AFEC - Adaptive Forward Error Correction for 802.11a Wireless LAN

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Abstract

Degradation in channel condition due to fading and multipath effects can corrupt transmitted frames in wireless networks. To improve performance, one viable approach is to use forward error correction (FEC) schemes such as Reed-Solomon or similar codes. We analyze the performance of several Reed-Solomon codes applied to 802.11a wireless local area network (WLAN). The codes differ in their error correcting capability. Quantitative analysis shows that in an adverse environment, it is beneficial to use a more powerful error correcting code. But in a more benign environment, a reduced-strength code can be benefucial. Based on the results, an adaptive FEC (AFEC) is proposed. It adaptively selects error correcting scheme appropriate for the current environment. Through cross-layer information interchange, the method can be implemented easily and leads to better performance in WLAN. Issues related to the incorporation of the scheme into the 802.11a frame structure are also addressed.

Keywords: Reed-Solomon code, FEC, adaptive FEC, cross-layer, performance analysis

1. Introduction

Wireless local area network (WLAN) is one of prevailing wireless communication systems. In WLAN, the performance of transmission suffers due to multipath, frame collision and frame losses. Most of the ongoing works in WLAN focus on Carrier Sensing Multiple Access/Collision Avoidance (CSMA/CA) and hidden terminal problem. Frame error is another cause of performance degradation. Frame errors in WLAN usually occur due to non-ideal channel condition. The probability of frame error in wireless networks is typically much higher than wired counterparts. When the receiver receives an erroneous frame, it does not send acknowledgement (ACK) back to the sender. If the sender does not get ACK from the receiver, the frame will be retransmitted until a successful transmission occurs. More retransmissions will take more transmission time.

One of the approaches to improve transmission performance is forward error correction (FEC). FEC based on Reed-Solomon (RS) and other codes can correct frame errors and reduce the number of retransmissions. Although FEC can correct frame errors, it also requires extra parity bytes for implementation. In general, codes with higher error correcting ability also occupy more bytes in the transmitted frames. It is beneficial to use error correcting codes of lower complexity under good channel condition, and use codes of higher error correcting capability under poor channel condition.

We evaluate the frame error probability for different RS codes under various channel conditions. Based on the results, we propose a scheme called adaptive FEC on the MAC layer. By receiving information from the physical layer, the AFEC selects the error correcting code appropriate for the current channel condition to achieve better performance. We also examine issues related to the incorporation of the proposed scheme into the present 802.11a frame structure.

The contributions of the paper are in three aspects. First, performance of different-strength RS codes is studied quantitatively. Second, AFEC and its cross-layer implementation are investigated. Finally, a scheme is proposed which can seamlessly incorporate the AFEC in the existing 802.11a framework with only minor modification to the frame format, making the method highly compatible with the existing 802.11a standard.

2. Reed-Solomon Codes

Reed-Solomon codes [6] are non-binary cyclic codes with symbols made up of an d-bit sequence where d is any positive integer having a value greater than 2. They are denoted by RS(n, k) with n and k satisfying the inequality

(1) $$0 < k < n < 2^d + 2$$

where k is the number of data symbols being encoded, and n is the total number of code symbols in the encoded block. The error correction capability of RS(n, k) is characterized by the largest number t of erroneous symbols that can be corrected. The parameters are related by the following relation:

(2) $$(n,k) = (2^d - 1, 2^d - 1 - 2t)$$

RS codes are used in digital audio and video applications such as compact discs. Fig. 1 shows a block of RS code.

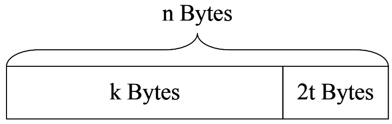

Fig. 1: A block of RS(n, k)

Let the error probability of an$d$-bit symbol be P_S. It can be evaluated by the equation $P_s = 1-(1-P_b)^d$, where P_b stands for bit error rate. For small values of BER, P_s can be approximated by dP_b. If an RS-coded block contains more than t symbols in error, the block as a whole can not be corrected. The probability of an RS-coded block with incorrigible errors is given by

(3) $$P_{RS}(n,k) = \sum_{i=t+1}^{n} \binom{n}{i} (P_s)^i (1 - P_s)^{n-i}$$

Clearly, error probability of RS-coded blocks increases with the bit error rate (BER). Different values of k give RS codes distinct error correcting capabilities for the same BER. In Fig. 2, the relation between block error rate and BER is demonstrated for several RS codes.

