Multiple service class TDMA protocol for healthcare applications

Abstract—**A novel medium access control (MAC) protocol designed for healthcare environments is proposed. The protocol is aimed to support different Classes of Service (CoS) with diverse needs, each including different kinds of medical applications. The highest priority class includes Tactile Internet applications, that require an end-to-end latency of less than 1 msec, while the rest of the classes are assigned graded priorities.The proposed protocol provides the highest priority class with the required bandwidth and guaranteed low delay while the other classes, which also include critical applications, do not starve. Two protocol versions are introduced with the second version exhibiting very good performance in terms of average delay and throughput.**

Index terms - Classes of service, healthcare applications, Tactile Internet, time division multiple access

Table I
HEALTHCARE ENVIRONMENT COS AND THEIR QOS REQUIREMENTS

CoS	Medical Application	Delay	Packet loss rate
A	Tactile Internet Medical (TIM)	< 1 msec	$< 10^{-5}$
B	Medical equipment remote control (MERC)	< 3 sec	~0
C	Real time critical health care (RTCH)	< 300 msec	$\sim 10^{-6}$
D	Real time non critical health care (RTNH)	<10 msec	$< 10^{-4}$
E	Office medical IT (OMIT)	< 1 sec	$< 10^{-2}$

I. INTRODUCTION

In the recent years many medical applications have been developed and are increasingly used in healthcare environments, such as hospitals and clinics. Most of these applications involve data transmission and thus rely on appropriate networks that are capable of serving their communication needs. However, healthcare applications vary and have different Quality of Service (QoS) necessities. Therefore, to serve their individual needs in a better way it is important to classify network traffic into CoS with different QoS requirements.

On the other hand, TDMA protocol has been extensively studied ([1], [2], [3], [4], [5]), as a simple and utterly collision-free method of coordinating multiple access to the same medium. Numerous variations of TDMA have been developed for different kinds of networks, such as vehicular ([6], [7]), wireless ad hoc [8], wireless multi-hop [9] and Passive Optical Network standards (Gigabit PON [10] - Ethernet PON [11]). The support of multiple CoS in TDMA-based protocols has been studied in [12], [13], [14] and [15]. In [12] the call admission region for a TDMA system supporting applications with different QoS requirements is determined, where QoS is defined by the maximum tolerable packet delay and dropping probability. Also, in [13] the Erlang capacity of a TDMA system which employs adaptive modulation and coding is evaluated. In [14] and [15] the achievable QoS is determined for a TDMA system serving competing applications.

In [16] five CoS are proposed that include all traffic in a medical facility. In Table I the five classes appear according to their priority. Also, their requirements in delay and packet loss are shown. The most demanding class is Tactile Intenet Medical which includes Tactile Internet applications, such as tele-diagnosis, tele-surgery and tele-rehabilitation. These applications require delay to be lower that 1 msec or else a "cyber sickness" phenomenon, similar to motion sickness, is experienced. Applications included in MERC class involve transmission of instructions to medical devices such as infusion pumps, which control drug infusion to patients. Monitoring of patients' physiological functions, such as blood pressure and heart rate, is included in RTCH applications. Traffic class RTNH involves real time medical image transfer, teleconference for medical issues and VoIP. Finally, OMIT applications have the lowest QoS requirements, since they are office applications such as email, web browsing and file transfer of patient records.

In this paper a distributed random TDMA protocol for healthcare environments is introduced, called Medical-Class TDMA (MC-TDMA), that is specifically designed to support the five CoS depicted in Table I. MC-TDMA protocol provides TIM class with guaranteed low delay, while also meeting the other classes' needs. This is achieved by dividing the TDMA frame in two phases. During the first phase only packets of TI class are transmitted, while during the second phase packets of the rest of the CoS are sent. Each of the non-TI classes is assigned a different probability of transmission according to the hierarchy appearing in Table I. Two versions of this protocol have been developed, the simple MC-TDMA and the Highest available class MC-TDMA (HMC-TDMA), with the second version improving throughput significantly by minimizing idle slots. The operation of the two protocols was simulated and delay of TI class was found to be very low and far within bounds in both versions. Non-TI classes' delay is also within restrictions, however, HMC-TDMA protocol induces less delay than MC-TDMA. Additionally, the two versions' throughput results differ remarkably, with HMC-TDMA protocol performing a lot better.

