Proposed Energy Efficient Multi-Layer MAC Protocol for Massive MTC over LTE Wireless Network

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Abstract

Energy efficiency is one of the prime consideration in designing Machine Type Communication (MTC) networks, because of the battery-powered machine nodes. Therefore, extending the network lifetime can be done by using more energy efficient techniques. The dramatically increase in the number of machine nodes in many aspects of our life makes the wireless standards to adopt Machine to Machine (M2M) communication in its new specifications. The massive number of machines need a new MAC protocol that makes full use of the node's battery, so that node can live longer time. In this paper, a new protocol called Multi-Layer MAC (ML-MAC) will be suggested, and then integrating this protocol into LTE network will be made. Calculations of energy efficiency, delay, and throughput as a performance parameter will be done. Simulation results show that proposed ML-MAC protocol is more energy efficient compared to traditional IEEE 802.11 MAC protocol and Sensor MAC (S-MAC) protocol. Moreover, prolonging the network lifetime can be done by using the new ML-MAC protocol than others.

1. Introduction

Nowadays, researchers pay intention to IoT (Internet of Things), because of its widespread applications all over the world. M2M or MTC is the communication between machine nodes without any human intervention, and it is indispensable part of Internet of Things (IoT). Examples of M2M applications are, remote monitoring, emergency alert, tele-health, Home security, and smart city management. There is an expectation that number of machine devices will reach nearly 50 billion devices by 2020 [1]. Increase demand on M2M denoted many vendors to adopt it in next 5G mobile generation [2], [3], [4]. Also, as its widespread deployment though the world 3GPP also made an intensive research to integrate M2M into LTE and LTE-A standards [5], [6], [7].

5G or next generation network is expected to deal with massive connected devices, as mobile operators need to enlarge their business to become a total service provider, this done by offering a greater range of services and providing a mobile smart life to every user. As a consequence, number of active machine nodes that will be served per one cell can go up to 20,000 per kilometer square [8]. If machine nodes are always battery-powered, an energy-efficient MAC protocol is required to manage the access of all nodes, so that collision can be reduced, hence energy consumption decreases. This can efficiently increase network life time. Obviously, this can be used with non-human based devices that have delay-tolerant traffic.

In [9], authors made a survey for contention free, contention based, and hybrid MAC protocols and studied the advantages and drawbacks of applying these protocols for M2M. Beside we can deduce that IEEE 802.11 which depends on CSMA/CA technique is the simplest and the most widely deployed MAC protocol in most transmission issues, but it is inefficient for massive M2M communication, because of the energy wasted by this protocol due to collision and idle listening. The adaptation of random access protocols for M2M was discussed in [10], where M2M communication is characterized by its small and sporadic data packets. Therefore, it is energy inefficient to perform Ping-Pong authentication and transmit reservation packets of length larger than data packet length. S-MAC is a protocol was designed for WSN and based on IEEE 802.11 protocol but with periodic listen-sleep, that can save energy consumption [11]. ML-MAC protocol is a development of S-MAC protocol, which based on dividing the listening time into many layers, each group of devices contending in a predetermined layer, this lead to reduction in collision and idle listening [12]. This protocol was designed for ad-hoc or mesh-type network where there is no central access point like that in the cellular system and neglected the channel condition and device position. EXALTED is a European project that aims to embed M2M communication into the current LTE cellular system, this project provided LTE-M which is the LTE version supporting machines, that can be a standalone system or integrated with LTE system [13]. In case of coexistence of H2H and M2M, QOS is needed to distinguish between normal H2H traffic, delay sensitive M2M traffic, and delay tolerant M2M traffic [14]. Basic differences between MTC and H2H communication are massive number of devices, few short packets to be transmitted per machine, low duty-cycle traffic patterns, and the uplink traffic is mostly larger than downlink traffic, so it is the dominant one in such cases.

