IEEE 802.11 MAC-Level FEC Scheme with Retransmission Combining

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Abstract— **In this paper, we evaluate and enhance the performance of a Forward Error Correction (FEC) scheme for IEEE 802.11 Medium Access Control (MAC). A novel retransmission combining technique is proposed to enhance the performance of the MAC-level FEC scheme. We also identify the problem with the IEEE 802.11a physical (PHY) layer when it is used with the MAC-level FEC. A new PHY frame format, backward compatible with the original format, is proposed to resolve the problem. Finally, we analytically evaluate the error performance of the MAC-level FEC, and its enhanced performance via retransmission combining and new 802.11a PHY frame format in AWGN environment. Additionally, we present and discuss the results from simulations using TCP/UDP traffic in more realistic channel environments.**

Index Terms— **IEEE 802.11 WLAN, MAC-level FEC, IEEE 802.11a PHY, Reed-Solomon (RS) code, retransmission combining.**

I. Introduction

In recent years, IEEE 802.11 wireless local area network (WLAN) has emerged as a prevailing technology for the (indoor) broadband wireless access for the mobile/portable devices. The IEEE 802.11 standard defines a single Medium Access Control (MAC) and multiple Physical (PHY) layers [1]. An 802.11 device implements the single MAC and one or more PHYs. Today's most WLAN devices implement IEEE 802.11b PHY [2], which supports 1, 2, 5.5 and 11 Mbits/s raw data transmission rates at the 2.4 GHz unlicensed bands. On the other hand, IEEE 802.11a is a high-speed PHY, supporting 8 different PHY rates, namely 6, 9, 12, 18, 24, 36, 48, and 54 Mbits/s, at the 5 GHz unlicensed bands [3].

In this paper, we consider a MAC-level Forward Error Correction (FEC) scheme, based on a well-known Reed-Solomon (RS) code, for more reliable transmission of data frames. The audio/video (AV) applications of 802.11-enabled home electronic devices could take advantage of this feature since such applications require the reliable transmission of frames within short delivery delay. With the 802.11 MAC, any erroneous (i.e., uncorrectable if the MAC-level FEC is used) frame is retransmitted by the sender up to a certain limit. We propose a novel retransmission combining technique, which combines multiple versions of partially corrected frames to reconstruct the complete frame. We also identify the problem of IEEE 802.11a PHY [3] when it is used along with the MAC-level FEC. That is, a part of the PHY header, called the SERVICE field, can be less reliable than the RS-coded MAC frame body, thus degrading the utility of the MAC-level FEC. We propose a new, but backward-compatible, PHY frame format, which resolves the identified problem by making the SERVICE field more reliable.

There have been efforts to enhance the reliability of IEEE 802.11 using FEC schemes at the MAC or above. These previous schemes can be classified into two categories depending on the degree of the modification of the legacy 802.11 MAC. The scheme found in [4] is based on the IEEE 802.11b PHY, but it requires a new MAC protocol since it proposes a selective repeat Automatic Repeat reQuest (ARQ) to selectively retransmit erroneous FEC blocks in an erroneously-received frame. Note that such a mechanism is not supported by the current 802.11 MAC.

On the other hand, the enhancement proposed in [5] and [6] can be achieved without the modification of the current WLAN MAC since the FEC codec is located between the IP layer and IEEE 802.2 Logical Link Layer (LLC) layer[1]. This is a flexible approach, but some performance loss is expected. For example, the MAC will not figure out if an erroneously-received frame is eventually corrected by the FEC decoder located above MAC, and hence an unnecessary retransmission will occur. Our MAC-level FEC requires a minor change in the MAC layer for the FEC encoding/decoding, and also the indication of the RS-coded frame. Moreover, our scheme is thoroughly studied for the 802.11a PHY-based operation even though it can be also used with the popular 802.11b PHY. Note that all the previously-mentioned schemes were based on the 802.11b PHY.

Another related work in [7] considers a class of MAC-level FEC-based ARQ schemes running on top of the old Lucent Wavelan PHY. Among the schemes considered in [7], one is similar to that in [4] and another is similar to the scheme considered in this paper. The authors conclude that the latter, i.e., the scheme similar to the one considered in this paper, is the best option in terms of the computational complexity and practicality. Actually, a scheme similar to the proposed retransmission combining has been also proposed for optical burst switched (OBS) networks [16], where partial information receptions can occur due to burst collisions resulted from the

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[1]Note that the LLC sits right above the MAC.

MAC Header	Frame Body Payload	FCS
24	239*(N-1)+1 ~ 239 *N	4

(a)

MAC Header		Frame Body (N Blocks)							FCS
Header	Header FEC	$Payload_1$	FEC	$Payload_2$	FEC	----	$Payload_N$ + "FEC FCS"	FEC	FCS
24	16	239	16	239	16	----	1 ~ 239	16	4

(b)

B0 B1	B2 B3	B4 B7	B8	B9	B10	B11	B12	B13	B14	B15
Protocol Version	Type	Subtype	To DS	From DS	More Frag	Retry	Pwr Mgt	More Data	WEP	Order

(c)

Fig. 1. IEEE 802.11 MPDU format without and with the MAC-level FEC, where each number represents the corresponding size in octets, where $N =$ 1˜10: (a) MPDU without RS blocks, (b) MPDU with RS blocks, and (c) Frame Control field in MAC header.

limit of contention resolution. However, it is different from our work in the considered environment since the channel errors can be ignored in this type of optical networks.

