Medical-Grade Quality of Service for Real-Time Mobile Healthcare

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A wireless electrocardiogram case study suggests that current CDMA2000 cellular technology has considerable potential in medical telemetry. Modifications to the network protocol stack ensure the highest data integrity and lowest service delay.

Wireless communications are rapidly becoming an essential component of modern healthcare, enabling patients to enjoy a greater level of mobility. The compelling benefits of patient freedom from wired medical equipment and the bureaucracy associated with medical treatment are major motivators for the recent explosion of mobile healthcare (m-health) systems and applications.[1–3] Because m-health heavily depends on collaborative interaction among mobile medical devices wirelessly connected to back-end clinical systems, the key challenge in m-health is how to achieve medical-grade quality of service (QoS)—a level of transmission speed, reliability, privacy, and security that provides real-time, confidential, and accurate service. A wireless system that can deliver medical-grade QoS must have broad coverage, a low error rate, and a low upper limit on service latency.

Several proposed systems have advocated both IEEE 802.11 wireless LANs (WLANs) and cellular technology as platforms for medical telemetry applications.[4–6] WLANs are cost-effective and are the platform of choice in many hospitals. Cellular networks are inherently more expensive, but they offer broader coverage, are a proven infrastructure to support high mobility, and use licensed frequency bands to avoid interference from other networks. Moreover, implementation on an existing cellular infrastructure can greatly reduce cost, thus mitigating the cellular platform's main disadvantage. These features make cellular technology a strong candidate for medical telemetry and other m-health applications.[4,5]

To explore the practical concerns associated with selecting a cellular platform, we evaluated the QoS requirements of some key medical applications and then developed a wireless system architecture based on CDMA2000 1xEV-DO[7] cellular technology, which uses code-division multiple access (CDMA) and time-division multiple access (TDMA) multiplexing to maximize throughput. Evolution-Data Optimized (EV-DO) is shorthand for a version of EV, a telecommunications standard for the wireless transmission of data through

