Poster: Conservative Modulation and Coding for Low-latency Robust Transmission of Scalable ECG over LTE MTC

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ABSTRACT

This study introduces a novel conservative modulation and coding scheme to minimize and stabilize the delay incurred during the process of electrocardiogram (ECG) transmission over a wireless medium, while maintaining the desired level of the ECG pattern quality required for improving the chance of its interpretation. A machine-type communication system is adopted for the delivery of ECG data to benefit from its inherent reliability, pervasiveness, security, and performance of 4G long-term evolution 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 even under significantly deteriorated channel conditions.

CCS CONCEPTS

• **Networks** → **Error detection and error correction**; **Cyber-physical networks**; *Layering*; • **Information systems** → *Data streaming*; • **Human-centered computing** → *Mobile computing*;

KEYWORDS

Electrocardiography; low-latency; conservative modulation and coding; machine-type communications

1 INTRODUCTION

A crucial issue pertaining to electrocardiogram (ECG) data transmission over long-term evolution (LTE) machine-type communication (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) [1], 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 clinical situations that demand instantaneous monitoring. Therefore, the advisory recommended the use of hard-wired telemetry systems instead of wireless systems for instantaneous ECG monitoring.

We propose a novel approach focusing on the latency aspect, which is an enhanced spatio-temporal scalable system with a novel conservative modulation and coding scheme for low-latency delivery of ECG data over LTE MTC to meet two crucial QoS considerations for instantaneous monitoring: 1) extremely short delay and 2) 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. Consequently, major elements that can lead to nondeterministic and significant delays in the systems were successfully identified, and unnecessary buffers and delays from those elements were eliminated. Initially, any ECG data encoding steps that demand a considerable level of the 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 the end-to-end latency.

Subsequently, a novel scalable media encoding and communication error control scheme was introduced to cope with the limitations induced by those system-level restrictions. By analyzing the exact amount of physical information that is required using various clinical environments, ECG service profiles were categorized into three levels: mandatory profile for real-time LCD display, standard profile for 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. Thus, the provision of a minimum margin for medically required level of service in real-time monitoring services under various channel conditions is guaranteed with extremely short system delays. It was observed that by protecting the essential portions of ECG signals, the proposed system surpasses the original ones in terms of the total signal distortion, especially under poor channel conditions.

2 SYSTEM ARCHITECTURE

A wearable wireless ECG sensor, which consists of multiple electrodes, a wireless transmitter, and a receiver, is used to continuously

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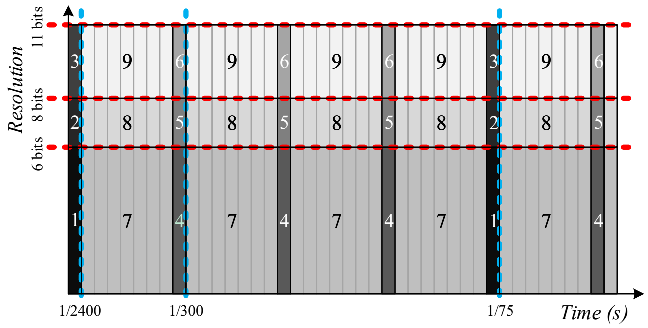


Figure 1: Sequence order of spatio-temporal scalable coding.

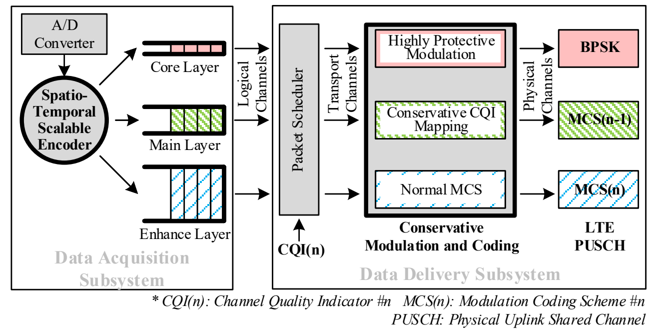


Figure 2: System architecture using conservative modulation and coding.

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 to 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, the resulting data rate of the wireless ECG application is $\mu_{\text{ECG}} = \varepsilon f \eta$. 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.

2.1 Spatio-Temporal Scalable ECG Coding

Fig. 1 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 the j-th spatial level $B(i, j)$ can be calculated as

$$B(i,j) = f_D(i-1)\max(\eta_D) + \{f_D(i) - f_D(i-1)\}\,\eta_D(j), \tag{1}$$

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.

2.2 Conservative Modulation and Coding

LTE systems adopt link adaptation technology by varying the modulation scheme and the code rate according to the channel conditions, called adaptive modulation and coding. Higher order modulation schemes, such as m-ary quadrature amplitude modulation 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, the base station estimates the uplink channel quality of the user equipment (UE) using sounding reference signals 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 the incremental redundancy of the forward error correction technique to maximize the spectral efficiency and the data rate.

This study introduces a novel conservative CQI to MCS mapping scheme, which minimizes the 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. 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 the mandatory portion of total signals, *main layers* for transferring up to a temporal standard profile level, and *enhance layers* for beyond the temporal standard profile.

Fig. 2 shows the overall signal processing steps for the proposed CQI mapping scheme. 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 in 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 of high-priority layers.

3 PERFORMANCE EVALUATION

Simulations were performed on the Vienna LTE-A uplink link-level simulator [2], using ECG data from PhysioBank [3]. The main simulation parameters of the simulated LTE MTC are listed in Table 1.