Finally, the MAC-level FEC was once considered as part of the IEEE 802.11e MAC enhancement [15] while this is not found in the up-to-date 802.11e draft. The basic FEC scheme considered in this paper is similar to that found in [15] while they are not exactly the same in terms of the frame header formats, RS block size, etc. However, extra proposed schemes including the retransmission combining and new PHY header format were never considered in the 802.11e. The retransmission combining is actually an implementation issue, and hence it is not something, which a standard should deal with. On the other hand, the 802.11e is a MAC enhancement so that a PHY header formant change is not within its scope. In fact, there is a school of thoughts, which questions about the utility of the MAC-level FEC. However, as we demonstrate in this paper through both analysis and simulations, the MAC-level FEC can improve the error performance as well as the throughput performance of the IEEE 802.11 WLAN. The MAC-level FEC technique should be considered complementary with the existing FEC scheme residing in the PHY. Note that the proposed FEC scheme in the MAC can work over any 802.11 PHY. Moreover, the MAC-level FEC allows us to utilize a new technique such as the retransmission combining proposed in this paper to further improve the performance. Note that it is not easy to apply this combining technique in the PHY.

The rest of this paper is organized as follows: Section II describes the proposed MAC-level FEC, and Section III presents a novel retransmission combining scheme. After identifying the problem of the 802.11a PHY and proposing a new SERVICE field format to resolve it in Section IV, Section V analyzes the error performance of the MAC-level FEC with and without the new PHY frame format as well as the proposed retransmission combining. After evaluating the proposed schemes based on both analysis and simulation results in Section VI, the paper concludes in Section VII.

II. IEEE 802.11 MAC-Level FEC

Fig. 1 shows the MAC Protocol Data Unit (MPDU) format (a) without and (b) with the proposed MAC-level FEC. An MPDU is the transmission unit in the 802.11 MAC's perspective. Basically, (255,239) Reed Solomon (RS) code, defined in GF(256), is used. Note that the implementation of this code is widely available in the market in various forms. The payload of an MPDU can be either a full MAC Service Data Unit (MSDU), from the higher layer, or a fragment of an MSDU (if a fragmentation is employed.) Note that an MSDU can be fragmented into multiple MPDUs if the MPDU size with the full MSDU is supposed to be larger than the FragmentThreshold value. Since an MSDU can be much larger than 239 octets, and be up to 2304 octets[2], the payload may be split into (up to 10) multiple blocks, and each block is encoded by the RS encoder separately. The last RS block in the frame body can be shorter than 255 octets by using a shortened code. (40,24) RS code, which is a shortened version of (255,239), is used for the MAC header, and CRC-32 is used for the Frame Check Sequence (FCS). Note that any RS block can correct up to 8-byte errors. The outer FCS allows the receiver to skip the RS decoding process if the FCS is correct. The inner FCS (referred to as ”FEC FCS” in the figure) allows the receiver to identify a potential false decoding of the RS decoder since the RS decoder may incorrectly decode any RS block.

In one 802.11 WLAN, there may co-exist both FEC-capable stations (STAs) and legacy STAs without the FEC capability. Note that a legacy STA would use the original MPDU format shown in Fig. 1 (a), and even an FEC-capable STA may use the original MPDU format somehow. For example, as discussed in Section 6.2, the usage of the FEC may result in a worse throughput performance due to the FEC redundancy when the channel condition is very good. Therefore, an FEC-capable STA should be able to identify an incoming MPDU to determine which type this frame belongs to. For this purpose, we use a currently-reserved bit in the MAC header to indicate the usage of the MAC-level FEC. That is, bit 7 (referred to as MAC FEC bit in our scheme) in the Frame Control field of the MAC header is currently not used for the data type frames. The Frame Control field represents the first two octets of the MAC header, and its format is shown in Fig. 1 (c). An FEC-capable STA set this bit to one when the MPDU is RS-coded. However, note that this MAC FEC bit could be reversed due to the channel error in a received frame, and hence the receiving STA should not rely on the MAC FEC bit as it is. In order to handle this problem, an FEC-capable STA processes any incoming MPDU in the following steps:

1) STA receives an MPDU, and checks the FCS of this received MPDU.
2) If the FCS is correct, STA sends an ACK frame. The process ends here.
3) If the FCS is incorrect, STA runs the RS decoder to decode the MAC header RS block, i.e., the first 40 octets of the MPDU.

[2]Actually, the payload of an MPDU may include both MSDU (or its fragment) and extra 8 octets if the encryption based on Wired Equivalent Privacy (WEP) is employed. In such a case, the maximum payload size becomes 2312 octets.

4) If the decoding fails or the MAC FEC bit of the MAC header after the RS decoding has value zero, the process ends here.
5) If the MAC FEC bit has value one after the RS decoding, STA continues to decode the entire MPDU through the RS decoder.
6) If the entire RS decoding processes complete without a decoding failure, the FEC FCS is checked.
7) If the FEC FCS is correct, STA sends an ACK frame.
8) The process ends here.

