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M2M 원격심전도를 위한 스케일러블 코딩 및 링크 적응기법

Scalable Coding and Link Adaptation for Machine-to-Machine Telecardiology

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Abstract

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Medical telemetry is one of the most demanding applications in recent wearable computing era. Telecardiology, which uses the power of telecommunications for the remote diagnosis and treatment of heart diseases, is one of the key telemetry applications that leverages IoT-based technologies to improve patient care. Based on recent advances in wearable sensors and telecommunication technologies, this thesis proposes a universal platform for wearable daily cardiac monitoring service.

First, we propose an adaptive framework for layered representation and transmission of ECG (electrocardiography) data that can accommodate a time-varying wireless channel on cellular networks. The representation, combined with the layer-based earliest deadline first (LB-EDF) scheduler, ensures that the perceptual quality of the reconstructed ECG signal does not degrade abruptly under severe channel conditions and that the available bandwidth is utilized efficiently. Simulation shows that the proposed approach significantly improves the perceptual quality of the ECG signal reconstructed at the remote monitoring station.

Then we extend the proposed adaptive framework to support time-critical medical applications. In fact, the use of wireless technologies has been avoided for medical situations that demand instantaneous cardiac monitoring because of their considerable and nondeterministic end-to-end latency. This thesis introduces a universal platform for machine-to-machine (M2M) telecardiology over cellular networks, along with a novel conservative modulation and coding scheme to minimize and stabilize the delay down to 10 ms of ultra-low latency level, incurred during the process of ECG transmission over a wireless medium while maintaining the desired level of ECG pattern quality required for improving the chance of its interpretation. Machine-type communication (MTC) system is adopted for the delivery of patient ECG data to benefit from its inherent reliability, pervasiveness, security, and performance of 4G long term evolution (LTE) technologies with reduced cost and enhanced coverage. Extensive evaluations indicate that the proposed system provides a sufficient level of service for medical-grade instantaneous ECG monitoring in significantly deteriorated channel conditions.

Keywords: Electrocardiography, 3GPP Long Term Evolution Machine-Type Communications, Machine-to-machine communications, Internet of Things, Wearable sensors, Real-time Systems, Scalable coding, Link adaptation, Adaptive modulation and coding, Ultra-low latency communication
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Chapter 1

Introduction

1.1 Motivation and Objectives

Emergence of the Connected Era

Advances in semiconductor technology enables us to build lightweight, portable computing equipment [1]. And the contemporary wireless technology provides continuous data connectivity to mobile computing devices [2]. Recently, the concept of 'Internet-of-Things (IoT)', which enables numerous heterogeneous smart wearable devices to be connected with the cloud of the Internet, also has introduced as a consequence [3]. With the help of those technological backgrounds, the era of wearable computing has arrived. Among various kind of wearable equipments, personal healthcare devices are being penetrating our daily life [4–6].

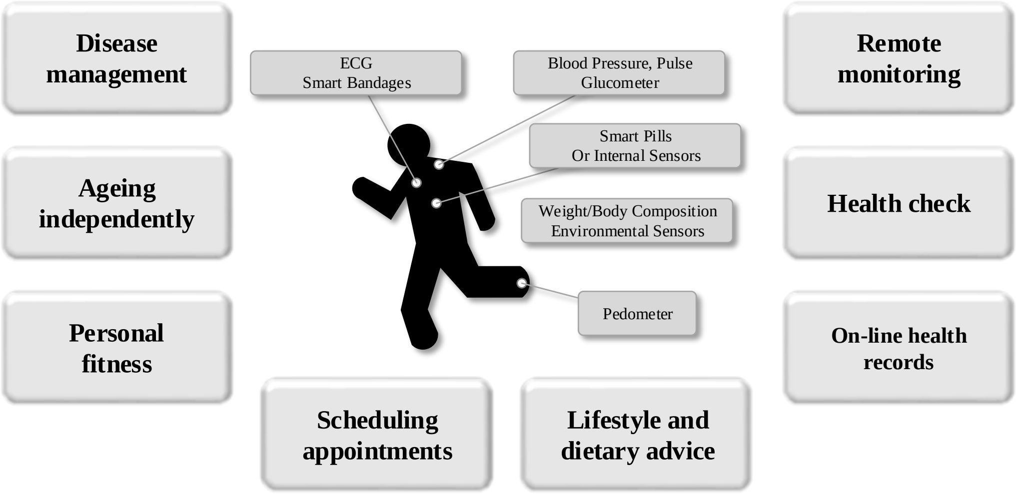


Figure 1.1: M2M for eHealth.

Machine-to-Machine for eHealth

E-Healthcare is a nascent market aimed at improving the quality of patient care and reducing healthcare costs [7,8]. Services include telemedicine to improve patient care by virtue of more accurate and faster reporting of changes in the patient's physical condition, automated connectivity of medical devices to the hospital network and remote management of these devices, and electronic representation and exchange of medical data between hospitals and medical groups such as laboratories or pharmacies to lower transaction costs [9–11].

To date, the healthcare industry has spent significant resources on telemedicine [12–14]. One of the primary services is remote patient monitoring and care, wherein a patient wears bio sensors to record health and fitness indicators [15]. In order to acquire the information on a patient's health or fitness, appropriate sensors have to be used. For this reason, the patient or monitored person typically wears one or more sensor devices that record health and fitness indicators such as blood pressure, body temperature, heart rate, weight, etc, as is shown in Fig. 1.1. It is also possible that the sensors used to monitor parameters related to the health condition of the patient are located somewhere in the environment of the patient.

With help of recent machine-to-machine (M2M) technology, M2M devices can forward their collected data to the M2M application server in the cloud automatically [16–18]. The M2M server responds to the collected data by sending alerts and appropriate medical records to medical providers. In emergency situations, an M2M device can directly provide the medical status of a patient on the route to the hospital in the ambulance, allowing physicians to prepare for treatment in advance of the patient's arrival. This is a scenario where reliable connectivity such as cellular communication networks are required.

M2M applications for eHealth enable

- the remote monitoring of patient health and fitness information,
- possibly the triggering of alarms when critical conditions are detected,
- in some cases also the remote control of certain medical treatments or parameters [19].

Cardiac Arrest Timelines: As Soon As Possible, Before Time Zero Approach

The Relation Between Agility and Prognosis

Acute cardiac arrest is one of the most common cause of human deaths worldwide. Immediate treatment is essential to survival of cardiac arrest. The problem is not whether cardiac arrest can be reversed but reaching the victim in time to do so. The American Heart Association supports implementing a "*chain of survival*" [20] to rescue people who suffer cardiac arrest. This chain consists of:

- Early recognition of the emergency and activation of the emergency medical services (EMS).
- Early bystander CPR (cardiopulmonary resuscitation).
- Early defibrillation when indicated.
- Basic and advanced emergency medical services
- Early advanced life support followed by post-resuscitation care delivered by healthcare providers.

The term *chain of survival* provides a useful metaphor for the elements of the ECC systems concept. Because a strong *chain of survival* can improve chances of survival and recovery for victims of cardiac arrest [21], various solutions including AED (Automatic External Defibrillators) [22], emergency reporting system with geographic information [23], and ACN (Automatic

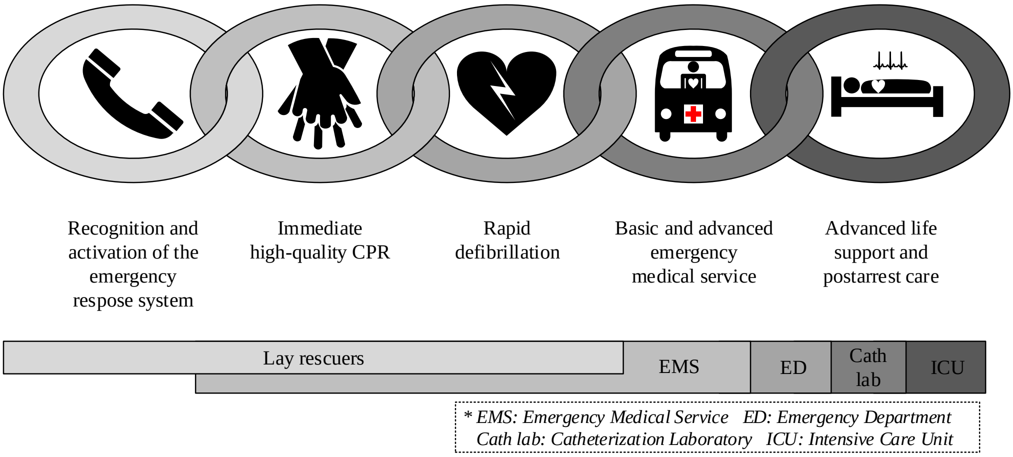


Figure 1.2: Out-of-hospital chain of survival

Collision Notification) [24] have been proposed to shorten the response time for the components of this chain.

Needs for Daily Cardiac Monitoring Service

Patients who have survived cardiac arrest, ventricular tachycardia or cardiac syncope, have an increased risk of sudden cardiac death [25, 26]. Many of those patients are normally living at home without any kind of arrhythmia monitoring system or cardiac alarm solutions. By using a wireless and wearable monitoring system for detection of arrhythmia situations, it is possible to provide quick alarms to a central safety alarm system and thereby take necessary action for an emergency rescue with geographic information. This solution is expected to dramatically improve the survival rate of the patients in cardiac arrest. In this thesis, we will propose a lightweight and dependable solution to enable these daily cardiac monitoring service, based on long term evolution (LTE) machine-type communication (MTC).

1.2 Research Contributions

• Quantitative Analysis of Data Requirement for Medical-Grade Service

Generally, medical information tend to be handled with very high level of computing resources with sufficient safety margins because of their clinical significance [27, 28]. This thesis analyzes the physical characteristics of the final output targets of these systems in a more sophisticated manner according to the clinical purposes of the corresponding ECG applications. As a result, adequate level of data amount for each presentation medium is determined as service profiles for various ECG applications.

• Spatio-Temporal Scalable Media Coding Differentiates Prioritized Data Portion

This study introduces spatio-temporal scalable media coding scheme based on ECG service profile. We have divided the ECG signal data into several spatial and temporal layers according to the ECG service profile, mentioned above. Then those data layers are sorted along with the clinical importance to form a scalably coded ECG stream. As a result we can deliver more prioritized portion with deteriorated wireless channels.

- **Conservative Modulation and Coding Ensures Instantaneous Transmission**

LTE systems adopt adaptive modulation and coding scheme for link adaptation technology by varing the modulation scheme and code rate according to the channel conditions. Standard MTC intentionally retain errors, which can be handled by retransmission to maximize the spectral efficiency. However this retransmission process can cause extra delay during the packet deliver. This thesis proposes a novel conservative channel quality indicator (CQI) to modulation coding scheme (MCS) mapping scheme, which minimizes end-to-end latency by eliminating retransmission process while maintaining appropriate level of ECG patterns by providing extra protection to higher prioritized layers by sacrificing the total spectral efficiency and throughput.

- **Dependable Instantaneous ECG Monitoring Service**

This study introduces a novel media encoding and link adaptation scheme to minimize and stabilize the delay incurred during the overall process of ECG transmission over a wireless medium while maintaining the desired level of ECG pattern quality required for improving the chance of its interpretation. As a result, the proposed scheme successfully provides dependable instantaneous ECG monitoring service by protecting clinically critical ECG patterns on a severely deteriorated wireless medium.

- **First Telecardiologic System Based on LTE MTC**

To the best of our knowledge, this work is the first MTC based telecardiology system. This thesis proposes a universal platform for M2M telecardiology based on 3GPP MTC systems. 3GPP MTC system benefits from the reliability, pervasiveness, security, and performance of 3G or 4G LTE. It also provides significantly increased battery life, with reduced cost and enhanced coverage. Furthermore, 3GPP MTC is co-existence with mobile broadband services, enabling continued innovations in the M2M business model. We also expect our work to provide a milestone for future studies on MTC based real-time streaming systems.

1.3 Orgranization of Thesis

The rest of this thesis is organized as follows:

In Chapter 2, some basics of ECG, along with related works about various wireless ECG monitoring system are presented to provide background for this thesis. We also discuss the appropriate wireless access medium for the proposed daily cardiac monitoring service by briefly comparing various candidate wireless technologies, categorized as wireless personal area networks, wireless local area networks and cellular networks.

Chapter 3 introduces our adaptive framework for cellular network-based daily cardiac monitoring services. This framework consists of a layered coding for ECG data and a cooperating ARQ (Automatic Repeat reQuest) based error control scheme, combined with a layer-based EDF (Earliest

Deadline First) scheduler to support the scalable and reliable monitoring of remote patients over time-varying cellular channels.

The recently announced extension of long term evolution (LTE) of communication service to support various non-human type mechanical automation scenarios, named machine-type communication (MTC) is introduced in Chapter 4. Then a novel conservative modulation and coding scheme based on LTE MTC combines with spatio-temporally scalable representations of ECG data for instantaneous wireless monitoring is proposed.

In Chapter 5, we summarize the results presented in this thesis and draw conclusions.

Chapter 2

Background and Related Works

2.1 ECG Generals

Electrocardiography

ECG is one of the most common diagnostic tools in modern clinical practice [29]. It gives a lot of detailed informations about the generation and propagation of cardiac action potential with comparatively simple non-invasive procedures compared to other complicated clinical examinations.

ECG not only provides clear evidences to detect the abnormalities of electric signal generation, such as arrhythmia, but it can also give a lot of sophisticated informations to localize the lesion of cardiac signal propagation problems, in case of ischemia or myocardial infarction, especially with help of multi-leaded ECGs, such as 12-lead ones [30]. Because of those simplicities and usefulnesses, ECG has been adopted on wide spectrum of cardiac applications from general-purpose diagnostic systems for rest state baseline examinations or treadmill stress tests to 24 hour ambulatory ECG recording systems, such as Holter monitor [31] for daily heart activity tracking or even critical real-time vital sign monitoring systems for operating rooms.

ECG Records Electrical Activity of the Heart

ECG is a non-invasive test and it records electrical activity of the heart. In each heartbeat, electrical signals spread from the base to the apex of the heart. As they travel, these signals causes the heart to contract and hence to pump blood. The process repeats in each new heartbeat, and the electrical signals set its rhythm. An ECG shows how fast your heart is beating, whether its rhythm is regular 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 (myocardial infarction or angina), arrhythmia, and chamber enlargement. A heart's electrical system is made up of three main parts: the sinoatrial (SA) node, located in the right atrium of the heart; the atrioventricular (AV) node, located on the interatrial septum, close to the tricuspid valve. Finally; and the His-Purkinje system, located along the walls of the ventricles.

Normal Impulse Conduction and ECG Pattern

A typical ECG trace of a normal heartbeat (or cardiac cycle) consists of a P wave, a QRS complex and a T wave, as shown in Fig. 2.1. During normal atrial depolarization, the main electrical vector is directed from the SA node towards the AV 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 depolarization 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, corresponds to the re-polarization 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 isoelectric line is measured as the portion of the tracing that follow a T wave and precedes the next P wave.

