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RESEARCH ARTICLE

Design of a medical-grade QoS metric for wireless environments

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ABSTRACT

In this letter, we introduce medical-grade quality of service (QoS) for wireless healthcare applications. We first investigate the basic QoS requirements of medical applications. We point out that the conventional QoS metric of the packet error rate (PER) is *insufficient* for evaluating the QoS level of medical applications. The most critical concern in medical-grade QoS is whether the received data can be diagnosed by medical personnel, that is, *medical diagnosability*. As a prevailing application, we present a medical-grade QoS metric for wireless electrocardiogram (ECG) transmission. The introduced QoS metric, called weighted diagnostic distortion (WDD), can properly evaluate medical-grade QoS by reflecting the main diagnostic features of an ECG signal. Our simulation results demonstrate that there can be a significant discrepancy between WDD and PER, which confirms the importance of developing a medical-grade QoS metric by properly taking into account the key characteristics of medical traffic. Copyright © 2014 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Recently, the convergence of healthcare and information technology (IT), so called medical IT, has been paid great attention as a means for improving quality of life. The applications of medical IT broadly range from electronic healthcare (e-health) to more specific cases of medical-grade networks in healthcare facilities. In particular, today's hospitals have deployed numerous devices over wires for various medical applications such as patient monitoring, diagnosis, treatment and medical alarm. In order to reduce the deployment cost and time for plugging in more devices, there exists a surge of demand for replacing wires by wireless technologies [1–6]. Wireless technologies not only reduce the deployment cost but also increase the mobility and comfort of patients by removing wires. In fact, major vendors are already manufacturing commercial medical devices based on various wireless technologies [7, 8].

The significance of introducing wireless technologies in healthcare facilities is far beyond reduced cost and improved mobility. Wireless technologies are expected to significantly improve the 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 cables from various devices), which is a serious potential hazard for patient safety [9]. Also, a stand-alone telemetry device for monitoring a patient's condition is ineffective unless a medical staff member is present in the room, resulting in a significant delay of a response to a sudden change in the patient's condition. The use of wireless technologies enable healthcare personnel to remotely monitor the patient's condition in real time. In addition, by introducing wireless technologies, we can prevent infection by contact of wires.

However, because of channel unpredictability, wireless communication is much less reliable than wired one and may become another safety hazard when used in an inappropriate manner. Hence, for successful deployment of wireless technologies in healthcare applications, it is a main challenge how to guarantee the required quality of service (QoS) level of wireless medical applications, which is called *medical-grade QoS*. For example, several medical IT companies are currently deploying IEEE 802.11 wireless LAN as a solution for medical-grade wireless networks. However, those deployment efforts have been mainly led by the industry as an ad hoc site-specific engineering issue rather than a fundamental network design issue by the research community. Though there have been recently a certain amount of research efforts in wireless medical networks, for example, [1–6], there still lacks a systematic network design paradigm that properly takes into account medical-grade QoS.

In this letter, we focus on medical-grade QoS for wireless healthcare applications. We first investigate the general traffic characteristics of various medical applications. Then, as a prevailing application, we provide an in-depth study on medical-grade QoS of wireless electrocardiogram (ECG) transmission. In particular, our main contributions are as follows:

- We investigate the connectivity issues among medical equipment. Specifically, we look into the general traffic characteristics of various medical applications, which are the basic requirements for medical-grade QoS.
- We introduce *medical diagnosability* as the main concern in medical-grade QoS. Then, as a prevalent medical application, we introduce a QoS metric for wireless ECG by properly incorporating medical diagnosability.
- We compare the medical QoS metric with the conventional packet error rate (PER). Simulation results demonstrate that there can be a significant discrepancy between the medical QoS and PER, which corroborates the significance of a medical-grade QoS metric.