Note that any erroneous MPDU without RS blocks may go through the entire decoding process unfortunately if the MAC header RS decoding results in the value one in the MAC FEC bit. While the probability that such a case actually occurs seems to be ignorable, this, however, will not still break the protocol since such an MPDU will be filtered out eventually thanks to the FEC FCS.

III. Retransmission Combining

We first describe the proposed retransmission combining mechanism. There are two important aspects of 802.11 MAC, which make the proposed retransmission combining important: 1) any erroneously received frame is not passed to the higher layer, which implies that when the MAC-level FEC is used, any RS-coded frame with uncorrectable RS block(s) will not be forwarded to the higher layer; and 2) there is no partial retransmission with 802.11, which implies that if any of N RS blocks is uncorrectable by the receiver, the sender should retransmit the whole frame again. Note that at the receiver side, there is always a non-zero probability that an RS decoder fails to correct the errors within a coded block. A partial retransmission mechanism could be implemented as was considered in [4]. However, such a mechanism requires considerable added complexity along with an extra protocol and new frame types, and hence we do not consider it in this work.

Our proposal is for the receiver to reuse partially corrected frames by storing the corrected RS blocks instead of discarding them, and by combining these stored blocks with other corrected blocks retrieved from the retransmitted frame later. The mechanism formally works as follows:

1) STA 1 transmits a frame with RS blocks to STA 2, where the set of RS blocks is represented by $\mathbf{A}$.
2) STA 2 finds the errors in a set of blocks, represented by $\mathbf{U}$, uncorrectable while all the errors in the rest blocks, i.e., the set $\mathbf{A}-\mathbf{U}$, are correctable. If $\mathbf{U}=\varnothing$, the ACK is transmitted by STA 2, and the process ends here.
3) If STA 2 finds that the first RS block, i.e., MAC header block, is not correctable, the process goes to Step 5.
4) STA 2 stores the set of corrected (or correctly received) RS blocks, i.e., the set $\mathbf{A}-\mathbf{U}$, instead of throwing them away, along with the header information, which includes the sender of the frame, i.e., STA 1.
5) STA 1 retransmits the whole frame again as the ACK frame is not received.
6) If the MAC header block of the retransmitted frame is correctly decoded, STA 2 can identify that it is a retransmission of an erroneously received frame. If not, the process goes to Step 5.
7) Now STA 2 finds that the errors in a set of blocks, represented by $\mathbf{U}_{new}$, are uncorrectable.
8) If $\mathbf{U}\cap\mathbf{U}_{new}=\varnothing$, STA 2 can reconstruct all the RS blocks in the frame successfully, and hence sends the ACK frame. The process ends here.
9) If $\mathbf{U}\cap\mathbf{U}_{new}\neq\varnothing$, STA 2 does not send the ACK, and the process goes to Step 4 above after setting $\mathbf{U}=\mathbf{U}\cap\mathbf{U}_{new}$.

Note that this retransmission combining can improve the system performance significantly depending on the channel condition by reducing the number of potential retransmissions. This also implies that the probability to meet the latency requirement in a marginal channel condition is increased since it will require smaller number of retransmissions to transmit a frame successfully.

TABLE I
Eight different modes of 802.11a PHY.

Mode m	Modulation	Code Rate r	Data Rate (Mbits/s)	BpS[3]
1	BPSK	1/2	6	3
2	BPSK	3/4	9	4.5
3	QPSK	1/2	12	6
4	QPSK	3/4	18	9
5	16-QAM	1/2	24	12
6	16-QAM	3/4	36	18
7	64-QAM	2/3	48	24
8	64-QAM	3/4	54	27

IV. IEEE 802.11a PHY Problem and Enhancement

The new IEEE 802.11a PHY [3] running at the 5 GHz bands is based on the orthogonal frequency division multiplexing (OFDM). The basic principle of OFDM is to divide a high-speed bit stream to a number of low data-rate bit streams, which are used to modulate separate sub-carriers in the frequency channel.

A. 802.11a Transmission Rates and Convolutional Coding

IEEE 802.11a PHY provides eight PHY modes with different modulation and code rates. As listed in Table I, the OFDM system provides a wireless LAN with capabilities of communicating at 6 to 54 Mbits/s. Forward error correction of the 802.11a PHY is performed by bit interleaving and rate-1/2 convolutional coding. The higher code rates of 2/3 and 3/4 are obtained by puncturing the original rate-1/2 code.

The convolutional coding has the error correcting capability proportional to d_{free}, which is inversely proportional to the coding rate, as analyzed in Section 5.1. On the other hand, the RS coding, which is a type of block coding, has the error correcting capability proportional to the size of parity bytes. At the receiver side, the RS decoder used for our MAC-level FEC can correct uncorrected errors out of the convolutional decoder (e.g., Viterbi decoder). One of the important properties of RS coding is that the unit of error correction is the symbol, which is one octet in (255,239) RS coding in consideration. Accordingly, it presents a powerful capability to overcome bursty errors at the convolutional decoder. This implies that

[3]BpS: Bytes per OFDM Symbol of 4 μs.