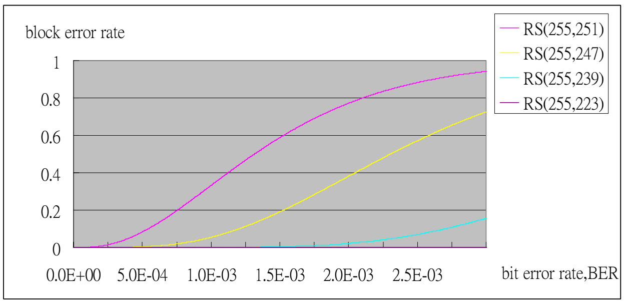

Fig. 2: Block error rate vs. BER for different RS codes

3. MAC-Level FEC

In [3], MAC-level FEC was proposed to enhance the transmission performance. An MPDU (MAC Protocol Data Unit) is divided into several blocks as shown in Fig. 3. The data and frame check sequence (FCS) portions of the MPDU are divided into N blocks, each of which is encoded separately. MAC header is also encoded using a separate block FEC called the header FEC.

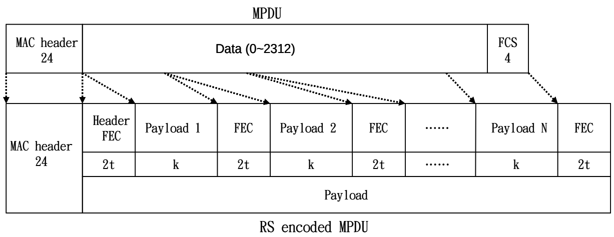

Fig. 3: MPDU with MAC-layer FEC

In [2], a new PLCP (Physical Layer Convergence Protocol) format was proposed to accommodate FEC. In order to allow MAC-level FEC, the first five bits of the reserved 11 bits of the service symbol are chosen to differentiate the FEC scheme used in a particular transmission (Fig. 4).

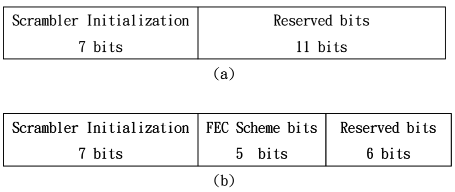

Fig. 4: Modified PLCP service symbol

These bits are called *FEC scheme bits*, the meaning of which is shown in Table 1. Incidentally, the binary value of the FEC scheme bits is the same as the number of erroneous bytes that can be corrected by the selected RS code.

Table 1: Meaning of the FEC scheme bits

FEC Scheme bits	FEC Scheme
00010	RS(255, 251)
00100	RS(255, 247)
01000	RS(255, 239)
10000	RS(255, 223)

If a frame is RS-coded, the new service bit in PLCP header is set to 1. The FEC scheme bits are then set according to the FEC encoding scheme selected. When the frame is received, the receiver chooses the FEC scheme based on the service bit and FEC scheme bits and decodes the frame. Afterwards, it checks the frame with FCS. If there are no errors in the frame, which could mean no errors occur during transmission or the errors have been corrected by RS codes, the receiver transmits a MAC layer ACK frame to the sender and passes up the frame to upper layers for further processing. If there are errors remaining in the frame, the receiver drops the received frame and interrupts. The sender waits for the ACK until the ACK timeout runs out. If ACK is not received in time, the sender will retransmit the frame. The transmission is not completed until the sender receives the right ACK.

4. Error probability of RS-coded frames

Four modulation schemes are defined in the physical layer of IEEE 802.11a: BPSK, QPSK, 16-QAM, and 64-QAM. For an AWGN channel, the BER for each of the schemes as a function of E_b / N_0 can be determined precisely using methods in [4] and expressed as various Q-functions. In general, BER for BPSK is the same as that for QPSK. Also, BER for 64-QAM is higher than that for 16-QAM for the same E_b / N_0. In turn the BER of 16-QAM is higher than that of BPSK and QPSK. Note different modes are defined in 802.11a, leading to different transmission data rate. Table 2 summarizes the various modes.