The remainder of the article is organised as follows. In Section 2, we present related work on wireless transmission of medical data, focusing on wireless ECG. In Section 3, we investigate the basic QoS requirements of medical applications. Design of a medical-grade QoS metric for wireless ECG transmission follows in Section 4. We give our simulation study on the comparison between the medical QoS metric and the conventional PER in Section 5. Finally, our conclusions follow in Section 6.

2. RELATED WORK

A representative example of wireless medical networks in healthcare facilities is the wireless medical telemetry service (WMTS) for patient monitoring [10]. There are two major trends in the WMTS technology. One is a vendor-specific technology in the dedicated WMTS bands and the other is an IEEE 802.11 network in the shared the industrial, scientific and medical (ISM) bands [2]. Each technology has its pros and cons. While that in the WMTS bands can use the dedicated frequency bands, it can only support a small number of narrow channels because of the small available bandwidth. In the meantime, an IEEE 802.11 telemetry system can reduce the cost by the standard-based deployment. In addition, it can also enjoy the large bandwidth of the ISM bands compared with the narrow WMTS bands. Furthermore, the standard-based deployment provides a solid ground for medical device interoperability. However, the ISM bands are unlicensed and are subject to interference from other devices such as Bluetooth, microwave ovens and cordless telephones.

There are quite extensive studies on wireless patient monitoring. For example, general requirements and analysis of wireless patient monitoring using the wireless LAN are studied in [1], which includes the use of the wireless LAN for patient monitoring in several different scenarios as well as analysis and design of architectures. In [2], it has been shown through substantial deployment experiences that the IEEE 802.11 WLAN technology in the ISM bands can significantly outperform a vendor-specific one in the WMTS bands despite potential interference. More recently, a wireless LAN architecture for remote ECG monitoring has been proposed in [4]. A comprehensive overview on wireless patient monitoring can be found in [1] and the references therein.

3. MEDICAL-GRADE QOS

In this section, we first look into the key attributes of healthcare applications, which constitute the basic QoS requirements. Then, we point out that the conventional QoS metrics are insufficient in terms of medical diagnosability.

3.1. Basic QoS requirements of medical applications

In order to differentiate the medical use of wireless technologies from general wireless networking, we have used the term, medical-grade wireless, in several places without a proper definition. In fact, medical-grade wireless is not a formally defined terminology. Rather, it denotes application-specific demand, which is determined by the medical features of each application. In a qualitative sense, medical-grade wireless implies characteristics such as predictable real-time performance, reliable connectivity under co-existence and support of required security and privacy. Consequently, in order to properly examine medical-grade wireless and medical-grade QoS, we need to look into the detailed characteristics of medical applications in use.

The typical QoS requirements for medical traffic in healthcare facilities can be found in [2], which are summarised in Table I. Note that the values in Table I are rather representative and could be slightly different from what can be found in a particular installation. For example, medical alarms should be announced within 10 s of the onset of the condition. Hence, a number much smaller than 10 s but practically achievable value of 200 ms is used in Table I. In fact, 200 ms is a typical value used for testing of medical devices [2].

The basic rule for allowable latency, which complies with [11], is as follows. For life-critical information such as telemetry and infusion pump data, latency smaller than 200 ms is enforced. For other medical applications, latency

Table I. Representative values for basic quality of service requirements of medical applications in healthcare 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	4100	41	1%	200
Guest access	100	10	1000	30	3%	1,000
Email	200	20.5	4100	41	1%	200

BCMA, barcode medication administration; EMR, electronic medical records.

between 200 and 500 ms is allowed, which is an acceptable level for user waiting. In the meantime, guest access, that is, network access by guests, is optional for medical networks. Hence, a value of 1000 ms is given as an acceptable latency. Data rates of applications are obtained as follows. For telemetry traffic, the value is for devices of a major manufacturer. As for the barcode medication administration, the value is an estimation 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 I.

3.2. Medical diagnosability

Though Table I provides the basic QoS requirements of various medical applications, it is *insufficient* for evaluating the QoS level of medical applications from the healthcare's viewpoint because those conventional metrics do not reflect the diagnostic features of medical data.