The paper is organized as follows. In Section II the two versions of MC-TDMA protocol are described. In Section III the two proposed protocols as well as RTDMA are compared in terms of average delay and throughput via simulation results. Finally, Section IV concludes the paper.

II. THE MC-TDMA PROTOCOL

The system model is a wireless network with one base station and N stations, which could be the end users of a healthcare facility such as hospital staff and medical devices. The nodes are able to transmit and receive packets of any service category from the base station. The network control is distributed and time is divided in timeslots.

The protocol operation is based on Random Time Division Multiple Access protocol (RTDMA, [17]). According to that protocol, timeslots are grouped into frames. During every timeslot a station is randomly selected to transmit a packet.

A. MC-TDMA

Next, the simple version of the MC-TDMA protocol is described. According to this protocol, each frame is divided in two phases, each consisting of N timeslots. Phase 1, which includes the first N timeslots of a frame, is dedicated to transmission of category A traffic (Table I). During timeslot i the next category A packet in queue of station i is transmitted. If station i does not have a category A packet in its queue then no transmission takes place and this slot remains idle.

During Phase 2, which consists of the next N timeslots of a frame, categories B, C, D and E are served. During each timeslot two random selections are made. The first selection concerns the category to be served and the second concerns the station that receives permission to transmit. The service category selection is random but different categories are assigned different probabilities of selection. These probabilities are chosen according to each category's needs. Specifically, probability of selection must be higher for higher priority categories. Next, the station that receives the right to transmit is randomly chosen. All stations have equal probability of selection. The selected station transmits the next packet of the selected category in its queue. If a packet of this category does not exist in the selected station's queue, then no transmission takes place and this slot remains idle.

B. Highest available class MC-TDMA

This version of MC-TDMA protocol differs from the simple MC-TDMA in the following points.

- During Phase 1, if station i does not have a category A packet in its queue, then it transmits a packet of the next higher category available. The category hierarchy is depicted in Table I.
- During Phase 2, if a packet of the selected category does not exist in the selected station's queue, then a packet of the next higher available category in the queue is sent. The priority of the categories is again as depicted in Table I, with the difference that, at this phase, packets of category A have the lowest priority.

Therefore, in both phases the only case in which a slot remains idle is when the queue of the selected station is empty.

III. SIMULATION RESULTS

In the following, Highest available class MC-TDMA protocol is compared to simple MC-TDMA protocol and to RTDMA in terms of average delay and throughput. Simulations

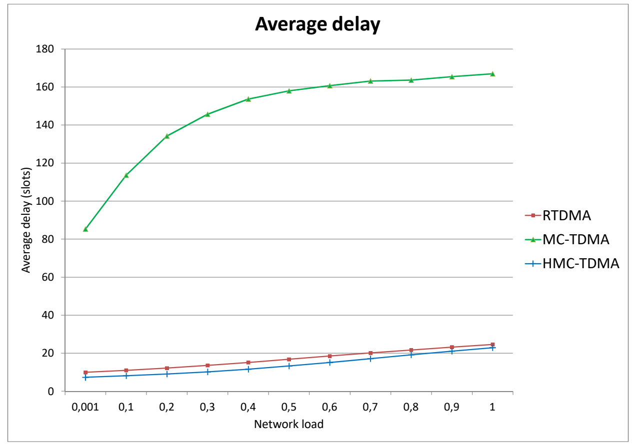

Figure 1. Average delay of protocols RTDMA, MC-TDMA and HMC-TDMA in slots versus network load

Figure 2. Average delay of CoS A with protocols MC-TDMA and HMC-TDMA in slots versus network load

have also been made for each service category separetely, for $N = 10$ stations and network load 0.1 to 1. All stations have equal probability of a packet arriving at them. Also, each arriving packet has equal probability to belong to any of the five CoS. During transmission Phase 2, classes B, C, D, and E have probabilities 0.4, 0.3, 0.2 and 0.1 respectively of being selected for transmission of a packet.

In Figure 1 it is seen that the average delay of the system is much higher in simple MC-TDMA protocol than in RTDMA and HMC-TDMA, with the latter having slightly better results than RTDMA. The maximum average delay of HMC-TDMA protocol is 21 slots for network load 1. Assuming a network throughput of 500 Mbps and packet size of 2000 bits, the slot size would be 4μsec and HMC-TDMA protocol's average delay would be at most 84μsec. In Figures 2- 6 the average delay of classes A to E are plotted to network load. Delay of class A is very low (< 13 slots) in both protocols. Again, assuming the same slot size, class A delay would be 52μsec at maximum network load, which is far lower than the bound of 1 msec.