In this paper, we deal with a standalone LTE-M system with delay tolerant traffic, in which our main consideration is the energy efficiency with accepted delay. LTE-M system was designed as follows: positioning and channel aware are considered to incorporate physical channel characteristics. Each machine node has a dedicated physical resource blocks (PRB) and access the Physical Random-access channel (PRACH) by one of three Different MAC protocols IEEE 802.11, S-MAC, and ML-MAC. We studied the effect of massive M2M access and its impact on the energy consumption and so the overall network lifetime. Performance parameters such as energy consumption, delay, and throughput are evaluated for previous protocols to show how each one can work under massive machine access.

The paper organization is as follows: In Section II, System model will be introduced. Proposed MAC Protocol will be described in Section III. In Section IV, simulation results will be investigated. Finally, conclusions will be made in Section V.

2. SYSTEM MODEL

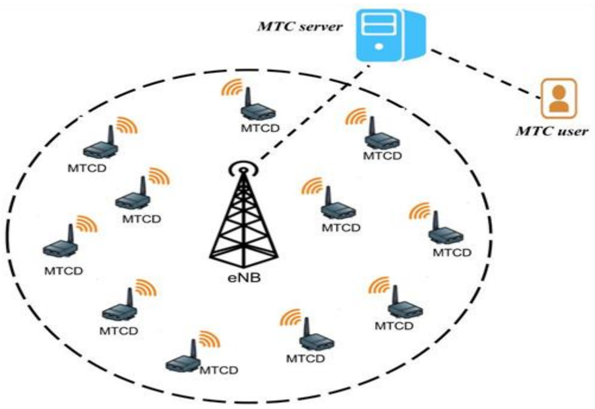


Fig. 1. System Architecture.

In this paper, we consider a homogenous M2M network that consists of one cell with eNB centered in the center, and N randomly deployed MTCDs (Machine Type Communication Devices) as shown in Fig. 1. As a homogenous, all machine nodes have the same priority to access the eNB. Based on currently M2M applications, such as intelligent transportation, smart metering, and e-health, the traffic load is expected to be dominate in the UL direction. Therefore, we will concentrate on Up-Link channel modeling.

2.1 Traffic Model

Suppose system traffic obeys Poisson distribution, where packet arrival follows a Poisson random process with intensity λ. Based on [15], t is the instant inter-arrival time between two successive packets and is exponentially distributed and its PDF (probability density function) is expressed by,

$$f(\mathrm{t}) = \lambda e^{-\lambda t} \quad (1)$$

where

$$\lambda = \frac{\alpha}{T} \,;\; \sigma = \frac{\alpha}{T - \rho}$$

Where, λ is the average packet arrival rate in packets/s, σ is the maximum burst rate, α is the average packet size in bits, T is the average inter-arrival time around which the instant inter-arrival time t varies, and ρ is a constant which limits the value of t within $[T - \rho, T + \rho]$. a small ρ is used for regular traffic and large one for burst traffic.

The shifted exponential distribution shown in Fig. 2 is a modification for exponential distribution and is denoted by,

$$f(\mathrm{t}) = \mathrm{b}\, e^{-b(\mathrm{t-a})} \quad \text{for } t \geq a \quad (2)$$

where

$$a = \frac{\alpha}{\sigma} \,;\; b = \frac{\sigma\lambda}{\alpha(\sigma - \lambda)} \,;\; t = a - \frac{\log_e(1-\mathrm{p})}{b}$$

where, a > 0 and it determines the minimum inter-arrival time; *b* is the factor that decides how fast the exponential function decays with time. p is a random number between open intervals]0,1[.

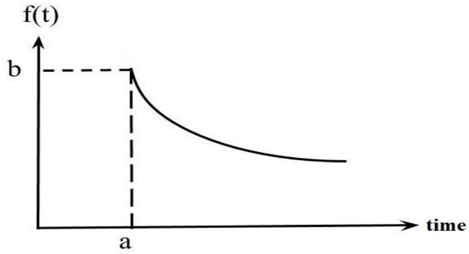


Fig.2. Shifted exponential function.