Hence, in order to properly evaluate the QoS level of medical applications in wireless environments, we have to consider *not only* conventional QoS metrics *but also* the level of medical diagnosability of the data. To this end, the key task is to determine a proper QoS metric for medical-grade transmission, which can measure the preserved amount of diagnostic information in the received data.

In summary, we need to introduce a proper medical-grade QoS metric that can quantify the preserved diagnostic information in the received medical traffic. Because the diagnostic features differ for different kinds of medical traffic, it is required to develop a QoS metric for each medical application.†

4. WIRELESS ECG TRANSMISSION

In this section, because it is formidable to develop a common QoS metric that can be applied to every medical application, we focus on the prevalent application of wireless ECG transmission and introduce an effective metric for medical-grade QoS. Development of a QoS metric for other medical applications will be a subject of future work.

4.1. ECG overview

An ECG is a painless test that records electrical activity in the heart. With each heartbeat, electrical signals spread from the top to the bottom of the heart. As they travel, these signals cause the heart to contract and hence to pump blood. The process repeats with each new heartbeat, and the electrical signals set its rhythm. An ECG shows how fast a heart is beating, whether its rhythm is steady or irregular, and the strength and timing of the electrical signals as they pass through each part of your heart. This test can be used to detect and evaluate many heart problems such as heart attack, arrhythmia and heart failure. The electrical system of a heart consists of three main parts: the sinoatrial node, located in the right atrium of the heart; the atrioventricular node, located on the interatrial septum, close to the tricuspid valve; and the His-Purkinje system, located along the walls of the ventricles.

A typical ECG trace of normal heartbeats consists of a P wave, a QRS complex and a T wave, as shown in Figure 1. During a normal atrial depolarisation, the main electrical vector is directed from the sinoatrial node towards the atrioventricular node and spreads from the right atrium to the left atrium. This creates the P wave on an ECG. The QRS complex is a recording of a single heartbeat on the ECG that corresponds to the depolarisation of the right and left ventricles. The PR interval is measured from the beginning of the P wave to the beginning of the QRS complex. The ST segment connects the QRS complex and the T wave and corresponds to the repolarisation of the ventricles. The interval from the beginning of the QRS complex to the apex of the T wave is referred to as the absolute refractory period. The last half of the T wave is referred to as the relative refractory period. Finally, the QT interval is measured from the beginning of the QRS complex to the end of the T wave. The baseline voltage of the ECG is known as the isoelectric line. Typically, the

†We have an analogous situation when we use different QoS metrics for audio and video applications, respectively, in multimedia communication.

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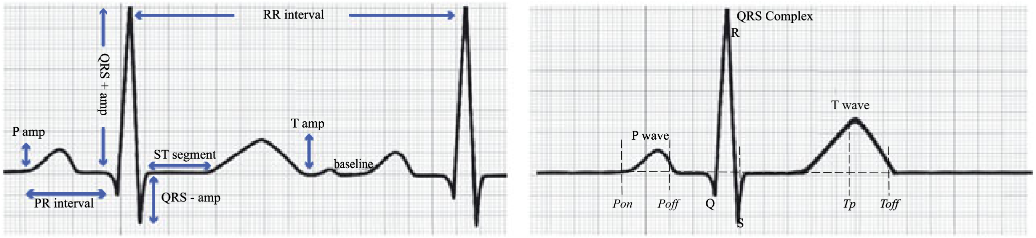


(a) Amplitude and duration features of an ECG signal (b) PQRST waves in one interval

Figure 1. Overview of an electrocardiogram (ECG) signal.

isoelectric line is measured from the portion of the trace that follows a T wave and precedes the next P wave.

4.2. Main features of an ECG signal

In order to design a QoS metric for wireless ECG transmission, first of all, we need to understand the key features of an ECG signal from the medical viewpoint.

