IEEE 802.11 WLAN for Medical-grade QoS

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ABSTRACT

In this paper, we study the problem of how to design a medical-grade wireless LAN for healthcare facilities. Unlike IEEE 802.11e MAC, which categorizes traffic primarily by delay constraint, we prioritize medical applications into access categories according to medical criticality. We design a fully-distributed contention control mechanism that can efficiently utilize wireless channel for improving medical-grade QoS. We further derive a sufficient condition for the convergence of the proposed algorithm. Our simulation result shows that our medical access categorization and the contention control mechanism significantly improve the performance of a medical network over the conventional IEEE 802.11e MAC.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless Communication*; C.4 [**Performance of Systems**]: Reliability, Availability, and Serviceability

General Terms

Algorithms, Performance, Reliability

Keywords

Wireless healthcare system, medical-grade QoS, IEEE 802.11e, contention control

1. INTRODUCTION

Today's hospitals are deploying numerous devices over wires for various medical applications such as monitoring, diagnosis, treatment, and alarm. In order to reduce the cost and the time required to rewire hospitals and their equipments for plugging more devices, there exists an increasing demand for replacing wires by wireless technologies [6, 11, 18, 21, 27]. This replacement not only reduces deployment cost, but also gives patients increased mobility and comfort by releasing them from wired connection. In fact, major vendors are already manufacturing medical devices based on wireless technologies [8, 10, 23, 32].

The significance of introducing wireless technologies in healthcare facilities is beyond reduced cost and improved mobility. Wireless technologies in addition to wires are expected to significantly improve the overall safety of medical systems. For example, current massive communication over wires in healthcare environments often results in the so-called "malignant spaghetti" (a crisscross of wires from various devices), which is a potential hazard for patient safety [19]. Also, a stand-alone telemetry device for monitoring a patient's condition is insufficient unless a medical staff member is present in the room, resulting in significant delay of a response to a sudden change in the patient's condition. The use of wireless technologies enables medical staff to remotely monitor the patient's condition in real time.

However, due to channel unpredictability, wireless communication is less reliable than wired one and could become a safety hazard when used inappropriately. Hence, for successful deployment of wireless technologies in healthcare applications, how to guarantee the required reliability of medical applications by wireless connection is a main challenge [3, 24, 25, 28]. The IT industry is currently marketing IEEE 802.11 wireless LAN as a promising solution for wireless medical networks [13]. However, those deployment efforts have been led by the industry as an ad hoc site-specific engineering issue rather than considering as a network design issue from the research community.

In the recent IEEE 802 Plenary Tutorial [17], "802.11 QoS for medical devices" is remarked as a main issue by Rick Hampton, a senior professional for RF management in many healthcare facilities.[1] Though there have been recently a certain amount of research efforts in wireless medical networks [1, 4, 6, 7, 11, 12, 18, 21, 26, 30, 31], there still lacks a systematic network design paradigm that properly takes into account medical-grade QoS. Consequently, a successful deployment of IEEE 802.11 WLAN in healthcare facilities is demanding a proper input for holistic characterization and design from the research community.

In this paper, we focus on how to design a wireless LAN with

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[1] Rick Hampton is involved in numerous projects to raise the awareness of healthcare professionals and manufacturers regarding wireless systems in healthcare facilities. Recently, Rick has been involved in the IEC/ISO 80001 standards effort to create a method for hospitals and other organizations to safely interconnect medical devices with the hospital WLAN. We are currently collaborating with Rick Hampton for Medical Device Plug and Play (MDPnP) [20].

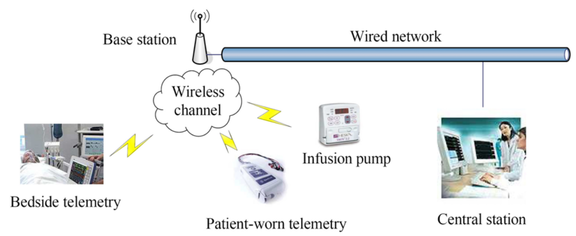


Figure 1: An illustrative structure of a wireless-enabled medical telemetry system in healthcare facilities.

medical-grade QoS for healthcare facilities. In particular, our contributions are as follows:

- We investigate how to conform IEEE 802.11 WLAN to healthcare environments. In particular, we study how to prioritize medical applications in healthcare facilities into access categories. Unlike the conventional 802.11e MAC, which categorizes traffic by delay constraint, we emphasize that the access priority of medical applications should be determined by *medical criticality* for safety of medical workflows.
- With a proper categorization for medical applications in hand, we design a contention control mechanism that can efficiently utilize wireless channel for improving medical-grade QoS. We propose a fully distributed algorithm for tuning the contention window size of each application. We further derive a sufficient condition for the convergence of the proposed algorithm.

