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# Design and Implementation of HomeTDMA: a TDMA Protocol for Home Networks

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## ABSTRACT

In this paper, we introduced our designed TDMA (Time Division Multiple Access) based MAC (Medium Access Control) protocol for Home Networks called HomeTDMA. We have implemented and tested it in a test bed using crossbow motes and TinyOS. We also have compared HomeTDMA and CSMA (Carrier Sense Multiple Access) in terms of space and time complexity, channel access time, delivery success ratio, and throughput. Based on our results, HomeTDMA has an advantage over CSMA on channel access time, throughput and delivery success ratio. In the case of complexity, HomeTDMA is more complex compared to CSMA. Thus, CSMA is more appropriate in wireless sensor networks (WSNs) where memory, energy, and throughput are important parameters to be considered. However, HomeTDMA has a natural advantage of collision free medium access and is very promising for home networks where a reliable transmission or data transfer and congestion control is highly preferred.

**Keywords**: CSMA, HomeTDMA, Home Networks, Wireless Sensor Networks.

## 1. INTRODUCTION

The significant interest in smart homes or home networks roots from the availability of low cost communication technology. Handheld devices with embedded technology and connectivity were already devised and these computing devices become progressively smaller and more powerful which makes home network environment pervasive. The home network environment allows us to control and monitor our appliances, actuators, and sensors in our home anywhere and any time we want.

Home networking [1] is defined as an interconnection of electronic products and systems enabling remote access and control of products and systems, with any available content such as music, video or data. A home network may consist of an Ethernet hub/switch, broadband modem for connection, a router connected between the broadband modem and the rest of the network, a PC or laptop, a wireless hub for connecting wireless devices, internet phones, and devices that are connected to the home network. These multiple devices would be accessed simultaneously hence, a medium access control protocol is needed [2].

In our study, we focused on media access protocols which influence the wireless connectivity of the network nodes. Lin Gu, had designed a TDMA-based MAC protocol named "PRIME" [3]. His latest implementation was in 2003 which is a simplified version of the PRIME protocol, called SPRIME. In his test on eight Mica2 motes sending at 1 packet/400ms, the packet delivery success rate is 95% which is 2.5 times higher than a CSMA-based MAC protocol. However, the only parameter they had tested is packet success ratio and their

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implementation is not already compatible with the current version of TinyOS and the hardware. As motivated by Lin Gu's work, we extended the study and determined the performances of TDMA and CSMA protocol through testbed implementation and evaluation using crossbow motes [4] and TinyOS 1.1.11 [5]. The purpose of our study is to test the feasibility of TDMA-based MAC protocol in Home Networks. Specifically, to be able to evaluate the HomeTDMA and CSMA protocol based on the following parameters: space and time complexity, success ratio and packet loss, channel access time and throughput.

## 2. RELATED LITERATURE

The MAC protocol regulates the usage of the medium through channel access mechanism. It specifies the rules by which a frame is transmitted onto the link; hence, the channel access mechanism is the core of the MAC protocol. The IEEE 802.11 MAC, a contention based medium access protocol, gained widespread popularity as a layer-2 protocol for wireless local area networks [6]. It has become ubiquitous and has been implemented in many wireless test beds and simulations. However, there are still inefficiencies in 802.11 MAC due to hidden and exposed nodes problems. MAC can become the bottleneck due to collisions and channel contention delays and these contentions greatly affect the performance of the high layer protocols. Hence, in order to provide a guarantee, it is necessary to characterize the delays and other performance metrics. According to [7], lack of comparison of TDMA, CSMA or other medium access protocols in a common framework, is a crucial deficiency of the literature.

There are many existing protocols that can be implemented in home networks. CSMA, CSMA with collision avoidance (CSMA/CA), TDMA, and hybrid protocols such as TDMA+CSMA are potential candidates. CSMA posed hidden and exposed node problems and though the RTS/CTS scheme mitigates the hidden node problem, CSMA could still degrade the network performance [2]. The TDMA based MAC protocol on the other hand, provides an upper-bound on access delay, where QoS is guaranteed. The hybrid protocol which is TDMA+CSMA also provides QoS capabilities; however, network efficiency and beacon generation between TDMA slots and CSMA/CA slots remain unsolved [2].

