An Efficient Scalable Hybrid Proposed MAC Protocol for M2M Networks

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Abstract

Machine to Machine (M2M) refers to the technology that allows the devices to communicate autonomously with other devices over the wired or wireless systems. Neither the contention based Medium Access Control (MAC) protocols nor the reservation based MAC protocols can provide a flexible, scalable solution for M2M networks that contain a large number of the devices. In this paper, a proposed hybrid MAC protocol for M2M network will be suggested which combines the main features of two different protocols. It composes of three main parts: Notification Period, Contention Period, and Transmission Period. Different devices contend on the transmission opportunities with the same contending probability during the Contention Period based on Non-persistent Carrier Sense Multiple Access (NP-CSMA) mechanism. During the transmission period, only the successful devices will reserve a time slots to transmit its data packet based on Time Division Multiple Access (TDMA) reservation based mechanism. Moreover, the proposed protocol performance can be measured in terms of three metrics: throughput, average delay time, and Packet Delivery Ratio. Extensive MATLAB programs are done to present a comparison between the Proposed Protocol with other conventional protocols.

1. Introduction

Machine to Machine (M2M) refers to direct communication between networked devices using any communications channel, including wired and wireless to exchange the information without or with limited manual assistance of humans.M2M communication can be used for remote control, robotics, traffic control, health care, and industries to control their real time monitoring. This type of communication involves a large number of low power intelligent objects sharing information and making individual decisions without any human interaction [1].

M2M includes a large number of the devices that are communicating with each other, there will be a large number of attempts from that devices trying to transmit to BS at the same time. Therefore, an efficient scalable, flexible MAC protocol with low power consumption and low latency should be provided for M2M networks. Actually, the weakness of the pure reservation based or pure contention based MAC protocols is the main reason for that the pure reservation based or pure contention based MAC protocols cannot supply a scalable, flexible MAC protocol for M2M networks. Therefore, a hybrid MAC protocols is used which combined the features of both contention MAC protocols as CSMA [2] and reservation based MAC protocols as TDMA [3]. The authors introduced a combination between contention and reservation protocols which were proposed [4-6].

In this paper, a proposed hybrid MAC protocol is introduced which consists of three parts: Notification Period (NP), a Contention Period (CP) and a Transmission Only Period (TOP). The operation is executed on frame by frame basis as each frame composes of these three main parts. The devices contend for transmission opportunities based on NP-CSMA mechanism during COP duration and only the successfully contending devices will be assigned a fixed time slot to transmit its own data packet during TOP duration based on TDMA mechanism. Also, comparisons between our proposed protocol performance and other protocols in terms of three different metrics will be made in the simulation results.The effect of changing the number of the devices on the three performance metrics: throughput, average delay time and packet delivery ratio will be presented.

This paper is organized as follows: Section II introduces Related Works. In Section III, System model will be investigated. The Proposed hybrid MAC Protocol will be explained in Section IV. Simulation Results will be given in Section V. Finally, conclusion will be done in Section IV.

2. Related Work

M2M communications includes large number of the same channel access from large number of M2M devices. Therefore, a scalable, flexible and more robust medium access control protocol is required for M2M networks asgiven in [4]. Actually, two main categories of MAC protocols exist: contention based MAC protocols and reservation based MAC protocols [7].

Although contention based MAC protocols such as NP-CSMA, S-ALOHA and P-ALOHA are popular due to its simplicity, flexibility, and efficient in sharing channels, more collisions occur when large number of M2M devices concurrently communicate to the BS and the network performance will be degraded [8]. Reservation based MAC protocols like TDMA avoid the collisions and the network performance will be improved with the heavy traffic by scheduling the transmission time in to number of time slot and each device is allowed to transmit only in a defined time slot. In uplink transmission wireless networks and in peer to peer ad-hoc networks, the reservation MAC protocols achieved a good QOS (quality of service) only at the cost of a lower channel utilization as illustrated in [9]. Hence, the pure contention based MAC protocols only or the reservation based MAC protocols are not able to provide a scalable, flexible solution for M2M networks. The researches combine the benefits of both contention based MAC protocols as CSMA and reservation based MAC protocols as TDMA resulting in a proposed hybrid MAC protocols as done in [4-6,11].