The remainder of the paper is structured as follows. In Section 2, we provide background for understanding the state-of-the-art technologies for wireless medical networks. In addition, we briefly introduce IEEE 802.11e MAC. Then, in Section 3, we study how to map medical applications in healthcare facilities into access categories according to medical criticality. We further design a fully distributed contention control mechanism to improve medical-grade QoS. We evaluate the performance of the proposed scheme in Section 4. The conclusion follows in Section 5 with several important future research avenues.

2. BACKGROUND

In this section, we briefly introduce the history of connectivity between medical devices. We further discuss currently-deployed medical networks in healthcare facilities. Then, as background, we introduce the basics of IEEE 802.11e MAC.

2.1 Wireless-enabled Healthcare Systems

Connectivity between medical equipments goes back at least 20 years to the Medical Information Bus [22] for bedside medical devices. This eventually led to a huge standardization effort for medical device communication, which resulted in the development of the joint ISO/IEEE-11073 standard [14]. Since 2004, the IEEE 11073 standard has approved the Nomenclature and Domain Information Models, which specifies all types of information exchange between devices, and has provided a sound framework for creating interoperable standards. In addition, standards have been approved for cable connections and infrared wireless connections, which specify everything from network topology to encoding strategies. Currently, many standard drafts are still waiting for approval for specific medical devices (pulse-oximeters, blood-pressure monitor, weighing scale, etc.) and other communication mediums (Cabled Ethernet, RF wireless, etc.). Evaluation on these new technologies in the medical environment is still in progress with recent findings [29].

One representative example of wireless medical networks currently deployed in healthcare facilities is the wireless medical telemetry system for patient monitoring [9], as shown in Fig. 1. There are two main trends in the deployment of the wireless medical telemetry system; a vendor-specific network in the dedicated WMTS bands and an IEEE 802.11 network in the shared ISM bands [4]. Each of these two solutions has its own advantages as well as disadvantages. While a telemetry system in the WMTS bands enjoys the dedicated bands, it suffers a small number of supported channels because of the small bandwidth of the WMTS bands. On the contrary, an IEEE 802.11-based telemetry system has benefit in cost by the standard-based deployment as well as significant gain in the number of channels owing to the large bandwidth of the ISM bands. Furthermore, the standard-based deployment provides a solid ground for medical device interoperability, which is a fundamental issue in the healthcare community [20]. However, the ISM bands are unlicensed and are subject to interference from other devices such as Bluetooth, microwave ovens, and cordless telephones. Nevertheless, it has been recently reported through substantial deployment experiences that an IEEE 802.11 medical network in the ISM bands can significantly outperform the conventional vendor-specific one in the WMTS bands [4].

2.2 IEEE 802.11e MAC

IEEE 802.11e MAC standard [15] provides hybrid coordination function (HCF) that utilizes two medium access mechanisms: (i) controlled channel access and (ii) contention based channel access. The controlled channel access is referred to as HCF controlled channel access (HCCA), which supports policing of stations and deterministic channel access through a special coordinator node called the hybrid coordinator (HC). The HC provides QoS support by polling the individual requirement of the stations. On the other hand, the contention based channel access, namely, the Enhanced Distributed Channel Access (EDCA), allows introduction of Access Categories (ACs) to serve different traffic classes with differing QoS requirement. Depending on the network load, HCF determines respectively at what time which one of these functions to use. Since we focus on the contention-based channel access for the traffic categories in medical applications, we describe EDCA mechanism from the perspective of structures for providing QoS services.

Table 1: Default values for EDCA parameters and access categories.

Service type	Access Category	Symbol	CW_MIN	CW_MAX
Voice	AC_VO	Priority 0 (high)	7	15
Video	AC_VI	Priority 1	15	31
Best Effort	AC_BE	Priority 2	31	1023
Background	AC_BK	Priority 3 (low)	31	1023

EDCA can be defined as the class-based QoS provisioning channel access mechanism. It provides traffic classification that has different user priorities mapped to four ACs as follows: background (AC_BK), best-effort (AC_BE), video (AC_VI) and voice (AC_VO) in the ascending order of priority as shown in Table 1. Background traffic is assigned a lowest priority of level 3 whereas the voice traffic has the highest priority of level 0. Packets before transmission are queued at their respective AC queues associated with each AC.