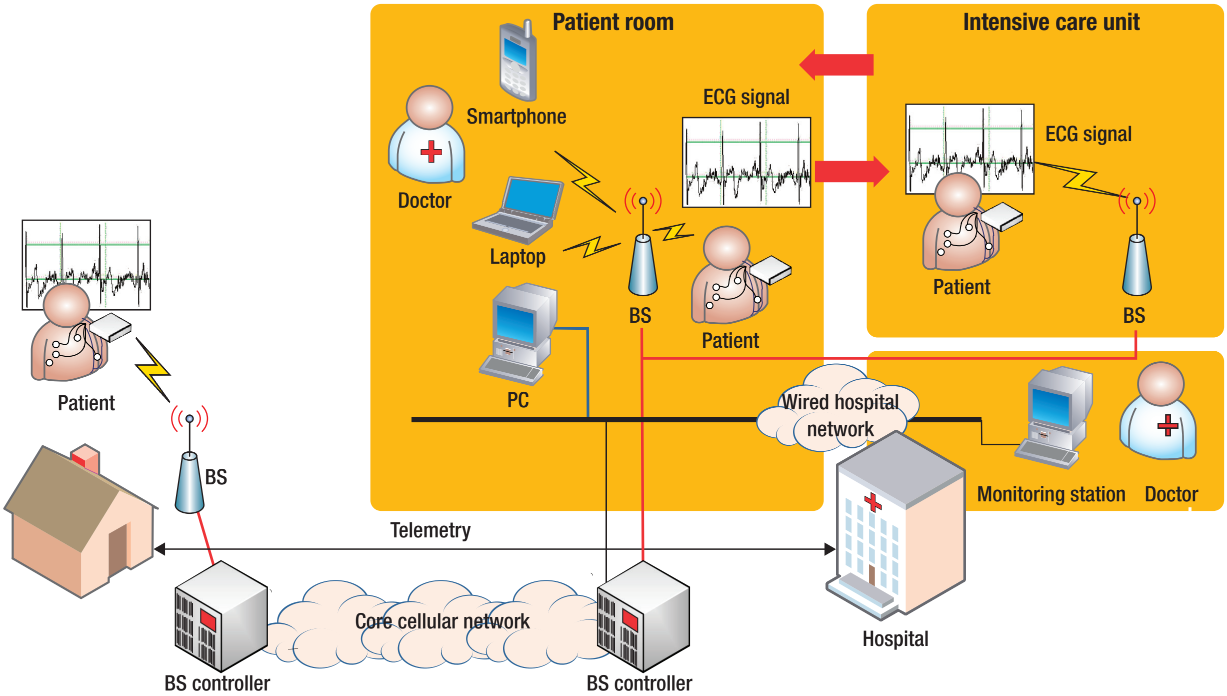

FIGURE 1. Continuous wireless electrocardiogram (ECG) service using cellular technology. Short-range wireless communication technologies such as Bluetooth receive signals from on-body sensors that measure the voltage difference between electrodes attached to the outer surface of the patient's skin. The signals then go to the patient's mobile device, which forwards data to the base station (BS) via an intermediate base station controller. The BS then sends the data to the appropriate hospital monitoring station in the patient's room or intensive care unit.

radio signals, typically for broadband Internet access.

To gauge the effectiveness of our architecture and to estimate key QoS metrics, we simulated continuous wireless electrocardiogram (ECG) monitoring across layers of our modified network protocol stack. In this focus, our work differs from recent studies of QoS in cellular-based m-health systems, which concentrate more on high-level system design than on network protocols.[2,6]

To test our proposed architecture, we chose an application that pushes the QoS envelope. As its name implies, continuous real-time ECG monitoring requires continuous real-time data transmission. The dropout rate can be at most a few seconds per hour; the packet error rate must be less than 0.1 percent, and service latency must be under 2 s. In addition, security and privacy must be at acceptable levels.[8,9]

Although continuous ECG monitoring requires a higher data rate than many m-health applications,[4] it is consistent with these other applications in its need for reliable transmission and low service latency,[8,9] since lost or corrupted data or late delivery obviously compromises any m-health application's effectiveness. Consequently, packet delivery ratio, security, service latency, and jitter are crucial QoS parameters not just for continuous wireless ECG monitoring but for m-health applications overall.

Regardless of the particular application, our study shows the need to examine the tradeoffs in implementing cellular networks in this domain. On the one hand are higher patient mobility and lower deployment cost; on the other are possible reductions in reliability and security along with increased transmission delay. Understanding the optimal tradeoff requires careful analysis.

REQUIREMENTS OF CONTINUOUS ECG MONITORING

In a continuous wireless ECG monitoring system, patients move around as they would normally, and clinicians have immediate access to their ECG data. In this sense, continuous monitoring differs from systems that collect data but store it for later downloads or systems that transmit data only if an event, such as arrhythmia or cardiac arrest, occurs.

Monitoring with a cellular network

Figure 1 shows a possible continuous wireless ECG scenario that uses a cellular system.

The system must have a way to sample, digitize, and group the analog ECG signals into packets. The chosen sampling frequency and digitization method determine traffic characteristics during transmission. The data rate depends on the number of sensors, bits, and sampling frequency. If L sensors sample the electrical signals from a patient's heart, and the system digitizes each sensor's output at r samples per second with a resolution of S bits, the resulting data rate is (LrS) bits