Normal ECG Waves

P Wave

The P wave corresponds to the atrial excitation. Generally it occurs by the impulse formation in the sinus node. The electrical stimulus spreads from the high right atrium in the direction of the AV node. Normal configuration: Orientation: broadly positive, usually negative in V1, aVR and III, biphasic

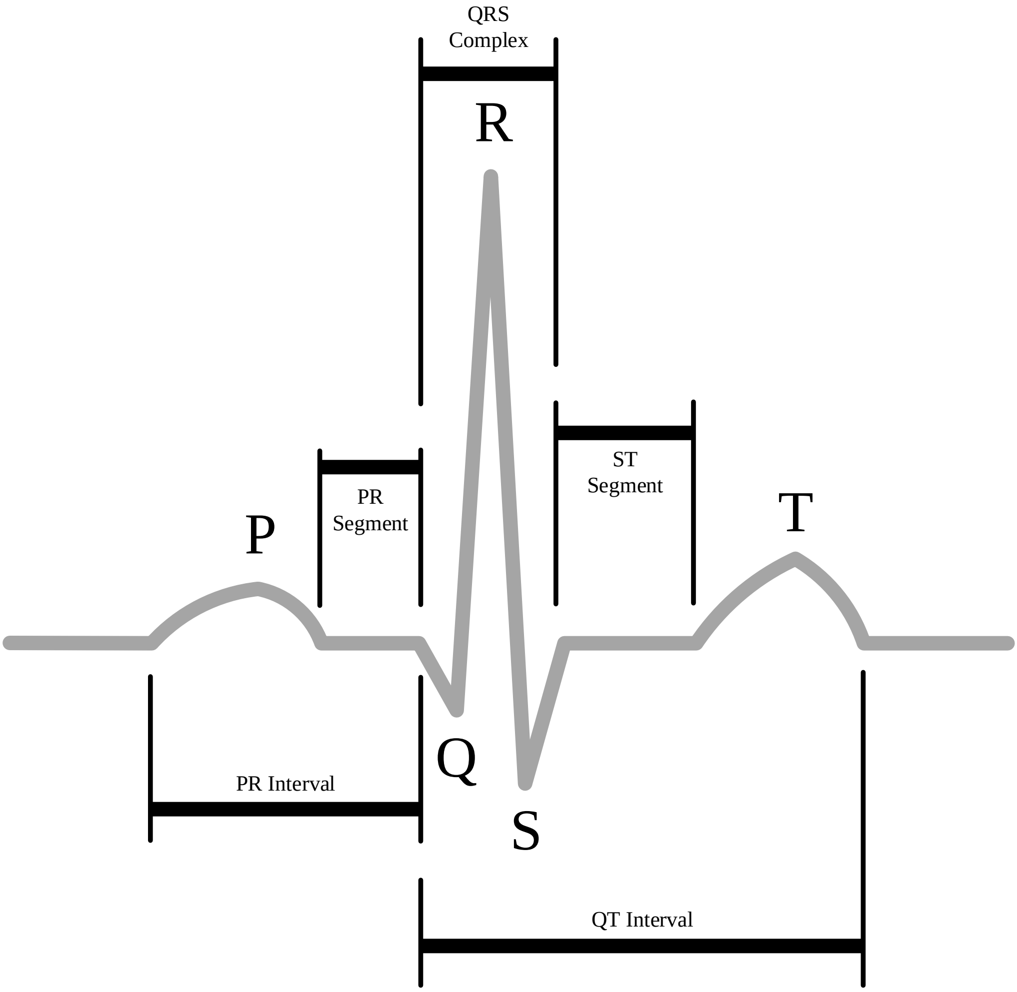


Figure 2.1: Normal sinus rhythm.

in right precordial leads

- Duration: max. 100 ms
- Amplitude: 0.1-0.3 mV

Arises the electrical excitation is not in the area of the sinus node, but for example, caused by an extra bounce in the atrium area (supraventricular premature beat), so the configuration of the above vary significantly. Mostly, there is then also an atypical PQ time.

QRS Complex

The QRS complex (max. 0.10 s) (without pathological change is found in up to 21% of the population values to 0.12 s) corresponds to the excitation chamber, wherein Q has the first negative deflection, with R the first positive deflection and with S of the negative swing are designated by the R-wave.

T Wave

The T wave corresponds to the repolarization of the chambers. Since it runs from the apex to the cardiac base due to different line speeds in different Ventrikelregionen (and thus in the opposite direction of the ventricular excitation), it creates a positive deflection on the ECG. In a hypokalemia it comes to flattening of the T wave in the hyperkalemia they are tall and pointed.

ECG Paper

The ECG can be printed on graph paper or displayed electronically. Fig. 2.2 shows the simple dimensions of standard ECG papers. The horizontal writing speed is standardized as 25 mm/s and the vertical scale for electric voltage is 10 mm/mV. One millimeter corresponds in direction 0.02 s in time axis and the height of 0.1 mV in amplitude axis. Before recording, most ECG devices print-out a calibration wave, which corresponds to a box of 1 mV over 100 ms. When properly normal operation this calibration wave is thus 1 cm high and 5 mm wide at a writing speed of 25 mm/s. Thus, the calibration wave serves as a reference for the following derivation and allows control of the device function. In older manually operated devices, the calibration spikes generated by pressing a button and applying a voltage of 1 mV, the duration of which had no meaning. These older devices were sometimes displayed by repeatedly pressing in the ECG recording, which derivative has been written, the recorded curves were labeled only subsequently.

2.2 Wireless ECG

ECG is Common Medical tool

Nowadays, various kinds of medical equipments are being connected with each other via a variety of communication mediums from traditional wire connections to contemporary heterogeneous wireless networks. Among many medically critical devices, ECG is one of the most common tools that has

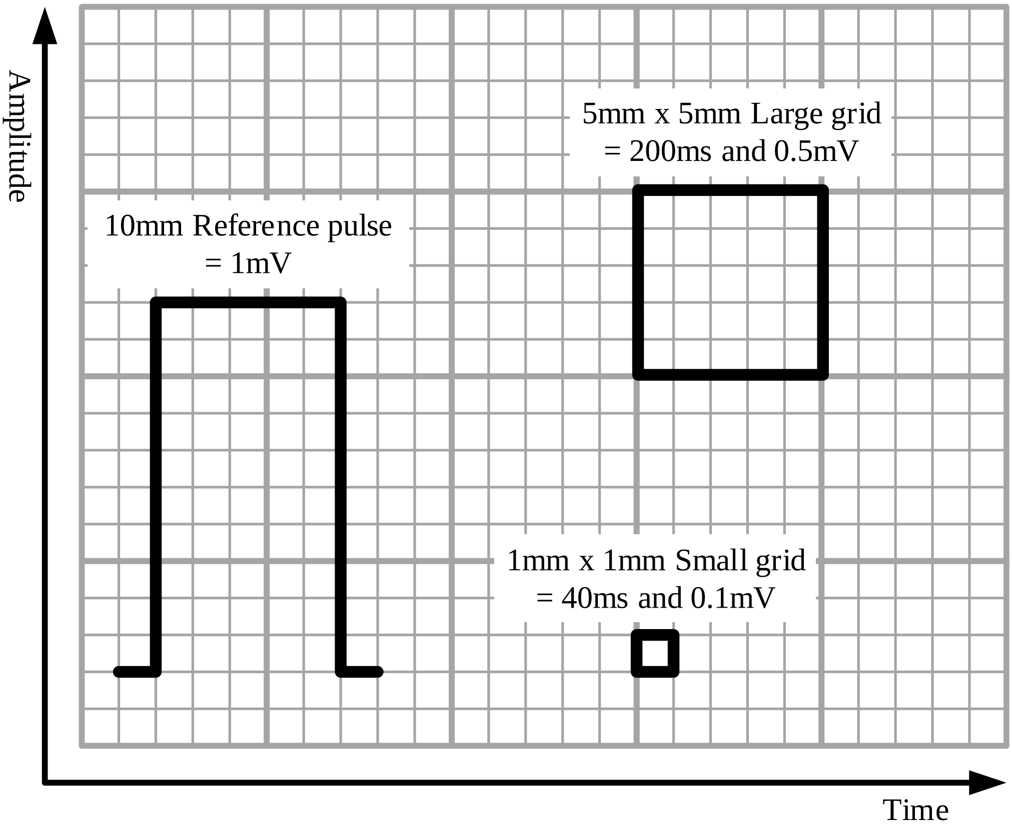


Figure 2.2: ECG paper.

a wide spectrum of usage from general-purpose 12-lead ECG systems to 24 hour ambulatory cardiac activity recording systems, such as Holter monitor [31] or even critical vital sign monitoring systems for operating rooms. ECG cannot only immediately provide critical informations on current heart status, such as bradycardia, tachycardia, arrhythmia or fibrillation but it also can give a lot of sophisticated details to diagnose the pathological cause of the abnormal cardiac symptoms more precisely. For this reason, ECG has become popular among the various medical equipments [32, 33].

Advantages of Wireless ECG

Recently, the trend to provide wireless connectivity for medical devices becomes another notable point of modern medicine researches. Actually, wireless technologies can also bring a lot of additional benefits to ECG systems in various clinical environments [27, 34]. For example, wireless ECG can removes obstacles from clinicians to access the patient more freely, and this clearness make the operators feel more comfortable to concentrate on important medical tasks. Moreover, in some cases, without annoying procedures of physical wire reconnecting, some wireless ECG systems can also spontaneously deliver cardiac informations via wireless media, such as Wi-Fi, wherever the patient mobilizes among the different places in the hospital, such as wards, examination rooms, intensive care units or even in the operating rooms [35]. For these reasons, various solutions have been announced to provide wireless connectivity to ECG systems.

Wearable Vital-Sign Sensors Based on Wireless Sensor Networks or Mobile Ad-Hoc Networks

Wearable vital-sign sensors can wirelessly monitor a patient's ECG condition over wireless sensor networks or mobile ad-hoc networks, alerting healthcare personnel to changes in status while simultaneously delivering data to an back-end archival system for longer-term storage [36,37]. Alarm-Net [38], is an assisted-living and residential monitoring network that opens up new opportunities for continuous monitoring of the elderly and those in need of medical assistance. MEDiSN [9] is a wireless sensor network for automating the process of patient monitoring in hospitals and disaster areas.

These approaches are mainly focused on aspects of ad-hoc communication. Varshney et al. [14,39] reviewed the ways in which wireless technologies can be used to implement reliable systems for pervasive healthcare, and Baker et al. [40] have taken a broad view of the various aspects of IEEE 802.11 wireless technology that affect its suitability for medical telemetry as well as the issues surrounding its deployment in hospitals. However, none of these works have considered dependable connectivity to enable emergency report functionality.

Signal Processing for Wireless ECG

To cope with limitations of wireless connections, many signal processing schemes for ECG have been proposed, especially focused in the data representation and compression techniques for minimizing the bandwidth requirements. Those approaches can be grouped into two categories: direct methods and transform methods [41]. In direct methods, the compression is done directly on the ECG samples; examples include the amplitude zone time epoch coding (AZTEC), the turning point (TP), the coordinate reduction time encoding system (CORTES), the scan-along polygonal approximation (SAPA), peak-picking, cycle-to-cycle, and differential pulse code modulation (DPCM) [41–44]. In transform methods, the original samples are transformed to another domain in the hope of achieving better compression performance, examples include Fourier descriptors [45], Walsh transform, Karhunen-Loève transform (KLT) [46], discrete cosine transform (DCT) [47–49], and the recently developed wavelet transform [50–53]. However, those studies are mainly focused on the aspect of efficiency for data compression, rather than end-to-end latency for ECG data transmission.

Real-time Instantaneous ECG Monitoring

Real-time instantaneous ECG monitoring for vital sign monitoring involves instant acquisition, transmission, and presentation of ECG data sampled from the patients. Many of those ECG systems must guarantee a certain level of real-time feasibility. Moreover, in case of operating room monitoring system during surgery, the medical professionals demands extremely short feedback latency to check suitability of current operation immediately. For this reason, the vital monitoring systems of nowadays still relies on annoying wired systems, which assures instant signal transmission.

Challenges of Wireless ECG

As ECG has utilized among diverse clinical environments for various medical purposes, the requirement conditions for its transmission medium also become complex. Those different usage of ECG demands adequate level of bandwidth for each medical applications, from the recoding systems with periodic reporting to real-time monitoring or observation systems. And because of the time-varying characteristics of the wireless channels, the transmission medium for ECG will experience a significant amount of bandwidth fluctuation along the time, and this instability of channel capacity limits the ECG system very small amount of bandwidth with guaranteed manner. Moreover, the ECG monitoring systems often utilize asymmetric wireless networks, which has designed mainly for download-rich applications with relatively small upload traffics, and in that case, those monitoring applications will encounter a shortage of reverse link capacity for uploading their acquired ECG data. Unlike the wired connections, which has a definite number of physical connection terminals, the wireless medium usually has uncertain limit of concurrent connections. For this reason, the most of the wireless networks involve some way of admission control mechanisms to preserve a certain level of service for current nodes.

2.3 Wireless Medium for Telecardiology

There are several solutions available for portable Holter monitoring [54] and cardiac event recording. These systems either use standard ECG electrodes and a wired connection to a recording unit, or function by pressing a recording device directly to the patient's chest when symptoms arise [55]. To alleviate the inconvenience caused by cumbersome cables while allowing a high degree of patient mobility, an increase in the use of wireless technologies for wireless ECG is being attempted. There are several products and projects [56] within mobile ECG recording that use Internet solutions [32], Bluetooth technology [57], cellular phones [58], wireless local area networks (WLAN) [59], and global system for mobile communications (GSM) [60]. These approaches to provide wireless connectivity to ECG systems can be simply categorized into the following three types depending on the background wireless networking technologies: wireless personal area network (WPAN)-based, WLAN-based, and wireless wide area network (WWAN)-based.

2.3.1 Wireless Personal Area Networks

First of all, ECG systems based on WPAN, such as Bluetooth or ZigBee has some advantages over other technologies to become a most popular wireless solution for ECG, that these systems can be implemented with low cost for tiny feature size. Several ongoing international projects [57, 61–66], where wireless sensors are used within the framework of a standardized body area network (BAN), are focusing on improving patient ability to freely move around in a daily situation while being monitored by a wearable system. Sachpazidis et al [67] are trying to develop a robust platform for real-time monitoring of patients at home and transmitting data to doctors at hospital. This "@HOME" concept aims to measure several vital parameters, but the applied sensor technologies have not been published so far. Several authors describe solutions based on sensors using a wireless Bluetooth communication protocol and a standard personal digital assistant (PDA) [27, 68]. Jovanov et al [69] propose the use of a personal area network with wireless intelligent sensors to acquire data.

WPAN systems consume a small amount of energy because they utilize low power radio resources, which are suitable as a substitute for the wires between patients and ECG machines. However, because of the short radio transmission range and point-to-point connection style of WPAN protocols, the annoying pairing process for initiating the connection needs to be repeated whenever the patient moves around. Moreover, the unstable characteristic of the narrow communication bandwidth inhibits the widespread acceptance of WPAN-based systems in mission-critical situations, such as intensive care units or surgical environments.

2.3.2 Wireless Local Area Networks

Secondly, the wireless ECG systems based on WLAN represented by Wi-Fi, which provide far more stable radio resources with much broader bandwidth compared to the WPAN-based ones, supported by the mass popularity of Wi-Fi technology [5, 6, 59] are emerging nowadays. With the help of WLAN technologies, the mobility of systems could be further enhanced compared to those based on WPAN, and frequent pairing procedures are not required. However, such systems demand not only more hardware resources, but also larger physical dimensions to support the higher communication requirements. These systems also consume more energy as well as more computational resources. Although these WLAN-based systems provide longer communication range, they can hardly be adapted to out-door or vehicular conditions. For this reason, another type of wireless technology is required to support daily monitoring systems with emergency reporting function.

2.3.3 Cellular Networks

Finally, WWAN-based systems could be regarded as the only feasible solution to provide emergency reporting functionality because they utilize wireless technologies that provide wide area coverage with high level of mobility support [58, 70, 71]. WWAN-based systems also provide more reliability to support mission-critical clinical tasks, as these systems clearly guarantee a certain level of QoS. However, the extremely high communication costs together with more complex system architecture and higher power consumption restrict the dissemination of WWAN technologies to special cases for seamless ECG data transmission, such as telemetry systems for ambulances or expensive monitoring systems for high cardiac risk groups. These are the primary reasons for considering LTE MTC as a means of communication for wireless ECG monitoring.

Chapter 3

Scalable ECG Transmission over Cellular Networks

In this chapter, we present an adaptive framework to support high-quality remote ECG monitoring over error-prone cellular networks.

Challenges: Volume, Fluctuation, and Error

To enable daily cardiac monitoring service over cellular networks, we need to be able to monitor several people in real time over a limited-bandwidth wireless connection. This is a challenging task because of the following reasons:

- *Large volume of data*: The uncompressed data, even for a single patient, could be huge. If a patient with a heart abnormality is remotely monitored, then with a 12-lead ECG of 11 bit resolution and 2400 Hz sampling frequency, the data for one day can easily occupy around 3.4 GB. When several residents are to be monitored in the same facility, the amount of data generated could be tremendous. To process and transfer this large amount of data in real time is difficult.

- *Bandwidth fluctuations*: First, the throughput of a wireless channel may reduce because of multi-path fading, co-channel interference, and noise disturbances. Second, the capacity of a wireless channel may fluctuate with the variation in distance between the base station (BS) and the wireless transmitter attached to the ambulatory patient. Moreover, when a patient switches between networks, the available bandwidth may change drastically. Finally, when a handoff takes place, a BS may not have enough unused resource to meet the demand of a newly connected patient. As a result, bandwidth fluctuation is a serious problem for real-time ECG transmission over wireless networks.
- *High channel error rate*: Compared with wired links, wireless channels are typically much noisier and suffer from both multi-path fading and shadowing, making the packet error rate (PER) very high. Moreover, these errors occur in bursts. Such error bursts have a devastating effect on ECG presentation quality. Therefore, there is a critical need for reliable transmission of ECG data over wireless channels

To cope with these challenges, we introduces an adaptive framework for cellular network-based telecardiolgy. Our proposed adaptive framework consists of a layered representation of ECG data and an error control scheme based on automatic repeat request (ARQ) combined with a layer-based earliest deadline first (LB-EDF) scheduler. The LB-EDF scheduling algorithm support the delivery of scalable ECG streaming over lossy channel in real-time. Scalable ECG streaming data have timing constraints because of their sensitivity to delay and jitter, and thus, the use of the EDF policy has the critical advantage of ensuring that higher (less important) enhancement layer(s) (EL(s)) can be discarded so that the base layer (BL) and the lower enhancement layers have a greater chance of arriving at the remote monitoring station (RMS) on time. Working in conjunction with the ARQ scheme, the proposed LB-EDF scheduler greatly improves the signal readability at the RMS by rescheduling the packets such that the more important lower-layer packets are transmitted first. This ensures *Graceful quality degradation* and efficient use of the bandwidth in a way that maximizes the perceptual quality and the resulting ECG readability, thus facilitating a correct diagnosis.