An ECG signal has several diagnostic features that are crucial for medical interpretation. In general, the diagnostic features can be categorised into three groups: duration features, amplitude features and shape features. Among these three categories, the duration features are the most critical in most cases. Some duration and amplitude features of an ECG signal are shown in Figure 1(a). A more detailed descriptions on important duration and amplitude features are summarised in Table II.

In general, the relevant diagnostic information lies in the PQRST complex features as shown in Figure 1(b). The main features in PQRST complex are the location, duration, amplitudes and shapes of the wave. In order to extract these features, first of all, we need to segment the ECG signal, that is, determine the location of each wave shown in Figure 1(b). After finding these points, the decision on the waves, amplitudes and shapes will become straightforward. The waves can be located as follows: firstly, we recognise the QRS complex, which has the highest frequency component in the ECG signal. Then, the T wave is recognised, and finally, the P wave is determined. In fact, there are several algorithms available for ECG segmentation, for example, [12].

4.3. QoS metric for wireless ECG transmission

As we have already mentioned, the most important criterion for evaluating the QoS level of medical applications is diagnosability of the received data. For example, in the case of wireless ECG transmission, the error criterion should be chosen in such a way that it can measure the level of the relevant diagnostic information. The main issue is how to develop such a metric that can quantify the amount of medical information in each packet. Conventional QoS metrics such as PER is inadequate for evaluating medical-grade QoS because these conventional metrics treat every packet in an equal manner regardless of its medical importance. In medical applications, the amount of diagnostic information differs for each packet, which should be properly quantified to design a medical-grade QoS metric.

Here, in order to develop a quantitative measure for medical-grade QoS of wireless ECG transmission, we first capture the main features of an ECG signal, which are critical for medical interpretation. Then, as a QoS metric for wireless ECG transmission, we introduce the weighted diagnostic distortion (WDD), which was originally proposed for evaluating the distortion level of ECG signal compression [13]. In a nutshell, the WDD compares the original ECG signal and the received one by focusing on the key diagnostic features described in the succeeding text. It should be noted that higher WDD implies worse QoS as WDD is a metric measuring the distortion level.

Table II. Duration and amplitude features of an electrocardiogram signal.

Feature	Feature description	Unit
RR_{int}	Time duration between the current and the previous locations of the R wave	ms
QRS_{dur}	Time duration between the onset and the offset of the QRS complex	ms
QT_{int}	Time duration between QRS_{on} and T_{off}	ms
$QT_{p\,int}$	Time duration between QRS_{on} and T_p	ms
P_{dur}	Time duration between P_{on} and P_{off}	ms
PR_{int}	Time duration between P_{on} and QRS_{on}	ms
QRS^{+}_{amp}	Maximum positive amplitude of QRS complex	0.1 mV
QRS^{-}_{amp}	Maximum negative amplitude of QRS complex	0.1 mV
P_{amp}	Amplitude of P wave	0.1 mV
T_{amp}	Amplitude of T wave	0.1 mV

For the original ECG signal and the received one, a vector of diagnostic features such as those in Table II can be obtained, respectively, as follows:

$$f^T = [f_1\, f_2 \cdots f_p];\ \text{features of the original signal,}$$
$$\hat{f}^T = [\hat{f}_1\, \hat{f}_2 \cdots \hat{f}_p];\ \text{features of the received signal}$$

where p is the total number of features used in the WDD measure. Here, each f_i is given as a scalar value. For example, the time duration features are scalar values in ms as described in Table II.

With given f and $\hat{f}$, the WDD measure can be calculated as

$$WDD(f,\hat{f}) = \Delta f^T \cdot \frac{\Lambda}{tr[\Lambda]} \cdot \Delta f \qquad (1)$$

where Δf is the the normalised difference vector given as

$$\Delta f^T = [\ \Delta f_1\ \Delta f_2\ \cdots\ \Delta f_p],$$
$$\Delta f_i = \frac{|f_i - \hat{f}_i|}{\max\{|f_i|, |\hat{f}_i|\}}$$

and Λ is a diagonal matrix of weights of features; that is, $\Lambda = diag[\lambda_i], i = 1, 2, \cdots, p$. The values of λ_i, the relative importance of each feature, can be determined on the basis of the medical knowledge of healthcare personnel.