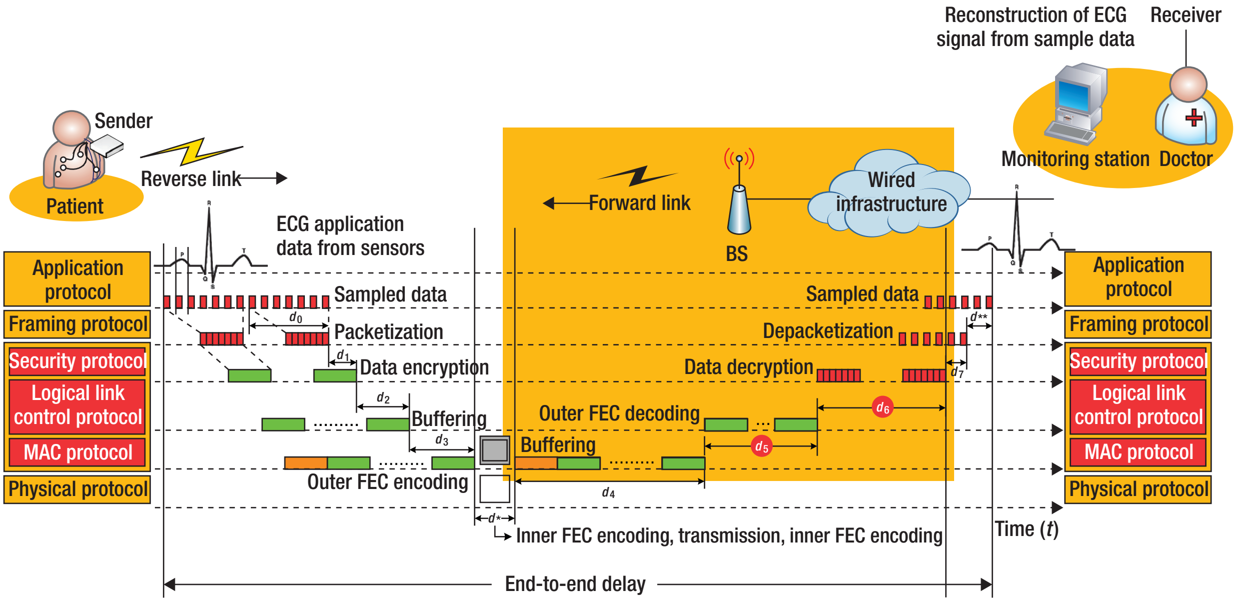

FIGURE 2. Modified protocol stack and delay sources. The stack is based on the use of the CDMA2000 1xEV-DO (code-division multiple access, Evolution-Data Optimized) cellular technology in continuous ECG monitoring. Delay sources (d_n) stem from functions across layers. Delays in black circles vary depending on the conditions of wireless channel. FEC: forward error correction; MAC: media access control.

per second. Thus, 12 sensors providing 500 samples per second at a resolution of 16 bits yields a data rate of 96 Kbps—a typical value for cellular ECG monitoring applications. This example illustrates the significance of a target data rate in tailoring cellular infrastructure to an ECG application.

Providing medical-grade QoS

The stringent QoS requirements of continuous wireless ECG monitoring require modifications to the network protocol stack, particularly in the data-link and physical layers.

Data-link layer. Link control provides reliable and secure communication through three main functions.

A *security function* authenticates devices and networks, ensures that data is not modified in transit, and encrypts transmitted data to ensure privacy.

Logical link control compensates for the bursty error processes inherent in a wireless channel. Error control can be based on retransmission, in which the system retransmits only errors and adapts easily to changing channel conditions. However, data delivery time can be unpredictable, which is unacceptable in m-health applications. The obvious alternative is forward error correction (FEC), which can both maintain throughput and control delay.

The third function in the data link layer is *media access control* (MAC), which determines when devices can access the communication medium. Either CDMA or TDMA techniques will satisfy an m-health application's timing requirements, offering a more predictable delay than the random-access or contention-based methods that IEEE 802.11 networks currently use.

Physical layer. Channel coding and digital signal modulation in the physical layer aim to optimize throughput and reliability. Channel coding introduces redundancy to cope with bits that are flipped because of noise or interference. FEC techniques such as turbo and convolutional coding typically provide this redundancy. Turbo coding is more effective when physical layer packets are several hundred bits or more.