3.1 System Architecture

Fig. 3.1 shows the architecture of the proposed system for remote ECG monitoring. A wearable wireless ECG sensor (also called electrode) continuously measures the heart activity of a mobile patient. The resulting digital stream is grouped into packets that then transmitted wirelessly to remote healthcare professionals in real time through cellular networks.

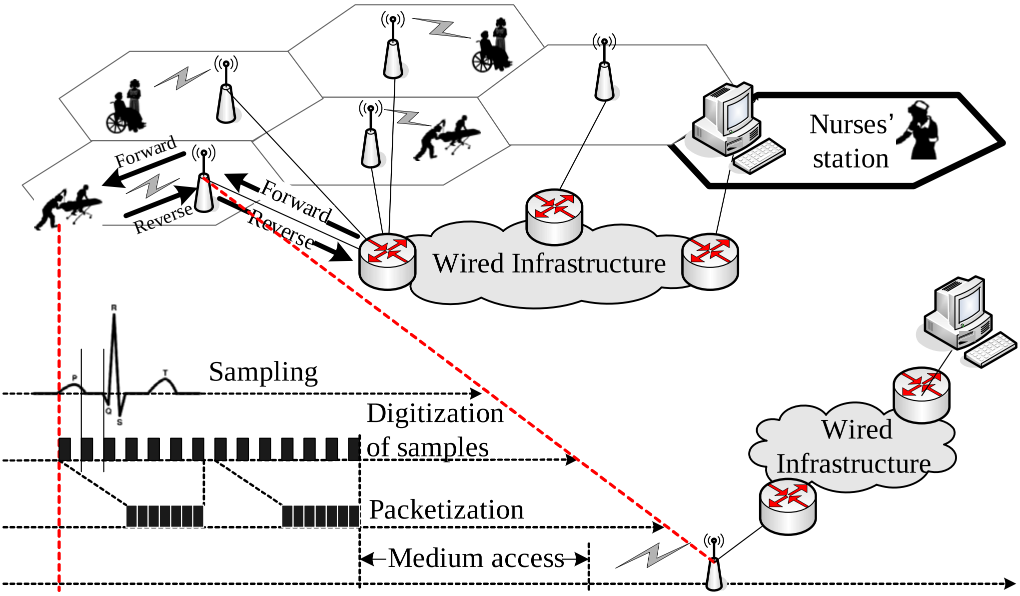


Figure 3.1: Wireless system architecture.

3.2 Scalable Representation of ECG Data

In general [34], an η-lead ECG is one in which η different electrical signals are recorded almost simultaneously, and it is often used as a one-off recording of an ECG. If η leads are recorded, and if the ECG output for each lead is digitized at a rate of R samples per second, each of which has a resolution of L_{smpl} bits, the resulting data-rate μ_{ecg} of the wireless ECG application is given as $\mu_{\text{ecg}} = \eta R L_{\text{smpl}}$. The digital stream is packetized and then sent to an RMS over a wireless channel.

It is clear from this definition that the quality of the obtained ECG signal improves with an increase in the sampling frequency. In a standard environment, scalability is achieved through a layered structure, where the ECG information is divided into two or more discrete bit streams corresponding

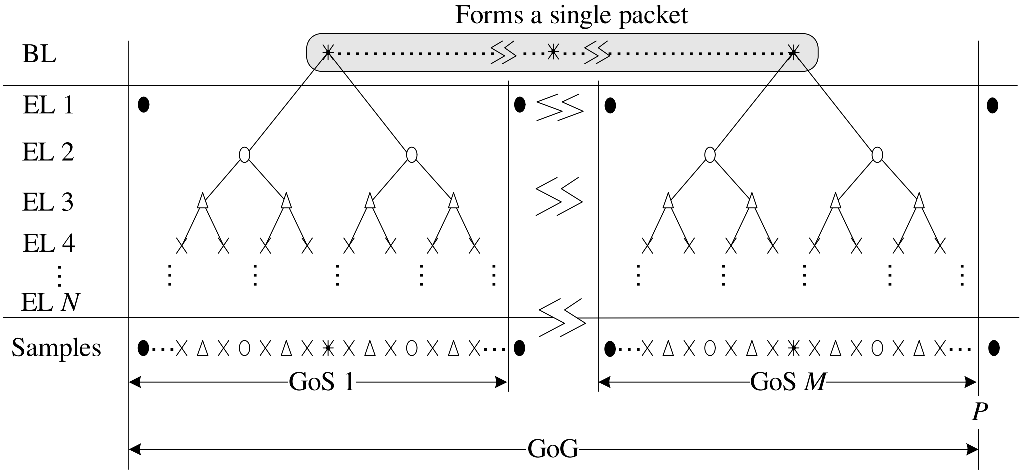


Figure 3.2: Framework for layered temporal scalability, and packetization for transmission over the wireless channel.

to different layers, as shown in Fig. 3.2. The BL ECG stream contains fundamental ECG information that is periodically sampled at a low frequency. The EL contains ECG data sampled at higher frequencies in different time domains to produce the expected scalability.

Temporal scalability involves the partitioning of a group of samples (GoS) into a single BL and multiple ELs. Samples at the center of each GoS are packed into a single BL packet according to their sequence numbers; then this BL packet is transmitted with the highest priority. Assuming that the size of a packet and that of each ECG sample is L_{payload} and L_{smpl}, respectively, constructing a single BL packet requires $M = L_{\text{payload}}/L_{\text{smpl}}$ GoSs, and the interval of M GoSs is known as the period P. A layered structure for representing ECG data with N ELs is shown in Fig. 3.2.

Now, let S_0 and S_n $(1 \leq n \leq N)$ be a set that contains ECG samples corresponding to the BL and the nth EL, respectively; $\sigma_{i,j}$ is the ith ECG sample of the jth GoS. Then, S_1 includes the first ECG sample from each GoS; thus, it is defined as

$$S_1 = \{\sigma_{1,j} | j = 1, 2, 3 \ldots\}. \tag{3.1}$$

The BL sample in the jth GoS is located at $(\sigma_{1,j} + \sigma_{1,j+1})/2$. Next, the set S_2 contains two elements from each GoS, and it can be defined as follows:

$$S_2 = \left\{ \frac{\sigma_{1,j} + \frac{\sigma_{1,j}+\sigma_{1,j+1}}{2}}{2}, \frac{\sigma_{1,j+1} + \frac{\sigma_{1,j}+\sigma_{1,j+1}}{2}}{2} \right\}. \tag{3.2}$$

The first element of the set S_1 and S_n $(n \geq 2)$ corresponds to the $(2^{(N-n)}+1)$th ECG sample and the first ECG sample, respectively, whereas the interval between two consecutive elements of S_n is 2^{N-n+1}. Therefore, set S_n can generally be defined as follows when n is greater than one:

$$S_n = \{\sigma_{2^{(N-n)}+1,1} + 2^{N-n+1}k | k = 1, 2, 3 \ldots\}. \tag{3.3}$$

The number of samples in the BL $|S_0^g|$ and in the nth EL $|S_n^g|$ $(n \geq 1)$ in a period P is respectively defined as follows:

$$|S_0^g| = M,\ |S_n^g| = 2^{n-1}M\ (n \geq 1). \tag{3.4}$$

Now, the total number of samples R_g in a period P is

$$R_g = M \sum_{n=0}^{N} |S_n^g| = 2^N M. \tag{3.5}$$

As a result, the sampling frequency in the BL and in the nth EL is $R_B = M/P$ and $R_E^n = 2^{n-1}M/P$, respectively, where $R = R_B + \sum_{n=1}^{N} R_E^n$ and $P = R_g/R$.

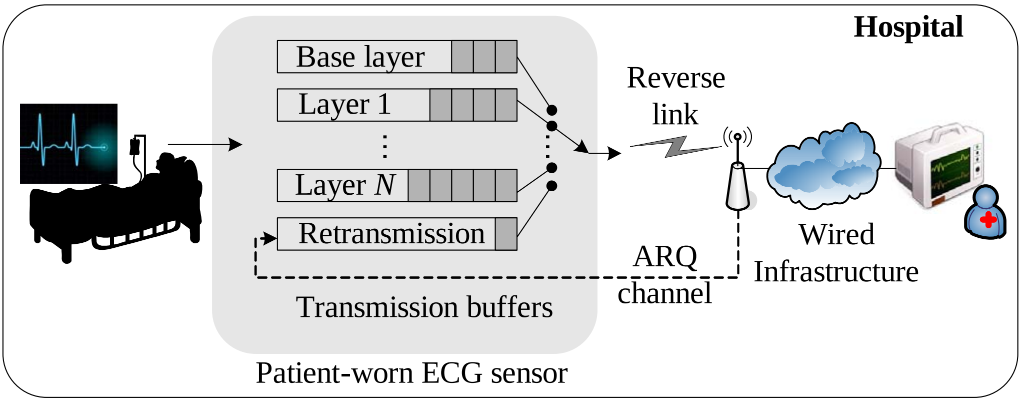


Figure 3.3: Structure for packet transmission and retransmission over wireless channel.

3.3 ARQ-Based Error Control Using LB-EDF

We adopt an ARQ-based retransmission scheme to enable reliable data transmission over a wireless channel. Fig. 3.3 shows the error-control structure for reliable ECG streaming. The buffers in the ECG sensor are used to provide some tolerance for variations in the network delay and the data consumption rates. The scheduler in the ECG sensor controls the packet transmission sequence.

Owing to the proposed layered representation of ECG data, it is intuitive to consider relative "*importance*" of the data in the scalable ECG stream in order to avoid an abrupt degradation in the quality of the ECG signal. The loss of consecutive ECG symbols has a greater effect on the ECG signal than the loss of a few random symbols. Therefore, it is desirable to prioritize the delivery of packets in the BL or lower ELs, even under severe channel conditions.

For this purpose, we assign higher priority to packets in the lower layer, these can then be transmitted earlier, with a greater opportunity for retransmission in the case of loss. Packets in the same layer are served according to EDF policy. The scheme improves bandwidth utilization and the readability of the ECG signal in the case of some data loss via the prioritization of the low-frequency data in the BL or lower ELs. A detailed description of the algorithm is provided in Algorithm 1.

Algorithm 1 Layer-based EDF scheduling algorithm

```
$d_p$: deadline of packet $p$
$O_p$: timeout value of packet $p$
$t_c$: current time
$B$: set of packets in the transmission buffers of the sensor
for every $\varphi$ time-slots do
    for $\forall p \in B$ do
        if $t_c > d_p$ then
            Remove the packet from the transmission buffer
        end if
    end for
    Select packet $p' \in B$ with the lowest layer and the earliest deadline
    Send $p'$ to the BS
    $O_{p'} \leftarrow (t_c + \delta + \mathrm{RTT})$.
    if the sensor gets an ACK of $p'$ from the BS within $O_{p'}$ then
        Remove $p'$
    else
        Move $p'$ into retransmission buffer
    end if
end for
```

3.4 Performance of Wireless ECG Transmission

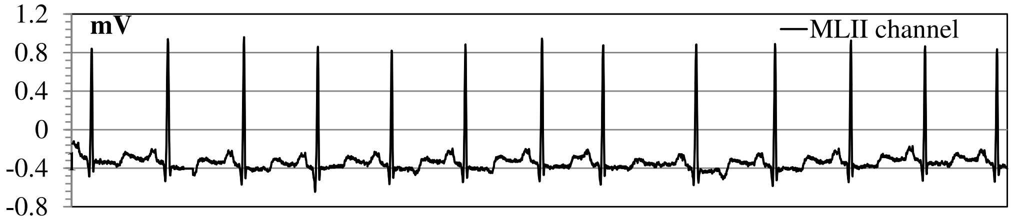
In the simulation, we set the packet size to 512 bits; each packet contains a maximum payload of 490 bits and a packet header of 22 bits. The fundamental timing unit for packet transmission is set to 1.67 ms, as per the CDMA2000 1xEV-DO Revision A standard [72]. The transmission of a packet requires one time-slot, and the resulting reference channel data-rate is 307.2 kb/s. All the parameters used in our simulation are listed in Table 3.1.

The relative advantage of our framework can clearly be seen in Fig. 3.4, which depicts a snapshot of the original ECG signal obtained from patient and that of the corresponding signal reconstructed in the RMS when the channel error rate is 0.1 and the patient moves at 2 km/h (channel errors were modeled using the threshold model suggested by Zorzi et al. [73]). It is observed that compared to the original ECG signal in Fig. 3.4a, the ECG signal reconstructed with conventional transmission framework (CTF), which serially packetizes consecutive symbols in order, frequently omits important ECG information; this might lead a physician to misinterpret a patient's condition.

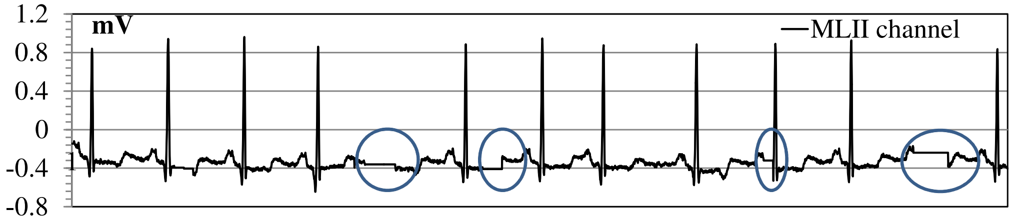
However, for the same pattern of error in the wireless channel, the perceived quality of the reconstructed signal degrades very gracefully in our framework, as shown in Fig. 3.4c, with the help of layered representation and by selectively recovering packets with higher priority. *This provides the physician with a better chance of arriving at an accurate diagnosis.*

Table 3.1: Simulation parameters.

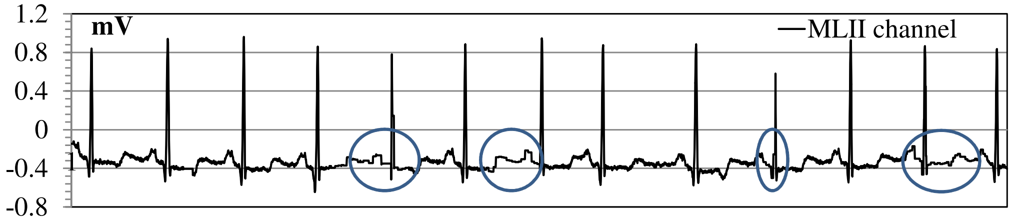
Symbol	**Value(s)**	**Description**
τ	1.67 ms	Duration of a time-slot
φ	3	Interlacing factor
N	3	Number of layers
L_{pkt}	512 bits	Length of a packet
L_{payload}	490 bits	Length of payload in each packet
ϵ	0∼0.1	Steady-state PER
v	2 km/h∼5 km/h	Mobile speed of patients
f_c	1.8 GHz	Carrier frequency
μ	307.2 kb/s	Reference channel data-rate
η	2	Number of leads
R	360Hz	Samples per second
L_{smpl}	11 bits	Sample size
μ_s	3.96kb/s	Data-rate of each ECG channel
μ_{ecg}	7.92 kb/s	Total data-rate of ECG recordings
δ	1 time-slot	Feedback delay



(a) Original signal



(b) Reconstructed signal at the RMS using conventional framework



(c) Reconstructed signal at the RMS using the proposed framework

Figure 3.4: Snapshot of ECG signal fluctuations for MLII channel when the channel error rate is 0.1 and the patient moves at 2 km/h.

The proposed adaptive framework can effectively limit the effect of error bursts that are commonly occur in a wireless channel, hence ensures that the *perceptual quality degrades gracefully under severe channel conditions*.

Chapter 4

Conservative Modulation and Coding for Instantaneous ECG Monitoring over LTE MTC

Emergence of MTC

Recently, the third generation partnership project (3GPP) has announced a series of standards [74–82] to extend the long term evolution of communication services for supporting various kinds of non-human type mechanical automation scenarios, called M2M communication, or MTC [83–86]. European telecommunications standards institute (ETSI) also published several technical standards [19, 87–89] to cope with those increasing demand for various type of M2M applications.