Fig. 3 compares the differences between a conventional real-time streaming system and the proposed scheme under significantly poor air conditions. Although the conventional real-time streaming system is capable of reducing the communication latency, it cannot

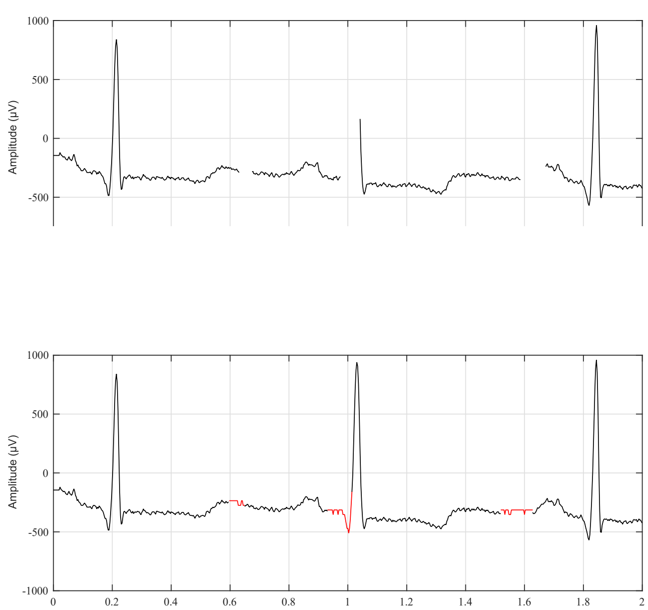
Table 1: Simulation Parameters

Parameter	Value
Carrier Frequency	2.4 GHz
MTC channel bandwidth	1.4 MHz
Antenna configuration	SISO
Channel model	AWGN/WINNER phase II [4]
Number of UEs	1
UE speed	3 km/h
Number of HARQ processes	0
TTI duration	1 ms
Number of slots per subframe	2
Number of subframes per frame	10
Number of ECG electrodes	2
ECG Sampling frequency	2400 Hz
Bit resolution of ECG data	11-bits

AWGN: Additive White Gaussian Noise
TTI: Transmission Time Interval

mitigate accidental episodes of transient errors that cause signal skipping. 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 compares the weighted diagnostic distortion (WDD) [5] for a standard best-effort MTC uplink, real-time streaming without



(b)

Figure 3: Difference of delivered ECG pattern under deteriorated channel condition (PER 5%). (a) Signal skip in real-time streaming. (b) Peaceful in-time quality degradation in the proposed scheme.

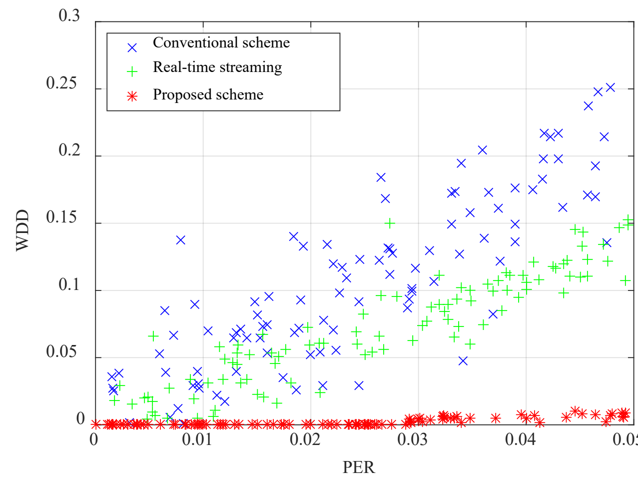


Figure 4: WDD comparison.

It segments ECG data into layers, and provides enhanced protection by adopting a conservative CQI mapping scheme for the core data which is essential to clinical interpretation of the signal.

4 CONCLUSIONS

This study 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 the end-to-end latency, while maintaining adequate signal quality over a severely deteriorated wireless medium. Various simulation results ensured the validity of the proposed system.

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REFERENCES

[1] M. P. Turakhia, N. M. Estes, B. J. Drew, C. B. Granger, P. J. Wang, B. P. Knight, and R. L. Page. 2012. Latency of ECG displays of hospital telemetry systems a science advisory from the American Heart Association. *Circulation* 126, 13 (Sept. 2012), 1665–1669. https://doi.org/10.1161/CIR.0b013e31826ae459

[2] M. Rupp, S. Schwarz, and M. Taranetz. 2016. The Vienna LTE-Advanced Simulators: Up and Downlink, Link and System Level Simulation. Springer, Singapore.

[3] A. L. Goldberger, L. A. Amaral, L. Glass, J. M. Hausdorff, P. C. Ivanov, R. G. Mark, J. E. Mietus, G. B. Moody, C.-K. Peng, and H. E. Stanley. 2000. Physiobank, PhysioToolkit, and PhysioNet: Components of a new research resource for complex physiologic signals. *Circulation* 101, 23 (June 2000), e215–e220. https://doi.org/10.1161/01.CIR.101.23.e215

[4] P. Kyösti, J. Meinilä, L. Hentilä, X. Zhao, T. Jämsä, C. Schneider, M. Narandzić, M. Milojević, A. Hong, J. Ylitalo, and V.-M. Holappa. 2007. WINNER II Channel Models (IST-4-027756 WINNER II D1.1.2 V1.1). (Sept. 2007). Retrived August 8, 2017 from http://projects.celtic-initiative.org/winner+/phase_2_model.html

[5] Y. Zigel, A. Cohen, and A. Katz. 2000. The weighted diagnostic distortion (WDD) measure for ECG signal compression. *IEEE Transactions on Biomedical Engeering* 47, 11 (Nov. 2000), 1422–1430. https://doi.org/10.1109/TBME.2000.880093