MEDICAL DEVICE PERFORMANCE IN IEEE 802.11 NETWORKS
Evaluating IEEE P11073.1.1 Use Case Scenarios in Wireless LANs

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Abstract: We study in this paper use of IEEE 802.11 wireless technologies for medical devices. The simulated use cases are derived from the ones specified in IEEE P11703.1.1 document. We consider the use cases where a WLAN using IEEE 802.11 is providing connectivity to medical, voice (VoIP) and IT applications simultaneously. This use case is interesting to hospitals because it provides potential cost savings. We model IEEE 802.11e QoS features and we use a wireless channel model with high and stable SNR to observe MAC protocol behavior. Our results indicate that QoS of medical and VoIP devices is met when they operate in dedicated channels, that is, without any IT and in good channel conditions. The inclusion of background IT load, affects QoS of both medical devices and VoIP. We quantify the performance improvement for medical devices when using IEEE 802.11 voice category and compare it with using best-effort category. The power consumption of wireless devices is not considered in this work.

1 INTRODUCTION

Use of wireless networking technologies in medical environments is attractive due to the benefits it provides to patients, hospitals and care providers. For example, it alleviates the need for healthcare providers to be near patients, enable ambulation of patients for faster recovery and regular and frequent monitoring of patient's vital signs. The wireless technologies also enable integration of patient data in electronic health records. It is attractive for hospitals to use wireless technologies because it gives them flexibility to place and use medical equipment while reducing the chances of error due to increasing wire clutter around patients. In home care scenarios it provides the convenience of connecting patient monitoring data to care givers while providing ease-of-use. Furthermore, ubiquitous availability of wireless technologies makes it possible to provide healthcare services anytime, anywhere (IEEE Std P11073-00101/D04, 2008; Istepanian et al., 2004).

However, unlike in wired communications where typical available bandwidths are far in excess of needs of medical equipment, a wireless network capacity is often much lower and dependent on the wireless signal strength and signal-to-noise ratio (SNR) within a coverage area. The dynamic nature of wireless channels affects the quality-of-service (QoS) provided to medical equipment and it is critical to satisfy QoS for life-critical medical applications, such as telemetry. Also, whereas, in the past, bandwidths for medical application were typically isolated and reserved by using VLAN (virtual local area network) technologies and dedicated infrastructure, the wireless channel is often used, or desired to be used and shared, by non-medical applications such as email and web access. A motivation for sharing the existing installed wireless technologies with medical applications is significant cost savings achieved by doing so (Soomro and Cavalcanti, 2007).

Due to the fact that different medical applications have different QoS requirements and service level agreements (SLA) requirements, the dynamic nature of capacity/throughput of a wireless channel and variety of non-medical applications with varying data traffic characteristics, it is a non-trivial task to estimate whether a given network would be able to support, in terms of QoS, a set of medical applications, with a given wireless technology and channel conditions and in presence of some set of non-medical IT applications. The theoretical analysis provides some insight (Mangold et al., 2003), however, the assumed network traffic conditions to arrive at the analytical results do not correspond well with the expected use case scenarios (Cavalcanti et al., 2007). Whereas,

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an experimental setup can also provide insights, it is costly, labor intensive and it usually takes much longer time than simulations. For example, it takes a large amount of effort to assemble and configure large number of terminals to use a particular set of applications. Moreover, it is often a non-trivial task to measure QoS parameters, such as delays and throughput from live terminals. Therefore, we study the performance in selected scenarios through network simulations and compare the results. We use OPNET Modeler software to do the wireless network simulations.

In this article, we first give an overview of the use case scenarios considered in IEEE P11073.1.1 standard - Guidelines for the Use of RF Technology (IEEE Std P11073-00101/D04, 2008). We focus on 802.11 (Wi-Fi) technologies and its performance, and therefore, we will cover in greater detail the use cases which are expected to use WLAN technology and stress the network. In section 2 we give a summary of uses cases described in the IEEE P11073.1.1 standard. An overview of IEEE 802.11 technology and different features which could provide capabilities to differentiate medical traffic and provide the needed QoS is also given in this section. In section 3 we describe the simulation model and scenarios that we used to study and compare the performance achieved with different 802.11 protocol modes, the number of devices and the simulated medical and non-medical applications. In section 4 we present and discuss our simulation results. Finally, we end the paper with concluding remarks in section 5.