From Equation (1), unlike conventional QoS metrics, WDD can properly quantify the distortion in medical diagnostic information in an ECG signal. Hence, we can evaluate the medical-grade QoS level of each wireless technology by calculating WDD rather than conventional QoS metrics. We anticipate that a medical-grade QoS metric such as WDD will be vital for research on medical-grade wireless networks.

5. SIMULATION STUDY

In this section, we present our simulation study, which compares the medical QoS metric, WDD, with the conventional metric of PER for wireless ECG transmission. Because PER does not take into account diagnostic features of an ECG signal, there can be a significant discrepancy between WDD and PER.

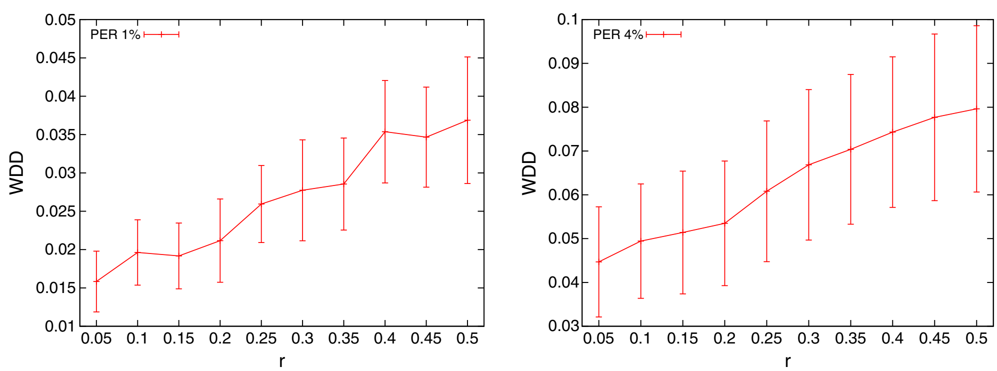
5.1. MIT-BIH ECG database

We use the MIT-BIH arrhythmia database [14] for our simulation study. The MIT-BIH arrhythmia database consists of 48 two-lead (MLII and V5) ECG registers, each of 30 min duration. The sampling rate is 360 samples per second with a resolution of 11 bits per sample, and hence, the resulting data rate is 7920 ($= 2 \times 360 \times 11$) bits per second. Although the database was originally created as the standard test material for the evaluation of arrhythmia detectors, it is widely used for testing new ECG monitoring schemes. Note that we do not assume any data compression in ECG transmission.

5.2. Simulation setup

In the simulation, we use three features for calculating WDD in Equation (1) as follows: $f_1 = RR_{int}$, $f_2 = QRS^+_{amp}$, and $f_3 = QRS^-_{amp}$ in Table II, which are the most critical features with the weight vector $\Lambda = diag[2\ 2\ 2]$ in Equation (1) according to [13].

It should be noted that we only consider the wireless channel error in our simulation study without taking account of other protocols for compensating channel errors. Though it will give more specific results to consider a realistic network scenario, our intention here is *not* to provide a thorough investigation on the performance of WDD under a specific network protocol stack *but* to stress the fundamental difference between the conventional QoS metric and WDD in a wireless environment. A more specific study on the performance of WDD will be the subject of future work.



(a) When the average PER = 1% (b) When the average PER = 4%

Figure 2. Weighted diagnostic distortion (WDD) versus channel parameter, r, for fixed values of the average packet error rate (PER).

