Energy-efficient Interleaving for Error Recovery in Broadcast Networks

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Abstract

We analyze the performance of MAC-layer Reed-Solomon error recovery in the cdma2000 1xEV-DO Broadcast and Multicast Services (BCMCS) environment, with respect to the size of the error control block (ECB) and the air-channel condition, and establish the relationship between ECB size, error-recovery capacity and energy consumption. Real-time traffic, such as voice and video streaming, is very sensitive to delay, but can stand a certain level of packet loss. We therefore propose an energy-efficient size of the ECB to reduce the average energy consumption during error recovery while minimizing the reduction in service quality for real-time multimedia applications. Extensive simulation results suggest that a significant amount of energy can be saved with negligible performance degradation by selecting the appropriate ECB size for the bit error-rate of the forward traffic channel, instead of always choosing the largest possible ECB, with the sole aim of increasing error recovery performance.

1 Introduction

The proliferation of high-bandwidth applications over wireless networks requires efficient means of distributing information, especially when a large number of users want an identical, high data-rate service. This requirement may be satisfied by broadcasting or multicasting, both of which reduce the amount of data on the network and use its resources more efficiently. In an attempt to standardize these services, 3GPP2 has recently baselined the specification for the cdma2000 high-rate broadcast packet-data interface [1][2][3][4][5].

In designing a mobile device, battery life is often deemed more critical than the performance of application programs, because of strict limits on battery size and weight. The life of a battery can be extended by reducing the energy consumption of the hardware, which is in turn strongly linked to the execution of programs on components such as the CPU, memory and I/O devices. Thus we can save energy through the adoption of energy-efficient software. This implies the need for the systematic development, modeling, analysis and measurement of energy-saving techniques. However, there has been no comprehensive effort to analyze the energy problem at the software level for devices operating in a 3G cellular broadcast environment.

The objective of this paper is to characterize and analyze the energy consumed by a mobile device that is receiving broadcast services, especially during error recovery. Since a wireless radio network is prone to errors (i.e., has a high bit error-rate) and these occur in bursts, error control is essential in a mobile device designed to receive broadcast services. Forward error correction (FEC) has been adopted for this purpose in video broadcast applications because of the strict delay requirements and the semi-reliable nature of video streams. In cdma2000 1xEV-DO BCMCS, Reed-Solomon (RS) coding performs FEC at the MAC layer [4][5]. The RS decoding process must be a major target for energy saving because all multimedia data transmitted to a mobile device are subject to the RS decoding process.

We analyze the energy consumption of RS decoding with different sizes of cache in the mobile device, under varying air channel conditions, and with varying sizes of ECB. We have found that energy efficiency can be improved by selecting appropriate caching and interleaving in the ECB, based on the energy characterization of the decoding process with respect to I-cache and D-cache size and the choice of RS codes. We intend to determine the most suitable cache settings for energy-efficient interleaving of the ECB, and to investigate the tradeoffs between the performance and energy requirements for error recovery. This will enable us to present the best ECB size for each RS code under different channel conditions, and we will show that significant energy saving can be obtained with negligible performance reduction. Our experiments have been conducted on an ARM testbed using a measurement tool called SEE [6]

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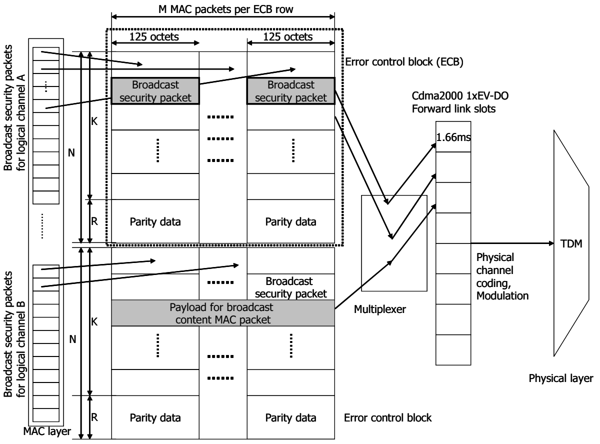


Figure 1. Structure of the ECB and the data transmission scheme for BCMCS.

which has proved reliable and accurate in previous work.