The tradeoff between transmission bit rate and reliability drives the choice of modulation type and FEC code rate: a more robust modulation type that can tolerate higher levels of interference has a lower transmission rate. A higher FEC code rate increases redundancy, allowing the system to tolerate higher interference levels, which improves transmission reliability but erodes the effective bit rate. Generally, m-health applications fit better with modulation and coding schemes that favor reliable transmission rather than a high data rate, although adaptive modulation and coding is suitable if the system architect knows the precise tradeoffs required.

WIRELESS ECG WITH CDMA2000 TECHNOLOGY

With QoS requirements in hand, we looked at how to adapt the protocol stack for continuous ECG monitoring in the CDMA2000 1xEV-DO cellular system.

Protocol layers

Figure 2 shows our proposed protocol stack and the interactions among layers. This arrangement is based on the standard air specification for CDMA2000 multicast services.[10] The framing protocol, which packs higher layer data into frames, helps determine higher layer data boundaries.

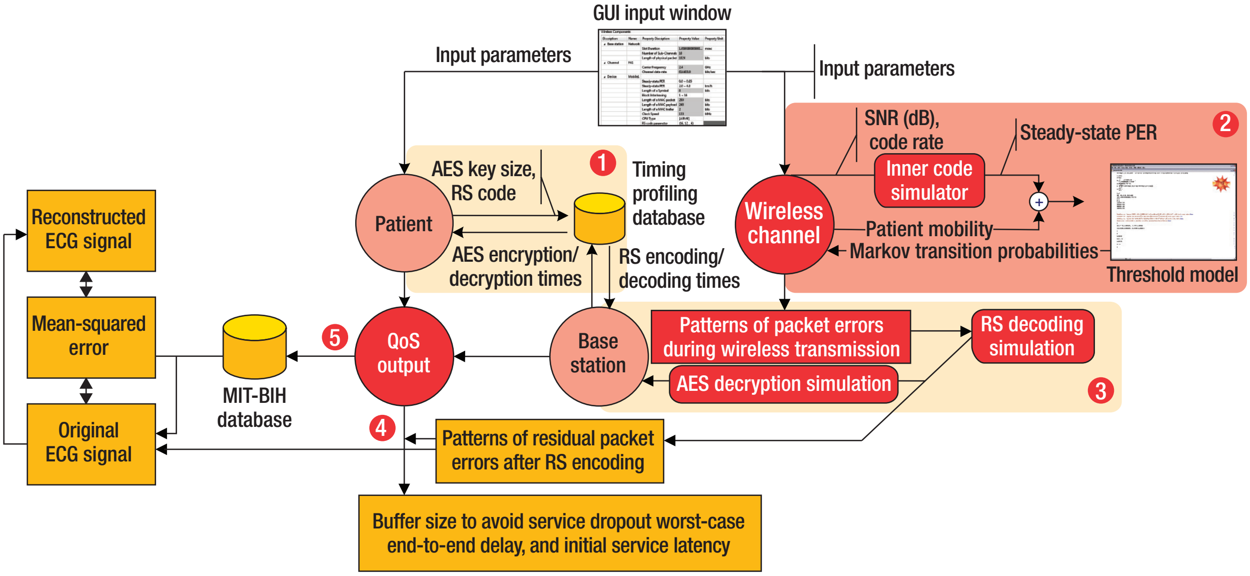

FIGURE 3. Simulation of a wireless continuous ECG monitoring system. (1) The system obtains the delays from Reed-Solomon (RS) coding and Advanced Encryption Standard (AES) encryption/decryption and (2) derives packet errors during wireless transmission using a threshold mode. The base station then (3) simulates RS decoding and AES decryption. Finally, the system (4) analyzes quality of service (QoS) metrics and uses the results to (5) estimate the mean-squared error. PER: packet error rate; SNR: signal-to-noise ratio.

However, the lower layers require significant modifications.

Security and logical-link layers. In the security layer, data encryption uses the Advanced Encryption Standard (AES),[10] which operates on 128-bit blocks using a 128-bit key. In the logical-link layer, the outer FEC code combines with the inner FEC (turbo) code in the physical layer to form an effective product code. Our stack uses Reed-Solomon (RS) outer codes because of their superior performance at low error rates—ideal for continuous ECG monitoring.