In TDMA, the time on the channel is divided into time frames which are further divided into time slots that are generally of fixed size. Slots are usually organized in a frame, which are repeated on a regular basis. TDMA is perfectly fair and helps eliminate collisions, since each node in the network is allocated a certain number of slots when it could transmit. [8]. However, according to [9], TDMA protocol has two major drawbacks. First, a node is limited to an average rate even when it is the only node with packets to send. Second, a node must always wait for its turn in the transmission sequence, even when it is the only node with a frame to send. In addition, it is not easy to change the slot assignment within the decentralized environment for traditional TDMA, since all nodes must agree on the slot assignments [7].

CSMA is a contention-based MAC protocol while TDMA is a contention-free MAC protocol. Contention causes message collisions which are very likely to occur when traffic is frequent and correlated. On the other hand, a MAC protocol which is contention-free would not allow any collisions. In TDMA, the time on the channel is divided into time frames which are further divided into time slots that are generally of fixed size. Slots are usually organized in a frame, which is repeated on a regular basis. CSMA introduces hidden node and exposed node problems which could degrade network's performance. CSMA protocol is prone to collisions and packet data loss. It introduces hidden node and exposed node problems which could degrade network's performance

The CSMA protocol has some serious drawbacks for wireless communication too. CSMA is a random access protocol where a transmitting node always transmits at the full rate. When collision occurs, each node involved in the collision just repeatedly retransmits its frame until the frame gets through without a collision. However, when a node experiences collision, it doesn't necessarily retransmit the frame right away; instead, it waits a random delay before retransmitting the frame. Each node involved in the collision chooses independent random delays and it is possible that one of the nodes will choose a delay that is sufficiently less than the delays of the other colliding nodes. In this way, the node will be able to sneak its frame into the channel without a collision. Though all nodes perform carrier sensing, collisions may still occur [1]. These back-offs and retransmissions may also increase latency and battery power loss.

## 3. DESIGN AND IMPLEMENTATION OF HomeTDMA

### 3.1 Motivation

A MAC protocol specifies how nodes share the channel and hence, plays a central role in the performance of a wireless network. There are different kinds of MAC Protocols found in the literature: contention-based and contention-free MAC protocols. CSMA is widely known contention-based MAC protocol and one of the earliest mechanisms adopted for ad hoc networks. However, CSMA introduces hidden node and exposed node problems which could degrade network's performance. Contention also causes message collisions which are very likely to occur when traffic is frequent and correlated. On the other hand, a MAC protocol which is contention-free would not allow any collisions; hence, we studied a contention-free MAC protocol such as TDMA for its characteristics are very promising for home networking applications.

The breakthrough of digital signal processing and VLSI technology enabled the possibility of TDMA use in wireless networks. In TDMA, each user can access the full bandwidth of the channel bandwidth. Unlike other techniques, TDMA ensures that users on the same frequency band would not experience interference from other simultaneous transmissions which results to an increase in efficiency of TDMA. According to [10], TDMA is the multiple access scheme highly suited for digital transmission. It offers a number of advantages to others since it can be easily adapted to the transmission of data as well as voice communication. There are already TDMA-based radio systems being developed and one of the examples is the European GSM system (Global System for Mobile communication). According to [11], TDMA has an ability to carry data rates of 64kbps to 120 kbps which enables personal communication-like services including fax, voiceband data, short messages services (SMSs) as well as bandwidth-intensive applications such as multimedia and videoconferencing. Hence, we proposed a Home-TDMA MAC protocol for home networks, suggesting that TDMA is suitable in a Home Network environment.

### 3.2 Mathematical Framework

We have adopted a timed-token protocol belonging to a type of token-passing protocol in which each station receives a guaranteed share of the network bandwidth. Each could access the channel for a fraction of the time on a periodic and in an orderly basis. We based our network model to the framework proposed in [12]. We discussed it here in our paper for more information and clarity. If there are $n$ streams of synchronous data, $S_1,..,S_n$, with stream $S_i$ originating at node $i$, each synchronous-message stream $S_i$ can be characterized as $S_i=(C_i, P_i, D_i)$, where $C_i$ is the maximum amount of time required to transmit a message in a stream which includes the time to transmit both the payload data and the message headers. $P_i$ is the interarrival period between the messages in the stream and $D_i$ is the relative deadline of messages in the stream which is the maximum amount of time that can elapse between a message arrival and completion of its transmission. The first message in stream $S_i$ arrives at node $i$ at time $t_{i,1}$ while the $j$th message in stream $S_i$ will arrive at node $i$ at time $t_{i,j}=t_{i,1}+(j-1)P_i$ where $j \geq 1$.