This paper is organized as follows: In Section 2, we introduce the error recovery mechanism that operates in cdma2000 broadcast networks; and in Section 3 we explore the energy consumption of RS decoding with various cache sizes, coding schemes and numbers of octet errors in each codeword. Our analysis of energy consumption is given in Section 4, and this analysis allow us to identify the most energy-efficient RS ECB size under realistic air-channel conditions, as described in Section 5. In Section 6 we draw some conclusions.

2 Background

2.1 Broadcast Services in cdma2000

The cdma2000 1xEV-DO wireless standard is the first to support the delivery of broadcast and multicast services (BCMCS). These scalable, high-bandwidth transmissions of content from a single server to many users simultaneously complement unicast services, which provide content to subscribers individually. In unicast services, a subscriber's forward-link data-rate depends on the local RF conditions [7][8], but BCMCS enable service providers to use a common speed to send data to all subscribers in a cell. The delivery of consistent high-quality data over a large coverage area relies on the Reed-Solomon error-correction scheme.

2.2 Error Recovery in Current BCMCS

Unlike the unicast cdma2000 1xEV-DO standard, BCMCS do not use an error-control scheme based on ARQs (automatic repeat requests), because there is no reverse link to carry the ACK/NAK signal from the access terminal to the access network. Instead, error control is provided by a forward error-correcting product code, comprising an inner turbo code and an outer Reed-Solomon code. Fig. 1 shows the structure of error recovery using Reed-Solomon coding within the context of data transmission in current BCMCS [9]. The broadcast framing protocol fragments higher-layer packets at the access network; the broadcast security protocol provides encryption of framing packets; and the broadcast MAC (medium access control) protocol defines the procedures used to transmit over the broadcast channel, and additionally specifies an outer code which, in conjunction with the physical-layer turbo code, forms the product code. As already mentioned, Reed-Solomon was chosen as the outer code for cdma2000 BCMCS, and the broadcast MAC layer packets have a fixed size of 125 bytes. The protocol is completed by the broadcast physical layer, which provides the channel structure for the broadcast channel.

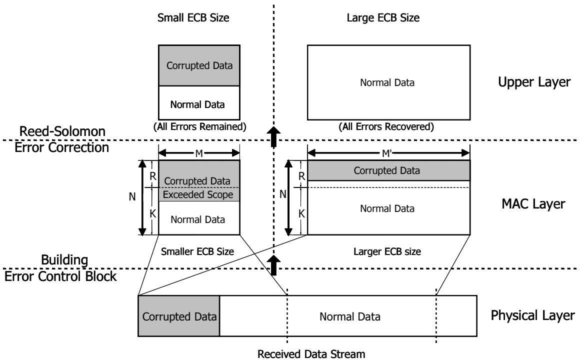


Figure 2. Correlation between ECB size and error-recovery capacity.

Each logical channel uses error control blocks (ECBs) with M MAC packets per ECB row (see Fig. 1). The variables N and K represent the number of octets and security-layer octets in a Reed-Solomon codeword. R is the number of parity octets: the Reed-Solomon decoder can recover up to R octet erasures in each codeword. Reed-Solomon coding is applied to the columns of the ECB, and then the

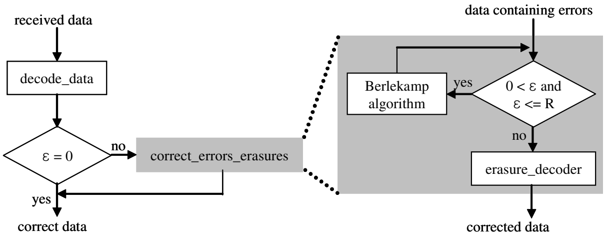
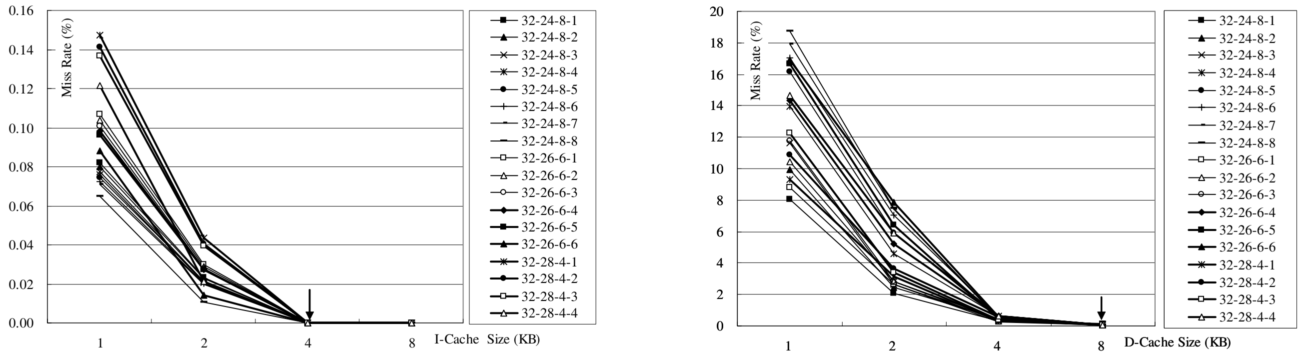