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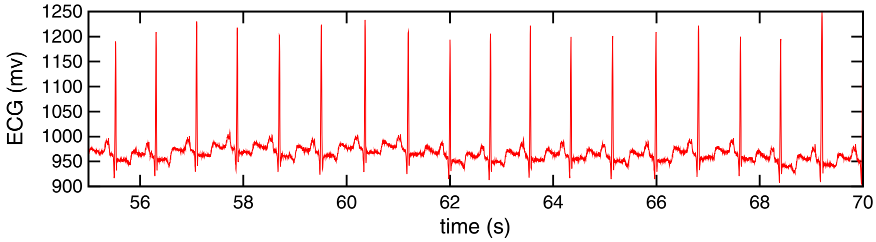
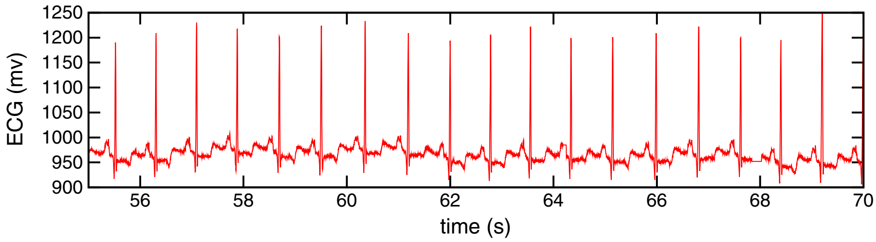
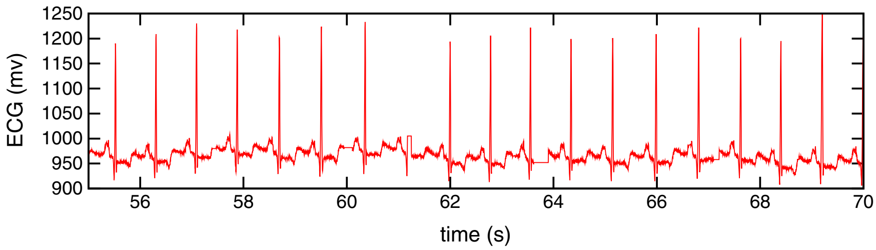


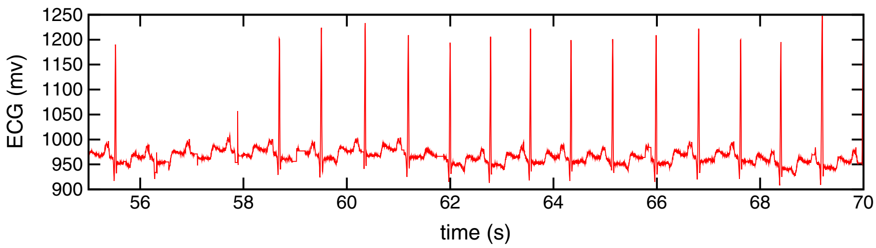
(a) Original ECG signal



(b) Received ECG signal when $r = 0.1$



(c) Received ECG signal when $r = 0.2$



(d) Received ECG signal when $r = 0.4$

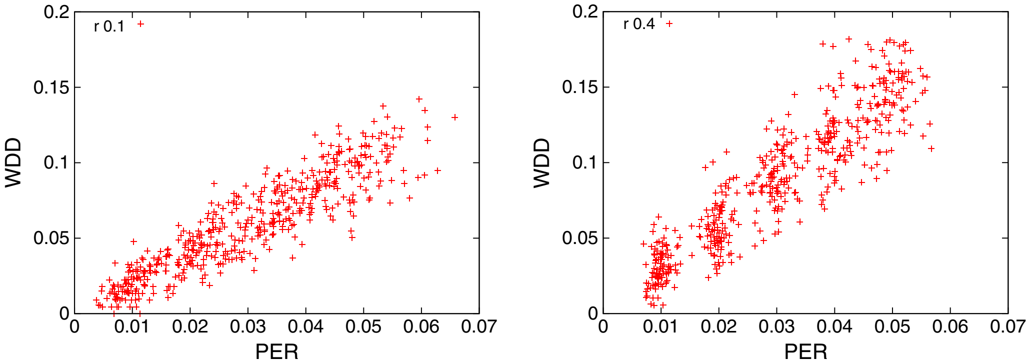
Figure 3. 15-s interval of original and received electrocardiogram (ECG) signals for different values of r with a fixed average packet error rate of 5%.