In the following, we analyze the error rate of a frame (FER) which has used FEC of various strengths. To distinguish the transmission modes, the superscript m is used. Let $P_e^1(36)$ denote the error probability of the PLCP header. The superscript 1 refers to the fact that mode 1 at 6 Mbps is always used to transmit the PLCP header. First, consider the error probability of a frame which does not use FEC at all. In addition to the PLCP header, there are 24 bytes of MAC header, 4 bytes of FCS, and N blocks of 255-byte payload.

Table 2: Transmission modes used in 802.11a

Modes	Data rate	Modulation	Coding rate
1	6	BPSK	1/2
2	9	BPSK	3/4
3	12	QPSK	1/2
4	18	QPSK	3/4
5	24	16QAM	1/2
6	36	16QAM	3/4
7	48	64QAM	2/3
8	54	64QAM	3/4

For comparison, we assume each block is 255 bytes in length and is composed entirely of data. The number in the parentheses indicates the number of bits in a field or block. Any error in the bit stream will cause an error. Thus,

(4) $$P^{m}_{E,noRS}(N) = 1-(1-P^{1}_{e}(36))(1-P^{m}_{e}(8\cdot(28+255\cdot N)))$$

Similarly, the error probability of an RS-coded frame is

(5) $$P^{m}_{E,RS}(N) = 1-(1-P^{1}_{e}(36))\cdot(1-P^{m}_{RS}(24+2t,24)) \cdot(1-P^{m}_{RS}(255,255-2t))^{N}$$

In the above formula, P^{m}_{RS} is the same as that given in (3) with the superscript m to indicate the mode used. In MAC layer, 4 bytes of FCS are encoded as part of the last block in the MPDU. Extra overhead including TCP header, IP header, SNAP header, and LLC header makes a total overhead of 48 bytes. As a result, the effective length of an RS(n, k)-coded frame is (kN – 52) bytes. The ACK frame is 14 bytes long and the error probability for it is

(6) $$P^{m}_{E,ACK} = 1-(1-P^{1}_{e}(36))\cdot(1-P^{m}_{e}(14\cdot 8))$$

5. Performance of RS FEC Schemes

Three possible scenarios for a frame transmission are depicted in Fig. 5. The first scenario is that the entire transmission process is successful: the receiver correctly receives the frame from the sender, and the sender correctly receives the ACK in time from the receiver.

The second scenario is that the sender receives erroneous ACK from the receiver. After the receiver correctly receives the frame from the sender and sends ACK back to the sender. The sender checks the ACK using FCS. If the ACK is in error, the sender will retransmit the frame after EIFS (Extended Inter-Frame Space).

The third scenario is that the sender sends a frame, but doesn't receive an ACK within the specified timeout interval. The receiver checks a received frame using FCS. If there are any remaining errors in the frame after FEC is applied, the receiver will not send ACK back to

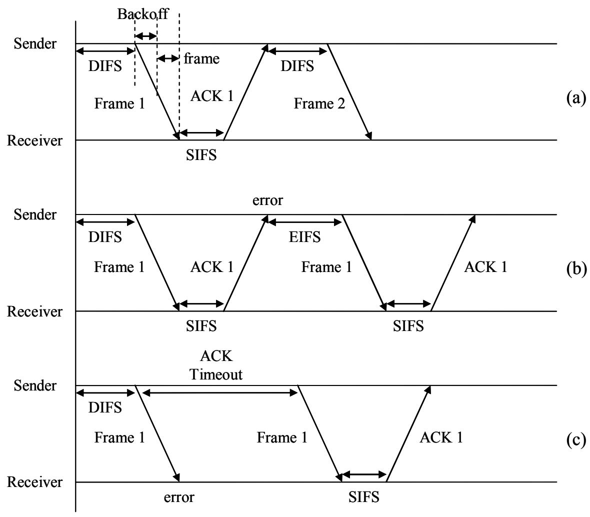

Fig. 5: Three scenarios of packet transmission.

the sender. Besides, the frame may be lost during the transmission. In that case, the receiver also doesn't send ACK back to the sender for obvious reason. Another possibility is that the receiver correctly receives the frame and sends ACK back to the sender, but the ACK is lost on the way. In all of the above circumstances, the sender will retransmit the frame.