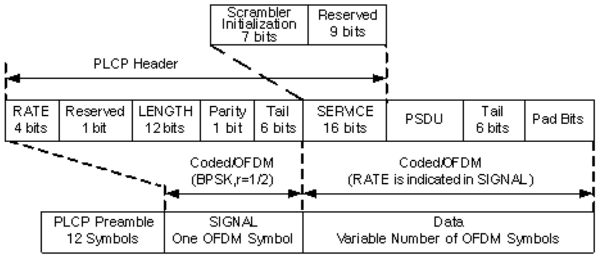


Fig. 2. PPDU format of 802.11a PHY.

the proposed MAC-level FEC is complementary with the convolutional coding at the 802.11a PHY.

B. 802.11a PHY PPDU

During the transmission, an MPDU is encapsulated by a physical layer convergence procedure (PLCP) preamble and a PLCP header to create PLCP protocol data unit (PPDU) as shown in Fig. 2. At the receiver, the PLCP preamble and header are processed to aid the demodulation of the MPDU. The PPDU format of the IEEE 802.11a PHY includes PLCP preamble, PLCP header, MPDU, tail bits, and pad bits.

The PLCP preamble field, with the duration of 16 μs, is composed of 10 repetitions of a short training sequence (0.8 μs) and 2 repetitions of a long training sequence (4 μs). The PLCP header except the SERVICE field, with the duration of 4 us, constitutes a separate OFDM symbol, which is transmitted with BPSK modulation and rate-1/2 convolutional coding. The 6 "zero" tail bits are used to return the convolutional decoder to the "zero state," and the pad bits are used to make the resulting bit string to be a multiple of OFDM symbols. Each OFDM symbol interval is 4 μs. The 16-bit SERVICE field of the PLCP header and the PLCP Service Data Unit (PSDU) along with 6 tail bits and pad bits, represented by DATA, are transmitted at the data rate specified in the RATE field. Note that PSDU is equivalent to MPDU forwarded from the MAC.

The SERVICE field can be detailed as follows: the scrambler initialization bits are used to synchronize the descrambler at the receiver of the frame. Therefore, a single error in these 7 bits will result in the erroneous reception of the whole frame. Note that the SERVICE field can be transmitted at up to 54 Mbits/s while the SIGNAL field is always transmitted at 6 Mbits/s. The problem arises when the 802.11 MAC FEC is used since the SERVICE field may be even less reliable than the following PSDU (or MPDU). In this case, the error performance of the SERVICE field ends up being the bottleneck of the error performance of the whole frame transmission, which in turn makes the 802.11 MAC-level FEC less effective.

C. New SERVICE Field Format

Fig. 3 shows the modified PPDU format, which can overcome the above-described problematic situation. That is, we use a single OFDM symbol using the most reliable scheme, i.e., 6 Mbits/s, for the SERVICE field[4]. Whether the new format/rate of the SERVICE field is used or not is specified in the NEW SERVICE bit in the SIGNAL field. Note that this bit is reserved in the current 802.11a PHY, and hence not used. This one bit indication makes the new frame format backward-compatible with the legacy 802.11a PHY.

[4]The SERVICE field is extended from 16 bits to 24 bits so as to fit into the additional OFDM symbol.

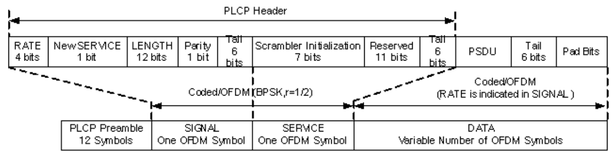


Fig. 3. Modified format of 802.11a PPDU.

By using this new format, one can avoid the SERVICE field becoming the bottleneck of the error performance of the whole frame transmission since the error performance of this new SERVICE field will be as good as the preceding SIGNAL field at the cost of the potential increase of the frame transmission time by 4 us, i.e., one OFDM symbol duration. Depending on the length of the PSDU field, the frame transmission time may not be increased thanks to the Tail bits after PSDU. One can minimize this increased overhead by using this new SERVICE field format only for the frame encoded with the 802.11 MAC-level FEC and transmitted at a data rate higher than 6 Mbits/s. Since we have a bit, that indicates the use of this new format in the SIGNAL field, this adaptive usage of the new format is possible.

V. Performance Analysis

In this analysis, we assume that the noise over the wireless medium is white Gaussian with spectral density $N_0/2$. Although this additive white Gaussian noise channel (AWGN) model is not a realistic assumption, we believe that our error performance analysis based on the AWGN model will show the same trend with that based on a more realistic and complicated channel model, and hence the results presented in this paper can be a good guidance for the reality.