2.2 Battery Model

Each machine node is equipped with a battery, we assumed a linear battery model that was discussed in [16]. In this model, battery is considered as a linear electric current source. Therefore, the remaining battery capacity is computed by,

$$C = C' - It_d \tag{3}$$

where C' is the initial battery capacity, and I is the constant discharge current for the period of time t_d. Milliampere-hour (mAh) is the unit considered for the battery capacity, one milli-ampere-hour is equal to 3.6 Coulomb (ampere-seconds). We measure the capacity of batteries with a number of Joules that can be spent, the battery is said to be exhausted when the number of remaining Joules reach zero. Moreover, we used standard AA batteries with a nominal voltage of 1.5 V, and an initial load of 500 mAh. Thus, the power that can be provided with this battery equal 750mWh, which is equivalent to 2700 Joules.

2.3 Performance Metrics Calculation

Each machine node has RF section adapted with LTE specifications [17], which has a minimum and maximum transmit power. As each node located at different position, so transmission distance, path loss and transmission power is different from one node to another one. Therefore, we use the uplink link budget for LTE to evaluate the transmission power in mW for machine node as follows [18], [19], [20].

$$P_{ti} = PL_i + S + M + s_i - G_{tx} \tag{4}$$

where, S is the receiver sensitivity in dBm, M is the system margin in dB, s_i is the shadow effect in dB, G_{tx} is the gain of transmitting machine node in dBi, and PL_i is the distance depended path loss in dB between machine node i and the eNB and is calculated as [17],

$$PL_i = 128.1 + 37.6 \log_{10} R_i \tag{5}$$

where R_i is the distance in Km between machine node i and eNB. Energy consumption of any machine node i can be formulated by,

$$E_i = (\mathrm{P}_{ti} + \mathrm{P}_c)\,\mathrm{t}_{ti} + P_l t_{li} + P_{si} \tag{6}$$

where P_{ti}, P_c, P_l, and P_s are transmit, circuit, listen, and sleep powers, respectively. t_{ti}, t_l, and t_s are transmit, listen, and sleep times, respectively. Total energy consumption of the system consisting of N machine nodes is calculated from,

$$E_T = \sum_{i=1}^{N} E_i \tag{7}$$

Average energy consumption is defined as,

$$E_{av} = \frac{E_T}{N} \tag{8}$$

Mean energy consumption per network throughput is denoted by,

$$E = \frac{E_T}{m\alpha} \tag{9}$$

System throughput is determined as the amount of data successfully transmitted over the wireless channel from source to destination in a specific period of time, and calculated for N machine nodes as

$$Th = \sum_{i=1}^{N} Th_i = \sum_{i=1}^{N} \frac{n_i \alpha}{t_b - t_a} \tag{10}$$

where, t_a is the generation time for the first packet, and t_b is the delivery time for the final packet.

End-to-End delay for a packet is the interval taken between packet generation time at transmitter t_g and time when this packet is successfully received at receiver t_r, including delays caused by transmission, propagation buffering, queues, retransmission. n_i number of successfully received packets for node i.

Average end-to-end delay is the total end-to-end delay divided by the total number of successfully delivered packets m, as shown in the following equation.

$$W = \frac{\sum_{i=1}^{m} t_r^i - t_g^i}{m} \tag{11}$$

Network life time calculated as,

$$N_L = Simulation\_time * Battery\_capacity / \text{Consumed\_Energy} \tag{12}$$

3. MAC Protocols

In this paper, we simulated three different contention-based protocols as shown in Fig.3. The three protocols based on slotted CSMA/CA.

IEEE 802.11 protocol [15], [21] is an international standard of physical and MAC layer specifications for wireless networks. It is built on CSMA/CA. It is the most widely used protocol in MANET (Mobile Ad hoc networks), because of its simplicity and reliability. However, it is not suitable for M2M because of nodes always listen to the channel as shown in Fig.3 (a), and so it is not an energy efficient protocol. However, number of researchers are currently modifying and developing the IEEE 802.11, because of its reliability and simplicity.