We specify an RS code by (N,K), which captures the idea that the encoder takes K data symbols and adds $(N - K)$ parity symbols to create an N-symbol codeword. A decoder can correct up to t symbol errors (in an unknown location), or up to $2t$ symbol erasures (errors in known locations), where $2t = N - K$. The location of erased symbols is often available in a digital communication system because the demodulator commonly flags incoming symbols that are likely to contain errors.

Because error bursts can defeat FEC codes designed for random errors, we added interleaving,[11] a simple process that spreads error bursts over time, allowing FEC to correct them and thus enabling RS codes to deal with error bursts.

To handle error bursts at the sender side, the system inserts security layer data into a buffer memory, or on *error control block* (ECB), a table of N rows and M columns, in a left-to-right, top-down fashion, and applies RS encoding along the columns. A reverse process of decoding and unpacking takes place at the receiver side. ECB width determines the length of error burst that interleaving can correct. Increasing the M value can correct longer error bursts but at the cost of a larger buffer and increased latency.[11]

MAC layer. The CDMA2000 MAC protocol specifies the procedures to transmit on both forward and reverse traffic channels. The reverse link uses CDMA techniques and Walsh codes to transmit data and employs a long pseudonoise sequence to identify mobile devices. The forward link uses both CDMA and TDMA techniques to transmit data.[7]

Physical layer. A CDMA2000 1xEV-DO Revision A system supports reverse-link data rates from 4.8 to 1,843.2 Kbps. The data rate is based on payload, modulation type, and how much redundancy turbo coding introduces.

Delay sources

As Figure 2 shows, an ECG application running on a CDMA2000 network has multiple sources of end-to-end delays. The accumulation delay in filling a frame (d_0) is 10.4 ms with a 1,000-bit frame and an ECG data rate of 96 Kbps. Encryption introduces an additional delay (d_1). Given this frame size, an RS code of (16,12), and two security layer packets in each ECB row ($M = 2$), writing to the ECB causes a 250 ms delay ($12 \times 2 \times 1{,}000/96$) ($d_2$).

Entering the security-layer packets into the ECB row by row and performing outer FEC encoding along the columns incurs an additional delay (d_3). Naturally, further coding and propagation delays (d^*) occur in the physical layer's hardware, including the inner FEC encoder and decoder, but these delays are small enough to be insignificant in our analysis.

TABLE 1. System parameters for wireless ECG.

Parameter	Value
Network	
Inner turbo code rate (*r*)	1/4
Physical-layer packet length	1,024 bits
Sample outer RS code (*N*,*K*)	(16,12)
Symbol size in RS erasure codes (*s*)	8 bits
Block interleaving level (*M*)	1–8
Security layer packet length	1,000 bits
MAC-layer packet length	1,002 bits
AES cipher block unit size	128 bits
Cipher key size	128 bits
Physical channel	
Carrier frequency	1.8 GHz
Modulation	Phase-shift keying
Reference channel data rate	153.6 Kbps
Worst channel signal-to-noise ratio	–2.77 dB
Estimated wireless channel mobile velocity	2–4K mph
Wireless ECG	
Number of sensors	12
Sampling frequency per ECG sensor per second	500 Hz
Sample size	16 bits
Data rate	96 Kbps
Medical devices	
Mobile patient device	ARM9TDMI at 250 MHz
Base station (modem proc.)	ARM11 at 400 MHz

MAC: media access control; RS: Reed-Solomon; AES: Advanced Encryption Standard

The base station performs inner FEC decoding and buffers packets into the ECB, which fills at a fixed rate because CDMA2000 uses a TDMA technique to access the medium. Thus, the buffering delay (d_4) is constant. Once the ECB is full, the base station performs outer FEC decoding and decrypts security-layer packets, and the monitoring station depacketizes them to obtain the original ECG data. These actions incur three additional delays (d_5, d_6, and d_7). (We ignored the application processing delay (d^{**}), since it is unrelated to the wireless system.)