A. 802.11a PHY Bit Error Probability

The analysis of the 802.11a PHY error performance here is based on those given in [8] and [9] as part of the link adaptation and energy efficiency analysis of the 802.11a WLAN, respectively. The symbol error probability for an Mary QAM with M = 4, 16, and 64 is given [10] by

$$P_M = 1 - (1 - P_{\sqrt{M}})^2,$$

where the symbol error probability for the -ary QAM with the average signal-to-noise ratio per symbol is given [10] by

$$P_{\sqrt{M}} = 2 \cdot (1 - \frac{1}{\sqrt{M}}) \cdot Q\Big(\sqrt{\frac{3}{M-1} \cdot \frac{E_{av}}{N_0}}\Big).$$

In general, one QAM symbol per useful OFDM sub-carrier is transmitted. The bit error rate (BER) for an M-ary QAM with Gray coded constellation mappings can be approximated by

$$P_b^{(M)} \approx \frac{1}{log_2 M} \cdot P_M. \tag{1}$$

For the BPSK modulation, the BER is the same as the symbol error probability given by

$$P_b^{(2)} = Q\Big(\sqrt{2\frac{E_{av}}{N_0}}\Big). \tag{2}$$

For rate-r convolutional code, used for the selected PHY mode m, the BER after the Viterbi decoding is bounded [10] by

$$P_b^m \le \frac{1}{k'} \sum_{d=d_{free}}^{\infty} b_d \cdot P_d, \tag{3}$$

where k' is the numerator of the rate $r = k'/n'$, d_{free} is the free distance of the convolutional code, b_d is the total number of non-zero information bits on all weight-d paths in the trellis diagram of the convolutional code, and P_d is the probability that an incorrect path at distance d from the correct path being chosen by the Viterbi decoder. Note that m is used as index indicating the PHY mode of operation. When hard-decision decoding is used, P_d is given by

$$P_d = \begin{cases} \sum_{k=(d+1)/2}^{d} \binom{d}{k} \rho^k (1-\rho)^{d-k}, & d = \text{odd}, \\ \sum_{k=d/2+1}^{d} \binom{d}{k} \rho^k (1-\rho)^{d-k} + \\ \quad \frac{1}{2} \cdot \binom{d}{d/2} \rho^{d/2} (1-\rho)^{d/2}, & d = \text{even}, \end{cases}$$

where ρ is the BER for the modulation scheme selected in PHY mode m, and is given by Eq. (1) or Eq. (2). The values of b_d can be obtained either from the transfer function or by a numerical search [11].

B. 802.11 RS Code Error Performance

The probability P_{PLCP}^m of error in the PLCP header including both SIGNAL (of 24 bits) and SERVICES (with 7 scrambler initialization bits) fields, when PHY mode m is used for the SERVICE field of the PPDU, can be determined by

$$P_{PLCP}^m = \begin{cases} 1 - (1 - P_e^1(24)) \cdot \\ \qquad (1 - P_e^m(7)), & format = \text{old}, \\ P_e^1(31), & format = \text{new}, \end{cases}$$

where the probability of error in a block of length l bits, assuming random errors with the BER P_b^m of PHY mode m given by Eq. (3), is determined by

$$P_e^m(l) = 1 - (1 - P_b^m)^l.$$

Note that we ignore the error events in the reserved bits in the SERVICE field as they do not affect the error performance of the frame at all.

For (n, k) RS code, the error probability of an RS code block is given [10] by

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

where the error correction capability $t = \lfloor (n-k)/2 \rfloor$ and the symbol error probability P_s^m, when PHY mode m is used, is given by

$$P_s^m = P_e^m(8).$$

Finally, we obtain the error probability of the RS-coded MPDU with N code blocks in the frame body as follows:

$$P_{E,RS}^m(N) = 1-(1-P_{PLCP}^m)(1-P_{RS}^m(40))(1-P_{RS}^m(255))^N, \tag{4}$$

where the numbers 40 and 255 represent the size of a single RS block for the MAC header and frame body, respectively. On the other hand, the error probability of a non-RS-coded MPDU transmitted at PHY mode m with $(239{\cdot}N)$-byte frame body can be approximated as:

$$P_{E,noRS}^m(N) = 1-(1-P_e^1(24))\cdot(1-P_e^m(7+8\cdot(28+239\cdot N))). \tag{5}$$

Note that number 28 represents the number of octets for the MAC header and FCS field.

C. Error Performance with Retransmission Combining

The probability that an RS-coded frame transmission is successfully transmitted at the $(R-1)$-th retransmission, when the retransmission combining described in Section 2 is *not* used, is given by

$$P_{retrans}(R) = (P_E^m)^{R-1}(1 - P_E^m).$$

Accordingly, the probability that the frame is not successfully transmitted within R transmissions is obtained by

$$P_{error}(R) = 1 - \sum_{i=1}^{R} P_{retrans}(i) = (P_E^m)^R. \tag{6}$$

When the retransmission combining scheme is used, the receiver needs to receive the RS blocks, that were never correctly decoded in the previous receptions. Each uncorrectable frame can be classified into two categories: 1) one with errors in the PLCP header or uncorrectable errors in the MAC header; and 2) one with no such errors in headers and uncorrectable errors in the frame body.