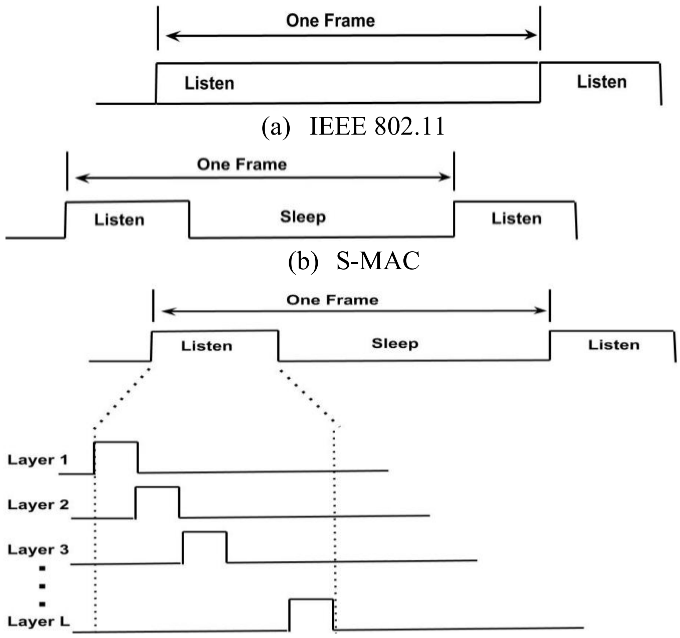
S-MAC is a contention-based protocol and a modified version of IEEE 802.11 standard, that was designed for sensor networks to decrease energy consumption [11]. As shown in Fig.3 (b), the protocol divides the overall system time into basic units called frames, where each one is divided into period of sleep and active time4s. The duty cycle is the ratio of the active or listen period to the length of the frame. Transmission and reception of packets occur only in the listen or active period. Buffering process occurs for packets that are generated during the sleep period until the next frame.

This will result in an increase in the system's total end-to-end delay. The addition of a new node to the network is done by waiting for some time to get a schedule from another node and then follows that schedule. The duty cycle differs for different application, which controls the required quality of service. It is predefined before system establishment.

3.1 Our Proposed Protocol

In [12], ML-MAC was discussed; it is an improvement for S-MAC as shown in Fig.3 (c). In this protocol, listen period is divided into many sub-periods called layers, then total nodes of the cell are randomly distributed into these layers, where each group of nodes compete for a specific time based on its own layer. Fig.4 shows eight nodes compete for the channel access in two separate ways. The first way is the ordinary CSMA/CA in which all nodes access the channel simultaneously, and as shown some nodes will acquire long listening time and this will provide an increase in the energy consumption. The second access way is the ML-CSMA/CA in which nodes are divided into small segments of time named layers, each group of nodes have to transmit in its associated time segment and will be idle or sleep for the other segments, this causes a decreasing in the listen time for each node, and hence there will be a reduction in energy consumption. Therefore, applying the multi-layer concept for CSMA/CA will provide a gain in the energy efficiency than ordinary CSMA/CA.

Multi-layer concept can be applied for any random-access scheme beginning from Aloha to CSMA/CA. Here, we applied this concept for SMAC and called it ML-SMAC and into IEEE 802.11 and called ML-MAC. Then performance parameters are calculated to compare between the different protocols. Fig. 5 shows the flow chart of Multi-Layer process.