All these delays are fixed, except those from RS decoding (d_5) and AES decryption (d_6), which vary with the physical channel's condition. Implementing these processes in software greatly reduces this delay variation. In such an implementation, the system would require a buffer to absorb the delay variation, or jitter, which has a maximum amplitude of

$$2 \times \left(\overline{d_5 + d_6} - \underline{d_5 + d_6}\right),$$

where

$$\overline{d_5 + d_6}$$

is the worst-case time for RS decoding and the AES decryption of an ECB and

$$\underline{d_5 + d_6}$$

is the best-case time. The jitter buffer turns this maximum jitter into a fixed delay of the same magnitude (d_7).

QOS ANALYSIS

Optimizing a network for wireless ECG requires considering reliability and latency tradeoffs within a layer and between layers. To analyze these tradeoffs, we conducted a cross-layer simulation of a continuous ECG monitoring application in Java. Figure 3 shows the simulation process in which we varied channel and network parameters to obtain QoS metrics.

Our simulation uses software implementations of the RS erasure encoder and decoder (http://rscode.sourceforge.net) and Gladman's reference implementation of the AES algorithm (www.gladman.me.uk). We assume that the patient's mobile device has a low-power ARM9E processor core, but we consider a base station equipped with a more powerful ARM11 core as a possible alternative. We chose ARM processors because many 3G phones for the GSM and CDMA2000 networks use these processors.

We also chose the IAR embedded workbench for ARM (www.iar.com), which enabled us to profile execution times of AES encryption and decryption in the security layer and of RS encoding and decoding in the logical-link layer.

Simulation parameters

Table 1 lists the parameters in our simulation, which we took from CDMA2000 1xEV-DO Revision A.[7,10] Because the mobile device has limited RF power, it requires coding rates and modulation techniques that are less affected by poor channel conditions. Therefore we chose a reverse-channel data rate of 153.6 Kbps and the (16,12) RS code, which offers a particularly good tradeoff between coding gain and processing delay.[10]

Process

The simulation first obtains the delay caused by AES encryption (d_1) and RS encoding (d_2) in the patient's

TABLE 2. Quality-of-service metrics from simulation: delays and latency (ms) and jitter buffer and ECB sizes (bits) .

M	$\overline{PER}_r$	d_0	d_1	d_2, d_4	d_3	$\overline{d_5 + d_6}$	$\underline{d_5 + d_6}$	d_7	Jitter buffer size	Worst-case service latency	ECB size
1	3.3E-3	10.4	7.04	125	10.9	44.91	27.77	34.29	3,291	347.14	16K
2	4.8E-4	10.4	7.04	250	21.8	89.82	55.42	68.81	6,606	687.48	32K
3	1.4E-4	10.4	7.04	375	32.7	131.99	83.10	97.78	9,386	1,019.51	48K
4	4.1E-5	10.4	7.04	500	43.6	174.15	110.81	126.68	12,161	1,351.47	64K
5	3.8E-5	10.4	7.04	625	54.5	214.93	138.55	152.78	14,666	1,679.25	80K
6	2.7E-5	10.4	7.04	750	65.4	257.10	166.25	181.70	17,443	2,011.24	96K
7	2.5E-5	10.4	7.04	875	76.3	297.88	193.93	207.92	19,960	2,339.14	112K
8	2.4E-5	10.4	7.04	1,000	87.2	337.30	221.64	231.32	22,207	2,662.86	128K