Figure 3. Flow diagram of RS decoding.



(a) I-cache

(b) D-cache

Figure 4. Cache miss rate against I-cache size.

data is transferred row by row to the physical slot, where it forms one or more physical-layer packets. The ECB is designed to provide a structure such that, in the event of a physical-layer packet erasure, octets in the same position are lost from all affected Reed-Solomon codewords. To decode a Reed-Solomon codeword correctly, the broadcast MAC protocol needs to receive at least K of the N octets in that codeword. If all K data octets are received without errors, decoding is not needed. The data octets which have been successfully received are simply forwarded to the upper layer of the BCMCS protocol suite. The possible values of N in BCMCS are 32, 16 and 1, and K can take a value of 28, 26 or 24 when $N = 32$, or a value of 14, 13 or 12 when $N = 16$ [4][5].

One of the most significant environmental factors affecting channel condition is fading. This is correlated with the burstiness of errors. A slow-moving mobile node tends to receive longer bursts of errors than one that is moving more quickly, which escapes more rapidly from shadowed locations where reception is poor. A Reed-Solomon code of (N, K, R) cannot recover any lost data if the corrupted portion of a codeword is larger than R. For this reason, the performance of error correction will drop if the burst length of errors becomes so large that the ECB cannot interleave them sufficiently. This situation is shown schematically in Fig. 2. The burstiness of errors caused by bad channel conditions can be an important factor in selecting an appropriate data interleaving interval, determined by the width of the ECB, which is $M \times 125$ octets, as shown in Fig. 1. The BCMCS standard allows value of M up to 16. As the value of M increases, the time-diversity also increases and thus a mobile node which is in a time-varying shadow environment is able to recover more corrupted data. However, the amount of storage required at the mobile node also increases. Therefore, the value of M is an important consideration in achieving better error-recovery capacity for mobile nodes at the expense of system resource.

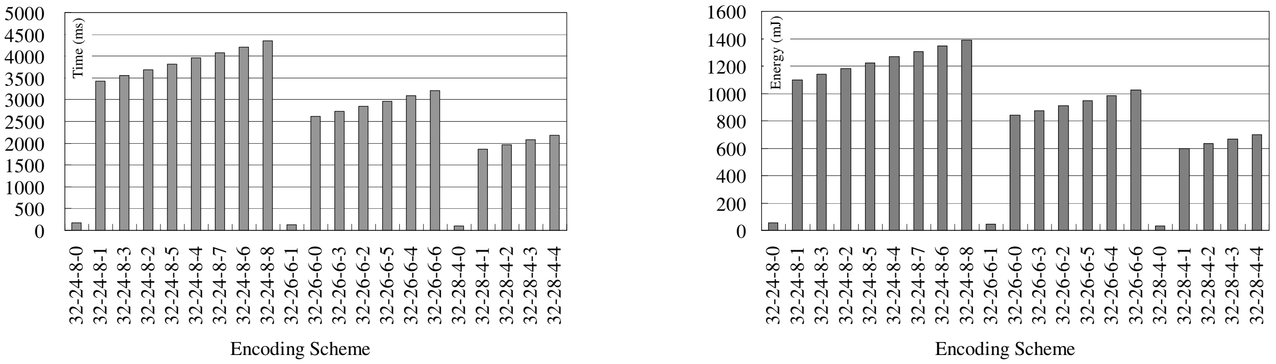
An RS decoder operates as shown in Fig. 3. When a data stream is received, syndrome bytes are created. Their number is proportional to the quantity of the input data, regardless of its quality. So the time required to generate a syndrome depends only on the quantity of data, and will be stable for a data stream with a static bit-rate. However, if there is an error in the data stream, additional work is required for error detection, location and correction. Errors are found using Berlekamp's algorithm [10], and the data can then be recovered by erasure decoding. The number of times that these procedures need to be executed is proportional to the number of errors, and so the time required for RS decoding is proportional to the input BER [11].