2 IEEE P11073.1.1 USE CASE SCENARIOS

IEEE P11073 group has undertaken effort to develop guidelines for the use of RF wireless technologies for point-of-care medical devices and it will be available as IEEEP1073.1.1 document (IEEE Std P11073-00101/D04, 2008). The goal of the document is to provide better understanding among all stake holders, for example, hospitals, care givers and patients by having common view of the wireless technologies. A review of the available and emerging wireless technologies, their capabilities and limitations, the ways to configure/specify each, the relevant medical devices and applications for each technology, and costs and drawbacks are covered in the document. Moreover, the document includes several generic models of typical healthcare use cases which could be used to analyze, evaluate, compare and optimize different wireless technologies and modes, or parameters within each, for the intended use cases.

2.1 Use Case Overview

The IEEE P11073.1.1 standard has outlined several use case scenarios which highlight the data characteristics and QoS needs of the medical applications, the number and type of such and network configurations in which they are expected to be served. The standard lists nine use case scenarios and they are: 1) Personal (Home/Mobile) Monitoring; 2) Sub-acute cases involving telemetry and basic vital signs monitoring for a single patient in a room; 3) and 4) Increasing complexity compared with (2) and ambulatory patients; 5) Cardiac patient moving through three areas; 6) Critical burn patient tracked from MedEvac to ER to ICU through recovery; 7) Rescue and MedEvac; 8) Ancillary; and 9) Maternity. The reader is referred to Appendix A in (IEEE Std P11073-00101/D04, 2008) for more details of these scenarios.

In this article we focus on the wireless local area networking (WLAN) technologies, that is, IEEE 802.11 wireless networking, and, therefore, would present the use cases where this technology is expected to be used. Among the use cases given in (IEEE Std P11073-00101/D04, 2008), the use case 4 stresses the network most and in this case it is expected that trends of performance achievable in different IEEE 802.11 modes of the operation would be easily observed. Therefore, we describe the use case 4 in detail next.

In the use case 4 there are sixteen patients and each patient has some medical devices connected to it. A patient is outfitted with a ambulatory monitoring device, PWD (patient worn device), which transmits 5 ECG vectors. In addition to ECG, episodic SpO_2 and blood pressure measurements are transmitted relatively infrequently; 1 and 15 min intervals, respectively. There are wrist RFID (radio frequency identification) tags, Nurse PDA, laptop PCs and VoIP (voice-over-IP) phones expected to operate in the scenario as well. Since, we consider IEEE 802.11 networks only; we exclude RFID and other technologies using non WLAN networking from the scenarios we have simulated. The QoS requirement for PWD is maximum latency of less than 500 ms and for VoIP the max latency should be less than 100 ms. Our objective in the simulation runs is to estimate the expected performance and QoS when WLAN is operating in the offered load environment. Since, applications like episodic SpO_2 and blood pressure measurements have very low throughput requirements, we do not include these in our simulation; doing so, does not affect the general observations we make about the performance obtained in the scenarios.

2.2 Brief overview of IEEE 802.11

The IEEE 802.11 standard (IEEE Std. 802.11, 2007), also known as Wi-Fi, specifies a single medium access control (MAC) protocol and multiple physical layer (PHY) modes. The 802.11 b and g modes operate in the 2.4 GHz band at data rates up to 11 Mb/s and 54 Mb/s, respectively, whereas the 802.11a PHY mode supports up to 54 Mb/s in the 5 GHz band. The legacy standard works by using CSMA/CA protocol in which the stations sense the channel before transmitting a packet. This is implemented by a Distributed Coordination Function (DCF) and most current IEEE 802.11 products use this mode. If multiple transmissions overlap, the stations retry after randomly selected backoff periods.

Subsequently, the 802.11e amendment (IEEE Std. 802.11e, 2005) has been proposed to enable QoS support in 802.11. The 802.11e amendment defines two basic mechanisms for QoS support, namely: Enhanced Distributed Channel Access (EDCA) and Hybrid Coordination Function Controlled Channel Access (HCCA). In this work we consider the EDCA mechanism, which provides prioritized QoS by defining four access categories: voice (AC_VO), video (AC_VI), best-effort (AC_BE) and background (AC_BK) traffic. Up to four backoff entities operate independently in a singe station, and each has its own MAC layer queue. Each backoff entity is associated with an access category and contends for the channel with different priorities. The different access priorities are realized by setting the following MAC layer parameters: i) arbitration interframe space (AIFS), which is the interval of time the medium has to be idle before a backoff entity initiates a frame transmission or starts counting down its backoff-counter; ii) minimal and maximal contention window (CWmin and CWmax), which determines the initial and maximum range of random backoff counter, respectively; and iii) transmission opportunity limit (TXOP limit), which is the duration during which the TXOP holder maintains uninterrupted control of the medium.