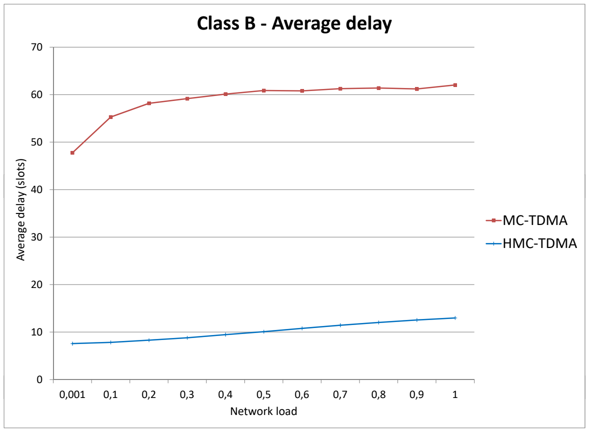

Figure 3. Average delay of CoS B with protocols MC-TDMA and HMC-TDMA in slots versus network load

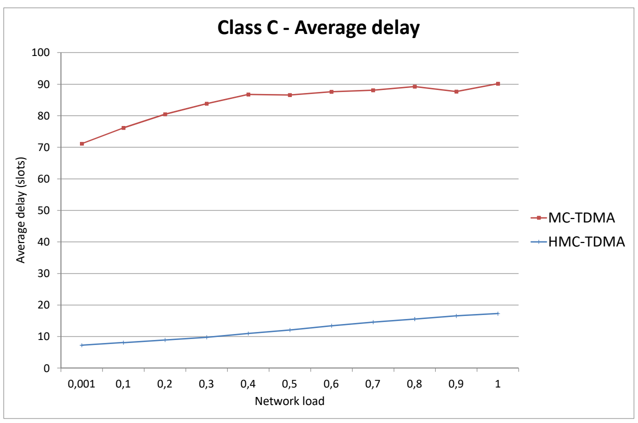

Figure 4. Average delay of CoS C with protocols MC-TDMA and HMC-TDMA in slots versus network load

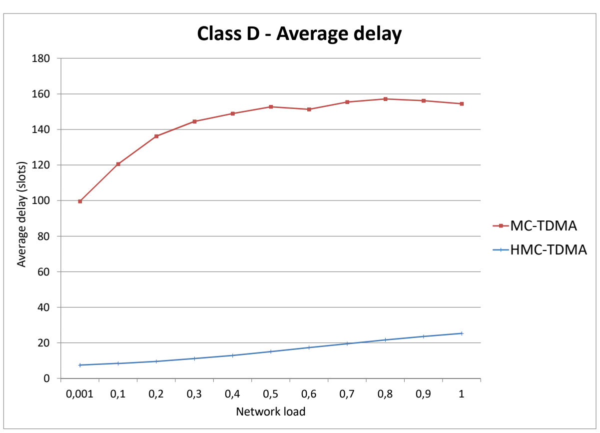

Figure 5. Average delay of CoS D with protocols MC-TDMA and HMC-TDMA in slots versus network load

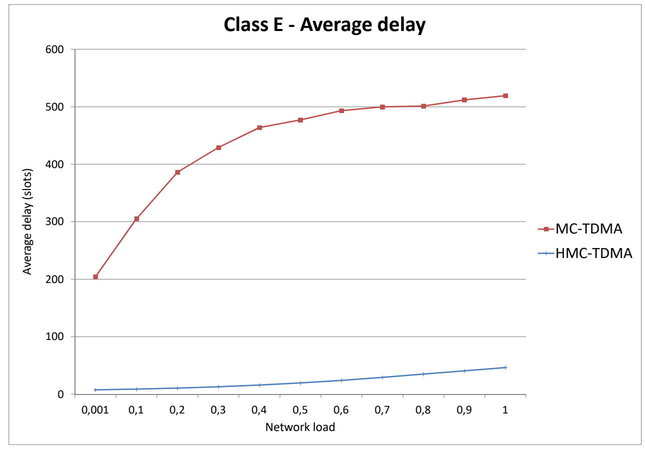

Figure 6. Average delay of CoS E with protocols MC-TDMA and HMC-TDMA in slots versus network load

