

# DS-MAC: Differential Service Medium Access Control Design for Wireless Medical Information Systems

Xiaojing Yuan, IEEE Member, Sumegha Bagga, Jian Shen, M. Balakrishnan, IEEE Member, and D. Benhaddou, IEEE Member

**Abstract**— The integration of wireless networking technologies with medical information systems (telemedicine) have a significant impact on healthcare services provided to our society. Applications of telemedicine range from personalized medicine to affordable healthcare for underserved population. Though wireless technologies and medical informatics are individually progressing rapidly, wireless networking for healthcare systems is still at a very premature stage. In this paper we first present our open architecture for medical information systems that integrates both wired and wireless networked data acquisition systems. We then present the implementation at the physical layer and differential service MAC design that adapts channel provisioning based on the information criticality. Performance evaluation using analytical modeling and simulation shows that our DS-MAC provides differentiated services for emergency, warning, and normal traffic.

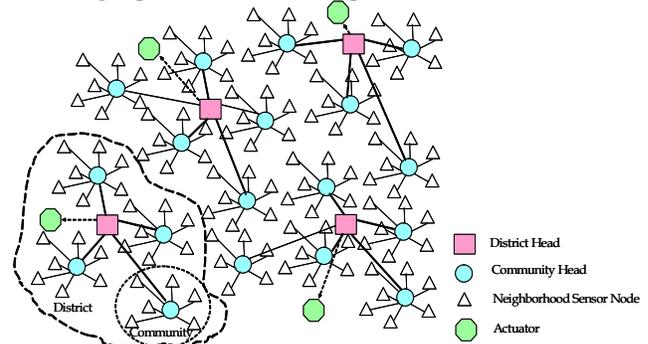
## I. INTRODUCTION

The integration of wireless networking technologies with medical information systems (MIS), i.e., telemedicine, will have a significant impact on healthcare services provided to our society. Applications of telemedicine range from personalized medicine to affordable healthcare for underserved population. Though wireless technologies and medical informatics are individually progressing rapidly, wireless networking for healthcare systems is still at a very premature stage [1]. There have been some efforts in embedding wireless communication capabilities into medical instruments and developing deployable healthcare wireless network architectures [1-10]; however, for the successful operation of the wireless network technology in medical premises such as inpatient and outpatient care and nursing homes, there is a need to analyze networking issues related to reliability, context-awareness and power consumption.

In this paper, we propose an architecture that utilizes wire-less sensor network along with smart phone platform to stream-line continuous monitoring of inpatient and outpatient care, which will have a huge impact on patient recovery after surgery. In this architecture we design a medium access protocol (MAC) that meet the quality of service (QoS) requirement of three types of context traffic: normal, warning, and emergency traffic. The low-cost wireless sensor nodes, with local sensing and processing have short range communication capabilities, while the smart

phones utilize established Wi-Fi communication backbone to relay data to the right healthcare personnel in the right time.

Fig. 1 shows the conceptual architecture of a hieratical scalable sensor network that can be applied to medical information system. Inexpensive sensors are generously embedded in the environment to automate vital sign monitoring and aggregation to health facilities in real-time. Embedded wireless sensors can facilitate affordable continuous health monitoring and will be a significant part of next generation telemedicine applications. Here a bio-medical device is interfaced with a wireless communication module that transfers the data through the dynamically established ad hoc network to a sink node. The sink node is connected to community head (can be a smart phone and/or base station connected to computer) for community wide processing and decision making before transferring necessary information to the right personnel in the hospital.



**Figure 1** Hierarchical Scalable Sensor Network Architecture

The organization of this paper is as follows. In section II, we describe in detail the MIS architecture based on the general architecture shown in Fig. 1 and the physical layer implementation of the system. Section III details the proposed MAC protocol with the analytical performance evaluation and simulation results from NS2 presented in Section IV. Finally, in Section V we conclude and point to future work.