Fig. 4.1 shows an overall system architecture of MTC [79]. MTC is mainly

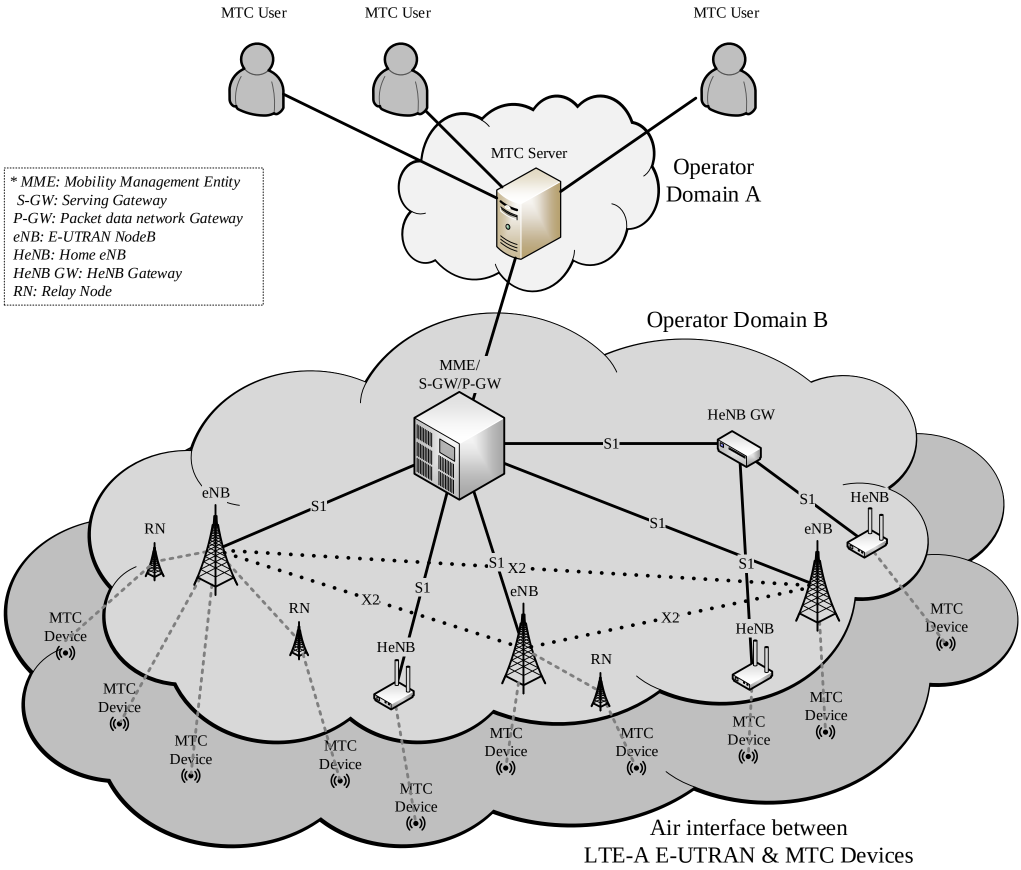


Figure 4.1: MTC system architecture.

designed to provide adequate uplink channel for smart metering, smart grids, and thus, they can achieve low-power consumption, small feature size, as well as simplified antenna architecture [90–92]. The 3GPP MTC is hoped to supply sufficient reliable wireless channels to cover wide area as well as provide low-cost, tiny-sized, energy efficient mobile hardwares at the same time [93–99].

As part of the upcoming release of the global 3GPP standard in an effort towards optimizing the LTE-Advanced for MTC, "LTE MTC" draws attention due to its many advantages, including: 1) benefits from the reliability, pervasiveness, security, and performance of 3G or 4G LTE; 2) significantly increased battery life, with reduced cost and enhanced coverage; and 3) coexistence with mobile broadband services, enabling continued innovations in the M2M business model. Therefore, it is expected that LTE MTC will play a key role among the multiple solutions required to connect the Internet of Everything in the near future. In this chapter, we proposes a univsersal framework to enable a dependable M2M ECG transmission over various cellular networks including the latest LTE MTC.

4.1 Architecture of Universal M2M ECG Platform

Service Architecture

In general, an ECG device can collect the continuous series of electrical signals from the heart. These signals are received by ECG sensors (electrodes) attached to the patient, sampled, and then digitized. Then adequate compression technique can be adopted to improve the bandwidth efficiency of the system.

ECG leads use different combinations of electrodes to monitor various signals from the heart. If the electrical signals from the heart are sampled by N_r leads, and the signal from each lead is digitized at a rate of N_s samples per second with a sample size of L_s bits, and the average compression ratio for the sample is CR_s, then the resulting data-rate of the wireless ECG application would be

$$\mu_{\mathrm{ECG}} = N_r \times N_s \times L_s \times CR_s. \tag{4.1}$$

The digital stream is packed into frames in a packetization process, and then sent to a remote monitoring device over a wireless channel.

Fig. 4.2 shows the architecture of the proposed system for remote ECG monitoring. A wearable wireless ECG sensor that consists of multiple electrodes, a wireless transmitter, and a receiver is used to continuously measure the heart activity of a mobile patient. The resulting digital stream is grouped into packets that then transmitted wirelessly to remote healthcare professionals in real time over a secure wireless connection.

In the proposed wireless system, the ECG monitoring application is developed based on the infrastructure mode, which requires a fixed base station (BS) to be connected to an established fixed network infrastructure. This BS provides a communication portal for wireless ECG sensors worn by patients within its range. The data collected from the ECG sensors worn by multiple patients is transmitted wirelessly to a nearby BS, following which the BS relays this data over wired infrastructure to an RMS, as shown in

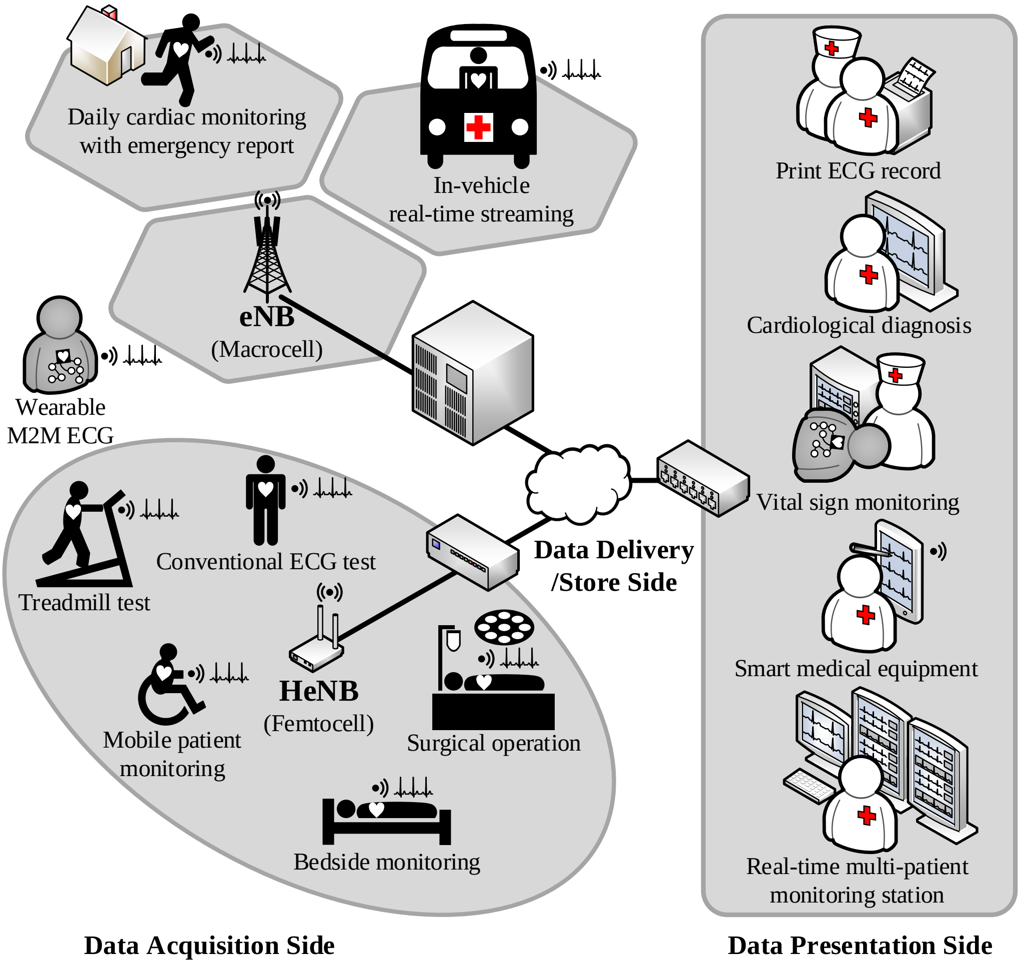


Figure 4.2: Service scenario of wearable telecardiology system.

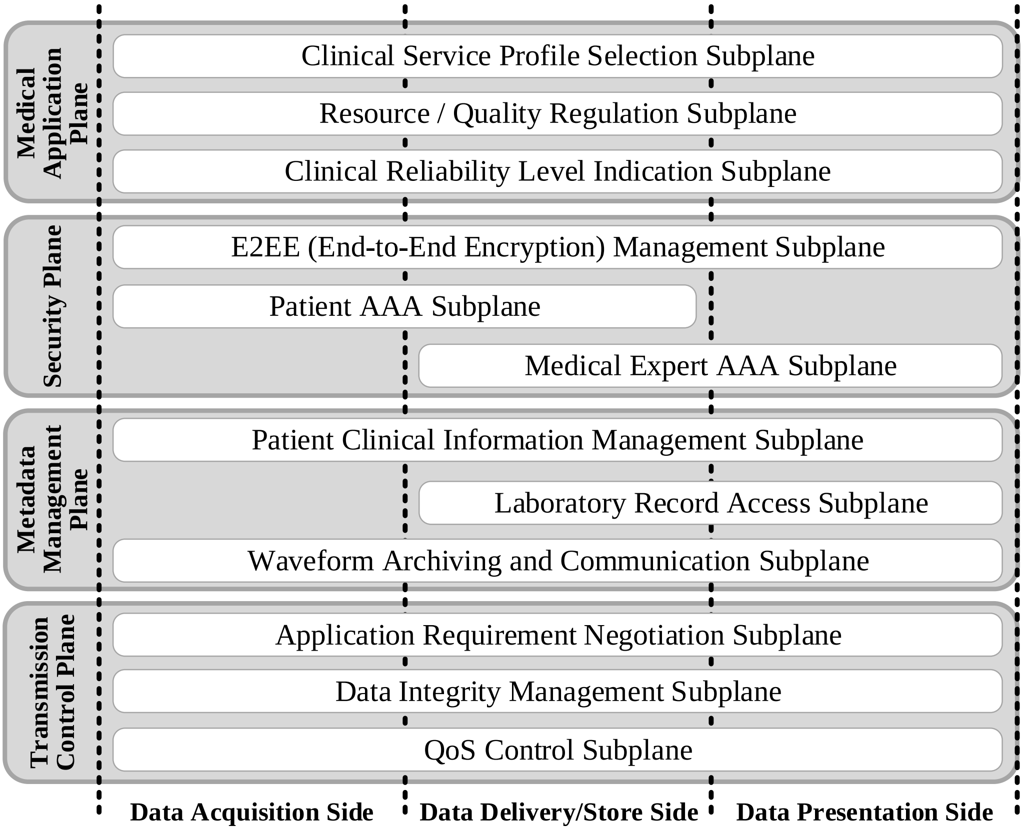


Figure 4.3: Universal M2MECG logical framework

Fig. 4.2. Wired infrastructure transmits data at higher speeds and with greater reliability than a wireless network, and therefore, all data losses and transmission delays can be attributed to the wireless network without significant inaccuracy.

4.2 Demand for Instantaneous Monitoring

A crucial issue pertaining to ECG data transmission over LTE MTC for remote monitoring is the delay between the real-time status of the patient and the information displayed on the remote monitor. According to the latest recommendation of the American heart association (AHA) [100], recent observations by healthcare providers indicate that most wireless hospital telemetry systems used for monitoring patients' heart rhythms tend to exhibit clinically significant delays between the current heart condition and the displayed ECG pattern. This temporal inconsistency of real-time cardiac information can compromise the safety of the patient in various clinical situations that demand instantaneous monitoring. For this reason, the advisory recommended the use of hard-wired telemetry systems instead of wireless systems for instantaneous ECG monitoring.

To handle this latency issue, this chapter extends the adaptive framework of previous chapter 3, which introduced an adaptive framework for temporal scalable layered representation and transmission of ECG data over CDMA2000 1xEV-DO network to accommodate a time-varying wireless channel. Based on this previously proposed adaptive framework, this chapter proposes a novel approach focusing on the latency aspect, which is an enhanced spatio-temporal scalable system with a novel adaptive modulation and coding scheme for the low-latency delivery of ECG data over LTE MTC to meet two crucial QoS considerations for instantaneous monitoring. These QoS considerations are extremely short delay, and effective representation and robust delivery of ECG data to enhance its interpretation.

To begin the research, the timing aspects for the overall process of real-time ECG monitoring systems, from ECG signal acquisition and sampling steps to the entire communication procedure of LTE MTC systems, was analyzed. As a result, three major elements that can lead to nondeterministic and significant delays in the system were successfully identified, and unnecessary buffers and delay from those elements were eliminated. To begin with, any ECG data encoding steps that demand a considerable level of buffering process were bypassed. Then, by adopting a dedicated channel allocation scheme, the latency of the packet scheduling process was made negligible and deterministic. Finally, the retransmission steps of hybrid automatic repeat request (HARQ) were eliminated to achieve a satisfactory level of end-to-end latency.

Subsequently, a novel scalable media encoding and communication error control scheme was introduced to cope with all the handicaps induced by those system-level restrictions. By analyzing the exact amount of physical information that is required by various clinical environments, ECG service profiles were categorized into three levels: mandatory profile for real-time LCD (Liquid-Crystal Display) display, standard profile for the purpose of diagnostic printout, and high precision profile to provide more sophisticated accuracy for high end medical services. Then, a spatio-temporal scalable ECG coding scheme that covers these levels of service profiles in a versatile fashion without any extra system delays was introduced.

Finally, the channel quality indicator (CQI) mapping process of LTE MTC systems was modified to provide additional protection against channel errors to the mandatory part of the ECG stream at the cost of the total channel efficiency and throughput. As a result, the provision of a minimum margin for medically required level of service in real-time monitoring services under various channel conditions with extremely short system delays is guaranteed. Moreover, it was observed that by protecting the essential portions of ECG signals, the proposed system surpasses the original ones in terms of total signal distortion, especially in poor channel conditions.

4.3 System Requirements for Instantaneous Monitoring Services

4.3.1 Latency Requirements and Analysis

Clinical Request for Instantaneous Monitoring Services

According to a recent advisory of the AHA [100], most of the current wireless ECG monitoring systems may exhibit clinically significant delays in displaying continuous ECG data on patient monitoring displays. Because delayed information transmission can threaten the safety of patients in situations in which instantaneous monitoring is preferable or necessary, the advisory recommends the use of hard-wired monitoring systems in such clinical situations instead of wireless ones.

In general, if a delay occurs between the actual current cardiac status and the ECG patterns displayed on the cardiac monitor, inappropriate medical assessments may be made, and this error can cause negligent treatment or malpractice. For example, an adverse event report for U.S. Food and Drug Administration describes unnecessary defibrillation shock induced by such temporal mismatching of current cardiac condition assessment [101]. After executing the first successful electric cardioversion, the physician misjudged the consequence of the shock as a failure because the wireless real-time monitor still displayed a series of atrial flutters that actually occurred several seconds before the first shock. In fact, the patient was successfully cardioverted to normal status at the first shock, but the normal sinus rhythm showed up several seconds later, during the execution of the second shock.

Likewise, there are various clinical situations that require assessing exact information about current cardiac condition without delay to prevent clinical malpractice. Table 4.1 from the AHA advisory [100] shows some examples of various clinical situations that require instantaneous monitoring.

Recommendation from AHA for Latency of ECG Displays: Wireless ECG Requires Shorter Latency with Guaranteed Worst Case Delay Bound

Recommendations for Healthcare Providers

When instantaneous assessment of the rhythm is preferable or necessary, telemetry systems with the potential for clinically significant latency or data dropout should not be used. Patients should be hard-wired to a bed-

Table 4.1: Clinical situations in which instantaneous monitoring is recommended

Emergency situations

- Resuscitation
- Hospital "codes"
- Defibrillation

Assessment of pacemaker function

- Interrogation or reprogramming of implantable pacemakers, defibrillators, and cardiac resynchronization devices
- Assessment or reprogramming of temporary pacing devices

Termination or cardioversion of arrhythmias

- Electrical cardioversion
- Administration of intravenous adenosine or other short-acting antiarrhythmic drugs

Bedside procedures

- Insertion of central venous or pulmonary artery catheters from jugular or subclavian approach
- Insertion of transvenous pacemakers
- Carotid sinus massage

side monitor in plain view of care providers. In addition, for cardioversion or defibrillation, it is advisable to connect separate monitoring leads directly to the monitor of the external defibrillator to ensure instantaneous assessment. When doing so, disconnection from the wireless telemetry system is not required as long as the hard-wired monitor is used for clinical assessment and care. For pacemaker or defibrillator testing or reprogramming, ECG leads should be connected directly to a monitor that displays the rhythm without delay, such as a pacemaker/defibrillator programmer. These same considerations apply to insertion of temporary pacing electrodes and central venous catheters, because arrhythmias can be provoked by cardiac instrumentation.