Each node is assigned a portion of Target Token Rotation Time (TTRT) or the expected token rotation time. This portion of TTRT is known as synchronous bandwidth ($H_i$) which is the maximum time a node is permitted to transmit synchronous messages, every time it receives a token. However, the period of transmitting synchronous message should not be longer than its allocated bandwidth as given by the equation below

$$\sum_{i=1}^{n} H_i \leq TTRT - \tau \qquad (1)$$

where $\tau$ is the token walk time around the network. This equation is commonly called as the protocol constraint. The deadline constraint on the other hand, states that the message must be transmitted before its deadline. If $s_{i,j}$ is the time that the message in stream $S_i$ is completed, $t_{i,j}$ is the arrival time and $D_i$ is the relative deadline, the deadline constraint requires that for $i=1,\cdots,n$ and $j=1,2,\cdots$ the following equation must be satisfied

$$S_{i,j} \leq t_{i,j} + D_i \qquad (2)$$

However the maximum amount of time that may pass between two consecutive token arrivals at a node can approach 2TTRT. Therefore, the satisfaction deadline constraint requires that for $i=1,..,n$

$$D_i \geq 2TTRT \qquad (3)$$

We also have considered the buffer constraint which states that the size of the buffers at each node must be sufficient to hold the maximum number of outgoing or incoming synchronous message that can be queued at the node. These constraints namely protocol constraint, deadline constraint and buffer constraint from [12] were considered in our design of HomeTDMA.

### 3.3 HomeTDMA Packet Format

A HomeTDMA frame is similar to Fig. 1. The bandwidth is shared by all nodes by dividing each logical channel into time slots and further combining $J$ of these slots into one frame. In every frame, every node has access to one dedicated time slot in which it can send and/or receive data on the entire bandwidth of this channel. This in turn makes it possible for the sending node to transmit its data at the highest data rate as the bandwidth of the current medium. In HomeTDMA, an active node performs two general actions in its timeslot as shown in Fig. 2. The slot scheduler and the packet transmission will be discussed in the next section.

### 3.4 HomeTDMA Functions

Generally, a node's schedule captures a window of traffic to be transmitted by the node. This information is periodically broadcast to the node's one-hop neighbors during scheduled access. The node then pre-computes the number of slots in the interval for which it has the highest priority among its two-hop neighbors. Because these are the slots for which the node will be selected as the transmitter, the node announces the intended receivers

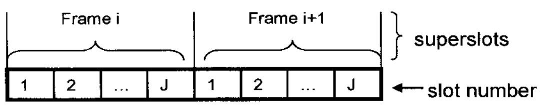



Fig. 1. HomeTDMA Frame.

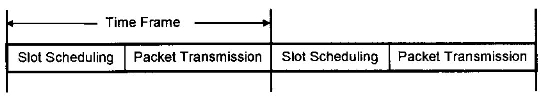



Fig. 2. A timeslot consists of two sections 1. Slot Scheduling 2. Packet Transmission.

for these slots [13]. Alternatively, if a node does not have enough packets to transmit, it announces that it gives up the corresponding slot(s).

The macros for the iterating sequence and for the slot management are defined in the program. The usage of superslots is being coordinated with another node. If a node has some packets to send, it should send a message to the other node first to tell that it will use the superslots in a period of time. The effective slot timer fires at the beginning of effective slots and restarts after the clock is synchronized. When there is a conflict in the slot assignment, the node with higher MAC address changes it schedule. The nodes have an order of priority and classified into three: a shouter who sends packets with strongest signal, a whisperer which is the weakest neighbor, and a listener.

On the other hand, the slot scheduler and transmission of packets is composed of three main functions as illustrated in Fig. 3. The slot scheduler has a priority in calling these functions for packet transmission. 1. Detect Interference 2. Invite Interference, and 3. SyncControl.