5.3. Two-state Markov channel model

In our simulation, we adopt the widely used two-state Markov channel model, which is also called the Gilbert–Elliot model. The model consists of two states, that is, good and bad. Each of them may generate errors as independent events at a state-dependent error rate $1 - k$ in the good state and $1 - h$ in the bad state, respectively. For simplicity, we use $k = 1$ and $h = 0$; that is, there will be no error in the good state while the bad state will always generate errors. Then, the model can be specified by two independent parameters q and r, where q is the probability that the transmission of the i-th packet is unsuccessful, given that the $(i-1)$-th packet was transmitted successfully, while r is the probability that the i-th packet is successfully transmitted, given that the $(i-1)$-th packet was not. Then, the average PER is given as $q/(q+r)$.

5.4. Evaluation of the WDD metric

In this section, we compare WDD and PER for wireless ECG transmission under various scenarios. Firstly, we plot



(a) WDD vs. measured PER when $r = 0.1$ (b) WDD vs. measured PER when $r = 0.4$

Figure 4. Weighted diagnostic distortion (WDD) versus measured packet error rate (PER) with fixed values of r.

WDD versus r, the channel parameter, while fixing the average PER ($= q/(q+r)$) by adapting q ($=$ PER $\cdot r/(1-$ PER $)$) proportionally to r. Large r results in large q, and they make the channel switching fast between good and bad states. Note that, because the duration of a simulation run is finite, the measured PER for each simulation run is a random variable with an average of $q/(q+r)$.

The simulation result for different values of the average PER is shown in Figure 2, where each simulation runs for 30 s, and each point is an average of 100 simulation runs. In addition, the error bar indicates one standard deviation. From Figure 2, we observe that, even when the average PER is fixed, WDD significantly varies as r changes; WDD tends to increase as r increases. From these observations, we can corroborate that PER is ineffective for medical diagnosability. More specifically, PER treats every packet in an equal manner regardless of its medical importance, which is a reasonable metric for typical data transmission. However, in terms of ECG transmission, the level of medical information contained in each packet significantly varies. For example, a packet corresponding to the QRS complex is much more critical for medical purpose than a packet to some flat part of ECG.

Next, we look into original and received ECG signals for different values of r with a fixed average PER of 5%. In the simulation, we determine whether each sample of the original ECG signal is received or not based on the channel state at the corresponding time index. The same interval of 15 s for each ECG signal is shown in Figure 3. The ECG signals in Figure 3 show that the loss of the QRS complex occurs more often as r increases because of the increase in burstiness of errors. Though the specific result would vary with different intervals, the overall trend is similar to Figure 3.

In order to see the effect of r on dependency between WDD and measured PER, we plot WDD versus measured PER for $r = 0.1$ and $r = 0.4$ in Figure 4, respectively. Firstly, for each r, we fix the average PER ($= q/(q+r)$) among each of the following values: [0.01 0.02 0.03 0.04 0.05]. Then, for each average PER, we plot the result of 100 simulation runs, that is, 100 points of (measured PER, WDD), resulting in the total of 500 points in each plot. Hence, there are five groups of 100 points in each plot around each value of [0.01 0.02 0.03 0.04 0.05] in the x-axis. In other words, let $(x_{100(M-1)+i}, y_{100(M-1)+i})$, $M = 1, \cdots, 5$ and $i = 1, \cdots, 100$, denote each point of (measured PER, WDD) with $\mathbb{E}[x_{100(M-1)+i}] = 0.01M$, where $\mathbb{E}$ denotes expectation. Then, for each M, $(x_{100(M-1)+i}, y_{100(M-1)+i})$, $i = 1, \cdots, 100$, constitute a group of 100 points around $x = 0.01M$. As shown in Figure 4, there is a certain correlation between WDD and the average PER; that is, WDD is proportional to the average PER. However, for a given average PER, say 0.01, the correlation between WDD and the measured PER becomes much weaker as r increases, which can be verified by comparing 100 points around PER $= 0.01$ in Figure 4(a) with those in Figure 4(b). This observation verifies that PER alone is insufficient to measure the diagnostic information of an ECG signal.