Recommendations for Hospitals and Care Facilities

Medical facilities with wireless telemetry systems should contact the manufacturers of their telemetry systems to determine the extent, if any, and severity of delays and to obtain product-specific recommendations. Facilities should educate clinical personnel with patient care responsibility (nurses, physicians, allied health professionals, trainees) about these delays. They should be instructed to avoid reliance on these systems for instantaneous rhythm assessment. Protocols or guidelines for appropriate use of hardwired real-time monitoring may improve adherence to these recommendations. A warning label affixed to the telemetry monitor that describes the problem and outlines recommendations for instantaneous monitoring may be an effective tool to alert and continue to remind care providers (Figure 2). Finally, wireless interference, network congestion, and duration of telemetry delays should be evaluated carefully at the time of installation and at regular intervals. Measures to reduce interference and congestion may result in substantial improvement in telemetry delays.

Recommendations for Industry

Although telemetry system manufacturers recognize the problems of latency and data dropout, these issues may not be clearly understood by purchasers or healthcare providers. We recommend that manufacturers communicate transparently and educate healthcare personnel about the delays that may be observed in their monitoring systems. Manufacturers should make it clear in all promotional materials and product specifications that use of these systems may result in latency. Although some manufacturers do appropriately differentiate real-time or instantaneous telemetry from near-time or near real-time use, the clinical implications of these differences should also be articulated during training and in-servicing. We also recommend that the regulatory standards of delay in display of the patient's cardiac rhythm and other hemodynamic and physiological parameters be reconsidered by industry and regulatory bodies, with guidance from clinicians, in an effort to reduce these delays to as short a time as is technically feasible. Specifically, regulatory standards should not only address individual component delays but also articulate the total acceptable delay from the time the rhythm occurs to the time it is displayed, based on intended use. We also recommend that a consistent regulatory definition of near-time and real-time be used.

Although AHA recommends the use of hard-wired telemetry systems for instantaneous monitoring, because of the significant and nondeterministic latency of wireless real-time monitoring systems, the goal is to design a wireless ECG monitoring system that has a level of latency equivalent to the hard-wired ones. In Section 4.4, an example of a reliable wireless instantaneous monitoring system based on LTE MTC is introduced.

System-level Latency Analysis for Ultra-Low Latency Instantaneous ECG Monitoring

To minimize the system-level latency for instantaneous ECG monitoring through wireless connections down to 10 ms of ultra-low level, the timing aspect of the overall process of real-time ECG monitoring system based on LTE MTC was analyzed. Wireless ECG monitoring systems can be divided into data acquisition, delivery, and presentation according to their physical and logical features. In general, end-to-end latency of these systems can be regarded as:

$$d_{total} = d_A + d_D + d_P, \tag{4.2}$$

where d_{total} is the total delay of the system and d_A, d_D, and d_P denote the delays in acquisition, delivery, and presentation, respectively.

As shown in Fig. 4.4, d_A is mainly caused by media encoder and d_D by the LTE system latency, such as packetizing, scheduling, and waiting time for retransmission. Because d_P is relatively insignificant and subordinate largely to media encoding and communication schemes on the data acquisition and delivery side, the analysis for the presentation side is included in the other two sides.

In the beginning, to shorten the latency of data acquisition side, d_A, the focus is on the media encoder. Media encoding latency, which is represented as d_1 in Fig. 4.4, can be dramatically lowered by skipping the data compres-

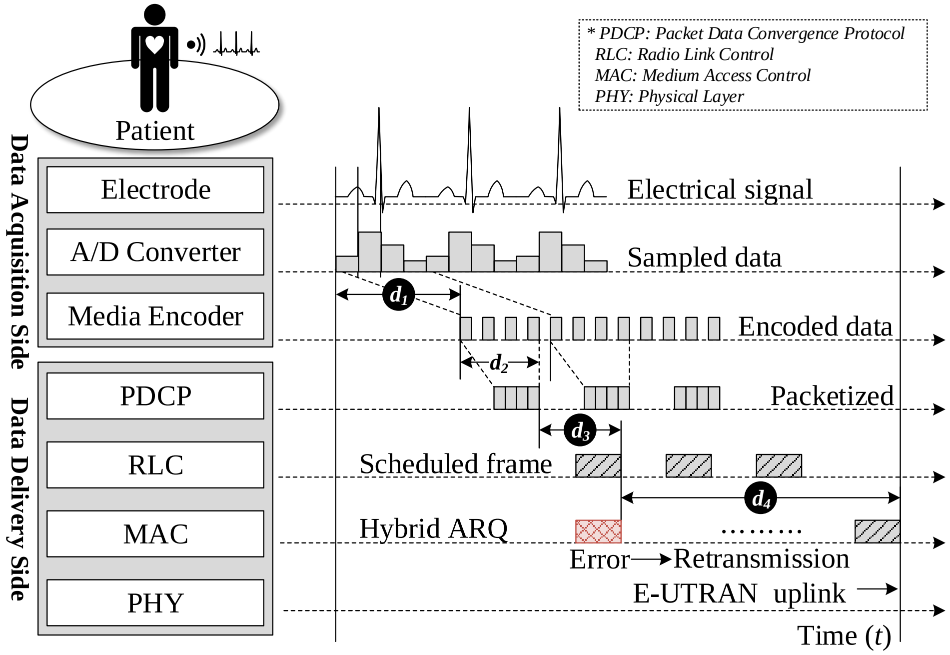


Figure 4.4: Latency of real-time ECG monitoring system.

sion procedures. The process of data compression usually demands a long buffering time to effectively compare every data segment with each other for searching data redundancy in spatial or temporal domains. For this reason, if data comparison procedures of data compressor are omitted, a huge amount of buffering delays can be prevented. However, without any data compression, the data rate for ECG could become much higher. To handle this high data rate problem, a spatio-temporal scalable media-coding scheme is adopted, which is discussed in Section 4.4.1.

Next, the timing aspect of the data delivery side, d_D is analyzed. In general, the LTE communication system has two levels of service planes [80, 102]. Control plane (C-Plane) is for signaling and control functions and user plane (U-Plane) deals with actual delivery function for user payloads. C-Plane latency is the time between idle and active states of user equipment (UE) before initiating the U-Plane communication. In order to minimize the huge amount of C-Plane delays, the monitoring system should be operated in contention free mode with preallocated system resources. Furthermore, U-Plane latency can be decreased by minimizing the scheduling delays, which are marked as d_3 in Fig. 4.4. To minimize the communication scheduling delays, dedicated service mode for predetermined channel bandwidth should be adopted.

Moreover, in order to save a huge amount of nondeterministic wait time for the LTE HARQ process, d_4 in Fig. 4.4, it was decided to omit the ARQ retransmission process. Instead, a novel physical layer modulation scheme, referred to as conservative modulation, was introduced as the error-level regulating mechanism. Additional details about the scheme are discussed in Section 4.4.2.

In addition to the selection of these encoding and communication schemes, minimizing delays associated with encoding, scheduling, and error controlling layers by adopting a minimum buffering scheme was also attempted. The proposed policy for buffer management involves maintaining the buffer at the lowest level and emptying it as soon as possible at an exactly scheduled timing point. To implement this minimum buffering policy, all the components of a system should be operated in harmony with a synchronized system-wide clock signal.

4.3.2 Presentation Requirements for Sufficient Clinical Accuracy

In general, data related to medical information services, especially for vital signals, tend to be handled with a high level of computing services because of their clinical significance. Redundant amounts of system resources are allocated as parts of the best efforts to provide sufficient safety margins for medical applications, which can have catastrophic consequences once their required threshold of service has been violated. However, the physical characteristics of the final output targets of these systems can be analyzed in a more sophisticated manner according to the clinical purposes of the corresponding ECG application. In the next section, a brief analysis of the actual level of medical information required based on the output device specifications is presented.

The actual horizontal length of the ECG pattern displayed on target presentation devices, L_P^X can be calculated as

$$L_P^X = \frac{N_P^X}{\lambda_P}, \tag{4.3}$$

where λ_P denotes the physical pixel density of the target presentation medium, which differs among different types of output devices from LCD panels to various kinds of print-out equipment. N_P^X is the actual number of effective horizontal pixels on that medium. In this case, if N_D of the sample information is delivered successfully, then every physical pixel on the target presentation medium will be fully utilized:

$$N_D \geq N_P^X = L_P^X \lambda_P. \tag{4.4}$$

The total number of samples acquired from electrode N_A is the product of the sampling frequency of the ECG stream f_A and its time duration τ_A:

$$N_A = f_A \tau_A. \tag{4.5}$$

To deliver a sufficient amount of N_D from these acquired samples, the sampling frequency of the delivery stream f_D should be greater than or equal to the number of effective pixels on the presentation medium over the displaying time duration τ_P on the presentation side:

$$f_D \geq \frac{N_P^X}{\tau_P}. \tag{4.6}$$

The duration on the presentation side is as follows:

$$\tau_P = \frac{L_P^X}{S_P}, \tag{4.7}$$

where S_P denotes display speed. By substituting (4.3) and (4.7) in (4.6), the following relation can be obtained:

$$f_D \geq \frac{S_P}{\lambda_P}, \tag{4.8}$$

where λ_P can be given by the output device resolution specifications, and S_P is standardized at 25 mm/s [29].

Likewise, the actual vertical length on the presentation side L_P^Y can be given by

$$L_P^Y = \frac{N_P^Y}{\lambda_P}, \tag{4.9}$$

where N_P^Y is the number of vertical pixels on the presentation side. In this case, to maximize the utility of those pixels, the number of resolution levels for the delivered sample, η_D is required to be greater than or equal to this number of effective pixels:

$$\eta_D \geq N_P^Y. \tag{4.10}$$

L_P^Y can also be given by the following equation:

$$L_P^Y = \frac{V_{PP}}{\sigma_P}, \tag{4.11}$$

where V_{PP} denotes the peak-to-peak voltage range to display and σ_P is the presentation density of electrical voltage amplitude over physical length of presented medium.

By substituting (4.9) and (4.11) in (4.10), the following relation is obtained:

$$\eta_D \geq \frac{V_{PP}\lambda_P}{\sigma_P}, \tag{4.12}$$

where V_{PP} and σ_P are given by the standard ECG paper specification as 10mV and 100 μV/mm, respectively [29].

As mentioned above, λ_P differs according to the type of presentation medium. For example, in the case of a conventional 72 PPI (Pixels Per Inch)

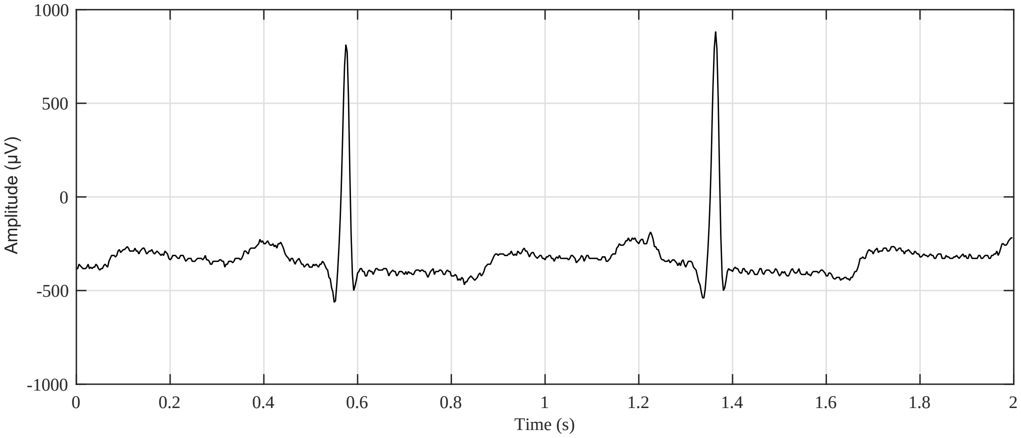
Table 4.2: Presentation device type and ECG delivery profiles

Presentation Device Type	72 PPI LCD Panel	300 DPI Inkjet Printer	2400 DPI Laser Printer
λ_P (pixels/mm)	2.8346	11.8110	94.4882
$min(f_D)$ (Hz)	70.8661	295.2756	2,362.2047
$min(\eta_D)$ (levels)	56.6929	236.2205	1,889.7638

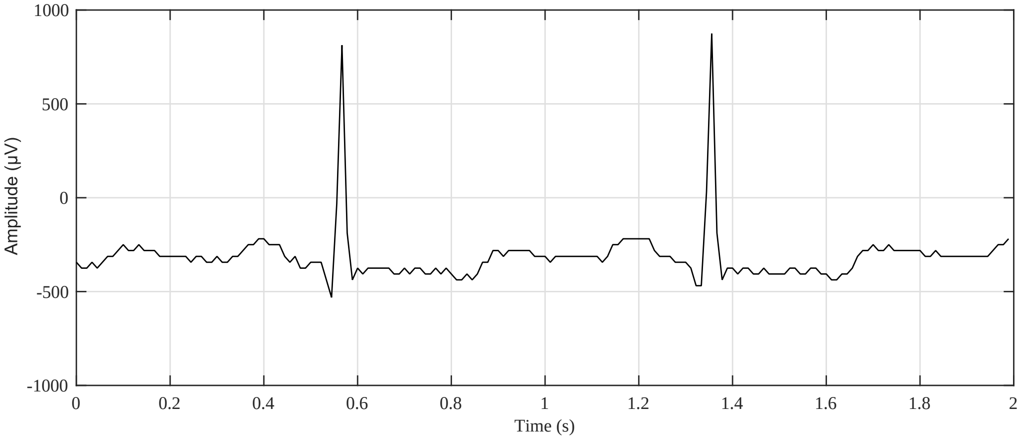
ECG profile	Mandatory	Standard	High-precision
f_D (Hz)	75	300	2,400
η_D (levels)	64 (6-bits)	256 (8-bits)	2,048 (11-bits)

LCD display for real-time ECG monitoring, λ_P is about 2.83 pixels/mm. A 300 DPI inkjet printer demands about 11.81 pixels/mm, and a 2400 DPI laser printer requires about 94.49 pixels/mm. The data required to present this number of pixels can be simply calculated by (4.8) and (4.12).

Table 4.2 shows detailed results for the f_D and η_D calculated for various presentation device types, and Fig. 4.5 shows the actual acquired quality level differences between the standard and mandatory profiles. The horizontal lengths of both graphs, which represent 2 s, are scaled to display at 5 cm in physical dimension according to the ECG standard. As it can be observed on various LCD displays, if a 6-bits partition of 75 Hz of the total acquired ECG signal is successfully delivered to the presentation side, it can provide sufficient information to fully utilize each effective pixel on a 72 PPI LCD display. Any extra information does not enhance the diagnostic quality of the ECG pattern presented on such low resolution presentation medium [103].



(a) Standard ECG profile.



(b) Mandatory ECG profile.

Figure 4.5: Presented ECG resolution according to the ECG profile.

For this reason, 6 bits 75 Hz of data stream were selected as the mandatory profile for real-time screen monitoring of the ECG, and 8 bits 300 Hz of data stream as the standard profile for diagnostic 300 DPI inkjet printing purpose. Similarly, 11 bits at 2400 Hz of the data stream are required for the highest resolution of 2400 DPI laser printer, called a high precision profile, which is the upper limit of the proposed profiles for the ECG data transmission.

4.4 System Architecture for Instantaneous Wireless ECG Monitoring using LTE MTC

Fig. 4.6 shows an example of a service scenario using the proposed system for remote ECG monitoring. A wearable wireless ECG sensor that consists of multiple electrodes, a wireless transmitter, and a receiver are used to continuously measure the heart activity of a mobile patient. The ECG sensor uses different combinations of electrodes to monitor signals from the heart. If the electrical signals from the heart are sampled be ε electrodes, and the signal from each lead is digitized at a rate of f samples per second with a sample size of η bits, then the resulting data rate of the wireless ECG application will be

$$\mu_{\mathrm{ECG}} = \varepsilon f \eta. \tag{4.13}$$

The digital stream is packed into frames using a packetization process and transmitted wirelessly to remote nodes in real time over a secure LTE MTC channel.