## II. MEDICAL INFORMATION SYSTEM ARCHITECTURE BASED ON AD HOC WIRELESS SENSOR NETWORKS

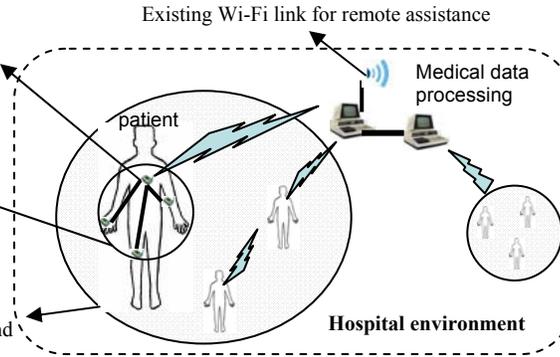
Most of the recent researches on wireless technologies for medical applications use single hop network and existing protocol standards, such as 802.15.4, to connect sensors to the healthcare gateway (PDA, Laptop, etc.). For example, Milenković, et. al. developed a one-hop WSN architecture [7] for personal health monitoring, in which sensors are directly connected to a sink (in their implementation, they

used personal data assistant (PDA)) that relay data to a central server. The implementation focused on the time synchronization and energy efficiency issues on the one-hop network between the sensor nodes and the PDA. Similar

**Community head:** In-body sensor node that communicates with the outside world, and is in direct communication range from other in-body sensors. Community head node is dynamically selected and rotated.

**Hierarchy 1:** In-body sensors form a 1-hop ad-hoc community network. Can operate in unused 412 MHz spectrum with 802.11e based QoS MAC protocol

**Hierarchy 2:** Inter-person communication (district network). Medical data diffusion to central processing facilities using the same band and protocols as the in-body network



**Figure 2:** Medical Information System Architecture in Hospital Environment

architecture was reported in [8] where multimedia devices extract information from nursing stations that interface to the health monitoring sensor network using a fixed Stargate™ network. The research in [11] evaluated the performance of 802.15.4-based biomedical single hop sensor network and argued that priority based services (network Quality of Service (QoS)<sup>1</sup>) are critical for any WSN based healthcare systems. For medical applications, information (health condition) criticality is the major influencing parameter, and preferential network treatment for medical warnings and emergencies is absolutely essential. Our MIS architecture as shown in Fig. 2 aims to address following challenges from networking perspective for medical information systems based on WSN:

- New MAC layer design that is contextual aware and provides differentiated services for critical information at different prioritized levels to the appropriate healthcare personnel in a timely manner.
- To enable such wide-area ad-hoc monitoring networks, design of robust routing protocols is essential. The routing protocol should mitigate issues such as sensor power level, link quality and network failures.

In this paper, we focus on the first challenge and present the DS-MAC design for prioritized channel access techniques in healthcare networks in extension of existing QoS resource control standards for wireless networks.

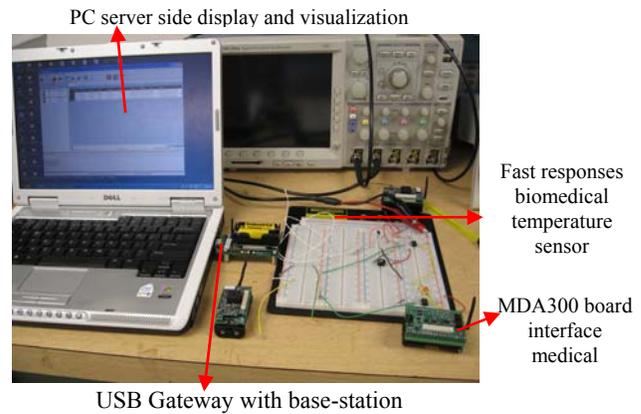
Fig. 2 shows how the conceptual architecture in Fig. 1 applies to a medical information system. The architecture does not require established wireless communication infrastructure since the inexpensive wireless nodes [4] can act as relay nodes, which can be deployed throughout the health surveillance region to provide a multi-hop path from

<sup>1</sup> Network Quality of Service (QoS) generally implies the capacity of a network to provide differentiated traffic services (such as channel time allocation), and the parameters that define the QoS vary based on the application.

the body sensor networks to the central data log and processing nodes.