Now, the probability that an RS-coded frame transmission is successfully transmitted at the $(R-1)$-th retransmission, when the retransmission combining is used, can be analyzed considering the following facts: 1) there can be $R'(R-R')$ frame receptions without (with) uncorrectable error in the headers, where $1 \le R' \le R$; and 2) the R-th transmission (which is the $(R-1)$-th retransmission) should not have any uncorrectable error in the headers, which makes $R' > 0$. Now, the error probability can be analyzed as Eq. (7), where e_i is the number of the RS blocks that were never correctly received after the i-th frame transmission without uncorrectable header error is received. Note that $e_0 = N$ and $e_{R'} = 0$ (for all R' values) as the frame is completely received by the receiver with the R-th transmission or equivalently R'-th frame transmission received without uncorrectable header error. The header error probability P_{hdr}^m is given by

$$P_{hdr}^m = 1 - (1 - P_{PLCP}^m)(1 - P_{RS}^m(40)),$$

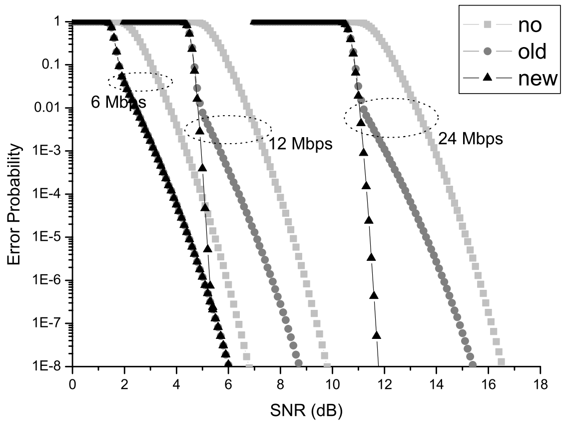
and the probability $P_E^m(i|j)$ that i out of j RS blocks for the frame body in an RS-coded frame is with uncorrectable errors is given by

$$P_E^m(i|j) = \binom{j}{i} P_{RS}^m(255)^i (1 - P_{RS}^m(255))^{j-i}.$$

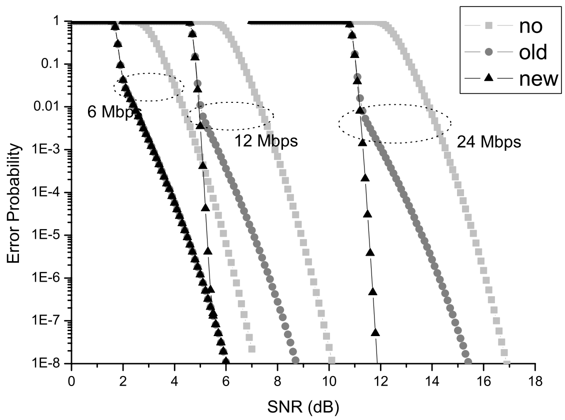
Finally, the probability that the frame is not successfully transmitted within R transmissions is obtained by

$$P_{error}^{comb}(R) = 1 - \sum_{i=1}^{R} P_{retrans}^{comb}(i). \tag{8}$$

$$P_{retrans}^{comb}(R) = \sum_{R'=1}^{R} \binom{R-1}{R'-1} (P_{hdr}^{m})^{R-R'} (1-P_{hdr}^{m})^{R'} \left(\sum_{e_1=1}^{N} \sum_{e_2=1}^{e_1} \cdots \sum_{e_{R'-1}=1}^{e_{R'-2}} \prod_{i=1}^{R'} P_E^m(e_i|e_{i-1}) \right) \quad (7)$$



(a) $N = 1$.



(b) $N = 9$.

Fig. 4. Frame error probability without retransmissions vs. SNR.

VI. Performance Evaluation

In this section, we evaluate the proposed schemes via the mathematical analysis presented in Section V, and then via simulation results considering more realistic channel environments.

A. Analytical Results

In this section, we evaluate the proposed new SERVICE field format along with the retransmission combining scheme based on the analysis presented in the previous section. First, Fig. 4 shows the error probability of a data frame without retransmissions for three different cases and three different transmission rates as the SNR increases when (a) $N = 1$, i.e., a 239-byte MSDU and (b) $N = 9$, i.e., a 2151-byte MSDU. Each figure shows the following three cases:

1) "no": the error probability when the FEC is not used using Eq. (5).
2) "old": the error probability when the FEC is used with the current 802.11a SERVICE field format using Eq. (4).
3) "new": the error probability when the FEC is used with the proposed new SERVICE field format using Eq. (4).

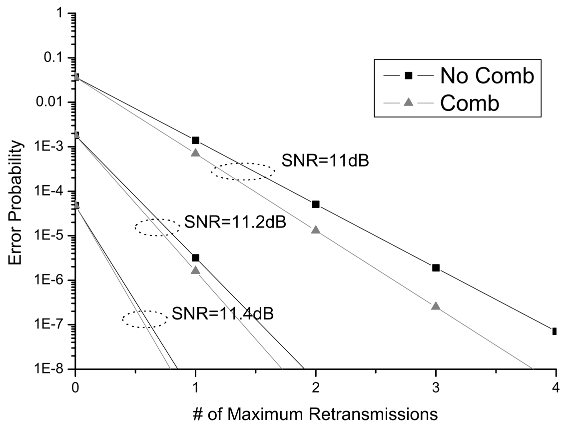
We first observe that with the RS coding, the frame error probability is reduced with the current format of the SERVICE field, but not that significantly. On the other hand, the error performance enhancement is more dramatic if the proposed new SERVICE field is used. By comparing Fig. 4 (a) and (b), we also observe that the effect of the MAC-level FEC is less evident with smaller number of RS blocks. Note that the more RS blocks, the more erroneous octets correctable for a given frame.