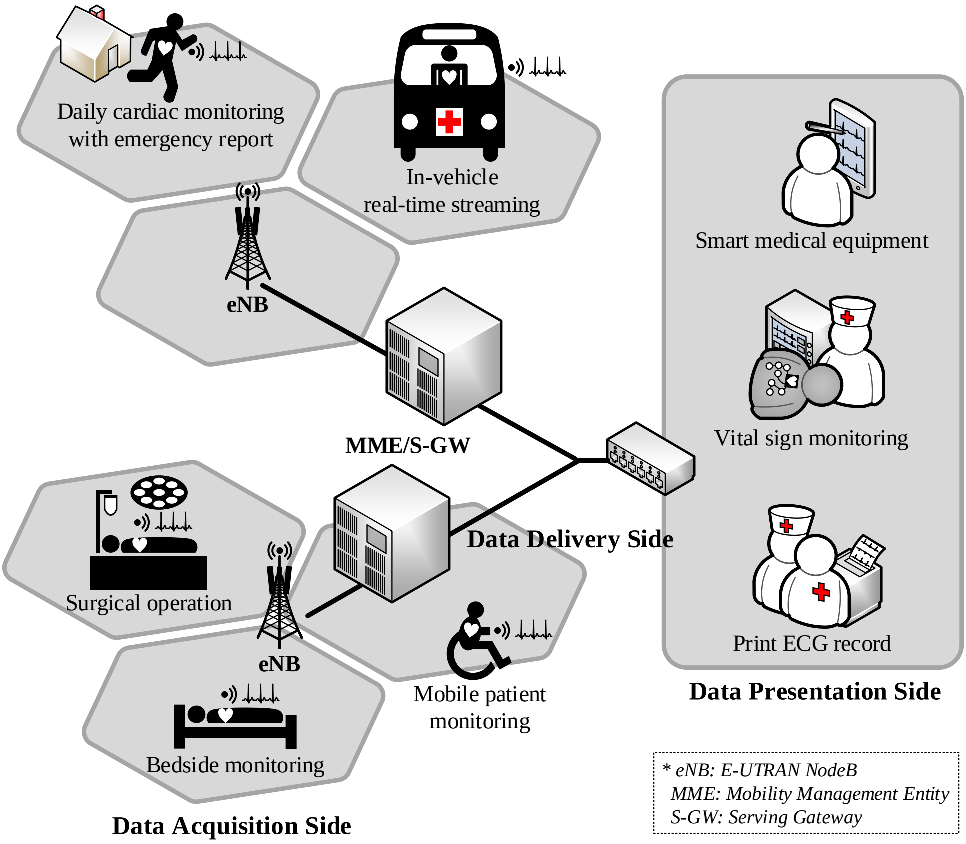


Figure 4.6: Service scenario of instantaneous ECG monitoring system based on LTE MTC.

4.4.1 Spatio-Temporal Scalable Media Coding for ECG signal

As discussed in Section 4.3.1, the latency of the data acquisition side can be minimized by avoiding data compression. In this section, a simple and effective method to make the ECG code scalable in both spatial and temporal domains is introduced.

In general, a continuous series of voltage fluctuations of the ECG signal acquired by the electrodes is converted to discrete digital data using a given sampling frequency and bit resolution by an analog-to-digital converter. The acquired raw data can be converted to a $(value - base)/gain$ form to express the waveform of the ECG. In this case, the ECG data can be normalized to a certain range of voltage fluctuations bound for a given time window. The normalized value can be arranged into a series of data bits from the most significant bit to the least significant bit. Then, the ECG data can be segmented into any bit count to form spatially scalable ECG codes. Temporally scalable ECG codes can be composed by selecting code groups from the acquired ECG signal according to their target sampling frequency, as is shown in Fig. 4.7.

Combining both spatial and temporal scalability, Fig. 4.7 presents the sequential order of the proposed spatio-temporal scalable coding. The marked numbers on each code segment denote their transmission priority, which increases along the spatial axis preferentially and then along the temporal way. In this case, the required bitrate to deliver the i-th temporal level and

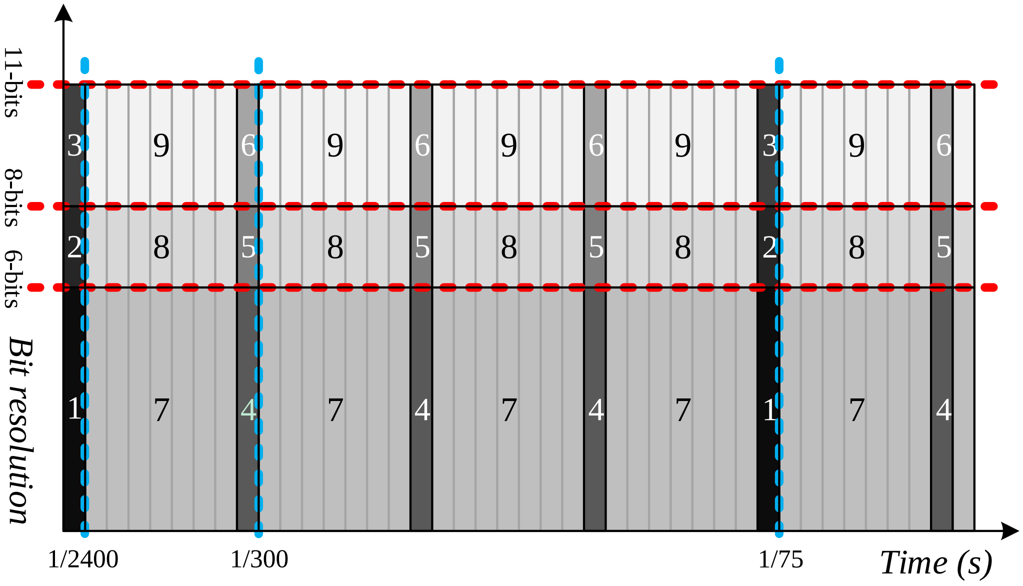


Figure 4.7: Sequence order of spatio-temporal scalable coding.

j-th spatial level, $B(i, j)$ can be calculated as

$$\begin{aligned} B(i, j) &= f_D(i-1)\max(\eta_D) \\ &+ \{f_D(i) - f_D(i-1)\}\,\eta_D(j), \end{aligned} \tag{4.14}$$

where $f_D(i)$ denotes the sampling frequency of the i-th temporal level, $\eta_D(j)$ denotes the number of bits for the j-th spatial level, and $\max(\eta_D)$ is the maximum bit count for the highest spatial level. The actual bitrates for the proposed spatio-temporal scalable layers are shown in the Fig. 4.8.

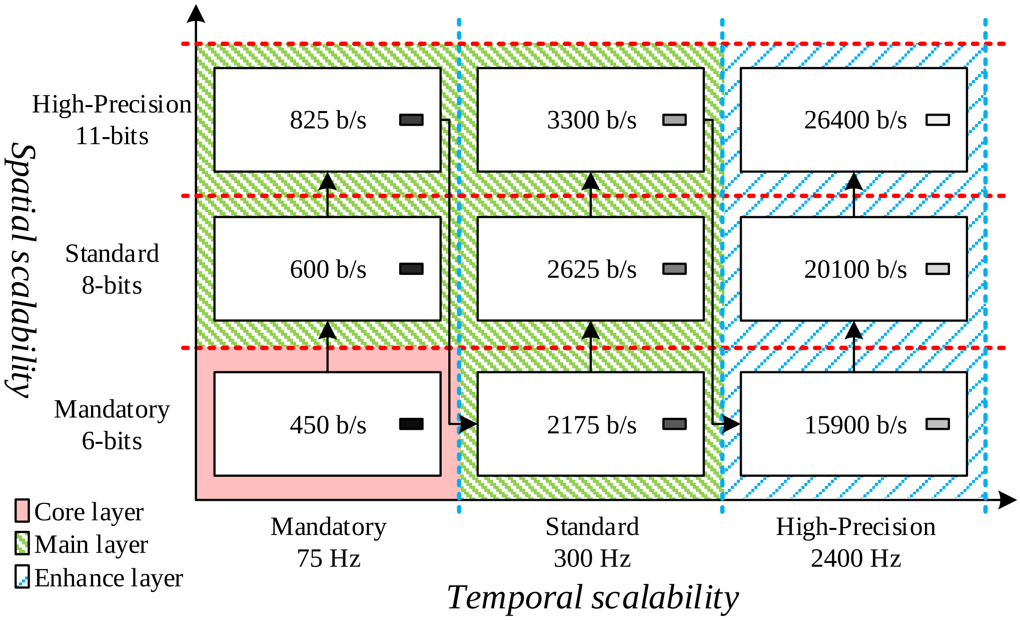


Figure 4.8: Service order and bitrate of each layer of spatio-temporal scalable coding.

Table 4.3: 4-bit MCS table

MCS#	**Modulation**	**Code Rate ×1024**	**Efficiency**
0		N/A	
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	16QAM	466	2.7305
11	16QAM	567	3.3223
12	16QAM	666	3.9023
13	16QAM	772	4.5234
14	16QAM	873	5.1152
15	16QAM	948	5.5547

4.4.2 Conservative Modulation and Coding to Provide Extra Protection for Higher Prioritized Scalable Layers

LTE systems adopt adaptive modulation and coding (AMC) scheme for link adaptation technology by varying the modulation scheme and code rate according to the channel conditions. Higher-order modulation schemes, such as m-ary quadrature amplitude modulation (m-QAM) have higher spectral efficiency, whereas lower order schemes such as binary phase-shift keying (BPSK) are more robust under error-prone conditions. In a standard MTC system [79, 80], the base station (eNodeB) estimates the uplink channel quality of the UE using sounding reference signals (SRSs) and assign the highest possible modulation and coding scheme (MCS). The standard intentionally retains errors, targeting the block error rate (BLER) of up to 10%, which can be handled by retransmission combined with incremental redundancy of the forward error correction technique to maximize the spectral efficiency and data rate. Table 4.3 shows the standard 4-bit mapping table of the given CQI to specific MCS, and Fig. 4.9 shows the simulation results of the MTC uplink AMC performance based on this mapping table over the additive white Gaussian noise (AWGN) channel. Further details on these simulations are presented in Section 4.5.

This study introduces a novel conservative CQI to MCS mapping scheme, which minimizes end-to-end latency while maintaining adequate quality of ECG patterns by providing extra protection to higher prioritized layers by sacrificing the total spectral efficiency and throughput.

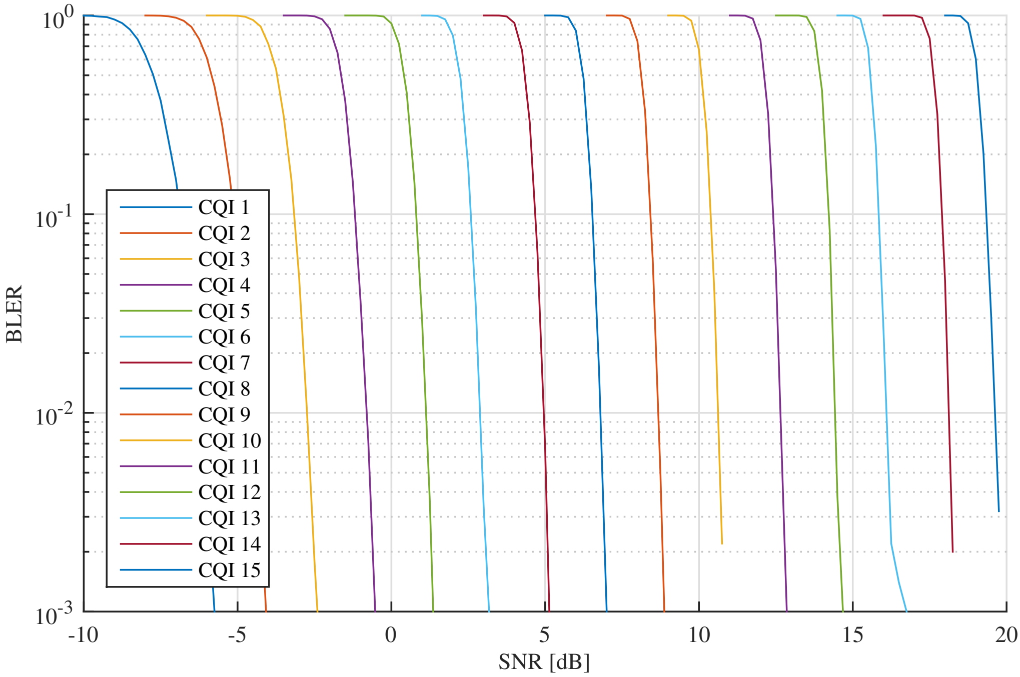


Figure 4.9: MTC uplink AMC simulation result BLER of 1.4 MHz bandwidth at 2.4 GHz carrier frequency.

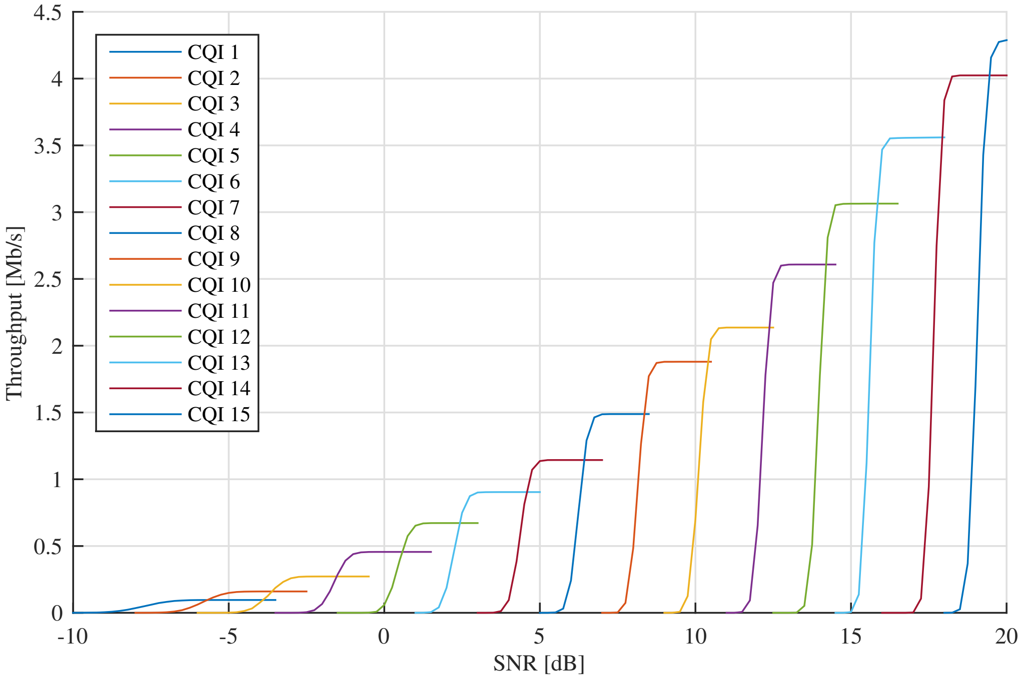
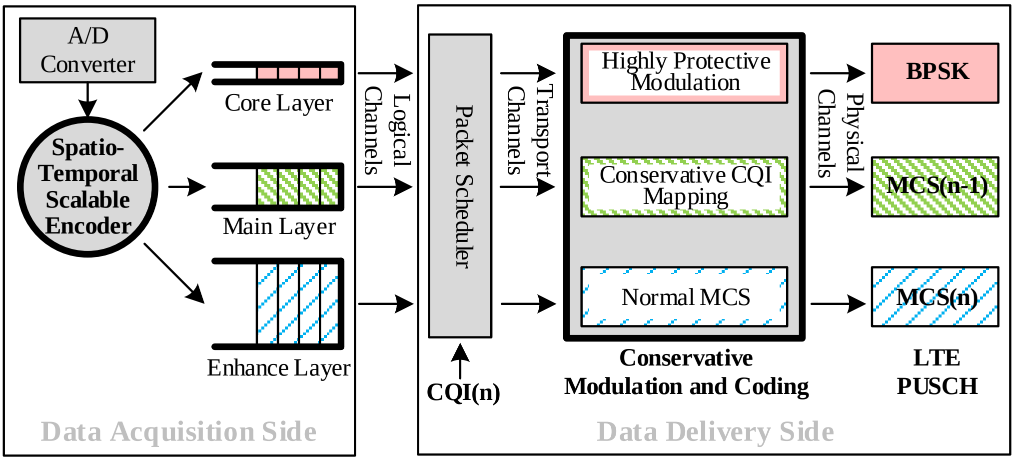


Figure 4.10: MTC uplink AMC simulation result throughput of 1.4 MHz bandwidth at 2.4 GHz carrier frequency.



** CQI(n): Channel Quality Indicator #n   MCS(n): Modulation Coding Scheme #n*
PUSCH: Physical Uplink Shared Channel

Figure 4.11: Conservative modulation and coding to protect higher prioritized layers.

As shown in Fig. 4.8, the previously introduced spatio-temporal scalable encoder classifies scalable data layers according to their profile levels. The data layers can be categorized in three groups: a *core layer* to deliver mandatory portion of total signals, *main layers* for transferring up to temporal standard profile level, and *enhance layers* for beyond the temporal standard profile.

Fig. 4.11 shows the overall signal processing steps for the proposed CQI mapping scheme. As discussed in Section 4.3.1, retransmission is eliminated from the error control process to minimize the latency in the system. Instead, the scheme utilizes the reserved channel bandwidth for retransmission to higher prioritized layers, such as core or main layers.