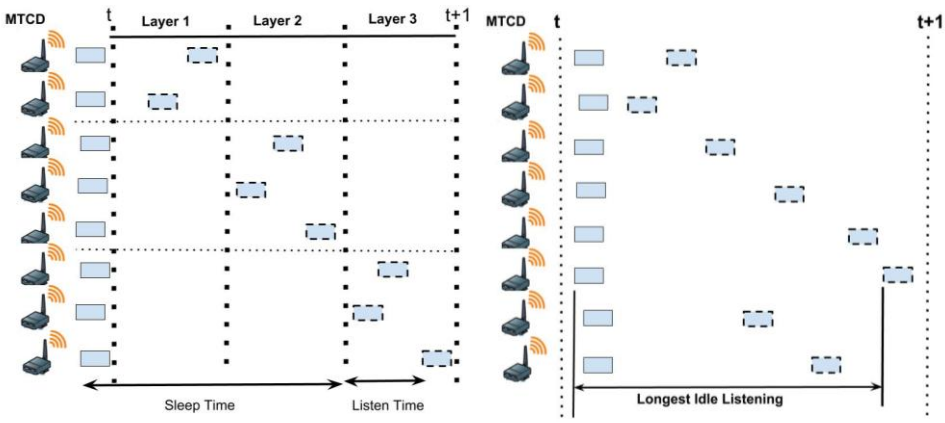


(a) IEEE 802.11

(b) S-MAC

(c) ML-MAC

Fig.3 Frame Structure.



(a) Ordinary CSMA/CA. (b) ML-CSMA.

Fig.4. Comparison between ordinary CSMA/CA and ML-CSMA.

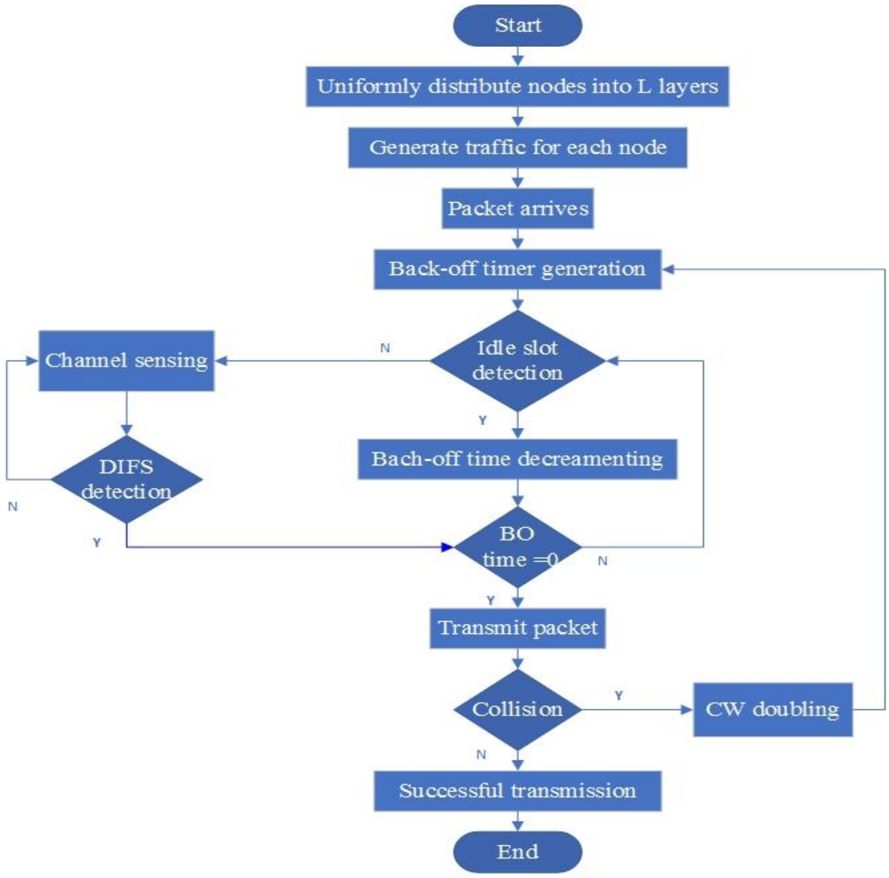


Fig.5 Multi-Layer process flow chart.