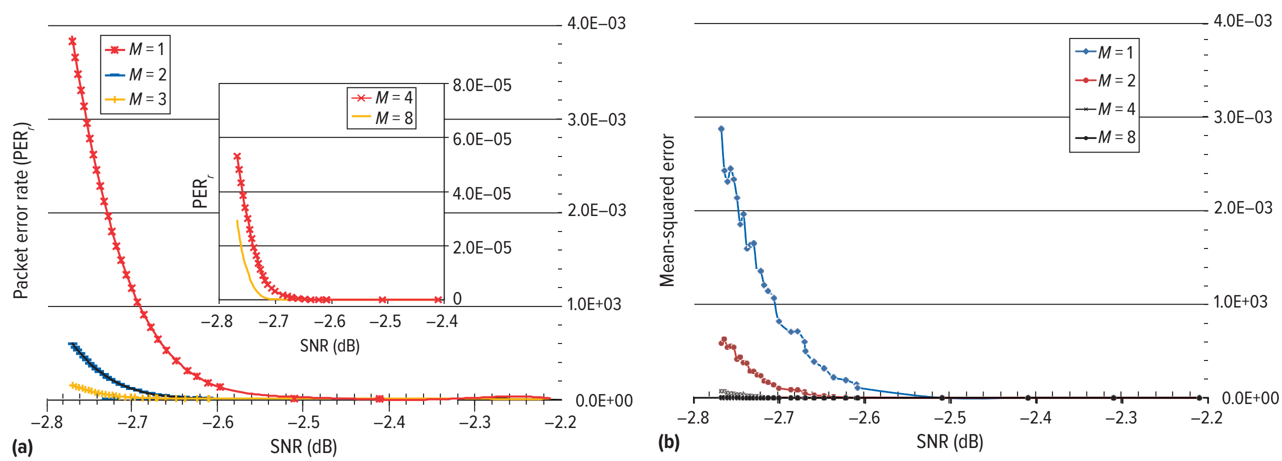

FIGURE 4. Average mean-squared error of reconstructed ECG signals. As M increases, error rate lessens only marginally, but latency grows, which suggests that beyond M = 4, performance gains are minimal.

(sending) device. It then uses the coded modulation library (www.iterativesolutions.com) to simulate inner turbo coding in the physical layer, which produces the channel's packet error rate (PER) with a given signal-to-noise ratio. This rate in combination with the patient's movement speed is the basis for simulating the occurrence of bursty packet errors in the wireless channel model.[12]

Having a model of the packet-error process in the physical layer enables the simulation of base station events. Simulating RS decoding in the logical-link layer and AES decryption in the security layer yields the pattern and number of residual errors in each ECB, together with the delays from RS decoding and AES decryption (d_4 and d_5).

Results go to an output control module that injects the residual errors into the MIT-BIH arrhythmia database,[13] which contains 48 half-hour excerpts from various ECG recordings. The control module then estimates the mean-squared error, which quantifies the difference between the ECG signals reconstructed at the remote monitoring station and the original signals from the patient; the required ECB and jitter buffer sizes; and the service latency.

SIMULATION RESULTS

Our simulation revealed some interesting patterns. For example, it showed that the delay from the AES decryption of a single security layer packet (d_1) will be 7.04 ms, while packetizing ECG data will create a delay (d_0) of 10.4 ms. Consequently, by the time the system packetizes a frame, the previous frame's encryption will already be complete, which means that AES encryption in the security layer will delay buffering by only 7.04

ms. For a particular ECB size, only the ECG data sampling rate will determine the buffering delays (d_2 and d_4).

Packet errors

Table 2, column 2, shows the upper bound on the residual packet error rate

$$\left(\overline{PER_r}\right)$$

in the data-link layer for different values of M, the block interleaving parameter. It also shows the worst- and best-case execution times for RS decoding and AES decryption and the delay corresponding to maximum resulting jitter. In the last columns are the buffer size to cope with this jitter and the corresponding service latency.

We also discovered an interesting pattern relating M values, the error rate, and latency. Although a higher value of M broadens the time scope of error bursts that FEC can handle, that flexibility comes with memory and buffering delays. However, our simulation showed that error-correction performance starts to saturate as M increases, until almost all the errors are corrected. Thus, as Figure 4 shows, increasing M further lowers the error rate only minimally, yet latency continues to increase, as Table 2 shows.