• *Detect Interference*: Nodes are scheduled to whisper/shout at the DETECT_INTERFERENCE_SLOT of the super slots. For a short period of time, it listens for incoming requests from passive nodes. After that, it transmits a control message at the INVITE_INTERFERENCE_SLOT which contains the possible reply to the invitation or communication request, together with other control and synchronization information such as slot schedule. By listening to the neighboring nodes, a node may have knowledge of their local neighborhood and through this, they can select an appropriate time slots.

• *Invite Interference*: It is in the INVITE_INTERFERENCE_SLOT where invitations or communication requests take place. If an invitation is made for the node, the node should be scheduled to shout and send a reply to the inviter. The invitation reply is sent to the inviter and upon

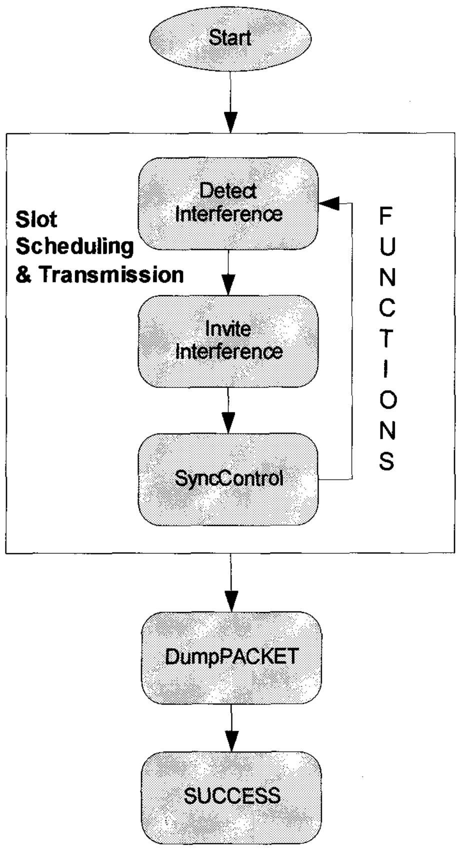



Fig. 3. HomeTDMA Block Diagram.

receiving a reply, the inviter needs to check whether interference has occurred in the shouting slot. Usually, nodes are competing for transmission in this said slot. Competing packets described by the head event are sent at the beginning of effective slots where the effective slot timer has fired. The active node will stop sending when it is already out of retry number. However, if there is still enough time, another transmission could take place. The listener node on the other hand, would leave the event, and abandon sending i.e. it could not transmit.

• *SyncControl*: A SyncPacket is being sent on the SYNC_SLOT to coordinate the usage of superslots among the nodes. It is the one in charge on the clock synchronization. It monitors the iteration sequence i.e. after all slots on the frame have been used in transmitting the packets, the effective slot timer will restart and the next iteration will take place.

## 4. IMPLEMENTATION OF HomeTDMA

The block diagram of ChirpHomeTDMA is shown in Fig. 4. It is an application that periodically sends a broadcast packet over the radio using a timer and uses the HomeTDMA, a collision-free MAC protocol which automatically detects interfering nodes in a network and uses TDMA to coordinate network transmission, so as to avoid collision.

The communication flow for the Chirp application that uses HomeTDMA is shown in Fig. 5. Basically, an application code is composed of module and configuration files. The module provides the application code which uses one or more interfaces while the configuration file assembles other components together and connects interfaces used by components to interfaces provided by others.

The GenericCommTDMA provides the SendMsg and ReceiveMsg which are basic interfaces for sending and receiving messages i.e. connects to both the Radio and the UART. It is the configuration file that uses HomeTDMA, the TDMA MAC protocol. HomeTDMA is a stand alone file which can replace the AMStandard. Each active message contains the name of a user-level handler to be invoked on a target node upon arrival and a data payload being passed as arguments.

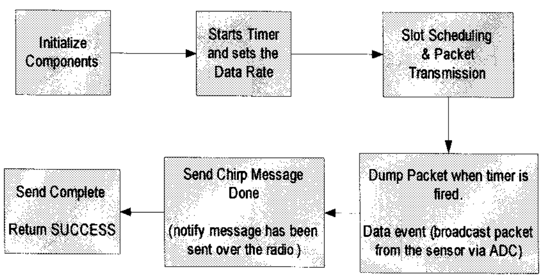



Fig. 4. The ChirpHomeTDMA Application.