4. Performance Evaluation

4.1 Simulation Setup

In this paper, simulation is carried using MATLAB program, as it is simpler than other simulators like OMnet++, NS2, and NS3. System Flowchart is shown in Fig.5, and simulation parameters are introduced in Table 1. The buffer is assumed to be of an infinite size, so there will not be any packet drop. Performance parameters are calculated based on the equations provided in subsection 2.3. Four protocols are simulated IEEE 802.11 MAC, S-MAC, ML-MAC, and ML-SMAC.

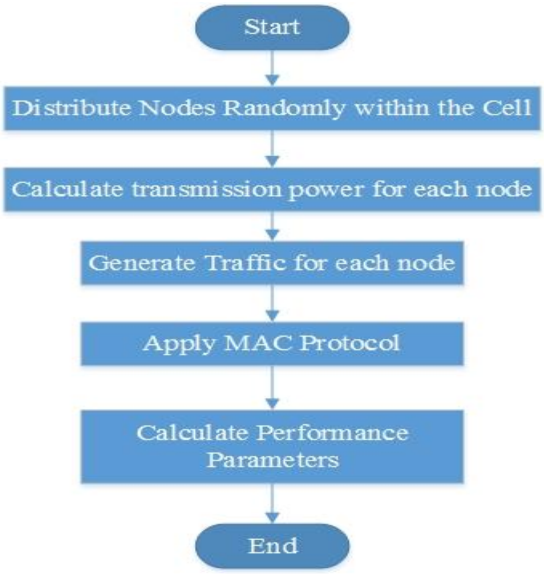


Fig. 6. System Flowchart.

TABLE 1. Simulation Parameters.

Parameter	**Value**
Simulation time	*2000 sec*
Number of Cells	*1*
Cell Radius	*500m*
Simulation Environment	*Macro Cell, Urban Area*
Number of eNB	*1*
Number of Machine Nodes (MN)	*500,1000,1500,2000,2500,3000,3500,4000,4500,5000*
eNB Antenna height	*15m*
MN Max Transmit Power	*23dBm*
MN Min Transmit Power	*-50dBm*
MN Listening Power	*1mW*
MN Sleeping Power	*15μW*
MN Circuit Power	*1mW*
Carrier Frequency	*2000 MHz*
eNB Antenna Gain	*17 dB*
eNB Cable Loss	*1 dB*
Noise Figure	*5 dB*
Shadow Effect	*6 dB*
eNB Sensitivity	*-136.5 dBm*
System Margin	*26.6 dBm*
Bandwidth	*61kHz*
Required SNR	*-7 dB*
Channel Capacity	*16 kbps*
ACK Time	*1ms*
Max Propagation Delay	*10 μs*

MN Antenna Gain	*-2 dBi*	
Buffer Size	*infinite*	
Battery Capacity	*2700 Joules*	
Back-off model	*Binary Exponential Back-off*	
Average Packet size	*20byte*	
Packet transmission time	*0.01 sec*	
Average Inter-arrival Time	60sec	
Frame duration	*1000ms*	
Number of layers	*3*	
Listen time	*IEEE 802.11*	*Frame duration*
	ML-MAC	*Frame duration/Number of layers*
	S-MAC	*30 % frame duration*
	ML-SMAC	*30 % frame duration / Number of layers*