Because the bitrate of the *core layer* is approximately 1-2% of the total ECG data, the BPSK modulation scheme was used for delivering all bits of the core layer data with *highly protective modulation*, which provides the best protection. This scheme enables a dramatic increase in the probability of perfect delivery of mandatory profiled data on extremely error-prone situations, without any further means of error control.

Then, the data of the *main layers* are handled with lower MCS for a given CQI. This scheme is called *conservative CQI mapping*. As shown in Fig. 6, by shifting one MCS, the received BLER can be reduced by an approximate order of 10^{-3}. In contrast, the bandwidth reduction is 7.91% when used with MCS #14, which has an efficiency of 5.1152, compared to MCS #15 with an efficiency of 5.5547. Similarly, the maximum bandwidth reduction is 37.82%, when MCS #3 is substituted with MCS #2.

By adopting highly protective modulation for the core layer and conservative CQI mapping to the main layer, the proposed conservative modulation and coding scheme makes use of retransmission-purpose bandwidth to successfully provide more protection to high-priority layers. In Section 4.5.2, the simulation result of performance enhancement for the proposed scheme is addressed.

4.4.3 System Parameter Analysis

To deliver total stream, bitrate of $B(i_{max}, j_{max})$ on MCS $\#n$ with spectral efficiency of $\Psi(n)$, the total amount of required radio resource is

$$R_{total} = \frac{B(i_{max}, j_{max})}{\Psi(n)}. \tag{4.15}$$

In this case, to deliver $i_{protect}$, $j_{protect}$ layer, bitrate of $B(i_{protect}, j_{protect})$

with lower spectral efficiency $\Psi(0)$ of BPSK based highly protective modulation, the amount of radio resource loss is

$$\begin{aligned} R_{protect}^{loss} &= \frac{B(i_{protect}, j_{protect})}{\Psi(0)} - \frac{B(i_{protect}, j_{protect})}{\Psi(n)} \\ &= B(i_{protect}, j_{protect}) \frac{\Psi(n) - \Psi(0)}{\Psi(n)\Psi(0)}. \end{aligned} \tag{4.16}$$

Therefore the amount of bitrate loss is

$$B_{protect}^{loss} = B(i_{protect}, j_{protect}) \frac{\Psi(n) - \Psi(0)}{\Psi(0)}, \tag{4.17}$$

and the loss rate for highly protective modulation is

$$\rho_{protect} = \frac{B(i_{protect}, j_{protect})}{B(i_{max}, j_{max})} \frac{\Psi(n) - \Psi(0)}{\Psi(0)}. \tag{4.18}$$

Fig. 4.12 shows variation of loss rate according to channel condition.

To deliver i_{shift}, j_{shift} layer, bitrate of $B(i_{shift}, j_{shift})$ with lower spectral efficiency $\Psi(n-1)$ of conservative CQI mapping, the amount of radio resource loss is

$$R_{shift}^{loss} = \left(B(i_{shift}, j_{shift}) - B(i_{protect}, j_{protect})\right) \frac{\Psi(n) - \Psi(n-1)}{\Psi(n)\Psi(n-1)}. \tag{4.19}$$

In this case, the amount of bitrate loss is

$$B_{shift}^{loss} = \left(B(i_{shift}, j_{shift}) - B(i_{protect}, j_{protect})\right) \frac{\Psi(n) - \Psi(n-1)}{\Psi(n-1)}, \tag{4.20}$$

and therefore the loss rate for conservative CQI mapping is

$$\rho_{shift} = \frac{B(i_{shift}, j_{shift}) - B(i_{protect}, j_{protect})}{B(i_{max}, j_{max})} \frac{\Psi(n) - \Psi(n-1)}{\Psi(n-1)}. \tag{4.21}$$

Fig. 4.13 shows actual loss rate curves according to channel condition.

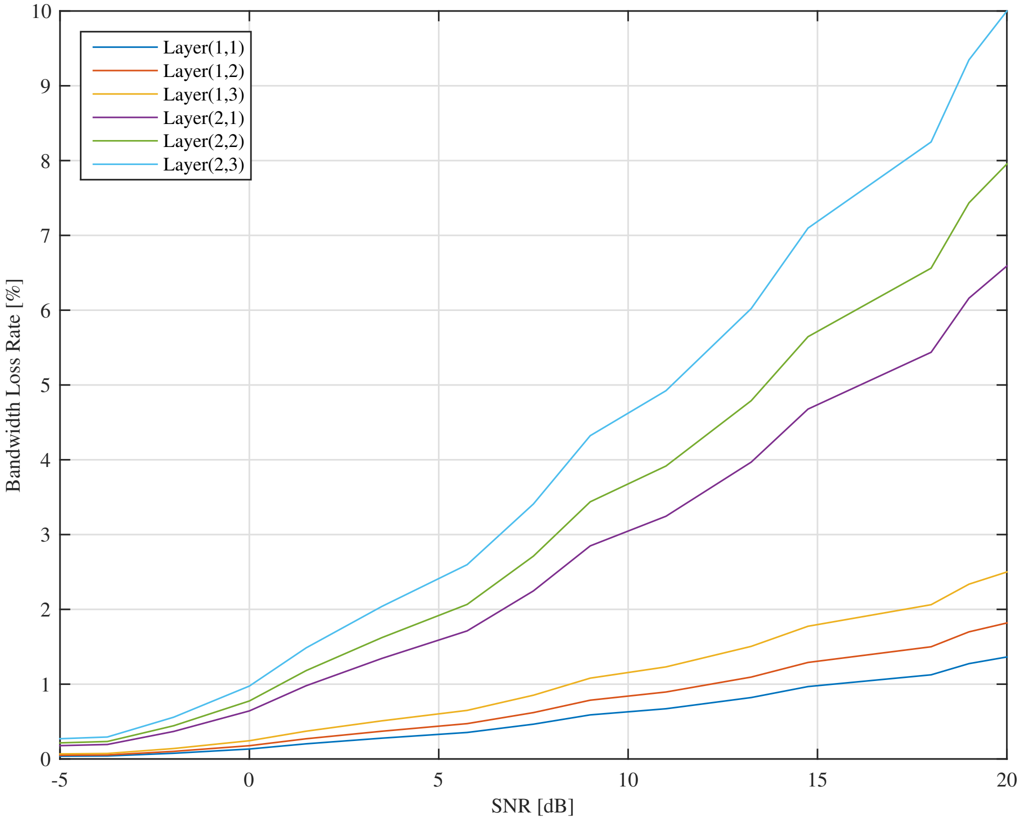


Figure 4.12: Bandwidth loss of highly protective modulation.

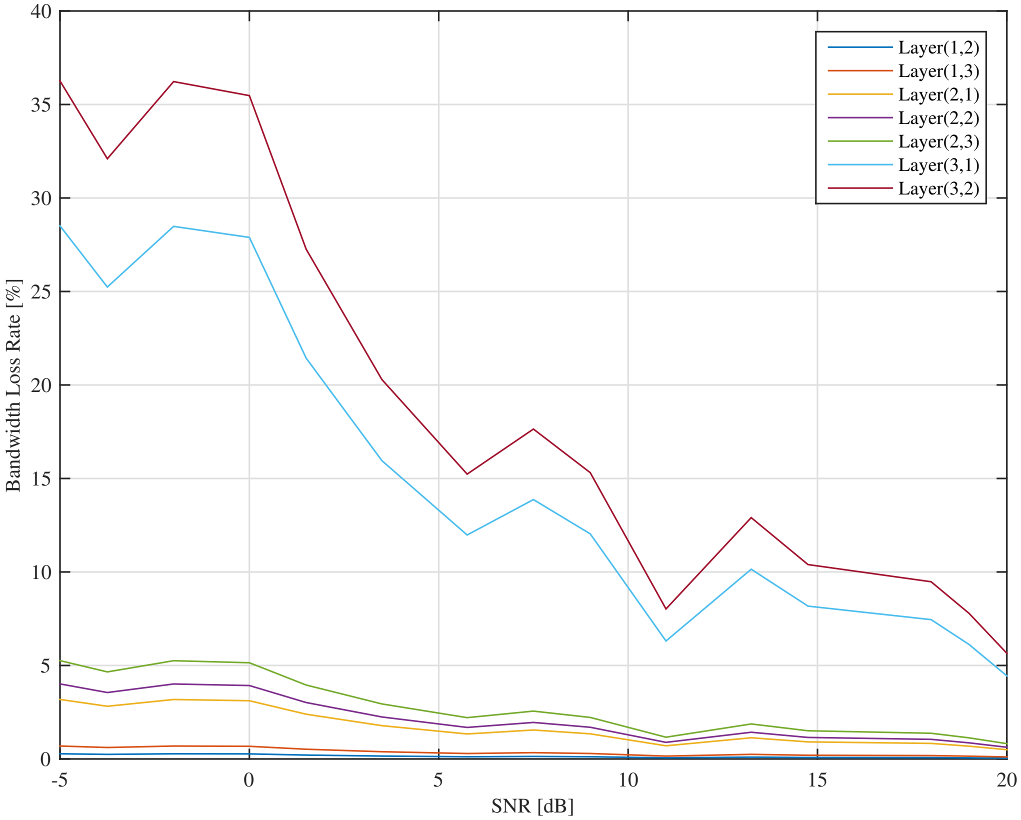


Figure 4.13: Bandwidth loss of conservative CQI mapping.

Table 4.4: Simulation parameters

Parameter	**Value**
Carrier Frequency	2.4 GHz
MTC channel bandwidth	1.4 MHz
Antenna configuration	SISO
Channel model	AWGN / WINNER phase II [106]
Number of UEs	1
UE speed	3 km/h
Number of HARQ processes	0
TTI duration	1 ms
Number of slots in one subframe	2
Number of subframes in one frame	10
Number of ECG electrodes	2
Sampling frequency of ECG data	2400 Hz
Bit resolution of ECG data	11-bits

4.5 Performance Evaluation

4.5.1 Simulation Environment

The simulations were performed on the Vienna LTE-A uplink link level simulator [104], and all the ECG signals were obtained from PhysioBank [105]. The main simulation parameters are listed in Table 4.4.

4.5.2 Simulation Results

Fig. 4.14 and Fig.4.15 compares the differences between a conventional real-time streaming system or reduced buffer scheme and the proposed scheme under significantly poor air conditions. Although the conventional real-time streaming system is capable of reducing communication latency, it cannot handle accidental episodes of transient errors that cause signal skipping. And the reduced buffer scheme requires frequent buffering delays, which distort the ECG pattern and timing durations. However, with the help of highly protective modulation, the proposed system can usually successfully deliver the mandatory part of the ECG signal, which ensures the basic readability of the transmitted ECG pattern

Fig. 4.16 compares the weighted diagnostic distortions (WDD) [107, 108] for the conventional, real-time streaming and the proposed systems that evaluate the diagnostic features of corrupted ECG signals. The proposed scheme outplays other competitors because only the mandatory part of the total ECG data can provide sufficient level of clinically meaningful features, whereas the random damage of the other two systems causes significant quality degradation.

Fig. 4.17 simulates the visual effect of the actual displayed pattern on various commonly available multi-parameter vital monitoring systems. As shown in the figure, the rendered ECG pattern of the proposed scheme displayed on the LCD of a common tablet-based monitor seems to be adequate for medical purposes, despite severely deteriorated channel conditions. However, the pattern skipping of the real-time stream system and buffering delay of the flow-controlled system induced by a shrunken buffer for latency reduction appears to have seriously disrupted the clinical usability of the transmitted ECG signals.

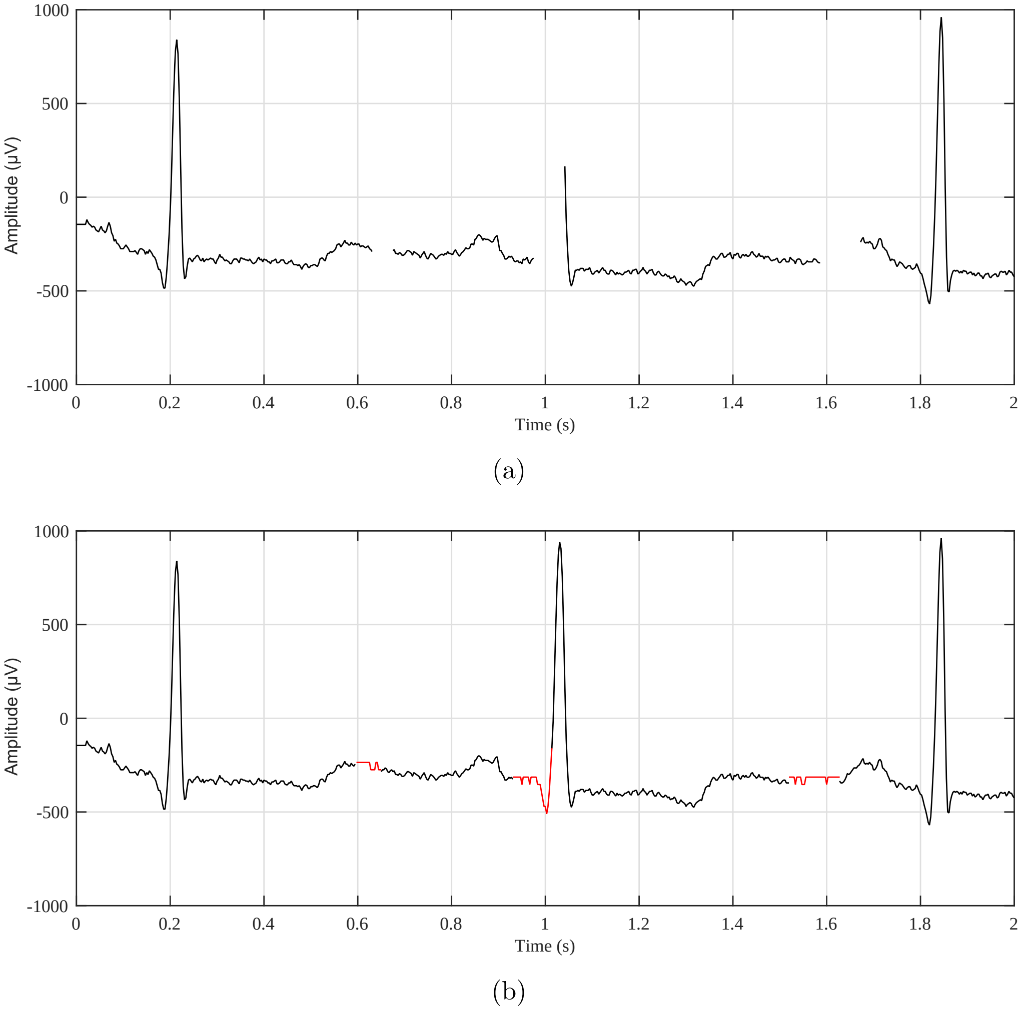
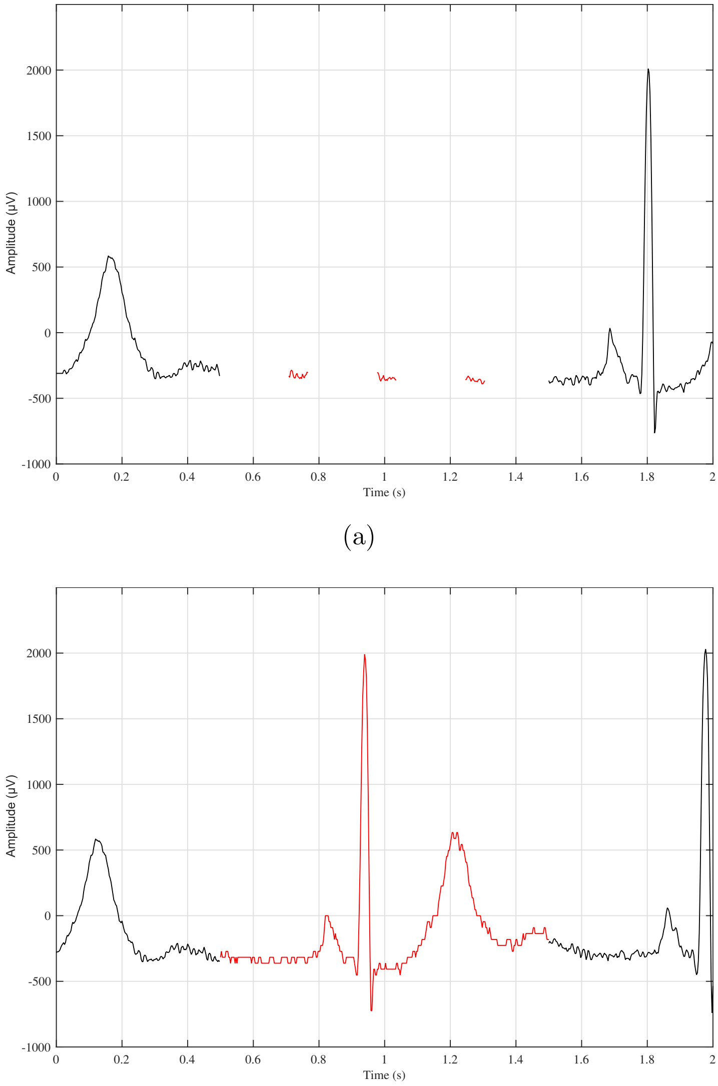


Figure 4.14: Difference of delivered ECG pattern in deteriorated channel condition (PER 5%). (a) Signal skip in real-time streaming. (b) Peaceful in-time quality degradation in the proposed scheme.