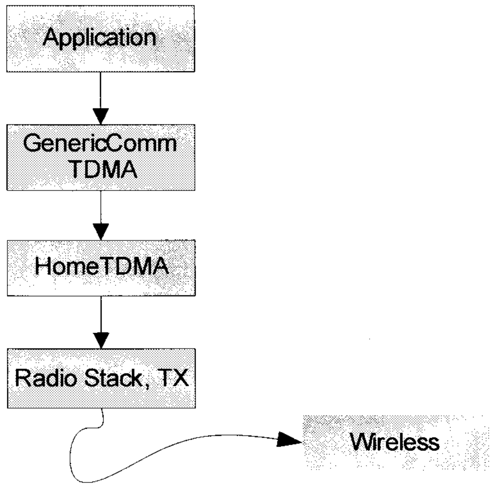



Fig. 5. Components and Interfaces for HomeTDMA.

The test system (Fig. 6) consists of a Window XP PC and crossbow [4] motes (Fig. 7), which consists of MIB600 and MIB510 as programming boards and Mica2 as network mote. The Mica2 mote is the communication module which utilizes a powerful Atmega128L micro-controller and a frequency tunable radio with extended range.

We arranged the remote motes 1.5 meters apart as illustrated in the actual test bed in Fig. 8. The default configuration is a 8-mote network where we assigned ID (0~7) to the remote motes, and mote 0 to the base mote. The ChirpHomeTDMA application is uploaded to Mica2 motes attached to MIB600, where MIB600 is connected to a switch via straight cable which is further connected to the

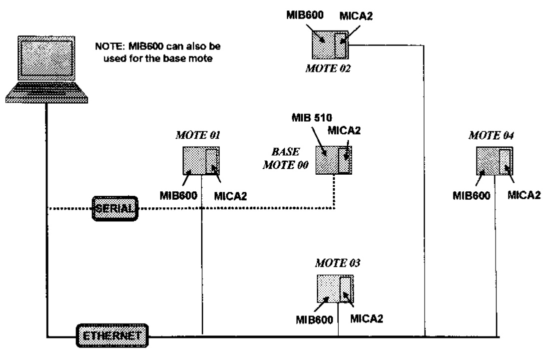
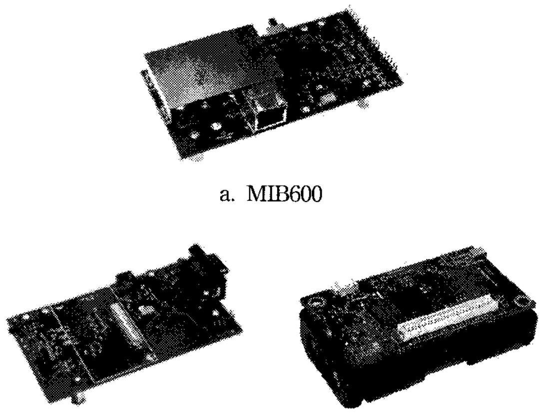



Fig. 6. Testbed Environment.



a. MIB600

b. MIB510 c. Mica2

Fig. 7. Crossbow Motes.

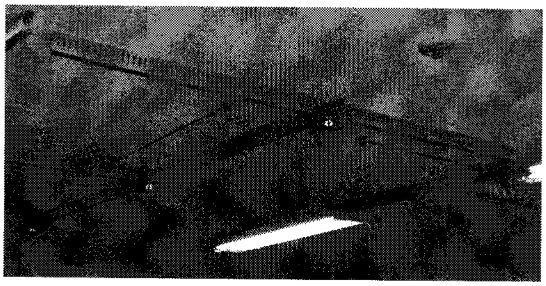


Fig. 8. Actual Testbed.

PC via cross cable. The MIB600 provides Ethernet (10/100 Base-T) connectivity to Mica2 family motes for communication and in-system programming. These attributes are very promising for home networks where MIB600 could serve as a gateway and at the same time, programming board of the sensors/devices in the home. We defined that the ChirpHomeTDMA application should transmit a maximum of 160 packets at a rate of 1 packet/400ms. We also set the CHIRP.CSMA application (uses CSMA MAC protocol) to transmit a maximum of 160 packets but at a rate of 1 packet/45ms.