A frame based hybrid MAC protocol which consists of a p-persistent CSMA contention period and a TDMA based transmission period had been introduced in [4-5] in which different devices contend on transmission during COP duration using CSMA based on their contending probabilities. Only the successfully contending devices reserved a time slot in TOP duration based on TDMA.

In [6], a scalable hybrid MAC protocol had been proposed which composed of a CSMA/CA based contention period and a TDMA based transmission period. The devices contend for transmission opportunities during COP duration and only the successful devices will obtain a time slot for transmission in the TOP duration assuming that each device has only one packet to transmit in its buffer. A hybrid proposed MAC protocol had been suggested for wireless sensor networks which composed of the strengths of TDMA and CSMA to increase the channel utilization which known as Z-MAC [10] in which the device is allowed to contend for transmission opportunities during COP duration andto transmit its data packet during TOP duration only when a time slot is not used.

3. System Model

The proposed M2M network consists of one base station (BS) and K number of devices $\{D_1 \ldots D_k\}$ as shown in Fig. 1 which are distributed around the BS following the uniform distribution. Because each of the K devices possess only one packet to transmit in its buffer with the same priority, it has to contend for transmission opportunities during COP only when it has data packet to transmit, so called active device. The successful devices in COP reserve a fixed time slot in TOP to transmit its data packet. If a device generates a new packet before its transmission, the old packet in its buffer will be replaced by the new one. In this model, the packet arrival process for each active device follows Poisson distribution with average packet arrival rate λ. All the devices have the same average packet arrival rate λ with the same priority.

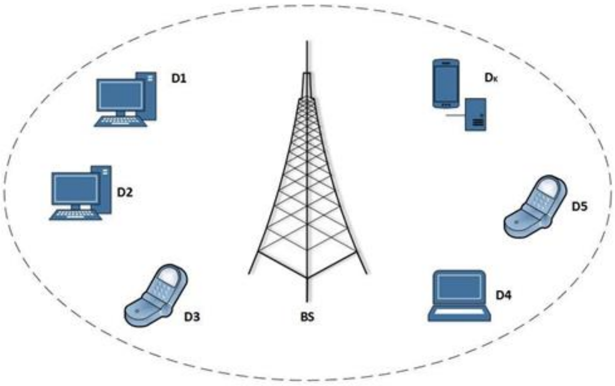

Figure 1: M2M Network Structure

Hence, all K devices will contend for transmission slots during T_{cop} in each frame with the same contending probability which follows Poisson distribution. The probability that a device generates n packets at time t following Poisson distribution given by,

$$P_n(t) = \frac{e^{-\lambda t}.(\lambda t)^n}{n!} \quad (1)$$

The probability that the first packet is generated after time t is denoted as follows;

$$P(t) = 1 - e^{-\lambda t} \quad (2)$$

$$\text{For } t=T_t \text{ , } \lambda=1/T_{int}, \ P(t) = 1 - e^{-\frac{T_t}{T_{int}}} = \frac{G}{M_{num}} \quad (3)$$

$$T_{int} = \frac{-T_t}{log(1-{G}/{M_{num}})} \quad (4)$$

Where, $T_t$represents the transmission time of one packet which equals to slot durationT_{slot}. T_{int} achieves expectation value of one packet generation interval. G is the offered traffic and M_{num} is number of devices.

4. The Proposed Hybrid MAC Protocol

This section introduces a proposed hybrid MAC protocol for M2M networks. The protocol architecture will be explained followed by some analytical analysis in the following parts:

A. The protocol architecture

The operation is performed on frame by frame basis. Each frame is divided into three main parts: Notification Period (*NP*), Contention Only Period (*COP*), and Transmission Only Period (*TOP*).

Notification Period (NP):BS broadcasts a notification messages to all K devices to notify the beginning of the contention at the start of each frame. Only the active devices will contend for transmission during COP duration when they receive the notification messages and their counters will be turned on to calculate the length of the COP duration and the begging time of the TOP duration. Other deviceswill keep its energy by entering the sleep mode.