The AC queues are prioritized by differentiating channel access parameters such as an arbitrary inter-frame space time (AIFS) and the contention window (CW) as given in Table 1. For the ACs of

Table 2: Representative values for QoS requirements of medical applications in heathcare facilities.

	Packets/s	Kb/packet	Peak (Kb/s)	Average (Kb/s)	Events/h or duty cycle	Maximum latency (ms)
Telemetry (diagnostic)	5	5.1	25.6	25.6	Stream	200
Telemetry (alarms)	5	1.0	5.1	0.1	10/h	200
Infusion pump (status)	1	1.0	1	1	Continuous	200
Infusion pump (alert)	1	1.0	1	0.1	1/h	200
Clinician notifier	5	2.6	12.8	0.1	20/h	200
BCMA	2	0.4	0.8	0.1	30/h	500
EMR images	200	20.5	4,100	41	1%	200
Guest access	100	10	1,000	30	3%	1,000
Email	200	20.5	4,100	41	1%	200

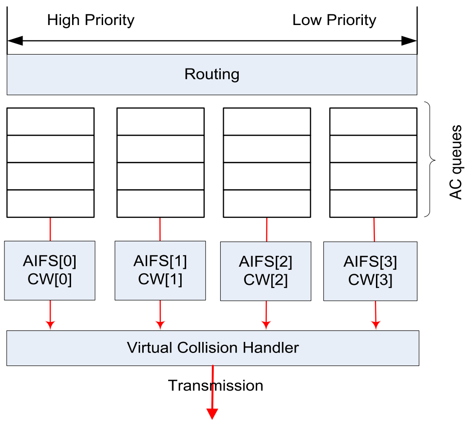


Figure 2: The architecture of EDCA in IEEE 802.11e.

higher priorities, these AIFS and CW duration is smaller compared to those of the low priorities. When a station has a packet to transmit, it contends for a transmission opportunity by initiating channel sensing. If the channel state is IDLE, it waits for the AIFS duration and starts backoff timer countdown for a random duration selected from the range of allocated CW. The AIFS duration in EDCA varies for each traffic category and thus is referred as AIFS [AC] as shown in Fig. 2.

For example, the duration in number of slots for AIFS [AC_VO] is less than the duration of AIFS [AC_BE] as shown in Table 1. Therefore, traffic category with AC_VO over AC_BE gets a higher priority to initiate transmission even when the packets are residing in both queues at the same time. After waiting for AIFS [AC] period, if the station senses a busy medium, it freezes the backoff timer and waits again for next AIFS [AC] duration. If the medium is found free, any queued packet is transmitted when the back off counter reaches zero.

The random CW value is picked up for the backoff counter from the given range of CW_MIN to CW_MAX for each AC as given in Table 1. Smaller the CW_MAX, the higher the medium access priority. Upon collision or packet loss, the sender node doubles its CW range until it reaches CW_MAX and wait for AIFS to attempt retransmission. To avoid collision among the ACs of the same node, virtual collision handler is further defined as in Fig. 2, which enforces the low priority AC to backoff in a similar manner to the node that encountered collision if higher priority AC has a packet queued for transmission.

3. DESIGN OF IEEE 802.11 WLAN FOR MEDICAL-GRADE QOS

In this section, we first categorize medical applications in healthcare facilities according to their medical criticality. With the categorization for medical applications in hand, we design a fully-distributed contention control protocol for medical-grade QoS.

3.1 Categorization of Medical Applications

Now, similarly as in IEEE 802.11e, we classify medical traffic into access categories. The typical QoS requirements for medical traffic in healthcare facilities can be found in [4], which are given as Table 2. Note that the values in Table 2 are rather illustrative information and could be slightly different from what can be found in a particular installation. For example, medical alarms should be announced within 10 seconds of the onset of the condition. Hence, a number much smaller than 10 seconds, but easily achievable value of 200 ms is given in Table 2.[2]

The basic rule for allowable latency, which matches with [16], is as follows. For life-critical information such as telemetry and infusion pump data, latency smaller than 200 ms is required. For other medical applications, latency of 200 – 500 ms is allowed, which is a reasonably acceptable level for user waiting. In the meantime, since guest access is an option for medical networks, a value of 1000 ms is given as acceptable latency. Data rates of applications are obtained as follows. For telemetry traffic, the value is for devices of a major manufacturer. Regarding barcode medication administration (BCMA), the value is just a guess based on the amount of data for a typical bar code. Values for infusion pump are again from a major manufacturer. Note that values less than 0.1 kb/s are listed as 0.1 kb/s in Table 2.