In [11] the p_e packet error model was proposed as an extension to TC-model. It assumes that a transmission fails when collision or packet error occurs. Hence, the probability of transmission failure is

(7) $$P_f = P_c + P_e - P_c \times P_e$$

where P_c is the error probability of collision and P_e is the probability of frame error. We focus on the analysis of transmission failures caused by frame errors. For the ensuing analysis, the meanings and values of key parameters for 802.11a are shown in Table 3 and Table 4.

Table 3: Parameters used in performance analysis

T_{FRAME}	Transmission time of a regular frame	L_{FRAME}	Frame length in Bytes
T_{ACK}	Transmission time of an ACK	$L_{MAC\ Header}$	MAC header (24 Bytes)
T_{PLCP}	Time of PLCP transmission	$L_{MAC\ FEC}$	Parity bytes in MAC header
T_{CW}	Contention window duration	L_{ACK}	ACK length (14 Bytes)
$R_{TRASMIT}$	Transmission rate	τ	Propagation Delay

In Fig. 6, the probability of the first scenario is given by $P_1 = (1-P_{FRAME})(1-P_{ACK})$ and the time it takes is T_1. P_{FRAME} is the probability that an error occurs in the transmission of the frame and P_{ACK} is the probability that an error occurs in the transmission of ACK.

Table 4: Key parameters of IEEE 802.11a

Slot time	9 μs	T_{PLCP}	24 μs	
T_{DIFS}	34 μs	CW_{ma}	1023	
T_{SIFS}	16 μs	CW_{min}	15	
T_{EIFS}	126	τ	1 μs	
$T_{ACK\ Timeout}$	280 μs	T_{PLCP}	PLCP preamble	16 μs
			PLCP header	4 μs
			PLCP symbol duration	4 μs

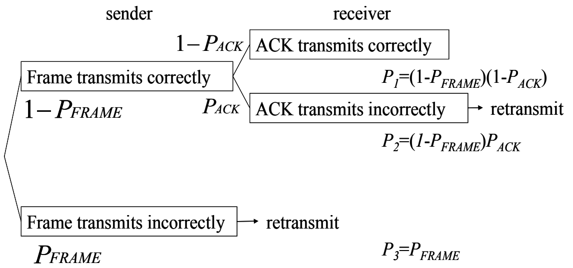

Fig.6: Packet transmission probabilities

The probability of the second scenario is given by $P_2 = (1-P_{FRAME})P_{ACK}$ and the time it takes is T_2. The probability of the third scenario is given by $P_3 = P_{FRAME}$ and the time it takes is T_3. The probability of packet retransmission is $P_{RET} = P_{FRAME} + P_{ACK} - P_{FRAME} \times P_{ACK}$. The expected number of transmissions required for a successful frame transmission is $1/(1-P_{RET})$, and the average transmission time is $P_1T_1 + P_2T_2 + P_3T_3$. So the expected time needed for a successful frame transmission (excluding the PLCP header) is given by

(8) $$T_{TRANSMIT} = \frac{1}{1-P_{RET}}(P_1T_1 + P_2T_2 + P_3T_3)$$

Finally, the transmission time of a complete frame is

(9) $$T_{FRAME} = T_{PLCP} + \frac{(L_{FRAME} + L_{MAC\ Header} + L_{MAC\ FEC}) \times 8}{R_{TRANSMIT}} + \tau$$

The transmission time of an ACK is

(10) $$T_{ACK} = T_{PLCP} + (\frac{8 \times L_{ACK}}{R_{TRANSMIT}}) + \tau$$

with τ being the propagation delay [9].
The transmission time of the first scenario is