As the new SERVICE field format relies on the performance of 6 Mbits/s transmission rate, it does not improve the performance at all in case of 6 Mbits/s transmission rate. Moreover, when the frame error probability is high, say 10^{-2} or above, the new SERVICE field format does not seem to improve the performance as in this situation, whenever there is error in the SERVICE field of the new format, there are enough number of errors in the following MPDU to make the RS decoder fail to correct. This suggests the importance of using the new SERVICE field format in an adaptive manner as the new SERVICE field format may use more bandwidth without gaining any error performance improvement under certain circumstances.

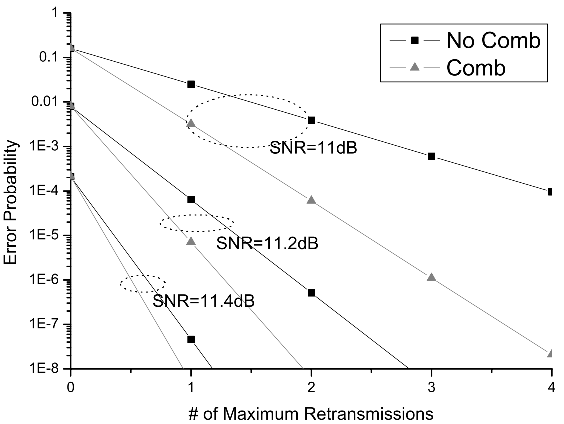
Fig. 5 shows the probability that the frame is not successfully transmitted for both without and with the retransmission combining, i.e., $P_{error}(R)$ and $P_{error}^{comb}(R)$ in Eqs. (6) and (8), respectively. As the number of maximum retransmissions $(R-1)$ increases, the improvement using the retransmission combing becomes bigger as it increases the chance to utilize the combining using more versions of the same frame. We observe that the advantage of the retransmission combining is significant when $N = 9$ while it is not with as the more RS blocks also imply more chance to utilize the combining. Actually, with $N = 1$, there is no gain by using the retransmission combining. Unless there is only a single RS block within an MPDU frame body, the proposed retransmission combining provides error performance enhancement at the cost of more memory needed to buffer the partially corrected frames.

B. Simulation Results

Since the analytical results in the previous sections are obtained under the assumption of the ideal channel environment, i.e., AWGN channel, it should be further confirmed how much the performance gain could be achieved in more realistic channel environments. We use network simulator (NS-2), which is modified in order to reflect the IEEE 802.11a PHY and Ricean channel model [12] with K factor of 3 dB in order to describe the indoor channel environment [13], where



(a) $N = 2$ & mode 5, i.e., 24 Mbits/s.



(b) $N = 9$ & mode 5, i.e., 24 Mbits/s.

Fig. 5. Frame error probability vs. the number of maximum retransmissions, $(R - 1)$.

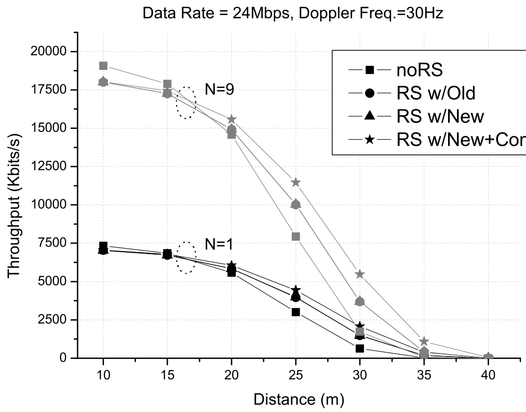


Fig. 6. Throughput vs. distance.

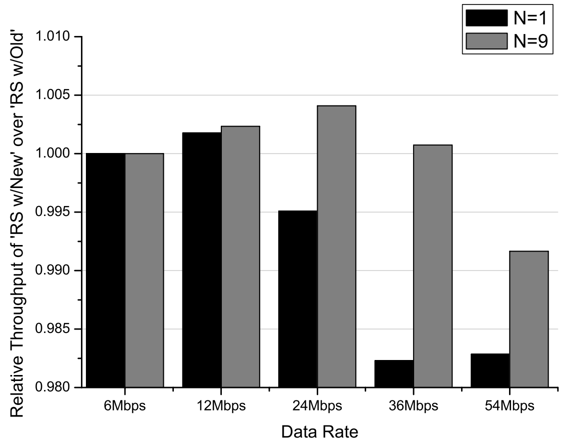


Fig. 7. Relative throughput gain vs. data rate.

2–4 dB are reported as the typical values at the 5.8 GHz bands. There are one AP and one STA in all of the considered scenarios, and both CBR/UDP (Constant Bit Rate over User Data Protocol) and TCP/IP (Transport Control Protocol over Internet Protocol) are considered as the traffic models. We first simulate the enhancement of error capability over the air link using end-to-end non-interactive traffic, i.e., the CBR over UDP traffic. Then, we investigate how the proposed schemes affect the performance of the end-to-end interactive traffic, i.e., TCP/IP.

First, Fig. 6 shows the throughput at MAC layer when an AP transmits the CBR traffic to a single STA with 24 Mbits/s data rate. The packet sizes of the CBR traffic are configured to investigate the effect from the different number of RS coding blocks, i.e., the smallest one is $N = 1$, and the largest is $N = 9$. For each case, the traffic generation rate is configured high enough to saturate the air link according to the simple calculation of theoretical capacity [8]. We change the distance between the AP and the STA from 10 m to 40 m with 5 m spacing. We observe that the throughput increases significantly at the marginal transmission range through RS coding. On the other hand, when the STA is located near the AP so that the packet error seldom occurs, "noRS" case outperforms all the "RS coding" cases due to the additional overhead of RS coding. In spite of the trade-off between the enhanced packet error rate (PER) performance and the required coding overheads, we observe that the considerable throughput gain is obtained across a broad range of transmission distances.