6. CONCLUSIONS

We have investigated medical-grade QoS, which is critical for the deployment of medical applications based on wireless technologies. We looked into the basic QoS requirements of medical applications and pointed out that the diagnosability of the received medical data should be the first concern. As a prevalent application, we presented an in-depth study on wireless ECG transmission. We have considered the key medical features of an ECG signal and have introduced an effective metric for medical-grade QoS. We then compared the proposed QoS metric for wireless ECG transmission with a conventional metric of PER. Our simulation results showed that there can be a significant mismatch between PER and the medical QoS metric, which confirms the importance of developing medical QoS metrics from the medical viewpoint.

There remain a lot of work for future research. In fact, our study is a small step towards holistic design of medical-grade wireless networks. A more thorough investigation on various medical applications is required for proper deployment of wireless medical devices, which

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will have a significant impact both on the IT and healthcare communities.

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REFERENCES

1. Varshney U. Pervasive healthcare and wireless health mornitoring. *Mobile Networks and Applications* 2007; **12**: 113–127.
2. Baker SD, Hoglund DH. Medical-grade, mission-critical wireless networks. *IEEE Engineering in Medicine and Biology Magazine* March/April 2008; **27**(2): 86–95.
3. *IEEE Wireless Communications, Special Topics on "Wireless Technologies for e-Healthcare"*, February 2010.
4. Kang K, Park KJ, Song JJ, Yoon CH, Sha L. A medical-grade wireless architecture for remote electrocardiography. *IEEE Transactions on Information Technology in Biomedicine* 2011; **15**(2): 260–267.
5. Lan K, Chou C, Wang T, Li M. Using body sensor networks for motion detection: a cluster-based approach for green radio. *Transactions on Emerging Telecommunications Technologies* 2014; **25**(2): 199–216.
6. Adibi S, Mobasher A, Tofigh T. LTE networking: extending the reach for sensors in mHealth applications. *Transactions on Emerging Telecommunications Technologies* 2013. DOI: 10.1002/ett2598
7. GE Healthcare. *Product Features–Wireless Technologies*. Available from: http://www.gehealthcare.com/ [14 March 2014].
8. Philips. *Patient Monitoring – IntelliVue Telemetry System*. Available from: http://www.medical.philips.com/ [14 March 2014].
9. *Malignant spaghetti: a symposium on wireless technologies in hospital health care*, November 14, 2008.
10. FCC. *Wireless Medical Telemetry Service (WMTS)*. Available from: http://www.fcc.gov/encyclopedia/ [14 March 2014].
11. IEEE. Draft Health Informatics - Point-of-Care Medical Device Communication. *Technical Report P11073-00101/D5*, Guidelines for the Use of RF Wireless Technology, 2008.
12. Kohler BU, Hennig C, Orglmeister R. The principles of software QRS detection. *IEEE Engineering in Medicine and Biology Magazine* January/February 2002; **21**(1): 42–57.
13. Zigel Y, Cohen A, Katz A. The weighted diagnostic distortion (WDD) measure for ECG signal compression. *IEEE Transactions on Biomedical Engineering* 2000; **47**(11): 1422–1430.
14. Moody GB, Mark RG. The impact of the MIT-BIH arrhythmia database. *IEEE Engineering in Medicine and Biology Magazine* May/June 2001; **20**(3): 45–50.