. Packet loss ratio increase when the distance between the eNodeB and the LTE-M device bypass 12 KM. In a direct comparison between LTE-M and LTE Cat-0, Figure 4 indicates that packet loss ratio increase more rapidly with LTE Cat-0. LTE-M offers a wider coverage in terms of coverage, better stability and higher throughput than LTE Cat-0.

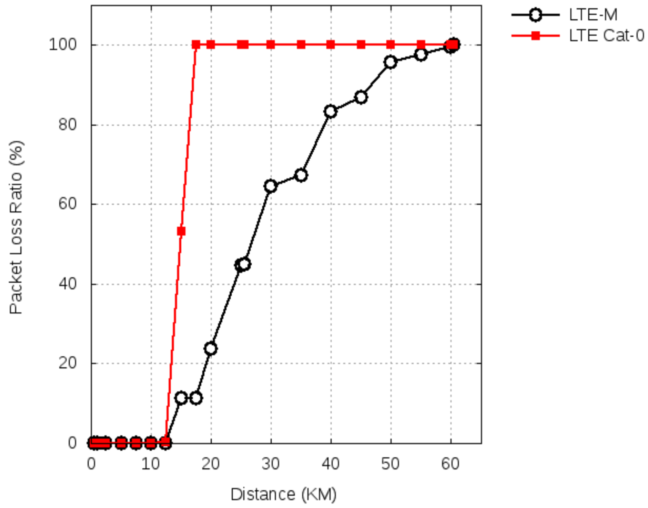

Fig. 4. Packet Loss Ratio variation with Distance

2) *Delay and Jitter variation with Distance*

In the same scenario, other than throughput and packet loss ratio, delay and jitter values are also traced and calculated through FlowMonitor.

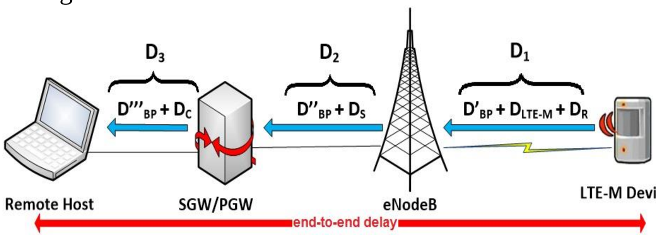

Fig. 5. End-to-End Delay distribution

In Figure 5, we present how the end-to-end delay is distributed between LTE network components. D_{BP} stands for buffering and propagation time delay during uplink and differs depending on the sending node (D'_{BP}, D''_{BP} and D'''_{BP}). D_1 represents the delay between the LTE-M device and the eNodeB and includes D'_{BP}, LTE-M device ($D_{LTE\text{-}M}$) delay and HARQ packet retransmissions delay (D_R). D_2 includes D''_{BP} and Ds which stands for scheduling process delay caused by the eNodeB at the MAC-layer level. And finally $D_{3,}$ which add to $D'''_{BP,}$ the delay that happens on the core network side (Dc). While varying distance and keeping all other parameters constant, LTE-M achieved a better delay than LTE Cat-0 during the whole simulation time as shown in Figure 6 below. The reason for this result is due to a more powerful resource block in LTE-M than in LTE Cat-0 which leads to a smaller packet transmission time from the sending to the receiver node. Another parameter affecting delay is the amount of HARQ retries which happens when M2M device is uploading data to the remote host. A stronger power will have less HARQ retries and thus a smaller retransmission delay which result a better overall delay for LTE-M. However, the Random Access Procedure included in the calculated end-to-end delay does not affect the mean value for a single node scenario. Even so, the impact of this process on delay for or a larger number of devices is higher on LTE-M than LTE Cat-0 due to its smaller bandwidth. Results show that the delay produced by LTE-M devices is not enough to support new M2M services and the vast amount of real-time applications which demands an extremely low latencies on the order of 1 ms accuracy.