Fig. 3 shows the prototype biosensor interface platform used in our lab for such a system. The biosensors are connected to MicaZ motes [12] using the sensor interface board. The signal is conditioned through a low pass filter and amplified before it is sampled and collected to the MicaZ's flash memory and sent to the sink node<sup>2</sup>. On the MicaZ mote, application is developed on top of the TinyOS – an event-driven operation system designed for resource constraint sensor nodes. The functions

implemented include: (1) a periodic *timer* triggers an event that *reads* the sensor data based on a pre-defined sampling rate; (2) the *AMSend* component is then used to broadcast the data and to reset the counter; (3) the sink node receives data using *AMReceive* component and relay the data to PC connected through *UART* messages; (4) on the server side the data are collected using *serial forwarder* and stored in pre-defined database TinyDB.



**Figure 3** Biomedical Sensor System Prototype

### III. DS-MAC: QoS MAC PROTOCOL FOR MEDICAL INFORMATION SYSTEMS

Application-centric (contextual) networking based on the information content will complement the medical information systems for synergetic improvements in the overall application performance. We design a differential service Medium Access Control (DS-MAC) protocol that enables prioritized channel provisioning. In this paper, we design a DS-MAC protocol for medical information system based on sensor networks. Based on 802.11e QoS MAC, the DS-MAC uses prioritized channel contention to provide

<sup>2</sup> We separate the sensor and radio to make it more flexible to connect various sensing device to the radio.

differentiated service between normal and warning medical information. It also extends the 802.11e QoS MAC by adding in a preemptive service scheduling algorithm to provide the highest and preemptive channel access precedence [12] for medical emergency traffic. The highest priority (emergency) traffic at a node can interrupt the *current* services of other data at that node.

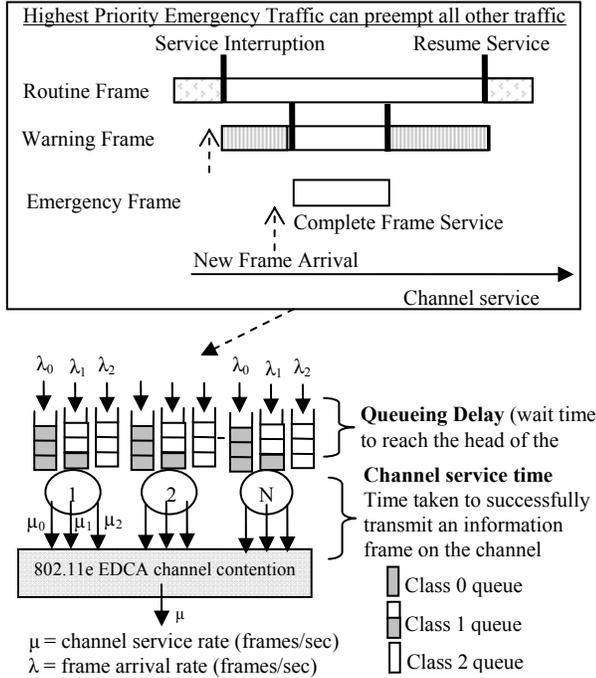


Figure 4. DS-MAC Model

Figure 4 shows the DS-MAC model with three major classes of health monitoring traffic: **Class 0 – Highest priority emergency data**, **Class 1 – Warning data (high priority)**, and **Class 2 – Routine data**. Every node maintains separate queues for each traffic class. Application generated frames are assigned to their respective queue and wait until it reaches the head of the queue (queueing delay). It then contends for the channel for successful transmission. In multiplexed environments, channel contention represents a significant component of per-hop delay. A node contends per information frame and sends all the packets comprising the frame in succession during channel access, unless service-interrupted by higher class traffic within the same node. At any instant, routine frames are not allowed channel access when the warning queue and emergency queue is non-empty. Similarly, warning frames will not be transmitted when the emergency queue is not empty. In short, due to the preemptive property, warning frames at a node never wait on the routine frames for channel service and emergency frames always have immediate channel service whether or not other queues are empty.