In the conventional IEEE 802.11e MAC, applications are categorized mainly according to their latency constraints, i.e., how large latency can each traffic tolerate. Hence, as explained in the last section, voice traffic is given the highest priority, and video, and so on. However, in medical environments, applications should be prioritized according to the consequences of its delivery failure. For example, the failure of a medical alarm could be a matter of life and death while that of guest access is irrelevant to the overall medical workflow.

Hence, we categorize medical traffic into four categories as given in Table 3. Alarm signals such as telemetry alarms and infusion pump alerts are given the highest priority. Real-time monitoring traffic for a patient's condition is considered as the second. Then, the next priority is given to other medical applications. Since guest access and email service are optional for medical networks, they are given the lowest priority.

3.2 Contention Control for Medical-grade QoS

Now, based on the categorization in Table 3, we study how to efficiently utilize wireless channel for improving medical-grade QoS of each AC. In particular, instead of the conventional binary exponential backoff (BEB) mechanism in IEEE 802.11 MAC, we design

[2]In fact, 200 ms is the value typically used for testing [4].

Table 3: Access categorization for medical-grade wireless LAN according to medical criticality.

	Applications	Criticality
AC0	Alarm signals (telemetry alarms, infusion pump alert)	Highest
AC1	Real-time streaming data (telemetry, infusion pump)	High
AC2	Other medical applications	Medium
AC3	Non-medical applications (guest access, email)	Lowest

a fully-distributed contention control mechanism for improving the performance of medical networks.

To this end, we focus on the characteristics of medical traffic in each AC. First, from Table 2, we can observe that the event of an alarm signal rarely occurs and its packet size is very small. Hence, we fix the CW value to CW_MIN for AC0 traffic in order to ensure the highest priority. It should be noted that this setting will not cause significant collision because of the rare event characteristic and the small packet size of AC0 traffic.[3]

Now, we look into the problem of how to ensure the QoS of AC1 traffic in Table 3. One key observation for AC1 applications is that they are streams with a given data rate. Hence, in order to properly deliver AC1 traffic, we introduce the following utility function, which should be maximized for each AC1 application.

$$U_i(p_i, \mathbf{p}_{-i}) = \int_{p_{min}}^{p_i} [c_i - r_i(\xi, \mathbf{p}_{-i})]\, d\xi, \qquad (1)$$

where p_i ($\in [p_{min}, p_{max}]$), and $r_i(\mathbf{p})$ are the channel access probability of node i and the MAC throughput of node i, respectively, and $\mathbf{p} := (p_1, \ldots, p_N)$ and $\mathbf{p}_{-i} := (p_1, \ldots, p_{i-1}, p_{i+1}, \ldots, p_N)$. From (1), for given $\mathbf{p}_{-i}$, $U_i(p_i, \mathbf{p}_{-i})$ is maximized when $r_i(p_i, \mathbf{p}_{-i}) = c_i$. In fact, the rationale for the utility function in (1) is to match the MAC service rate of each AC1 application to its input streaming rate in order to guarantee proper delivery of packets. Consequently, each node can match the input rate with the MAC service rate by maximizing its own utility as follows:

$$\max_{p_i \in [p_{min}, p_{max}]} U_i(p_i, \mathbf{p}_{-i}). \qquad (2)$$

Consider an iterative algorithm for each node, which maximizes (2). Since $\partial U_i(\mathbf{p})/\partial p_i = c_i - r_i(\mathbf{p})$, a gradient-based update algorithm for p_i, which solves (1), is given as

$$p_i(t+1) = p_i(t) - \alpha_i (r_i(\mathbf{p}) - c_i),\ i \in AC1. \qquad (3)$$

Note that the update algorithm in (3) is fully distributed among AC1 nodes. Hence, a critical issue is whether the overall updates of p_i, $i \in AC1$ will converge or not. The following result gives a sufficient condition for the convergence of (3).