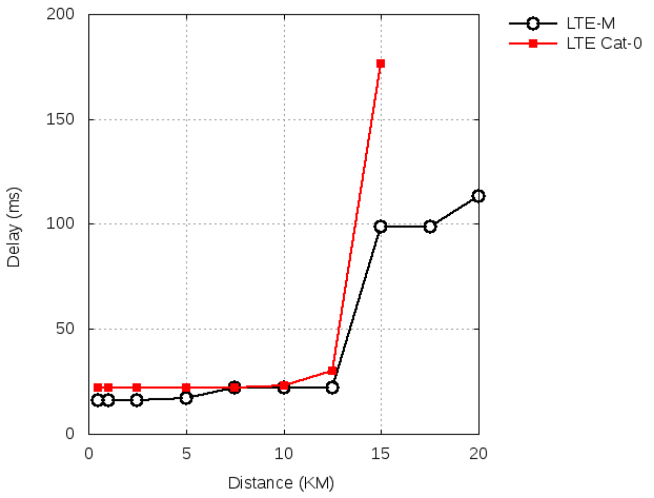

Fig. 6. Delay variation with Distance

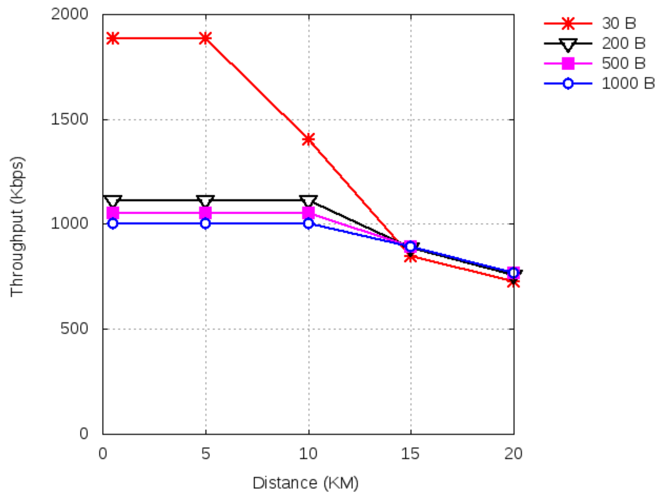

Fig. 8. Throughput and payload variation with Distance

Moreover, while keeping the same previous parameters for this single node scenario, Figure 7 illustrates how distance variation affects also Jitter and proves that Jitter is directly related to Delay variation. In terms of Quality of Service QoS, any application installed on a M2M device and sensitive to Jitter, is also sensitive to delay. Jitter starts to increase with LTE Cat-0 at a distance between 5 and 10 KM. However, in the case of LTE-M, the mean jitter remains stable for a longer distance and increase starting a distance of 12 KM. Other than mobility, payload size variation of packet transmitted in uplink affects also LTE-M device throughput and is presented in the following simulation.

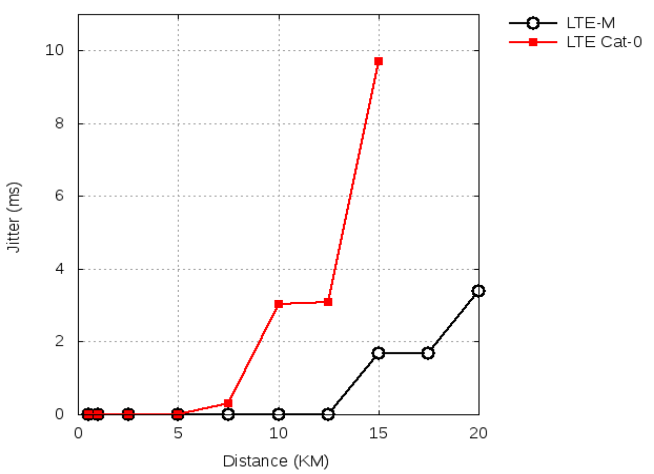

Fig. 7. Jitter variation with Distance

3) Throughput and Payload Size Variation with Distance

In this section, we evaluate LTE-M throughput with distance when packet payload size is modified. 20 B for IPv4 packet headers are considered with an 8 Bytes UDP header added at the network layer during encapsulation. The payload size generated by default in NS3 is 1000 Bytes which lead to a total size of 1028 B for each transmitted packet included entirely in throughput calculations. We replicate the simulation 4 times and each time we configure a different payload size (30, 200, 500 and 1000 B). As shown in Figure 8 below, the smaller configured payload packet size, the higher throughput is reached.