Interrupted or new frames will resume or begin channel service only after the successful transmission of all higher priority frames. Though this results in service starvation for routine traffic, in the context of healthcare applications,

warning data and medical emergencies should possess *preemption privileges*. DS-MAC employs the exact binary exponential back-off (BEB) method [13] of 802.11e. Within the scope of this paper, we list the contention parameters used in this work in Table 1, and direct the readers to refer [13] for details of EDCA contention.

Table 1. MACH parameters used in this work

General Parameters	Channel bit rate = 250 Kbps		
	One slot time ( $T_{slot}$ ) = 700 $\mu$ sec		
Contention Parameters	Short InterFrame Space time ( $T_{SIFS}$ ) = 16 $\mu$ sec		
	Class 0	Class 1	Class 2
Contention Parameters	AIFS[0] = 2 slots	AIFS[1] = 7 slots	AIFS[2] = 7 slots
	WMin[0] = 8 slots (0 to 7) = minimum contention window size	WMin[1] = 8 slots (0 to 7) = minimum contention window size	WMin[2] = 16 slots (0 to 15) = minimum contention window size
	WMax[0] = 8 slots (0-7) = maximum contention window size	WMax[1] = 16 slots (0 to 15) = maximum contention window size	WMax[2] = 64 slots (0 to 63) = maximum contention window size
	Only one back-off stage	2 back-off stages	3 back-off stages
	$m(0) = \log_2(WMax[0]/WMin[0]) = 0$ (last back-off stage)	$m(1) = \log_2(WMax[1]/WMin[1]) = 1$ (last back-off stage)	$m(2) = \log_2(WMax[2]/WMin[2]) = 2$ (last back-off stage)

#### IV. PERFORMANCE ANALYSIS AND SIMULATIONS

In this section, we first derive the analytical performance prediction based on queuing theory. Then give simulation results in NS2 to validate our analytical modeling result.

Assume  $N$  nodes are sharing the channel. The mean traffic generation rate of class 0 packets at a node is  $\lambda_0$  frames/sec. The mean channel service time (time taken to successfully acquire the channel and transmit a complete information frame) is  $X_0$  (sec/frame) =  $1/\mu_0$ . The corresponding statistics for class 1 and class 2 data are  $\langle \lambda_1, X_1 \rangle$  and  $\langle \lambda_2, X_2 \rangle$  respectively. Assuming Poisson traffic arrival process and general service times, each node can be analyzed as two independent M/G/1 queues [12], a queuing model which works well for distributed channel access schemes [14].

All nodes are configured to the parameter set of Table 1. The DS-MAC model allows for non-saturated traffic conditions i.e. every node has a non-zero probability of having empty queues. In addition, we assume that all nodes see the same channel state (one-hop case). From [12], the average time in the M/G/1 system (queuing and channel service delays) for a class  $c$  frame, under preemptive priority packet scheduling, is

$$T_c = X_c + \frac{R_c}{1 - \rho_0 - \dots - \rho_c} + \sum_{i=0}^{c-1} \rho_i T_c \quad \text{sec/ frame}$$

$$\text{where } R_c = \frac{\sum_{i=0}^c \lambda_i \overline{X_i^2}}{2} \quad \text{and } \rho_c = \frac{\lambda_c}{\mu_c} = \lambda_c X_c$$

$R_c$  is the mean residual time [12] for the class  $c$  traffic and  $\overline{X^2}$  is the second moment of channel service times. The second term (in  $T_c$ ) represents the average time required, upon arrival of a class  $c$  frame, to service all higher or equal class traffic (0 to  $c$ ) already in the system (queuing delay). The third term represents the waiting time for the service of higher class customers who arrive while class  $c$  traffic is in the system (in queue or in service), which is included as a result of the service preemption property. We can see that  $T_c$  is not influenced by lower priority class traffic ( $c+1$  or above), even if the lower priority class frames are already in the system. The first term in  $T_c$  is the channel service time ( $X_c$ ): the time taken to successfully transmit a class  $c$  frame on the channel, which is determined by the channel contention mechanism.