In our ECG application, setting M to 4 or 5 provided a reliability of 99.99 percent, an average mean-squared error of below 7.7E–7, and latency below 2 s. We assumed that the hospital had enough base stations to keep the signal-to-noise ratio above –2.77 dB.

Energy efficiency

Wireless technology for ECG monitoring must not only accurately deliver ECG data on time, but it must also manage energy in a power-constrained device. AES encryption and RS encoding in the data-link layer consume the most energy in our proposed wireless system.

We used an XEEMU simulator[14] to measure the average energy consumption of the reference software implementation of the AES cipher and RS encoder. XEEMU provides accurate energy data for the ADI 80200EVB XScale board, which uses the ARM9E instruction set.

We assumed that the core of our target processor for AES encryption and RS encoding (patient device) operates at 250 MHz; has separate instruction and data caches, both 32 Kbytes; and has a Micron 128-Mbyte SDRAM with a clock speed of 100 MHz (www.micron.com).

Table 3 shows the energy required to encrypt 128-bit data block and encode a codeword for common RS codes. Figure 5 shows energy consumption as the amount of energy in the data-link layer to handle a 1-byte data payload.

Table 3 shows that more energy is used to handle the data payload of one byte in the data-link layer as the number of parity symbols increases to improve the RS code's error-correcting capability. We expected this result, since

TABLE 3. Energy required to encrypt a 128-bit data block and encode an RS codeword.

		CPU	MEM	Total
Encryption (μJ)		**35.412**	**22.925**	**58.337**
Encryption (μJ)	(16,12)	15.130	9.371	24.501
	(16,13)	13.190	8.242	21.432
	(16,14)	11.090	7.143	18.233
	(32,24)	43.276	24.235	67.511
	(32,26)	36.768	20.911	57.679
	(32,28)	28.226	16.314	44.54

CPU: central processing unit, MEM: main memory

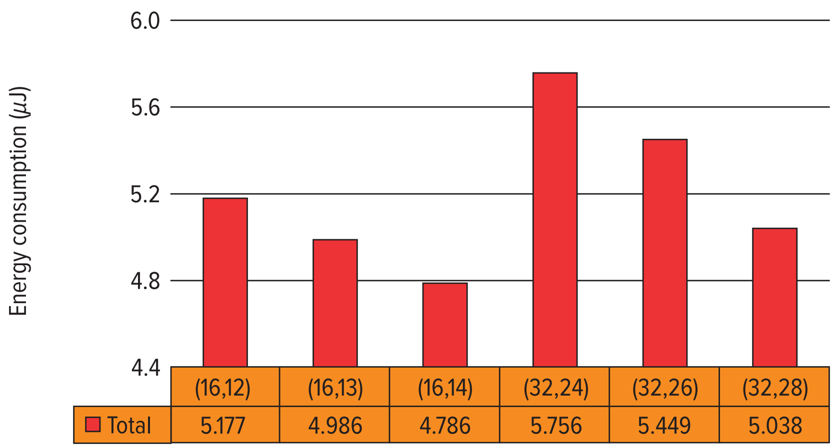

FIGURE 5. Energy consumption in the data link layer of the proposed cellular system for continuous ECG monitoring. Consumption reflects the energy required to handle a 1-byte data payload. Bars represent values with different RS code pairs.

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the complexity of computing the syndromes and erasure evaluator polynomials increases with the amount of parity information. For example, the RS code (16,12) requires 36.4 percent more energy for RS encoding relative to the (16,14) RS code. The implication is that an ECG application needs an RS code that saves significant energy while still guaranteeing the required QoS level. This tradeoff depends on the channel status that mobile medical devices might be expected to experience and the required battery life.

The results of simulating our sample cellular-based wireless ECG monitoring system suggest that current CDMA2000 cellular technology has considerable potential in real-time medical telemetry and m-health applications in general. Consequently, we expect to see more advanced 4G technologies that will support the emerging growth of mobile, personalized medical care.

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