Increasing the payload size decrease throughput as more radio resources are required for packet transmission. Eq.4 show the relation between packet error rate (PER) and the bit error rate (BER) where n is the total packet length expressed in bits including MAC and physical layer headers.

$$PER = 1 - (1 - BER)^{n} \quad [27] \qquad (4)$$

Hence, based on Eq.4 when data is transmitted with small payloads, the total packet length n will decrease. BER vary between 0 and 0.5 this is why when n decrease, PER decrease and the amount of HARQ retransmissions which be reduced. Hence, the smaller the payload is, the better delay and higher throughput are achieved. However, for a small payload of 30 B, overhead occupy 45% of the total transmitted Bytes. This poses a challenge in the future to decrease overhead and optimize LTE-M via payload aggregation or other clustering solutions.

B. Multi-nodes Scenario

In this simulation, we continue with the same network parameters but the number of connected devices to the eNodeB with LTE-M is increased to evaluate mean throughput variation in a congestion scenario. Authors in [28] varied users densities in LTE cell using both normal (Gaussian) and uniform distributions. Hence, in the first part, we deploy LTE-M devices on a surface of 15 KM^2 with random Gaussian distribution to simulate nodes on an error-less distance. In the second part, we modify scheduling algorithms and evaluate mean throughput of LTE-M devices deployed this time over a surface of 60 KM^2 with the random Uniform distribution.

1) Mean throughput variation with distance

Within a simulation area of 15 KM^2, LTE-M devices are distributed on a distance between 7 and 8 KM due to Gaussian distribution. We replicate the simulation 20 times in order to draw the interval of confidence illustrated in Figure 9 below. While taking into consideration that with LTE-M the maximum throughput transmitted is 1 Mbps, it can be seen that this rate was never reached and even with a very small number of devices the maximum mean throughput was around 800 Kbps and rapidly decrease to few Kbps when the number of LTE-M devices increase.

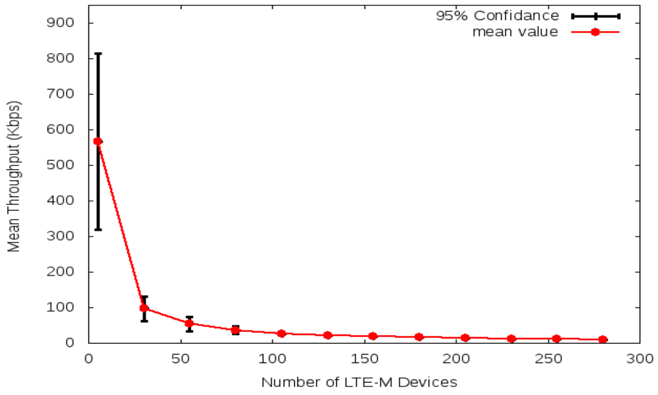

Fig. 9. Mean Throughput interval of confidence

Moreover, Figure 10 present how mean throughput vary with distance and the number of LTE-M connected devices. Maximum throughput of 450 Kbps is reached for a small number of connected devices and decrease to few Kbps when more than 50 LTE-M are simultaneously connected to the eNodeB. In addition, it should be noted that with LTE-M a higher number of low-throughput transmitting devices is achieved than in the case of LTE Cat-0 due to its smaller bandwidth which meet the needs of M2M communications in terms of enhanced energy efficiency, lower throughput and higher number of connected devices. Nevertheless, LTE-M is not up to the main challenge to support 100,000 MTDs in a cell under the premises of low cost and long lifetime as mentioned in [29]. Results show that throughput decrease rapidly in a congestion scenario but it can be improved if we use the appropriate scheduling policy. Hence in the following part, we compare and analyze throughput variation with different scheduling algorithms.