3 SIMULATION ENVIRONMENT

We have simulated wireless networking scenarios using a customized 802.11e OPNET Modeler simulation model. Figure 1 shows the simulated wireless network configured as in scenario 3. In the model, the terminals 'STA_x' represent PWDs and VoIP terminals are labeled as 'VoIP_x'. The terminals represented as 'IT_x' run IT applications, such as, email clients, web access clients, telnet sessions and are engaged in file transfers using FTP protocol. The wireless access point is labeled as 'AP' and it is connected to the application server through an ethernet switch.

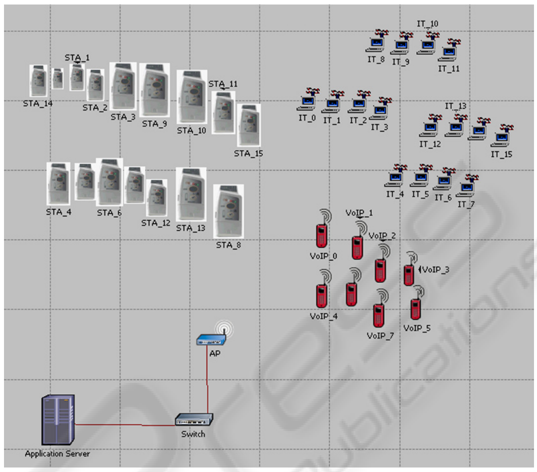

Figure 1: Simulated network configured as in scenario 3.

3.1 Applications and Scenarios

Table 1 lists the applications, the transport layer protocol used, the size of the respective transmitted objects, the objects' inter-arrival times (IAT), the application data rate and the traffic direction (UP: client to server, DN: server to client). As can be seen, the medical application, PWD, which includes one uplink traffic flow from the client device to a medical server, which is connected to the WLAN through an ethernet switch. The VoIP traffic is modeled after VoIP phones running the commonly used G.711 voice codec. For IT traffic, we have considered a mix of FTP, E-mail, HTTP, and Telnet applications. Thus, each IT station used in our simulations includes all four applications that form the IT profile.

There are eight different simulation scenarios which are summarized in Table 2. A set of four scenarios labeled 1 through 4 is run at the 802.11b PHY rates 5.5 Mbps, labeled 'a' and 11 Mbps, labeled 'b'. The respective PHY rates are used by all wireless nodes in a particular scenario. Throughout the simulations the VoIP traffic always uses the EDCA voice access category (AC_VO) and the IT traffic always uses best effort access category (AC_BE). The medical traffic uses either the EDCA voice category or the EDCA best effort category or DCF when using legacy IEEE 802.11. The IEEE 802.11 parameters used in simulations are given in Table 3.

Scenario 1 serves as a baseline scenario for PWD

Table 1: Simulated Applications.

APP	LINK	TRANS-PORT	OBJECT SIZE (bytes)	IAT* (ms)	RATE (kbps)
PWD	UP	UDP	Packet 312	125	20
VoIP G.711	UP/ DN	UDP	Packet 33	20	64
FTP	UP/ DN	TCP	File 10^6	80	N/A
Email	UP/ DN	TCP	Email 2000	20	N/A
HTTP	DN	TCP	Page 10k+ PIC 5× (10–4000)	10	N/A
Telnet	UP/ DN	TCP	Cmd 60-up/ 25-down	30	N/A

* IAT: Inter-arrival time.

Table 2: Simulated scenario number description.

No.	Rate	PWD		VoIP		IT	
	(Mbps)	Units	AC	Units	AC	Units	AC
1a	5.5	16	DCF	0	-	0	-
1b	11						
2a	5.5	16	VO	8	VO	0	-
2b	11						
3a	5.5	16	VO	8	VO	16	BE
3b	11						
4a	5.5	16	BE	8	VO	16	BE
4b	11						

traffic running over 802.11b without other traffic contending for the medium. In scenario 2 PWD shares the spectrum with VoIP and in scenarios 3 and 4 we add IT traffic. The difference between scenario 3 and 4 is the access category used by the PWD traffic.