THEOREM 1. *The update algorithm in* (3) *converges if* $\alpha_i < 1/[L_i \Pi_{j \neq i}(1 - p_{min})]$ *and* $p_{max} < 1/N$, *where* N *is the number of nodes in the network.*

PROOF. Here, we use the analysis in [5, Proposition 1.11 p. 194]. Let $f_i(\mathbf{p}) := -\partial U_i(\mathbf{p})/\partial p_i = r_i(\mathbf{p}) - c_i$ in (3). We first derive a sufficient condition on the step size α_i. The step size α_i should satisfy $0 < \alpha_i < 1/M$ where M is a positive constant such that $\partial f_i(\mathbf{x})/\partial x_i \leq M$, $\forall x, i$. Here, we use the following normalized throughput expression for our analysis: $r_i(\mathbf{p}) = L_i p_i \Pi_{j \neq i}(1 - p_j)$, where L_i is the payload size. By differentiating $f_i(\mathbf{p})$ with respect to p_i we have

$$\frac{\partial f_i(\mathbf{p})}{\partial p_i} = \frac{\partial r_i(\mathbf{p})}{\partial p_i} = L_i \Pi_{j \neq i}(1 - p_j) \leq L_i \Pi_{j \neq i}(1 - p_{min}).$$

Thus, the step size α_i should satisfy

$$0 < \alpha_i < \frac{1}{L_i \Pi_{j \neq i}(1 - p_{min})}. \qquad (4)$$

In addition, from [5, Proposition 1.11 p. 194], the following condition should be satisfied to make the iteration a contraction mapping:

$$\frac{\partial f_i(\mathbf{p})}{\partial p_i} > \sum_{k \neq i} \left| \frac{\partial f_i(\mathbf{p})}{\partial p_k} \right|. \qquad (5)$$

Since we have $\partial f_i(\mathbf{p})/\partial p_k = -L_i p_i \Pi_{j \neq i,k}(1 - p_j)$, (5) further becomes

$$\Pi_{j \neq i}(1 - p_j) > p_i \sum_{k \neq i} \Pi_{j \neq i,k}(1 - p_j). \qquad (6)$$

By dividing both sides of (6) by $\Pi_{j \neq i}(1 - p_j)$, we have

$$\frac{1}{p_i} > \sum_{k \neq i} \frac{1}{1 - p_k}. \qquad (7)$$

Since $1/p_i \geq 1/p_{max}$ and $1/(1 - p_k) \leq 1/(1 - p_{max})$, from (7) we have

$$\frac{1}{p_{max}} > \frac{N - 1}{1 - p_{max}} \Rightarrow p_{max} < 1/N. \qquad (8)$$

From (4) and (8), a sufficient condition for the convergence of the algorithm in (3) is $0 < \alpha_i < 1/[L_i \Pi_{j \neq i}(1 - p_{min})]$ and $p_{max} < 1/N$. □

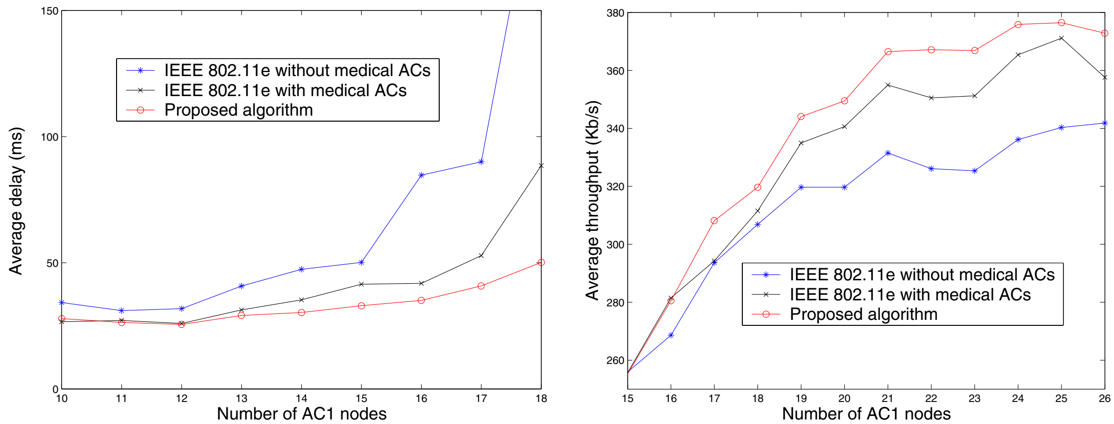
REMARK 1. *By properly assigning an utility function for AC2 applications, we can further design a contention control algorithm for AC2 traffic in order to improve the overall network performance without significantly sacrificing the performance of AC1 nodes. The detailed formulation is omitted here and is remained as our subsequent work.*

Finally, based on (3), we propose an update algorithm for the CW size of AC1 applications as Algorithm 1. Note that the CW size is updated with a granularity of one, which is the minimum possible value. Also, the fact that CW is inversely proportional to the access probability is taken into account in Algorithm 1.