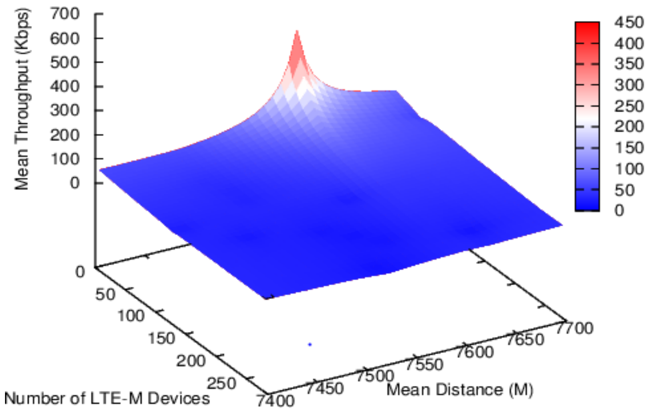

Fig. 10. Mean Throughput variation with Distance

2) Mean throughput variation with scheduling algorithms

In this last experiment, mean throughput variation is evaluated in a congestion scenario for multiple scheduling algorithms. LTE-M devices are distributed over a surface of 60 KM^2 with the random uniform distribution. Three scheduling algorithms are considered: Proportional Fair (PF), Maximum Throughput (MT), Round Robin (RR) schedulers. PF scheduler works by scheduling a user when its instantaneous channel quality is high relative to its own average channel condition over time. PF provides a fair chance for all users to be scheduled while maintaining scheduling prioritization for users with good channel condition. MT is a channel aware scheduler but does not take into account QoS for users. The eNodeB allocates the LTE-M device with largest instantaneous supportable data rate based on its channel condition. Thus, users with bad channel conditions are not fairly served. RR works in a cyclic mode and does not apply QoS for devices but offers the best fairness this is why RR is considered as the least complex scheduler. The payload of transmitted packet is 1000 Bytes and is considered constant in this experiment. Results in Figure 11 show the mean throughput variation for a maximum number of 60 connected devices in a cell. PF shows the best results because it takes in consideration the QoS for all LTE-M devices. However, among the three schedules, RR had the lowest throughput when the number of connected devices was less than 23 because it does not consider the channel condition of LTE-M devices during scheduling process. The worst mean throughput is reached with MT scheduler when the number of devices was higher than 23, this is because MT is a QoS unaware scheduler and only consider devices with good channel conditions. Hence, when the number of devices increase, network congestion will degrade channel conditions and decrease the mean throughput of LTE-M devices.

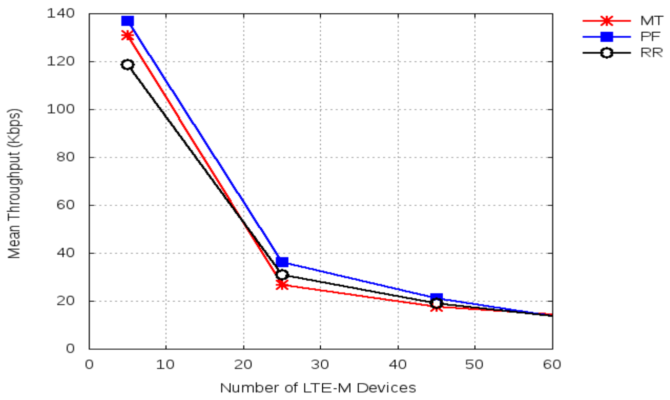

Fig. 11. Mean Throughput variation with scheduling policies

VI. Conclusion

M2M communications is one of the recent research areas where machines can communicate either directly with each other or through a network without human intervention. Due to the heavy amount of traffic produced by M2M devices in cellular networks, LTE-M is proposed by 3GPP to support M2M needs in terms of longer distance communications, lower throughput and a larger number of connected devices. This paper evaluates the network performance of LTE-M in uplink and inspects its behavior in single and multi-nodes scenarios compared to LTE Cat-0. In single node scenario, results show that with LTE-M a broader coverage distance can be measured while offering a better performance than LTE Cat-0 in terms of throughput, packet loss ratio, jitter and delay. Nevertheless, LTE-M is still not capable to support future applications for M2M which demands a better jitter and a delay less than 1 ms. In multi-nodes scenario, we evaluate mean throughput variation in uplink when the number of LTE-M devices connected to eNodeB increase with different scheduling algorithms. With LTE-M, the number of connected devices transmitting low throughput data is increased but this number is still not enough for IoT which requires a massive number of connected MTDs and a more reduced throughput. To achieve this goal in cellular networks, protocol modifications are considered by reducing the bandwidth in NB LTE-M on which we will focus in our future studies to reach an enhanced transmission efficiency in terms of energy and to support a larger number of connected LTE-M devices in a single cell.

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