4.2 Simulation Results

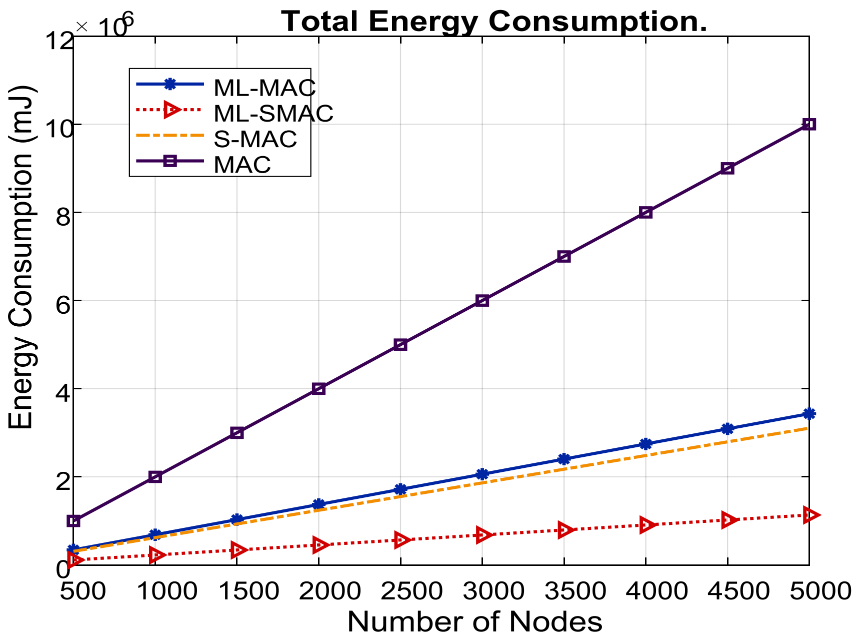


Fig. 7. Total Energy Consumption versus total number of nodes.

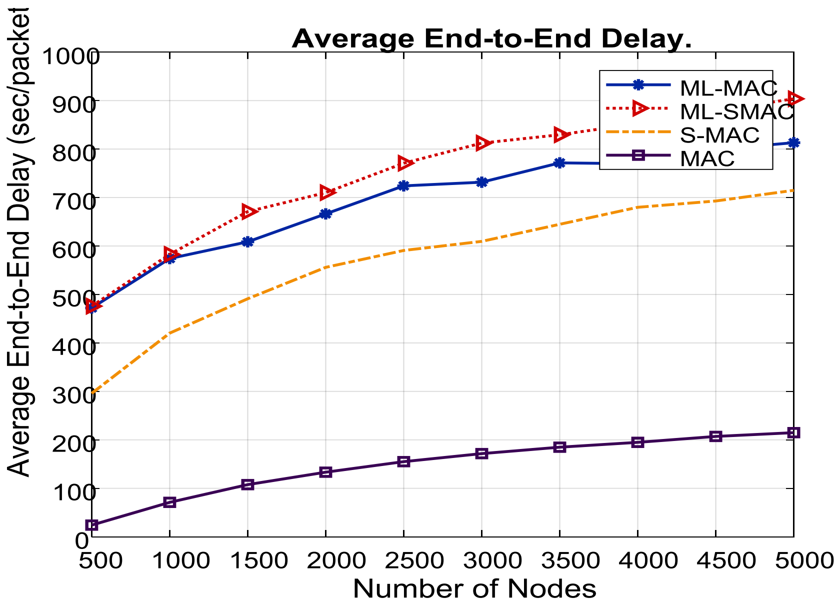


Fig. 8. Average End-to-End delay versus total number of nodes.

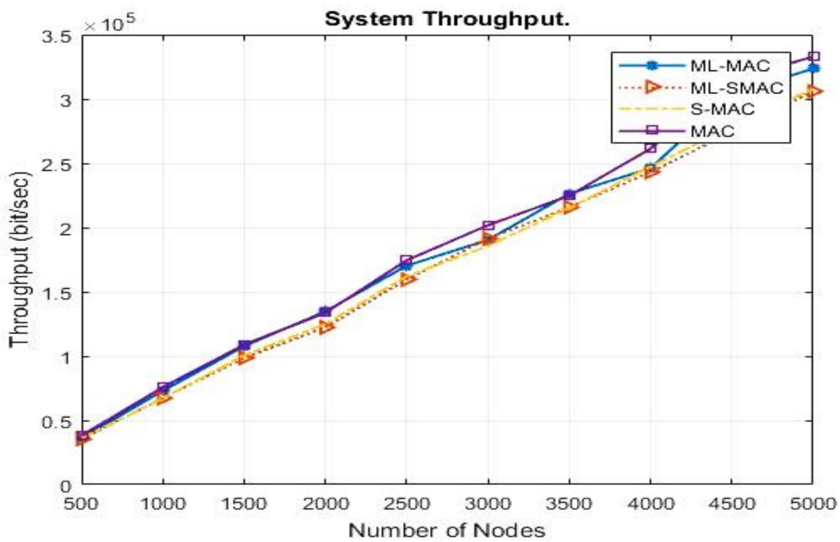


Fig. 9. System throughput versus total number of nodes.