We adopted the exhaustive 3D Markovian analysis of the 802.11e EDCA contention scheme with following modifications: (1) Allow non-saturated traffic conditions; (2) Compress it to our parameter set (Table 1), under three classes of healthcare priorities. Within the scope of this paper, we directly present the theoretical results, without detailing the Markov chain decomposition and the equation ( $X_c$ ) formulation. With service preemption, shorter wait times (AIFS) and lesser back-off durations, we can easily predict that the emergency data, on average, will have higher probabilities of winning channel access when competing with routine data.

Fig. 5 shows the NS2 simulation results for one-hop delay when there is equal probability of warning and routine traffic. Once the route is determined by the routing algorithm, the statistical distribution of multihop delay can be easily calculated from one-hop delay. We used seven nodes network for five simulations each lasting 400 seconds.  $\lambda_2$  is fixed at 1 frames/sec, and the one-hop delay per frame is depicted under varying  $\lambda_1$ . The average number of nodes competing for channel access is set to 6, which is a reasonable neighborhood density considering short-range sensors. We can see that the one-hop channel transmission delay of routine frames increases dramatically with increasing arrival rates of warning traffic at a node. The warning frame delay on the other hand increases only marginally from 37 ms to approximately 41 ms, even under heavy network traffic (both classes). Similar results can be observed from analytical modeling of pre-emptive emergency traffic as shown in Fig. 6. The simulation and analytical results all confirm our hypothesis that with DS-MAC, the warning and emergency traffic got higher priority with normal traffic, and this is what is required when medical emergency happens.

## V. CONCLUSION & FUTURE WORKS

In this paper we present an open architecture for medical information systems that take advantage of both wired and wireless net-worked data acquisition systems. We then present our hardware implementation and DS-MAC protocol design that adapts channel provisioning based on the information criticality. Performance evaluation using

analytical modeling and simulation shows that our DS-MAC provides differentiated services for emergency, warning, and normal traffic with respect to one-hop delay. The emergency traffic at a node would compete with the routine traffic at other nodes, and the prioritized contention algorithm ensures preferential channel access for higher priority traffic in those cases. This will be our future direction.

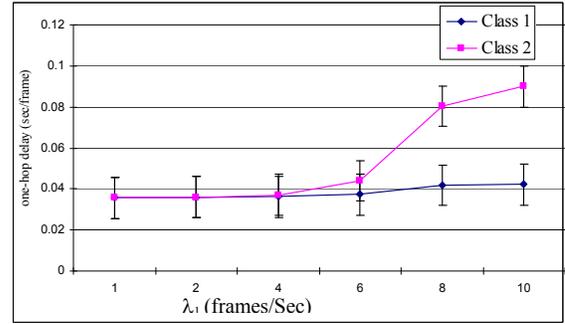


Figure 5. DS-MAC: Delay under varying warning traffic

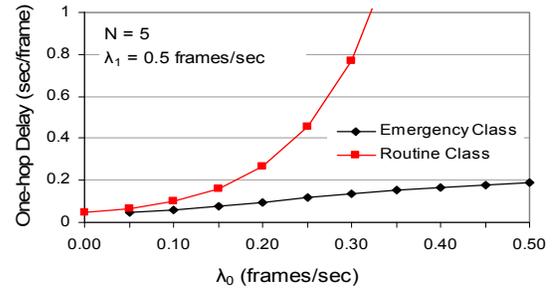


Figure 6. DS-MAC: Delay under varying emergency traffic

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