Contention Only Period (COP):the active devices only contend for the transmission opportunities based on NP-CSMA mechanism with the same priority. When only one device transmits a request message to the BS, this device is successfully contend for transmission and reserve a time slot in TOP duration. The successfully contending device receives an acknowledgement (ACK) message from the BS. The ACK message includes information about the time slot number which the device is allowed to transmit in TOP duration. Once receiving the ACK message, the device will stop sending REQ message to the BS.

Transmission Only Period (TOP): the device successfully contendsfor transmission during COP duration. Then it is assigned a time slot to transmit its own packet during the TOP duration.

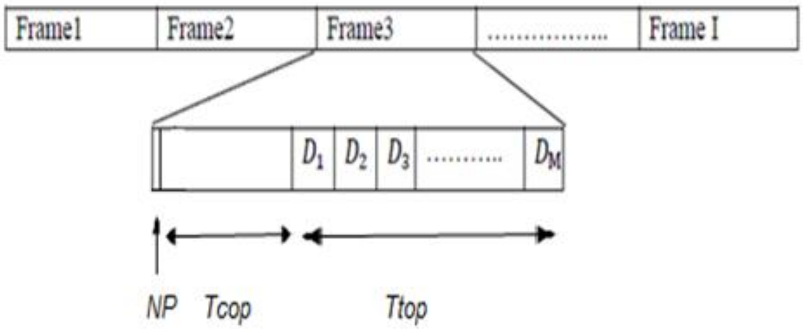

Figure 2. The frame structure

In the proposed protocol, the BS broadcasts a notification messages for all K devices during NP duration. Only the active devices are waked up and their counters are turned on to calculate the length of T_{cop} and the beginning time of T_{top} during T_{cop}. The devices that don't have any packets to send enter the sleep mode to preserve their energy. The active devices send a REQ messages to the BS.If only one device transmits a REQ message to the BS, that device successfully contends for transmission opportunities and it receive an ACK message from the BS including its time slot number. Otherwise, the collision occurs and a retransmission process using Poisson distribution will be happened for the colliding devices. The active devices enter the sleep mode till the next activity. Upon T_{top} duration, a time slot has been reserved for each successfully contending device.

B. The Analytical Analysis

In the proposed MAC protocol, the contending probability for all K devices during COP duration is the same. The time axis is divided into number of the frames, each frame with T_{frame} length contains two main parts: COP duration T_{cop} and TOP duration T_{top}. TOP duration splits in to number of time slots which has T_{slot} duration.

Based on NP-CSMA mechanism [5], the successful contention can be defined as the event that the transmission request from a device is successfully received by the BS. Let $t_i$is the time between the (i-1) th and the ith successful contention. Ni denotes the number of collisions that occurred duringt_i, then [6]

$$t_i=\sum_{j=1}^{N_i}\{[Idle_{i,j}+Colli_{i,j}]+IdleN_i+S_i\} \quad (5)$$

$Idle_{i,j}$ is the duration of the jth idle time that precedes the channel busy period (either collision or success) in each t_i duration. $Colli_{i,j}$ is the duration of the jth collision given that a collision occurs, S_i is the length of the request message.

Let, t_i is a matrix of x*1 dimension, A is also a random matrix of x*y dimension following Poisson distribution and T_{int} is a matrix of y*1 dimension, then

$$t_i = A\,.\,T_{int} \quad (6)$$

T_{cop} is the sum of random variable t_i, Donates the duration of the COP in each frame

$$T_{cop}=\sum_{i=1}^{M}t_i=\sum_{i=1}^{M}\{\sum_{j=1}^{Ni}[Idle_{i,j}+Colli_{i,j}]+IdleN_i+S_i\} \quad (7)$$

T_{cop} is assumed to be constant and equals to 3msec in this protocol.

The system throughput S can be calculated as a normalized by [11],

$$S=\frac{T*n}{R}=\frac{\left(P_{succ}/S_{rate}\right)}{t} \quad (8)$$

T is the quantity of information in a packet and n is number of packets successfully transmitted in a unit interval. R is data rate to be transmitted. S is also defined as ratio of number of packets successfully transmitted to the total number of packet transmitted in a time interval t.P_{succ} is the total offered capacity, S_{rate} is the symbol rate.