(11) $$T_{noERROR} = T_{DIFS} + T_{CW} + T_{FRAME} + T_{SIFS} + T_{ACK}$$

The transmission time of the second scenario is

(12) $$T_{ackERROR} = T_{DIFS} + T_{CW} + T_{FRAME} + T_{EIFS} + T_{CW} + T_{FRAME} + T_{SIFS} + T_{ACK}$$

The transmission time of the third scenario is

(13) $$T_{packetRROR} = T_{DIFS} + T_{CW} + T_{FRAME} + T_{ACK\ TIMEOUT} + T_{CW} + T_{FRAME} + T_{SIFS} + T_{ACK}$$

Assume the transmission rate is 54 Mbps (m = 9) and there are 9 blocks in a frame. The largest number of RS parity bytes in MAC header is 16 and it can correct at most 8 bytes of errors. When transmission starts, a frame is transmitted after backoff time which is given by $\text{Backoff} = \text{random( )} \times \text{slot time}$ where random( ) is a random integer between 0 and CW (Contention Window) and CW is an integer between CW_{min} and CW_{max}. The CW_{min} value of 15 is used for CW since collision is neglected in the current analysis. The average value of backoff time is 7.5×9 μs = 67.5 μs. The transmission time of the MPDU is $(255 \times 9 + 24 + 2t) \times 8/54 \cong 345.9\mu s$, so the transmission time of a regular frame is

$$T_{FRAME} = T_{PLCP} + T_{MPDU} + \tau = 24 + 345.9 + 1 = 370.9\ \mu s.$$

and the transmission time of an ACK frame is

$$T_{ACK} = 24 + \frac{14 \times 8}{54} + 1 = 27.1\mu s$$

Therefore,

(14) $$T_1 = T_{DIFS} + T_{Backoff} + T_{FRAME} + T_{SIFS} + T_{ACK} = 34 + 67.5 + 370.9 + 16 + 27.1 = 515.5\mu s$$

(15) $$T_2 = T_{DIFS} + T_{Backoff} + T_{FRAME} + T_{SIFS} + T_{ACK} + T_{EIFS} + T_{Backoff} + T_{FRAME} + T_{SIFS} + T_{ACK} = 34 + 67.5 + 370.9 + 16 + 27.1 + 280 + 67.5 + 370.9 + 16 + 27.1 = 1277\ \mu s$$

(16) $$T_3 = T_{DIFS} + T_{Backoff} + T_{FRAME} + T_{ACK\ TIMEOUT} + T_{Backoff} + T_{FRAME} + T_{SIFS} + T_{ACK} = 34 + 67.5 + 370.9 + 280 + 67.5 + 370.9 + 16 + 27.1 = 1233.9\mu s$$

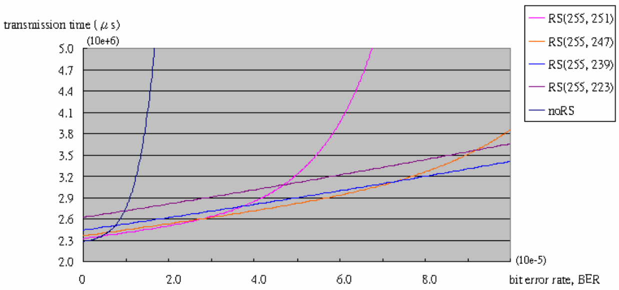

Fig. 7: The performance of the different FEC scheme under different BER (Part I)

We compare the performance of different FEC schemes under different channel conditions. Assume 100 MBytes of data are to be transmitted. The amounts of time required versus BER are plotted in Fig. 7 and Fig. 8 for four different FEC schemes.

When BER is low, schemes with higher error correction capability takes more time than those with lower correction capability. The reason is that the former use more parity bytes in the frame, which is detrimental to throughput. However, when BER is high, schemes of lower correction capability will take more time to transmit the data because of more retransmissions.

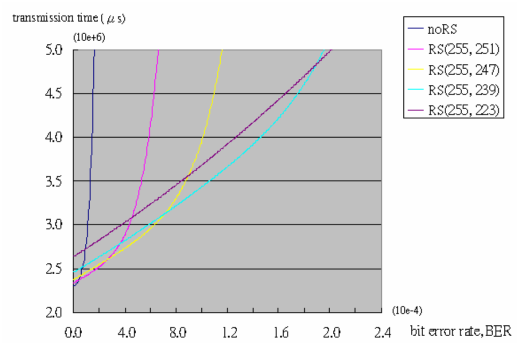

Fig. 8: The performance of the different FEC scheme under different BER (Part II)

The conclusion is that it is desirable to transmit frames with low-overhead FEC when the BER is low, and with FEC of high strength when BER is high.