The Mica2 mote programmed with TOSBase while being attached to MIB510 programmer acts as the base mote in our set-up. The MIB510 interface board is a multi-purpose interface board which provides an interface for a RS-232 mote serial port and reprogramming port. TOSBase is an application that acts as a simple bridge between the serial and radio links which filter out incoming radio messages that do not contain the same group ID and dumps received packets to UART which is captured by the "*Listen*" java program. Hence, TOSBase listens to the packets being transmitted among the motes while running the Chirp application. Data were obtained and displayed using listen java tool (e.g. xlisten), serial forwarder and time stamp function in Java. The packets sent by motes follow the TOS Message (TOS_Msg) format. The TinyOS data packet has a maximum length of 255 bytes and it is wrapped on both ends by a frame synchronization byte of 0x7E which is used to detect the start and of a packet from the stream. The format of the packet follows the AM standard given by Table 1.

Table 1. The TOS message format

| Bytes | Description |
|---|---|
| 0-1 | The UART serial address |
| 2 | The message type |
| 3 | Group ID |
| 4 | Data length |
| 5-6 | The address of the last forwarding node |
| 7-8 | The origin address |
| 9-10 | The sequence number |
| 11 | The hop count |
| 12 | Surge message type |
| 13-14 | Reading-not used |
| 15-16 | Parent Node address |
| 17-20 | Battery Voltage, surge sequence number |
| 21 | Raw light value |
| 22 | Raw temp value |
| 23 | Raw mag x value |
| 24 | Raw mag y value |
| 25 | Raw accel x value |
| 26 | Raw accel y value |
| 27-28 | CRC |

## 5. RESULTS AND DISCUSSION

We have compared the CSMA and HomeTDMA protocol based on the following parameters:

• *Time and Space Complexity*

Space complexity is the amount of memory needed by a program to run to completion while time complexity is the amount of computer time needed by a program to run to completion or simply a sum of compilation time and its run (or execution) time. In Fig. 3, the HomeTDMA has 3 more functions than traditional CSMA. Hence, in terms of time and space complexity, HomeTDMA is more complex compared with CSMA protocol.

• *Packet delivery ratio*

Every node knows how many packets it has received and these numbers are sent to UART or piggybacked in the wireless packets. Since we have set the maximum packets sent by the program, the packet delivery ratio or success ratio can be computed as

$$\text{Packet delivery ratio}(\%) = \frac{\text{number of packets received}}{\text{number of packets sent}} \times 100$$

Here we adopt the definition of packet loss as the number of packets dropped due to network congestion or buffer overflow. In our experiment, we performed three trials to test each parameter. We find that the packet delivery ratio of a 8-mote network in CSMA is 31.6%, and is lower compared to the success ratio of 97.12% in HomeTDMA protocol (Fig. 9). Since only one message can be on air at anytime, the motes are competing for the airtime. In CSMA, more motes are contending to each other that congestion had occurred and some packets were dropped. Thus, in CSMA, the packet loss increases as the number of nodes increases i.e. more packets are dropped due to congestion. On the other hand, success ratio is higher in HomeTDMA and only few packets are lost during transmission even in a 8-mote network.

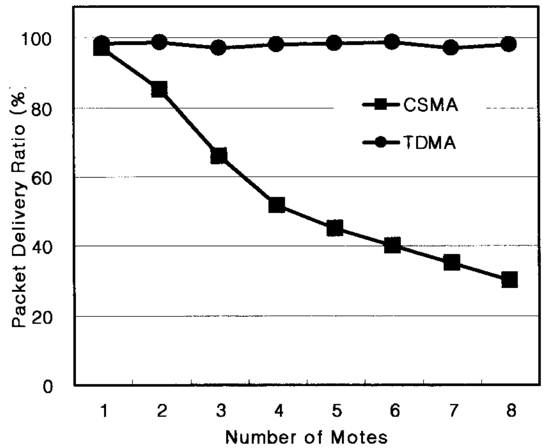



Fig. 9. Packet Delivery Ratio.

• *Throughput*

In communication networks, throughput is the amount of data per time unit that is delivered to a certain terminal in a network, from a network node or from one node to another, via a communication link. Usually, throughput is measured in bits per second, bytes per second or packets per second. The system throughput or aggregate throughput is the sum of the data rates that are delivered to all terminals in a network.