For all simulations the wireless nodes are non-mobile and the SNR is greater than 25 dB, the minimum recommended SNR for VoIP in 802.11b networks (Cisco Doc-ID: 70442, 2008). In addition, Cisco (Cisco 7920 Design Guide, 2005) recommends maximum of eight VoIP calls at 60 % of WLAN bandwidth. Note, that real world WLAN deployments involve many radio frequency (RF) challenges such as physical obstructions, interference and multipath effects which impact the channel capacity. These effects are not accounted for in our simulations.

Table 3: 802.11 parameters used in simulations.

PHY Parameters		
PHY rate (Mbit/sec)		5.5/11
DCF	DIFS (μsec)	50
	CW_{min}	31
AC_BE	AIFS (μsec)	70
	CW_{min}	31
	TXOP Limit*	0
AC_VO	AIFS (μsec)	50
	CW_{min}	7
	TXOP Limit (msec)	3.264

* A TXOP Limit value of 0 indicates that a single data or management frame may be transmitted during each TXOP.

4 RESULTS

In this section, we present and discuss the simulation results. The performance metrics selected for applications within each profile are described in Table 4. The focus of the following performance evaluation is on the end-to-end performance of each application, and all performance metrics are measured at the application layer. The data loss rate and end-to-end delay are used as performance metrics only for streaming applications that run over the UDP protocol, which includes PWD and the VoIP applications. The data loss rate for each application is calculated as the difference between all transmit and receive packets for each application type (voice and PWD). The IT applications are evaluated by their throughput and the average response time, which is the average time it takes to download/upload a complete object such as an email or file.

In scenarios 1 and 2 where only the PWDs and the VoIP phones share the network in the same access category both 5.5 Mbps and 11 Mbps PHY rates are able to deliver adequate QoS with the average delays of below 2 ms and the maximum jitter of 0.16 ms. Note, that the channel quality in these two scenarios was good with a minimum SNR of 36 dB.

In scenario 3 IT traffic was added and the PWD traffic operated in the voice access category. We see that the QoS for the VoIP applications is severely compromised when the PHY rate of 5.5 Mbps is used (scenario 3a). The VoIP data loss rate is close to 5 % and the average delay reaching up to 200 ms. At the same time, although the PWD traffic uses the same access category as the VoIP traffic, the PWD performance is acceptable with no data being lost and the maximum delay of 5.3 ms.

Table 4: Summary of results.

METRIC	APPLICATION	SCENARIO							
		1a	1b	2a	2b	3a	3b	4a	4b
Average delay (ms)	PWD	1.0	0.6	2.0	1.0	5.3	3.0	507.6	23.1
	VoIP	-	-	2.0	1.27	191.3	3.8	182.7	3.7
Jitter (ms)	PWD	0.04	0.02	0.13	0.05	0.63	0.29	248.6	10.4
	VoIP	-	-	0.16	0.03	30.74	0.5	37.0	0.35
Loss rate (%)	PWD	0.0	0.0	0.0	0.0	0.0	0.0	0.31	0.2
	VoIP	-	-	0.0	0.0	4.9	0.0	2.4	0.0
Throughput (kbps)	FTP	-	-	-	-	0.9	987.7	0.9	721.0
	Email	-	-	-	-	31.6	38.0	23.5	40.3
	HTTP	-	-	-	-	62.7	97.7	64.4	93.9
	Telnet	-	-	-	-	0.3	0.3	0.3	0.3
Response Time (sec)	Telnet	-	-	-	-	7.7	0.3	17.4	0.3
Upload Response Time (sec)	FTP	-	-	-	-	267.5	18.1	N/A	125.6
	Email	-	-	-	-	27.0	1.2	58.2	1.6
Download Response Time (sec)	FTP	-	-	-	-	N/A*	N/A	N/A	N/A
	Email	-	-	-	-	63.3	4.51	55.1	3.36
Page Response Time (sec)	HTTP	-	-	-	-	6.2	4.2	5.4	4.8

* N/A: Transactions did not complete in simulation time.