3 Basic energy consumption of RS without a channel model

3.1 Testbed for RS decoding

The execution time and energy consumption of RS coding were measured using the SEE (SNU Energy Explorer) [6]. In the following experiments, both the ARM core and the SEC 128 Mbit SDRAM array (K4S280832A) were operated at a clock speed of 100 MHz, and the cache we used has 4-way associativity. This organization is abstracted from the general ARM-based embedded system.

Fig. 4(a) shows how the I-cache miss rate varies with the number of octet errors per codeword for each encoding scheme. In the figures, 32-24-8-φ denotes a (32,24,8) code with φ octet errors in each codeword, and similarly for other codes. As the number of errors increases, the I-cache miss rate decreases. The Berlekamp algorithm runs more often but, because it is compact, it achieves many cache hits, so the absolute miss rate is low in all cases. The cache miss rate stabilizes when the size of the I-cache is 4KB, so we



(a) Execution time

(b) Energy consumption

Figure 5. Execution time and energy consumption per ECB, against encoding scheme and error count per codeword.

use an I-cache of this size. Similarly, the miss rate of the D-cache also stabilizes around 8KB, as shown in Fig. 4(b).

3.2 Energy consumption of RS as the number of octet errors in a codeword varies

We found that a 4KB I-cache and a 8KB D-cache are the most efficient in terms of speed and energy. Using these configurations, we conducted experiments to measure the energy consumption and execution time of RS per ECB decoded (with maximum interleaving, i.e. M=16) for varying numbers of octet errors in each codeword.

We see that the execution time and energy consumption of RS depends on the encoding scheme and the number of errors encountered during decoding. The number of loops performed by the Berlekamp algorithm when generating the polynomial, lambda and the syndrome bytes required for error detection and correction is proportional to the number of parity bits. Generating the polynomial takes a significant amount of time: with the maximum number of errors, execution takes 15% longer than it does when there is only one error in each codeword, and energy consumption grows similarly, as shown in Fig. 5(b). Also, there is a huge difference between the performance with no errors and with one error in each codeword. As shown in Figs. 5(a) and 5(b), execution time and energy consumption have steep slopes up to one error.

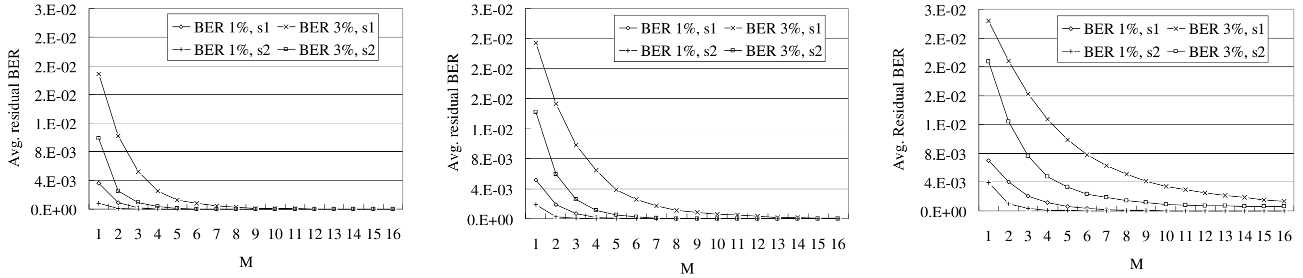
These results suggest that it is more energy-efficient to concentrate the bursts of errors across a smaller number of codewords, rather than to disperse them across many codewords. By making the ECB as small as possible without allowing a significant reduction in error recovery performance, the number of error-free intervals is increased. Energy is saved because fewer codewords contain errors.

4 Energy consumption and performance analysis of RS in a simulated channel model

4.1 Channel model

In this study, we used the Gilbert channel model [12][13][14] to simulate the behavior of data errors which arise in transmission over fading channels. This model incorporates a binary Markov process in which the receiver is deemed to have received a data bit when the fading envelope of that bit is more than some threshold value. If the fading envelope is below the threshold, receipt fails. A first-order two-state Markov process can simulate the error sequences generated by data transmission on a correlated Rayleigh fading channel: these errors occur in clusters or bursts with relatively long error-free intervals between them. Fading in the air channel is assumed to have a Rayleigh distribution.