The Average Delay Time can be calculated by [4,11],

$$Average\ Delay=\frac{\left(\frac{T_{delay}}{succ}\right)}{T_{slot}}=(T_{delay}/\text{succ}/T_{slot}) \quad (9)$$

$$T_{delay} = T_{delayy} + T_{cop} + T_{no}\,(N_s * T_{slot}) \quad (10)$$

T_{delay} is the total packet delay time. succ is the total number of successful packets (achieved capacity) and it equals to P_{succ} * packet length L_p.T_{slot} is the duration of a time slot. T_{no} is the notification period duration and T_{delayy} is the packet delay time from the previous frame. N_s is the number of busy slots.

The Packet Delivery Ratio can be defined as the ratio of the number of blocked packets (which equal to offered traffic minus throughput) to the offered traffic during the simulation duration.

5. Simulation Results

A. Simulation Setup:

The M2M network consists of one BS and K number of devices distributed around the BS following the uniform distribution in a certain area with a radius of r. Each device generates only one data packet based on Poisson distribution which is stored in its limited buffer. Hence, if a new packet arrives at a certain device which trying to successfully transmit the old packet, it buffered until that device finishes its transmission.Extensive MATLAB programs are done to simulate the performance of the proposed protocol. The system parameters are shown in Table-I [4,5]. In addition, comparisons of the proposed MAC protocol with contention based such as NP-CSMA, S-ALOHA, P-ALOHA were done. The effect of some parameters such as delay time, Packet Delivery Ratio and number of users will be investigated.

B. The system throughput

Figure 3 shows that the proposed hybrid MAC protocol achieves the highest throughput of 69.66 % compared with other contention protocols such as NP-CSMA [5], S-ALOHA [6], and P-ALOHA [11] in case of 500 devices. At the high values of λ above10 packet/sec/user, NP-CSMA, S-ALOHA and P-ALOHA reaches to 0.48, 0.33 and 0.077, respectively.The proposed protocol gives the maximum throughput value of 0.69 at the same value of λ. With growing number of the devices in the network, the proposed protocol reserve a time slot for each successfully contending device in COP duration to transmit its own data packet. If the collision occurs, a retransmission process using Poisson distribution will be occurred.

TABLE I: Simulation Parameters

Parameter Value	Parameter Name
T_{frame}=10msec	Duration of the frame.
T_{packet}=0.5msec	Duration of one data packet.
T_{cop} = 3msec	Duration of contention period.
T_{slot} = 0.5msec	Duration of one slot.
S_{rate}= 256kb/s	Symbol rate.
T_{No}=10 µsec	The length of notification period.
T_{ack} = 7 µsec	The length of the acknowledgement message.
T_{req} = 22µsec	The length of the request message
N_d =300,500,1000	Number of devices.

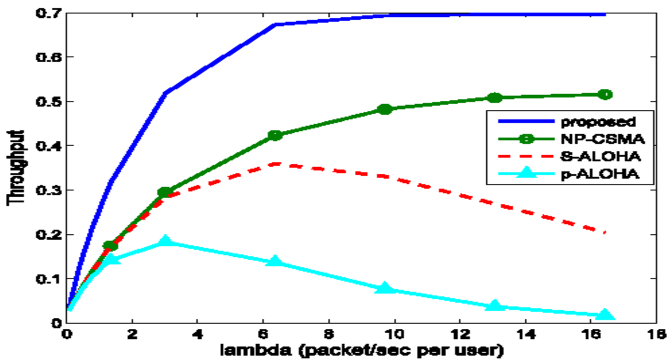

Figure.3: Throughput in terms of packet arrival rate λ when number of devices equal to 500

C. The system Average Delay Time:

Figure 4 approves that the proposed protocol gives the lowest average delay time in comparison with other contention MAC protocols such as NP-CSMA, S-ALOHA and P-ALOHA[5], [11] when the number of devices equal to 500 devices. The proposed protocol reserves a time slot for each successfully contending device to transmit its own packet in a defined time interval. It achieves a decreasing delay time curve which reached to 582 packets at λ= 6 packet/sec per user. NP-CSMA, S-ALOHA and P-ALOHA give higher delay time curves that reached to 671, 889 and 3142 packets, respectively at λ=6 packet/sec per user.