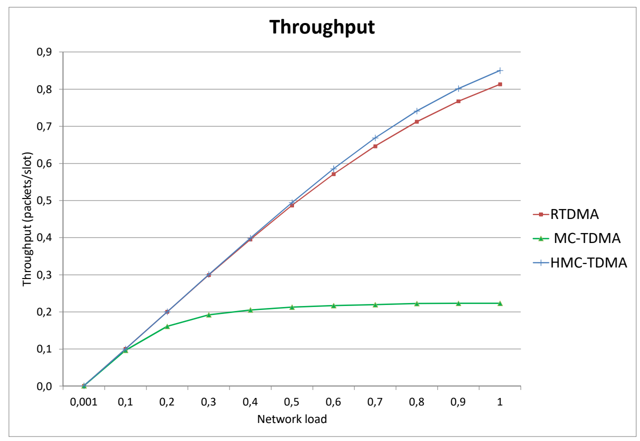

Figure 7. Throughput of protocols RTDMA, MC-TDMA and HMC-TDMA in packets/slot versus network load

For classes B, C, D and E it is seen in Figures 3 to 6 that HMC-TDMA protocol leads to a significantly lower delay than MC-TDMA. The maximum delay with noted for these CoS with HMC protocol is 47 slots for class E under network load 1, which is approximately 0.2 msec for slot size 4μsec. However both protocols are within bounds of TableI.

In Figure 7 it is seen that throughput of HMC-TDMA protocol is slightly higher than that of RTDMA and reaches 0.85 packets/slot under network load 1. The throughput of MC-TDMA under the same conditions is much lower at 0.22 packets/slot.

In figure 8 throughput of each CoS is appeared for HMC-TDMA and simple MC-TDMA protocols. All CoS have almost identical throughput performances, while performance for HMC-TDMA protocol is a lot higher that that of simple MC protocol. Here, the system throughput appearing in Figure 7 is basically divided equally in five parts. This derives from the fact that, in all simulations, every packet arriving at a station has equal probability of belonging to any of the five classes.

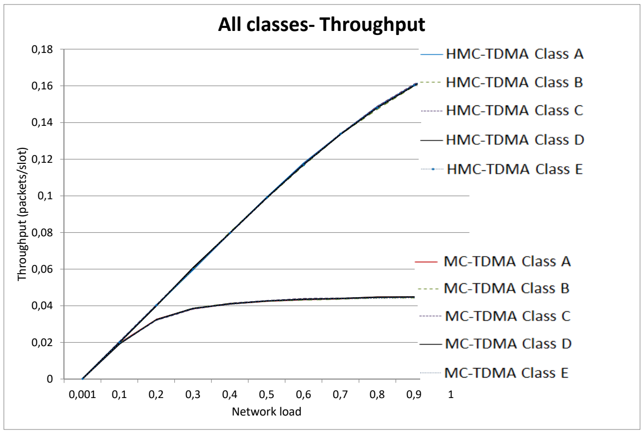

Figure 8. Throughput of all CoS with protocols MC-TDMA and HMC-TDMA in packets/slot versus network load

IV. CONCLUSIONS

In this paper MC-TDMA protocol, based on random TDMA, that is designed for healthcare applications is proposed. This distributed protocol manages to meet the TI class's high requirements while not neglecting the other CoS. This is achieved by dividing the TDMA frame in two phases, with the first phase serving only TI class and the second phase serving the rest of the classes. Two versions of this protocol are introduced, with HMC-TDMA performing significantly better than MC-TDMA in both delay and throughput aspects. Protocol HMC-TDMA accomplishes that by exploiting idle slots with transmission of the highest available class packet. Therefore, the proposed protocol manages to fully serve all medical CoS requirements with HMC-TDMA version offering extremely low average delay and very high throughput. Future work will be aimed towards developing a learning algorithm that further reduces idle slots. This will be achieved by increasing probability of selecting station i for transmission if station i is already transmitting, thus exploiting the fact that traffic from a station usually comes into bursts.

ACKNOWLEDGMENT

This research has been co-financed by the European Union and Greek national funds through the operation program Competitiveness, Entrepreneurship and Innovation under the call RESEARCH-CREATE-INNOVATE (project code: TIEDK-02489).

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