By choosing different values for the input bit error-rate and for $f_d T$ (which is the Doppler frequency normalized to the data-rate, where f_d is the Doppler frequency, equal to the mobile velocity divided by the carrier wavelength [15]), we can model different degrees of correlation in the fading process. The value of $f_d T$ determines the correlation properties, which are related to the mobile speed for a given carrier frequency. When $f_d T$ is small, the fading process has a strong correlation, which means long bursts of errors (slow fading). Conversely, the occurrence of errors has a weak correlation for large value of $f_d T$ (fast fading). In the following experiments, we used values of 0.00001 and 0.00002 for $f_d T$, which correspond to speeds of about 5 Km/h (*s1*) and 10 Km/h (*s2*) respectively, with a reference

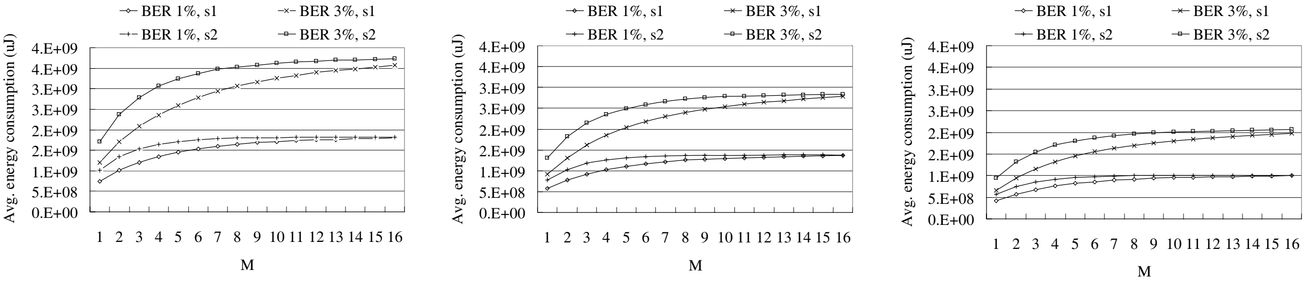


(a) (32,24,8) code

(b) (32,26,6) code

(c) (32,28,4) code

Figure 6. Average residual BER for different sizes of ECB (M).



(a) (32,24,8) code

(b) (32,26,6) code

(c) (32,28,4) code

Figure 7. Average energy consumption for different sizes of ECB (M).

channel data rate of 409.6 Kbps and carrier frequency of 900MHz. The maximum Doppler frequency of the system is given by $f_c v/c$, where v is the mobile speed, c is the speed of the electromagnetic wave, and f_c is the carrier frequency.

It has been suggested [4] that a data rate of 409.6 Kbps can be supported using a (16,14,2) RS code in more than 90% of network coverage with a dual receiver. Thus we have assumed the use of QPSK modulation with a 409.6 Kbps data-rate forward channel.

4.2 Energy consumption and error recovery capacity with different sizes of ECB

We investigated the relationship between the average value of the residual BER and the number of MAC packets per ECB (M) in a cdma2000 1xEV-DO broadcast environment. We will call the bit error-rate input to the RS decoder the input BER, and the bit error-rate after Reed-Solomon decoding will be called the residual BER. The three RS codes (32,24,8), (32,26,6) and (32,28,4) are used in these experiments.

For each $f_d T$, the average residual BER using Reed-Solomon coding is inversely proportional to M. Additionally, the reduction of the average residual BER is faster when fading is fast, because the error bursts are shorter than they are in slow fading. Short error bursts can be adequately interleaved in an ECB, and thus the average residual BER increases considerably with even a small increase of M. Because M is related to energy consumption and memory requirement, both energy and storage must be sacrificed to reduce the average residual BER. The energy consumption increases linearly with the size of the ECB, as shown in Fig. 7.

Fig. 7 shows the average total energy required to decode a payload of 100 Kbps continuously for 5 hours with varying input BERs, at speeds of *s1* and *s2*. These results can be analyzed in terms of three factors: input BER, ECB size (interleaving factor) and RS coding scheme. What is immediately clear is that the RS decoding process uses more energy as the input BER increases. This is a plausible result because the error correction routine has to run more frequently if more errors are input to the RS decoder. It is also apparent that the energy consumption increases as the value of M increases because error bursts are dispersed over more codewords, and the error correction process runs more frequently. This suggests that it is more energy-efficient to concentrate error bursts in a smaller number of codewords and to increase the number of error-free intervals, assuming that the required level of residual BER can be achieved.