We obtained the aggregate throughput of a 1-mote network to a 8-mote network and plotted it as shown in Fig. 10. CSMA had yielded a higher throughput compared to HomeTDMA to 6 motes.

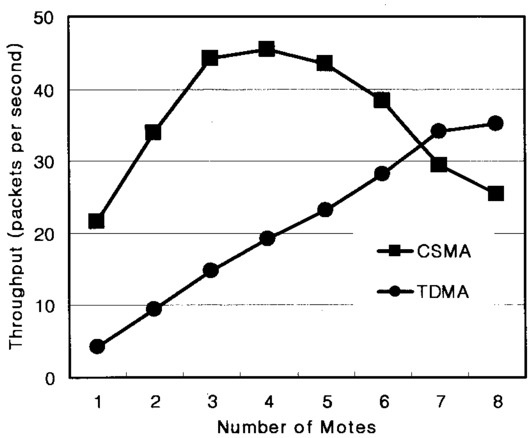



Fig. 10. Aggregate Throughput.

It is because the HomeTDMA throughput at low traffic loads is worse due to idle slots and limited average rate of the nodes. Even if it is the only node which has packets to send, it must wait for its own schedule before transmitting. However, CSMA throughput at high traffic loads gets worse due to backoff delay caused by collision.

• *Channel access delay*

The channel access delay is the total time it would take for a contending node before its contention in a channel is successful. The channel access delay is a very important performance metric especially for real-time services. In CSMA, the waiting time or the time a mote can access the channel increases as the number of motes increases in the network. Unlike CSMA, HomeTDMA has allotted a time frame for each mote's transmission where all nodes have equal time to access the channel (Fig. 11).

Based on our experiment, as the number of loads increases in a CSMA-based MAC protocol (Fig. 11), the channel access time of each node increases, though throughput still increases. However, the packet delivery ratio decreases because of collisions due to network congestion.

In HomeTDMA on the other hand, the channel access time of each node almost stays equal, hence

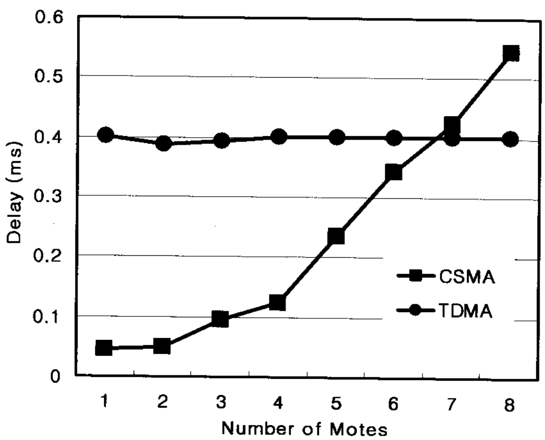



Fig. 11. Average Channel Access Delay.

fairness is guaranteed. Thus, HomeTDMA provides reliable transmission even in addition of other nodes. Besides, the aggregate throughput and the delivery success ratio are better than CSMA at high traffic load.

## 6. CONCLUSION

We have successfully designed and implemented a TDMA based MAC protocol we called HomeTDMA. It may be difficult for HomeTDMA systems to synchronize the nodes and to adapt to topology changes due to insertion of new nodes or broken links; however, HomeTDMA has a natural advantage of collision free medium access. On the other hand, CSMA has a promising throughput potential at lower traffic loads. However, the performance of CSMA may degrade as the number of motes increases which may be due to collisions. Sensor nodes often come with very limited battery and system resources, hence frequent time synchronization itself can be a burden to these nodes. Since memory, energy, and throughput are more important parameters in wireless sensor networks, CSMA is still better and practical to use. However, in home networks where reliability of transmission is more important, TDMA-based MAC protocol is more appropriate. HomeTDMA may suit very well on phone applications since these applications have very predictable needs i.e. fixed and identical bit rate. HomeTDMA is also very good to achieve low latency and guarantee of bandwidth where CSMA/CA is quite bad. Most of all, HomeTDMA provides reliable data transfer and congestion control. Hence, our proposed HomeTDMA is very promising MAC protocol for home networks.

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