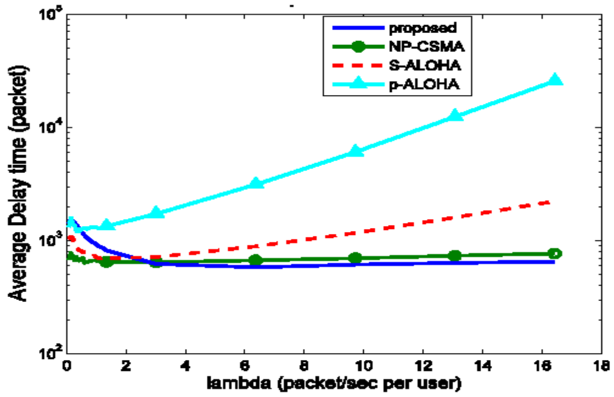

Figure.4: Average Delay time in terms of packet arrival rate λ in case of 500 devices

D. The system Packet Delivery Ratio:

Figure 5 shows that the proposed protocol achieves the lowest packet delivery ratio especially at high values of λ in comparison with the other contention MAC protocols such as NP-CSMA [5], S-ALOHA and P-ALOHA in case of 500 devices. However increasing number of devices that contend for transmission opportunities each with one data packet in its buffer shows that the proposed protocol preserves lower Packet Ratio with a maximum value of 0.82 than the other three contention MAC protocols. With increasing number of devices in the network to 500, NP-CSMA maximum Packet Ratio is high at 0.88, for S-ALOHA and P-ALOHA have high maximum Packet Ratio due to collision and no reservation technique found that reaches to 0.9114 and 0.9929, respectively at λ = 16 packet/sec/user.

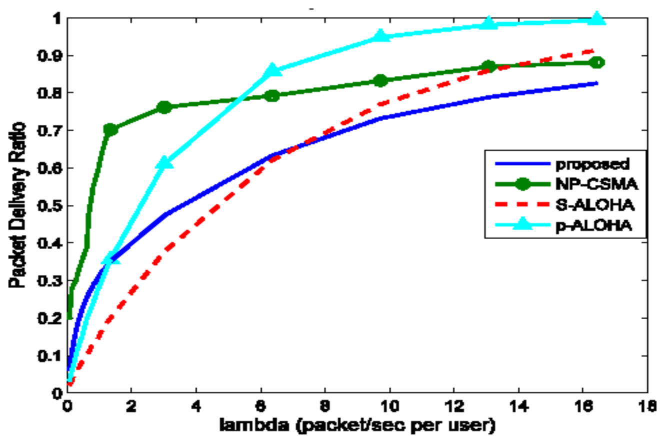

Figure.5: Packet Delivery Ratio in terms of lambda λ in case of 500 devices

E. The Effect of Varying Number of Devices:

Figure 6 presents three different throughput curves which are common in achieving the same maximum throughput at the highest value of λ in three different cases (when number of devices equal to 1000, 500 and 300). Although increasing number of devices in the network to 1000, the proposed protocol gives the same maximum throughputof 0.699 at the high values of λ above 10 packet/sec/user. The proposed protocol is designed to accommodate a large number of devices each with one data packet in its buffer by reserving a time slot for each successfully contending device. At a certain value of λ = 6 packet/sec per user, the proposed protocol gives three different throughput values of 0.69, 0.67 and 0.57 in the case of 1000, 500 and 300 devices, respectively.