(a)

(b)

Figure 4.15: Difference of delivered ECG pattern in burst erroneous channel condition. (a) Buffering delay in reduced buffer scheme. (b) Graceful quality degradation in proposed scheme.

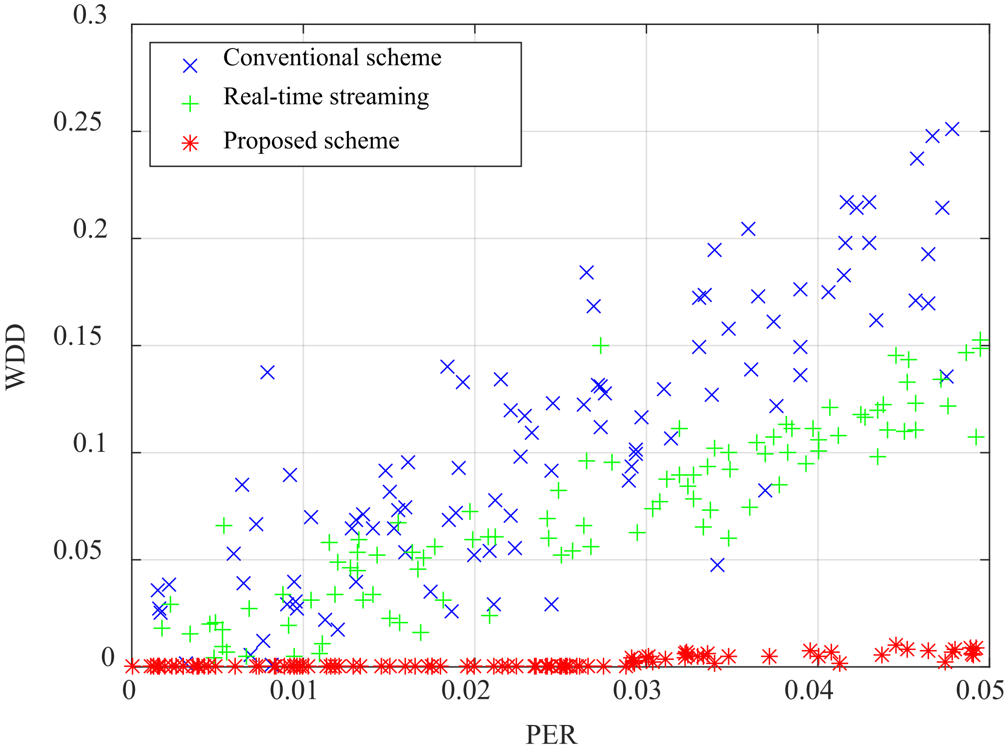
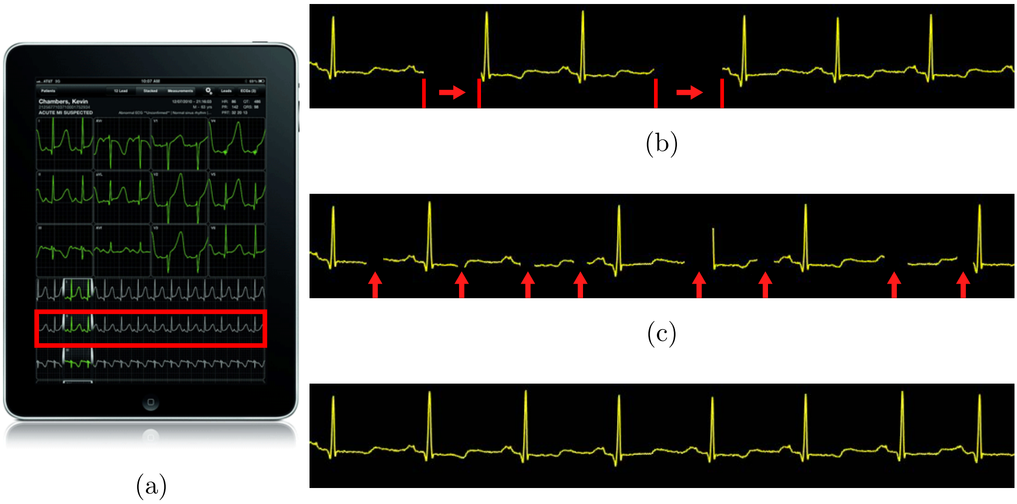


Figure 4.16: Weighted diagnostic distortion comparison.



(a)

(b)

(c)

(d)

Figure 4.17: Simulated results rendered in 765 x 113 pixels, similar dimension as on various vital monitors (PER 5%). (a) Example of ECG patterns on a common tablet-based ECG monitoring system. Marked red square for ECG section is 765 x 113 pixels. (b) Buffering delay in reduced buffer scheme. (c) Pattern skipping in real-time scheme. (d) Adequate pattern in proposed scheme.

4.5.3 Service Level Adjustment

According to the AHA's recommendations for the standardization of ECG [109], to reliably detect narrow pacemaker pulses, we need special processing technology known as "*oversampling*". If spikes of pacemaker's pulses are shorter in duration than 0.5 ms or it's amplitude is less than 20 μV, then more than 1000 hz of sampling frequency or over 8bits resolution is required to preserve the pattern. In that case, the propose profile of *high-precision temporal level* and *standard spatial level* can meet the demanding level of "*oversampling*" cases.

Another standard from AHA [110] describes the special ECG feature, named *VLP* (*Ventricular Late Potential*). In general, presence of VLP has prognostic significance with patients after acute myocardial infarction. The risk group should be diagnosed with special type of high-resolution ECG equipments because increased risk for sustained ventricular tachycardia is expected in those cases. The high-resolution ECG equipment removes base level noise to expose the presence of VLP. To deliver sophisticated pattern of VLP successfully, we should transfer *high-precision spatial level* of ECG data.

To support those high-precision level, the proposed scheme should adjust the system parameters of *highly protective modulation* and *conservative CQI mapping* according to their clinical requirements.

Chapter 5

Conclusion

5.1 Summary

Medical remote monitoring service is one of the most demanding applications in recent wearable computing era. Telecardiology, which uses the power of telecommunications for the remote diagnosis and treatment of heart diseases, is one of the key telemetry applications that leverages IoT-based technologies to improve patient care. Meanwhile, acute cardiac arrest is one of the most common cause of human deaths worldwide. Immediate treatment is essential to survival of cardiac arrest. Patients who have survived have an increased risk of sudden cardiac death. By using a wireless and wearable monitoring system for detection of arrhythmia situations, it is possible to provide quick alarms to a central safety alarm system and thereby take necessary action for an emergency rescue with geographic information. This solution is expected to dramatically improve the survival rate of the patients in cardiac arrest. However, to enable daily cardiac monitoring service over cellular networks, we need to be able to monitor several people in real time over a limited-bandwidth wireless connection. This is a challenging task because of large volume of data, bandwidth fluctuations and high channel error rate.

To cope with these challenges, we introduces an adaptive framework for cellular network-based telecardiolgy. We proposed a layer-based representation of ECG data that classifies a group of samples into BL or one of the ELs according to their recorded sampling frequency, to achieve temporal scalability. The quality of ECG signal improves gradually as more ELs are appended to the BL. Because the samples of each layer are packetized, the loss of packets during transmission over a wireless channel does not always imply corruption of consecutive samples. We also proposed an efficient and simple real-time scheduling algorithm, the LB-EDF scheduling algorithm, for delivery of scalable ECG streaming data over a lossy wireless network to the medical staff for remote heart monitoring. It gives higher priority to the retransmission of BL and lower EL packets so that they have a greater chance of arriving at the RMS on time. This help remote medical professionals to accurately read and interpret the ECG of a patient, even under severe channel conditions. The simulation result shows that in terms of MSE, our approach outperforms the conventional scheme. The low complexity of the scheduling algorithm also makes it suitable for use in real-time ECG applications.

Another critical issue pertaining to ECG data transmission over LTE MTC for remote monitoring is the delay between the real-time status of the patient and the information displayed on the remote monitor. According to the latest recommendation of the American heart association (AHA) [100], recent observations by healthcare providers indicate that most wireless hospital telemetry systems used for monitoring patients' heart rhythms tend to exhibit clinically significant delays between the current heart condition and the displayed ECG pattern. This temporal inconsistency of real-time cardiac information can compromise the safety of the patient in various clinical situations that demand instantaneous monitoring. For this reason, the advisory recommended the use of hard-wired telemetry systems instead of wireless systems for instantaneous ECG monitoring.

To handle this latency issue, this thesis extends a previously proposed adaptive framework [111]. Based on this adaptive framework, we proposes a novel approach focusing on the latency aspect, which is an enhanced spatio-temporal scalable system with a novel adaptive modulation and coding scheme for the low-latency delivery of ECG data over LTE MTC to meet two crucial QoS considerations for instantaneous monitoring. These QoS considerations are extremely short delay, and effective representation and robust delivery of ECG data to enhance its interpretation.

First, the timing aspects for the overall process of real-time ECG monitoring systems, from ECG signal acquisition and sampling steps to the entire communication procedure of LTE MTC systems, was analyzed. As a result, three major elements that can lead to nondeterministic and significant delays in the system were successfully identified, and unnecessary buffers and delay from those elements were eliminated. To begin with, any ECG data encoding steps that demand a considerable level of buffering process were bypassed. Then, by adopting a dedicated channel allocation scheme, the latency of the packet scheduling process was made negligible and deterministic. Finally, the retransmission steps of hybrid automatic repeat request (HARQ) were eliminated to achieve a satisfactory level of end-to-end latency.

Subsequently, a novel scalable media encoding and communication error control scheme was introduced to cope with all the handicaps induced by those system-level restrictions. By analyzing the exact amount of physical information that is required by various clinical environments, ECG service profiles were categorized into three levels: mandatory profile for real-time LCD (Liquid-Crystal Display) display, standard profile for the purpose of diagnostic printout, and high precision profile to provide more sophisticated accuracy for high end medical services. Then, a spatio-temporal scalable ECG coding scheme that covers these levels of service profiles in a versatile fashion without any extra system delays was introduced.

Finally, the channel quality indicator (CQI) mapping process of LTE MTC systems was modified to provide additional protection against channel errors to the mandatory part of the ECG stream at the cost of the total channel efficiency and throughput. As a result, the provision of a minimum margin for medically required level of service in real-time monitoring services under various channel conditions with extremely short system delays is guaranteed. Moreover, it was observed that by protecting the essential portions of ECG signals, the proposed system surpasses the original ones in terms of total signal distortion, especially in poor channel conditions.

As a result, this thesis introduced a novel, conservative modulation and coding scheme based on LTE MTC combined with spatio-temporally scalable representations of ECG data for instantaneous wireless monitoring.

The proposed scheme successfully reduced end-to-end delay down to 10 ms of ultra-low latency level, while maintaining adequate signal quality over a severely deteriorated wireless medium. Various simulation results ensured the validity of the proposed system.

5.2 Future Research Directions

In the future, with help of recent advances in non-contact ECG sensing technology [112, 113], more convenient signal acquisition method is expected to be integrated with the proposed system, which will accelerate the dissemination of daily cardiac monitoring services. And the proposed system can deliver ECG patterns to automatic diagnosis systems [114–116], which enables low-cost 24-hr continuous analysis process for screening purpose and automatically report suspicious symptoms to medical experts.

The proposed MTC based M2M telecardiology system is expected to enhance the survival rate of cardiac arrest by providing effective service platform for daily cardiac monitoring services ,if more sophisticated research follows to implement the proposed scheme as a commercial platform. For this reason, we will start to implement the actual platform as a subsequent work. We also need to further investigate various aspects of M2M medical signal monitoring systems to extend our platform to support a variety of clinical applications. We hope this work to provide a milestone for future studies on MTC based real-time streaming systems.

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요약

최근 웨어러블 컴퓨터의 시대를 맞아, 다양한 의료용 원격측정 기술에 대한 연구가 활발히 진행되고 있다. 심혈관계 질환은 대표적인 사망 원인 가운데 하나이다. 심정지에 따른 사망률 감소 및 환자 예후 향상을 위해선 심장 이상 증상 발생 시, 인지, 보고 및 응급처치의 신속성이 가장 크게 요구된다. 본 논문에서는 다양한 사물통신 기술의 발전을 토대로 사물통신기반 원격심전도 기술(M2M ECG)을 제안하였다. M2M ECG는 이동통신망을 이용하여 원격 환자의 심장 상태를 실시간으로 24시간 상시 모니터링한다. 또한, 심장 이상의 조기 징후 발견 시, 심정지가 실제 발생하기 전, 응급출동 서비스에 환자의 현재 위치 정보 및 주치의의 처방을 직접적으로 지시하여 응급조치함으로써 심장 마비를 미연에 방지할 수 있다.

우선, 본 논문은 이동통신망의 다양한 무선상태변동에 대응하기 위하여 ECG 데이터를 다계층으로 부호화한 후, 채널 상태에 따라 적응 전송하기 위한 적응형 무선통신 프레임워크를 제안하였다. 본 프레임워크는 이러한 계층 부호화 기법을 계층기반 기한 우선(Layer-Based Earliest Deadline First, LB-EDF) 스케쥴러와 함께 운용하여, 가용한 대역폭을 효율적으로 활용함으로써, 무선 상태가 심각하게 악화된 경우에도 급격한 서비스의 단락없이 재생 품질을 적절하게 조절하며 끊김 없는 ECG 전송을 가능케 한다. 다양한 시뮬레이션 결과, 제시된 프레임워크는 악화된 무선 조건에서 원격 수신된 ECG 신호의 임상적 품질을 현격하게 향상시킴을 확인할 수 있었다.

다음으로 본 논문은 상기 프레임워크를 미국심장협회(American Heart Association, AHA)에서 규정하는 즉각적 피드백을 요구하는 다양한 임상 분야의 지원을 위해 심화 발전시켰다. 무선 전송 과정에서 발생하는 불확실하고, 상당한 수준의 종단간 레이턴시(end-to-end latency) 때문에 AHA는 무선 심전도 기술을 즉각적인 피드백이 요구되는 다양한 임상 분야에서 사용하지 않도록

제한하고 있다. 본 논문에서는 최신 사물통신기술인 3GPP LTE MTC (Long Term Evolution Machine-Type Communication)에 기반하여 M2M ECG를 위한 범용 플랫폼을 제안하고, 시공간 계위적인 스케일러블 ECG 코딩기법 (spatio-temporally scalable ECG coding scheme)과 함께 L1/L2 링크 적응 방식(link adaptation)으로 보수적인 적응 변조 및 코딩기법(conservative modulation and coding scheme)을 고안하여 상기 플랫폼 상에서 운용하였다.

제안된 시스템은, 이동통신망의 다양한 채널 상황 하에 ECG를 전송하는 과정에서 발생되는 종단간 레이턴시를 최소화하여 10 밀리초의 초저지연(ultra-low latency) 수준으로 안정적으로 유지하면서, 동시에 수신된 ECG 신호 품질을 임상적으로 요구되는 수준이상으로 지속적으로 유지함으로써 다양한 시간-임계적인(time-critical) 임상 분야에서 안정적인 실시간 무선 원격 심전도 서비스를 제공할 수 있다. 본 논문은 심층적인 성능 평가를 통해 제안된 시스템이 심각하게 열화된 채널 상황에서도 충분한 임상적 품질의 초저지연 실시간 원격심전도 서비스를 안정적으로 제공할 수 있음을 검증하였다. 또한, 본 플랫폼이 기반하고 있는 3GPP LTE MTC 시스템은 4G LTE 기술의 안정성, 가용성, 보안수준 및 성능을 그대로 활용함과 동시에 작은 크기, 낮은 전력소비, 낮은 비용과 넓은 커버리지를 제공하여, 효과적인 상시 모니터링 시스템의 구현을 가능케할 것으로 기대된다.

주요어: 심전도(ECG), 3GPP 롱텀에볼루션 사물통신(LTE MTC), 사물 통신(M2M), 사물 인터넷(IoT), 웨어러블 센서(Wearable sensors), 실시간 시스템(Real-time systems), 스케일러블 코딩(Scalable coding), 링크 적응(Link adaptation), 적응형 변조(AMC), 초저지연 통신(Ultra-low latency communication)

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