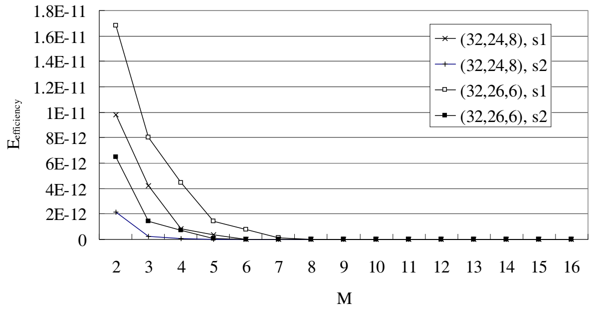


Figure 8. Energy efficiency when the BER is 0.01.

Finally, we note that RS codes with less parity information achieve a significant energy saving, at a cost in error recovery performance.

5 Selection of ECB size for energy efficiency

We can see from the way that energy consumption varies with the size of the ECB and the BER of the air-channel that energy can be saved if we select the smallest size of ECB that still provides an acceptable level of performance. To find the best ECB size, we propose the following energy-efficiency metric:

$$E_{efficiency}(\Delta M) = \frac{\phi_{residualBER}(\Delta M)}{\gamma_{energy}(\Delta M)},$$

where $\phi_{residualBER}(\Delta M)$ and $\gamma_{energy}(\Delta M)$ are, respectively, the reduction in residual BER and the increase in energy used as the value of M increases by 1. Thus $E_{efficiency}$ is the ratio between the drop in residual BER and the extra energy required as M increases.

Fig. 8 shows the values of this metric for a BER of 0.01, and (32,24,8) and (32,26,6) codes. In this example the energy efficiency of a mobile station which uses a (32,24,8) code and moves with a speed of *s1* drops almost to zero when the value of M is 6, which means that there is little performance gain to be obtained with by using more energy. But when a mobile node moves faster (*s2*), it saturates earlier, when M reaches 4. Thus it is most energy-efficient to choose the stated values of M in these two cases. Similar selections can be made in the case of a (32,26,6) code, but in this case the saturation point is delayed to a larger size of ECB, because the performance of error recovery degrades as the amount of parity information is reduced, and thus gains in performance extend to larger values of M.

Table 1. Energy savings achieved by recommended values of M.

RS code	Mobility	BER	
		0.01	0.03
(32,24,8)	*s1*	14.65%	11.69%
	s2	9.50%	5.91%
(32,26,6)	*s1*	13.69%	11.10%
	s2	8.58%	4.03%
(32,28,4)	*s1*	8.24%	8.09%
	s2	5.31%	3.84%

Table 2. Reductions in residual BER achieved by recommended values of M.

RS code	Mobility	BER	
		0.01	0.03
(32,24,8)	*s1*	0	0
	s2	0	0
(32,26,6)	*s1*	0	4.73×10^{-5}
	s2	0	8.07×10^{-5}
(32,28,4)	*s1*	2.21×10^{-5}	5.96×10^{-4}
	s2	9.09×10^{-5}	8.01×10^{-4}

By selecting the size of ECB in this way, a significant amount of energy can be saved in comparison with the maximum size of ECB ($M = 16$), as shown in Table 1. The average energy saving is 14.65% at speed *s1* and 9.5% at speed *s2*. Because all multimedia data transmitted to a mobile device are subject to RS decoding, using the recommended value of M achieves a significant reduction of total energy consumption with negligible performance degradation. The reduction in residual BER, compared with the residual BER when M=16, is presented in Table 2. As the MPEG decoder has its own error resilience, these reductions will have little influence on the playback quality of MPEG videos.

6 Conclusions

The Reed-Solomon error-correction scheme uses a data interleaving mechanism to increase error-recovery performance. This can be adjusted in current BCMCS by changing the size of the error control block. By increasing the size of the ECB, we can recover from bursty errors more efficiently; however, a larger ECB increases energy consumption, memory requirement, and service delay. We therefore make the ECB as small as we can without incurring significant performance reduction, while allowing for changing channel conditions. This has been shown to reduce the over-all average energy consumption of mobile nodes running a video application, with only minor reduction in playback quality. This is a significant improvement on the use of an ECB of the maximum size, without regard to the channel conditions.

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