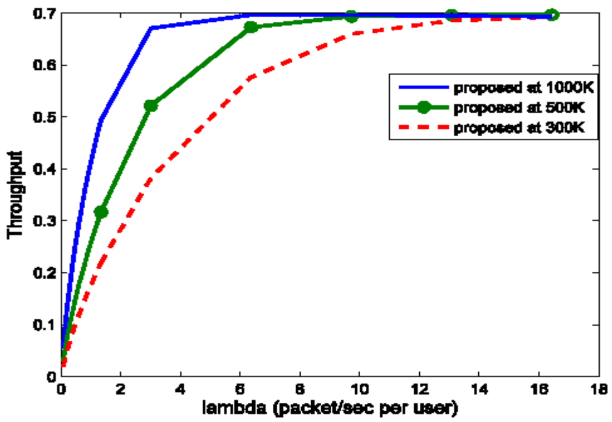

Figure.6: throughput in terms of packet arrival rate λ in case of different number of devices (1000, 500 and 300)

Figure 7 shows the variation of the average delay time in terms of λ in the three different cases when the number of devices equal to 300, 500 and 1000 devices, respectively each with one data packet in its buffer. The proposed protocol achieves the lower delay time around 440 packets in the case of 300 devices than with two 500 and 1000 devices cases. It achieves a delay time around 600 and 1200 packets for 500 and 1000 devices, respectively. With increasing number of devices each with a data packet in its buffer, more collision occur and more waiting time for the packets to be transmitted which results in large delay packets for large number of devices. At a certain value of λ = 12 packets/sec per user, the delay time reaches to 1220 packets in 1000 devices, 625 packets in 500 devices and 355 packets in 300 devices.

The proposed hybrid protocol achieves the lowest packet delivery ratio with a maximum value of 0.72 for the minimum number of devices in 300 devices as shown in Fig.8. The maximum packet delivery ratio values for 500 and 1000 devices are 0.82 and 0.9, respectively. Increasing number of devices results in more collision and more packet ratio. At a defined value of λ = 13 packet/sec per user, the proposed protocol achieves 0.67, 0.87 and 0.88 packet ratio values for 300, 500 and 1000 devices, respectively

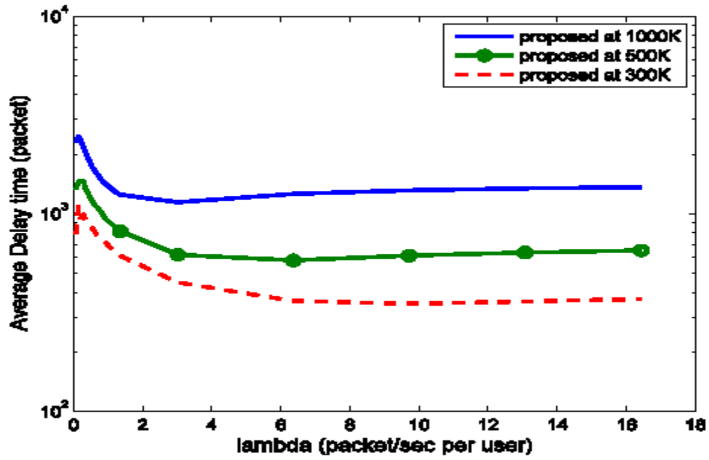

Figure.7: Average Delay Time in terms of lambda for different number of devices (1000, 500 and 300).

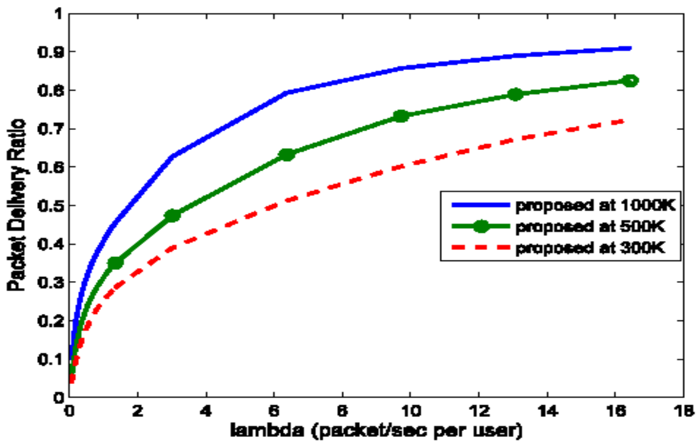

Figure .8: Packet Arrival Rate in terms of λ for different number of devices (1000, 500, and 300).