Algorithm 1 Update algorithm for CW_i of node i in AC1

$q_{current} \leftarrow queue\_length$ % current queue length
if $q_{current} - q_{prev} > 0$ **then**
  $CW_i \leftarrow CW_i - 1$
else
  $CW_i \leftarrow CW_i + 1$
end if
Reset timer $t \leftarrow T$ % update interval T in seconds
$q_{prev} \leftarrow queue\_length$ % previous queue length

[3]We assume that each node has traffic corresponding only to one AC, and thus we use a "node" interchangeably with an "application."



(a) Average delay vs. number of AC1 nodes

(b) Average throughput vs. number of AC1 nodes

Figure 3: Average delay and throughput vs. number of AC1 nodes for IEEE 802.11e without medical ACs, with medical ACs, and the proposed algorithm.

4. SIMULATION STUDY

In this section, we first describe the simulation setup in our numerical analysis. Then, we give simulation results on performance comparison between the conventional 802.11e, 802.11e with medical categorization, and the proposed scheme.

4.1 Simulation Setup

We performed simulation using ns-2 (version 2.33) to evaluate the performance of the proposed mechanisms. The medium access layer of TKN-EDCA version [2] was modified to adapt the update algorithm presented in Algorithm 1. In our simulation, the initial and the final values of each queue are read in the interval of 1 second. Also, for every one second, the contention window value of each AC1 queue is updated. We compare the performance of the three protocols, i.e., the conventional IEEE 802.11e EDCA, IEEE 802.11e EDCA with medical categorization according to Table 3, and Algorithm 1 with medical categorization. The static routing protocol is used to avoid routing overhead.

The simulation is performed in the 500 m $\times$ 500 m region with one access point (AP) in the center. The number of stations is increased from 64 to 80 nodes, which are randomly placed in the region. We implemented three types of medical applications and allocated priorities by Table 3. From 10 to 26 nodes generate real-time monitoring traffic, 4 nodes are the sources for alarm and rest are the sources for other medical applications. The results are generated by fixing the number of AC0 and AC2 traffic while varying the number of AC1 nodes from 10 to 26 nodes. Please note that we have not included non-medical applications. The real time applications associated with telemetric applications are implemented as the common bit rate (CBR) traffic with respective data rate given in Table 2. Each telemetry alarm application is implemented using an exponential traffic source while other medical applications including EMR Numeric, EMR image, Clinician Notifier, and BCMA are implemented using Pareto traffic. All nodes transmit packets directly to the AP in the center of the region. The data rate is set to 1 Mbps and RTS/CTS is disabled for all applications. The EDCA settings for contention window are used as in existing TKN-EDCA version of ns-2 simulator as shown in Table 1.

4.2 Simulation Results

We investigate the average throughput and the average delay of AC1 applications as given in Fig. 3. The average delay is calculated as the difference between the generation time of a packet and its received time at the AP. The average throughput is calculated as the total number of traffic of AC1 nodes received by the AP divided by the number of AC1 nodes. First, if we look into Fig. 3(a), our medical categorization significantly improves the delay performance of medical networks over the conventional IEEE 802.11e MAC. Furthermore, Fig. 3(a) show that the delay performance of wireless medical networks can further be improved with the proposed CW update algorithm together with the medical categorization. Similarly, Fig. 3(b) shows the throughput performance of the three cases. It can be also verified in Fig. 3(b) that our medical categorization as well as the proposed CW update algorithm improves throughput performance over the conventional IEEE 802.11e MAC.

5. CONCLUSION AND FUTURE WORK

Our ultimate goal is to ensure verifiable safety for interoperable medical devices in wireless-enabled medical systems. To this end, we are currently working for the Medical Device "Plug-and-Play" Interoperability (MDPnP) Program [20] in collaboration with Massachusetts General Hospital. We expect that our study here will become an efficient building block for improving the overall reliability and interoperability of wireless healthcare systems.

We point out several important issues for future research. First of all, since reliability is a major concern in medical applications, controlled channel access such as PCF and HCCA instead of contention-based one can be further investigated for deterministic guarantee of channel access. Study on admission control is also of critical importance for ensuring the required medical-grade QoS. In addition, the effects of other mechanisms such as rate control, power control, and carrier sense need to be thoroughly investigated for the overall performance of medical networks.

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