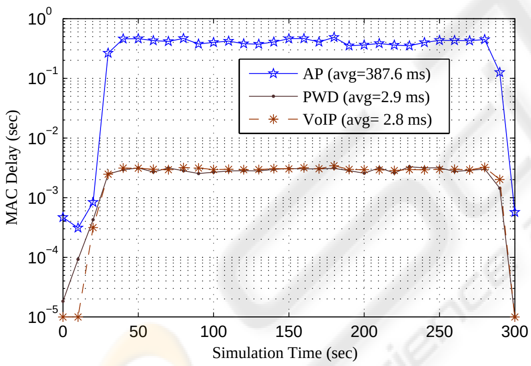

Figure 2: MAC delays at AP, VoIP and PWD stations.

In scenario 3a, upon closer inspection one can see that the high packet loss rate and delay is experienced by the downlink VoIP traffic only. Figure 2 shows that the MAC delay for the VoIP traffic transmitted by the AP is very high (387.6 ms) compared to the MAC delays of a randomly chosen PWD (2.9 ms) and VoIP phone (2.8 ms). The AP is contending for access to the channel with the same priority as the VoIP phones and PWDs, however it has to deliver a disproportionately high traffic load of 8 downlink VoIP streams and is unable to do so. The new automatic power save delivery (APSD) mechanism defined in IEEE 802.11e could reduce this problem, as the AP would deliver a downlink VoIP packet without having to contend for the channel. The problem could also be mitigated if the AP voice category used a higher channel access priority than the non AP's voice category.

When the physical data rate increased to 11 Mbps the network capacity increases enough to provide adequate QoS for VoIP and PWD traffic with no packets lost and an average delay of 3.8 ms and 3.0 ms respectively. As expected, the IT traffic benefits from the higher network capacity at 11 Mbps than at 5 Mbps resulting in higher throughput and lower response times as can be seen in Table 4.

Finally, in scenario 4, the PWD traffic uses the best effort category (AC_BE) while VoIP and IT traffic continue to use AC_VO and AC_BE. In scenario 4a, as we have see in scenario 3a, the traffic load exceeds the channel capacity at 5.5 Mbps. As a result, both VoIP and PWD experience severe QoS degradation. While moving the PWD traffic to a lower access category slightly improved the VoIP traffic performance, the average delay is still unacceptably high at 182.7 ms and so is the loss rate at 2.4 %. Figure 3 illustrates the problems of delivering 800 VoIP packets per second (the number of packets for eight calls in one second) in the scenarios with PWD and IT traffic and a PHY rate of 5.5 Mbps. The performance of the PWD application worsened dramatically with

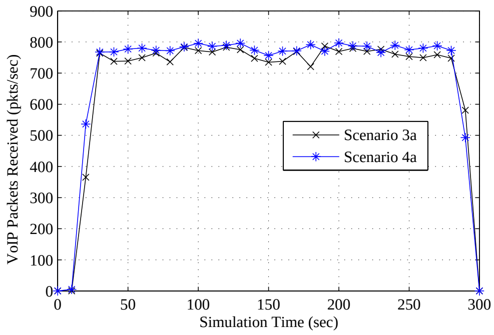

Figure 3: VoIP packets received in scenarios 3a and 4a.

the average delay rising to 507.6 ms and a loss rate of 0.31 %.

5 CONCLUSIONS

Our findings can be summarized as follows:

1) As a network becomes more congested the channel access category used by a node such as a PWD becomes more important for guaranteeing the required QoS. We recommend putting the medical traffic in the highest priority access category; and,
2) When the wireless nodes experience poor channel quality and lower their transmission rate the channel capacity is reduced and the recommended VoIP capacity for 802.11b can no longer be supported by the network.

In this paper we have estimated the QoS levels achieved by applications, specifically IEEE P11073.1.1 use case scenarios, while sharing a wireless channel. The knowledge gained by this work would help in designing an IEEE 802.11 wireless network in medical environments, for example, in hospitals, and estimating the QoS in the designed system.

In the scenarios that we examined good channel conditions were assumed. However, in real-world situations, some safety margins are included in the design specifications because: i) the channel is dynamic due to multipath fading; ii) the portable devices are mobile and channel conditions deteriorate at the fringes of the coverage areas; and, iii) there are vendor-to-vendor and device-to-device variations. Another interesting metric, which we did not consider in this paper, is the power consumption of the PWD devices. The power consumption of PWD in power save mode will increase as the network load reaches the channel capacity and more retransmissions occur due to contention increase. Because of the above stated reasons and prudent safeguards for life-critical applications, a network may have to be operated much below the capacity obtained in our simulations.

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