6. Adaptive FEC

In WLAN, the performance is often limited by the conditions of the wireless medium: BER, power level, dynamic environment change, and protocol architecture. Wireless mobile devices are also constrained in memory capacity, processor functions, and battery life. Besides, conventional protocol stack doesn't work well in WLAN. Cross-layer technique can improve the wireless network performance to meet user requirement. For example, MAC layer can adjust transmission power based on BER detected by physical layer.

In [5], a link adaptor is used to monitor the channel condition and previous transmission result. Based on the results, SNR (Signal to Noise Ratio) is estimated. If SNR changes in the wireless environment, the link adaptor will switch the transmission mode for the next frame. Extending the idea, we propose an approach called "Adaptive FEC". The method employs the link adaptor to estimate SNR and interchange cross-layer information. The architecture is illustrated in Fig. 9.

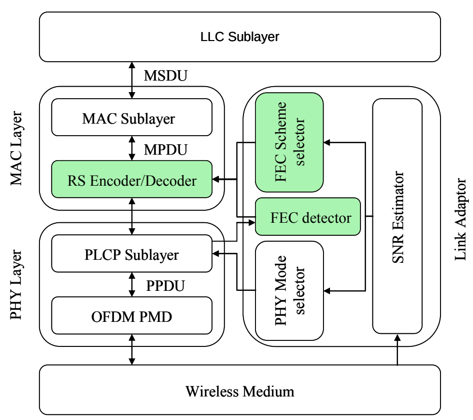

Fig. 9: Adaptive FEC with a cross-layer architecture

The link adaptor can estimate SNR in a time-varying channel using various SNR estimation algorithms such as those in [7] [10]. Other factors such as modulation, transmission rate, and frame length can also be added as part of the link adaptor functionalities. Based on these channel condition indicators, the FEC scheme selector chooses the appropriate FEC scheme and informs MAC and PLCP layers. MAC layer encodes the frame by the FEC chosen by the link adaptor. PLCP layer sets the rate bit, the service bit, and the FEC scheme bits based on the information from the link adaptor, and then sends the frame to the wireless channel.

The receiver determines the FEC scheme used in the frame after receiving it from the wireless channel. If the received frame is RS coded, PLCP layer informs the link adaptor the FEC scheme. MAC layer decodes the frame with the information provided by the link adaptor. Through the cross-layer cooperation, performance can be improved.

To avoid excessive AFEC switching, we utilize the hysteresis concept in soft handoff [8]. If the SNR variation does not exceed a threshold value, the FEC scheme will not be changed. In other words, a switch is triggered only if

$$|SNR_2 - SNR_1| \geq \Delta \qquad (17)$$

where Δ is the hysteresis margin, SNR_1 is the last-measured SNR value, and SNR_2 is the current SNR value.

7. Conclusions

FEC has been shown to be effective in countering adverse wireless transmission environments. Reed Solomon codes are particularly well suited for burst errors that are common place in wireless channels. With the advance in IC design and fabrication technologies, parallel encoding/decoding of RS FEC codes has become a reality, which makes it possible to incorporate such schemes into the stringent 802.11a wireless standard.

In order to distinguish RS codes used in a 802.11a frame, we suggested the inclusion of FEC scheme bits in PLCP header and the modification is easy to accommodate. Quantitative analysis of the relative performance of various RS codes was carried out for different BER values.

We found that in order to achieve optimal performance, the RS scheme used should be adaptively selected in response to the channel conditions. Subsequently, an adaptive FEC is proposed which makes use of information collected by physical layer to adjust the FEC adopted by MAC layer. Such cross-layer approach works well in wireless LAN. FEC based on RS codes has also been used in new wide-area wireless networks such as WiMAX defined in IEEE 802.16. Our analysis was applied to a simplistic AWGN channel. We are looking into the performance of FEC schemes used in conjunction with more sophisticated wireless channel models such as two-state models.

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