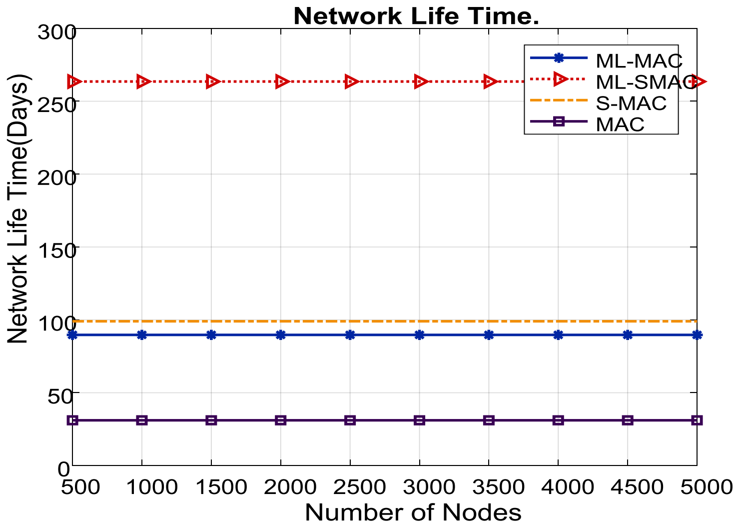


Fig. 10. Network Life Time versus total number of nodes.

The last figure give an indication for the improvement in energy consumption as fig.7 shows and hence prolonging network life time as shown fig.10. The improvement in network lifetime is larger than 150% when applying Multi-Layer concept for either IEEE 802.11 MAC or S-MAC. On the other hand, fig.8 shows that the Multi-Layer concept provided a delay for packet transmission. Therefore, that concept can be applied for delay tolerant applications such as smart metering, but not for delay sensitive applications such as e-health.

5. Conclusion

In this paper, we have designed an efficient protocol that consumes low energy for cellular LTE-M system based on multi-layer concept. The proposed multi-layer protocol provides an enhancement in the energy consumption, and hence increasing in network lifetime that can reach to 240 days for simple 2700 J battery. Because of using multi-layer concept average end to end delay increases, and so we can use this concept for delay tolerant application such as smart meters. For serving different application with different delay requirements in the same cell, QOS will be adopted, where delay sensitive nodes will be served first before delay tolerant nodes.

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الملخص باللغة العربية

نتيجة التطور الهائل وانتشار إنترنت الاشياء ليشمل أجهزة تحتاج إلى الاتصال بالإنترنت من خلال شبكة الموبايل اللاسلكية بالإضافة إلى أجهزة الموبايل التقليدية. أدي ذلك زيادة مطردة في عدد الأجهزة داخل الخلية الواحدة مما يؤدي بطبيعة الحال إلي زيادة عدد التصادمات الناتجة من إرسال بيانات تلك الأجهزة. ولأن الأجهزة تعتمد في الأساس على بطارية حيث أنه في أغلب التطبيقات يتم توزيع تلك الأجهزة في أماكن نائية لمتابعة تغير ما. فقد تم تصميم ماك بروتوكول يقلل من عدد التصادمات الناتجة وبالتالي يتم المحافظة على قدرة البطارية لتظل أطول وقت ممكن. هذا التصميم مبني على شبكة الجيل الخامس التي من المفترض ان تخدم عدد أجهزة يفوق بكثير جدا عدد الأجهزة في الجيل الرابع نتيجة تقديم خدمات مختلفة مرتبطة بشبكات الموبايل باستخدام إنترنت الأشياء.