6. Conclusion

This paper introducesa proposed hybrid MAC protocol for M2M network with a large number of devices in which each one has only one data packet in its buffer. This protocol divides the time axis in to number of frames with the same length. Each frame composes of three main parts: Notification Period (NP), Contention Only Period (COP) and Transmission Only Period (TOP). The BS notifies all K devicesat the beginning of the frame during NP interval. Only the active devices transmit a contending requests during COP duration and send its own data packet in TOP duration. From the simulation results, the proposed protocol achieves the highest throughput, lower average delay time and lower packet delivery ratio in comparison with other contention MAC protocols. Also, the proposed hybrid protocol achieves the same maximum throughput at high value of λ with changing number of devices.

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البروتوكول الفعال المختلط مقترحا للتحكم في الدخول إلي الوسط لشبكات الآلة الي آلة

آلة الي آلة (M2M) هي التكنولوجيا التى تسمح للأجهزة ان ترتبط بأجهزة أخرى عن طريق النظم السلكية أو اللاسلكية بتدخل بسيط او بدون اي تدخل بشري. تستخدم شبكات M2M في العديد من التطبيقات. تحتوي شبكات M2M علي عدد كبير من الاجهزة التي ترتبط ببعضها البعض لذلك سيكون هناك محاولات كثيرة من هذه الأجهزة لارسال البيانات الخاصة بها الي المحطة الرئسية. لذا تحتاج شبكات M2Mإلي بروتوكول قوى مرن ذو كفاءة للتحكم في الدخول إلي الوسط بالإضافة إلي أنه يستهلك كميات قليلة من الطاقة و يحقق تأخير زمنى اقل.

هناك نوعين من البروتوكولات اللازمة للتحكم في الدخول إلي الوسط وهما بروتوكولات عشوائية و بروتوكولات منظمة. بالرغم من أن البروتوكولات العشوائية مثل NP-CSMA تتمتع بالعديد من المميزات مثل بساطتها وممرونتها وكفائتها في استخدام قناة الإتصال إلا أنه مع زيادة عدد الأجهزة الموجدة بالشبكة تزداد التصادمات مابين هذه الأجهزة عند ارسال المعلومات الى المحطة الرئيسية. اما البروتوكولات المنظمة مثل TDMA تمنع مثل هذه التصادمات وتحسن من آداء الشبكة مع زيادة الحمل بها عن طريق تقسيم زمن الارسال بحيث يسمح لكل جهاز بأن يقوم بارسال البيانات الخاصة به في وقت معين. لكن البرتوكولات المنظمة ينتج عنها تأخير زمني طويل.

يهدف هذا البحث لطرح بروتوكول جديد يدمج مابين نوعين من انواع هذه البروتوكولات وهما NP-CSMA من البروتوكولات العشوائية و TDMA من البروتوكولات المنظمة جامعا مميزاتهما ومهملا لعيوبهما....اذ يقوم الجهاز خلال وجود بيانات تحتاج الى ارسال بالتنافس مع اخرين للحصول ع القناة خلال فترة تسمى فترة التنافس فإذا نجح حجزت لة القناة في وقت معين خلال فترة الارسال. ان فشل هذا الجهاز نتيجة التصادم عاود المحاولة بعد وقت معين. ويقاس جودة هذا البروتوكول عن طريق حساب عدد البيانات التي تم ارسالها بنجاج الى العدد

الكلي للبيانات المرسلة. وايضا عن طريق حساب زمن التاخيراللازم لارسال البيانات.

تم عمل مقارنة ما بين آداء هذا البروتوكول وعدد من البروتوكولات العشوائية مثل NP-CSMA,S-ALOHA, P-ALOHA باستخدام برنامج الماتلاب التى أظهرت تحقيق البروتوكول المقترح لزيادة معدل نقل البيانات الشبكة وايضا أقل معدل للبيانات المفقودة واقل تاخير زمنى مقارنة بالبروتوكولات المذكورة.

ايضا تم توضيح تأثير زيادة عدد الأجهزة الموجودة بالشبكة باستخدام نفس البرنامج والتي اوضحت تحقيق البروتوكول المقترح لاعلي معدل لنقل البيانات واقل تأخير زمنى واقل معدل لاحتمالية فقد البيانات مع اقل عدد من الاجهزة الموجودة بالشبكة.