As another interesting result, it seems that there is almost no throughput difference between "RS w/Old" and "RS w/New" even if the enhancement of PER performance was observed in Fig. 4. Note that when the PER is under 10^{-2}, it is generally difficult to observe any throughput gain even if the PER is reduced even further since the throughput is basically proportional to one minus PER, and the throughput values close to one actually look about the same in reality. Accordingly, we can easily imagine that the PER enhancement through the new SERVICE field is not much useful for the throughput performance. We further evaluate this issue with Fig. 7, which shows the relative throughput ratio of "RS w/New" over "RS w/Old" for other data rates. If the ratio is above the unity, it means that the "RS w/New" outperforms "RS w/Old," and vice versa. We observe that there is no definite superiority of

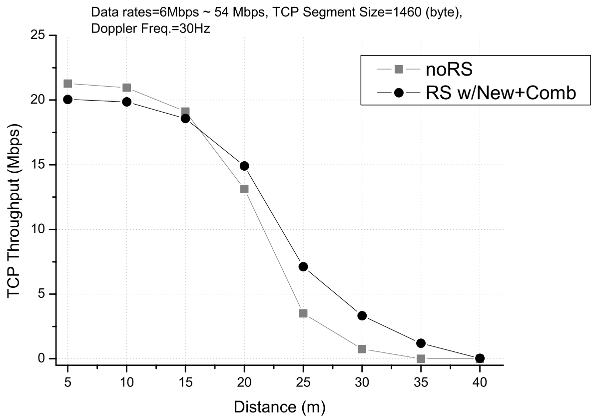


Fig. 8. Optimal TCP performance using the best transmission rates with and without the proposed schemes.

a scheme to the other. It could be explained from the trade-off between "RS w/New" and "RS w/Old". While "RS w/New" increases the probability of successfully decoding the PLCP header, it also makes transmission time slightly longer than "RS w/Old" because it may require one additional OFDM symbol to be transmitted in the lowest transmission rate (i.e., 6 Mbits/s). It is easily understood that such a negative effect is worse for the small MSDUs.

Now, we take a look at the end-to-end interactive traffic case considering TCP/IP traffic. 1460-octet TCP segment size and 30 Hz Doppler frequency are assumed. The optimal throughput performances of TCP for two cases, namely, (1) "noRS" or RS code is not used, i.e., the original 802.11a, and (2) "RSw/New+Comb" or RS with new SERVICE field and retransmission combining is used, are presented in Fig. 8. The optimal throughput value for a given distance corresponds to the throughput of the rate, which achieves the largest throughput, out of the eight possible data transmission rates. This type of optimal throughput performance can be achieved using an effective link adaptation algorithm (e.g., [8], [14]).

One distinction between TCP and UDP is that TCP has an error recovery scheme based on the retransmission of packets for the end-to-end reliable communication. The TCP source is supposed to retransmit a packet, e.g., due to retransmission timeout (RTO), when the transmission of the packet over the 802.11 link fails even after a number of MAC-layer retransmissions. When the TCP source retransmits the packet due to the frame transmission failure at the MAC layer, it eventually reduces its congestion window size so that the total throughput is also reduced. With our proposed MAC-level FEC, especially, with the retransmission combining, the chance to successfully transmit a frame within a given retransmission limit over the 802.11 link is increased, thus reducing the chance for the TCP source to reduce the TCP congestion window. This will make the TCP throughput performance with the proposed scheme even better at the marginal channel condition.

We observe that the throughput of "RSw/New+Comb" is smaller than that of "noRS" up to 15 m. Actually, all three points in the range of 5 15 m are from 54 Mbits/s transmission rate for both "RSw/New+Comb" and "noRS," and it implies that for this short range, where 54 Mbits/s transmission is the best, RS coding is not useful since the PER gain due to the RS coding is less than the throughput loss due to the increased overheads. We, on the other hand, observe that the gain due to the RS coding is considerable as we expected for the rest of the distance range in consideration. This implies that the proposed RS coding with retransmission combining can be very useful to extend the transmission range of the 802.11 WLAN. We conclude that the proposed scheme should be used in an adaptive manner. A simplest policy could be to employ the proposed schemes for the transmission rates excluding the highest 54 Mbits/s.

VII. Concluding Remarks

In this paper, we propose a MAC-level FEC for IEEE 802.11 WLAN. A novel retransmission combining technique is proposed to enhance the performance of the MAC-level FEC scheme. We also identify the problem with the IEEE 802.11a PHY when it is used with the MAC-level FEC. A new PHY frame format, backward compatible with the original format, is proposed to resolve the problem. Finally, we evaluate the error performance of the MAC-level FEC, and its enhanced performance via retransmission combining and new 802.11a PHY frame format based on both mathematical analysis and simulations in order to demonstrate the utility of the proposed MAC-level FEC schemes.

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