IEEE 802.11e MAC-Level FEC Performance Evaluation and Enhancement

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Abstract- In this paper, we evaluate and enhance the performance of the Forward Error Correction (FEC) scheme being defined in the upcoming IEEE 802.11e Medium Access Control (MAC) protocol. A novel retransmission-combining technique is proposed to enhance the performance of the MAC-level FEC scheme. We also identify a 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.

I. INTRODUCTION

In recent years, IEEE 802.11 wireless local area networks (WLANs) [1] have emerged as the prevailing technology for (indoor) broadband wireless access for portable/mobile devices. Today, IEEE 802.11 can be considered a wireless version of Ethernet by supporting best-effort service (without guaranteeing any particular service quality to applications). The IEEE 802.11 Working Group is currently defining a new supplement to the existing 802.11 MAC in order to support Quality of Service (QoS) [3][4]. The new 802.11e MAC will expand the application domain of 802.11 WLANs by, for example, enabling such applications as toll-quality voice and video services over WLANs.

The IEEE 802.11e Medium Access Control (MAC) optionally defines MAC-level Forward Error Correction (FEC), based on a well-known Reed-Solomon (RS) code, for more reliable transmission of data frames [3]. The audio/video (AV) applications of 802.11e-enabled home electronic devices can take advantage of this feature. With 802.11e, any erroneous (uncorrectable if 802.11 MAC-level FEC is used) frame is retransmitted, up to a certain limited number of times, by the sender. We propose a novel retransmission-combining technique, in which multiple versions of partially corrected frames are combined to reconstruct the complete frame. We also identify a problem of the IEEE 802.11a physical (PHY) layer [2] when it is used along with 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.

The rest of this paper is organized as follows: Section 2 describes the MAC-level FEC according to the latest draft specification of IEEE 802.11e, and Section 3 proposes the novel retransmission-combining scheme. After identifying the problem with the 802.11a PHY and proposing a new SERVICE field format to resolve it in Section 4, Section 5 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 in Section 6, the paper concludes with Section 7.

II. IEEE 802.11e MAC-LEVEL FEC

Fig. 1 shows the MAC Protocol Data Unit (MPDU) format defined in the draft specification of IEEE 802.11e [3]. Basically, a (224,208) shortened Reed Solomon (RS) code, defined in GF(256), is used. Since a MAC Service Data Unit (MSDU), from the higher layer, can be much larger than 208 octets, an MSDU may be split into (up to 12) multiple blocks, and each block is encoded by the RS encoder separately. The last RS block in the frame body can be shorter than 224 octets by using a shortened code. A (48,32) RS code, which is also a shortened RS code, is used for the MAC header¹, 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 (or FEC FCS) allows the receiver to identify a false decoding by the RS decoder.

Fig. 1. IEEE 802.11e MPDU format without and with the optional FEC, where each number represents the corresponding size in octets.

III. RETRANSMISSION-COMBINING

We first describe our retransmission-combining technique. There are two aspects of the 802.11e MAC, which make the proposed retransmission-combining important: 1) any erroneously received frame (or any RS-coded frame with uncorrectable RS block(s) if the MAC-level FEC is used) is not passed 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 has to retransmit the whole frame. Note that at the receiver, there is always a non-zero probability that an RS decoder fails to correct the errors within a coded block.

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 Note that the MAC header size is 32 octets instead of 30 octets because a two-octet field is newly added to the 802.11e QoS data frame header.
1) Station (STA) 1 transmits a frame with RS blocks to STA 2, where the set of RS blocks is represented by $A$.

2) STA 2 finds the errors in a set of blocks, represented by $U$, uncorrectable while all the errors in the rest of the blocks, i.e., the set $A-U$, are correctable. If $U = \emptyset$, the ACK is transmitted by STA 2, and the process ends here.

3) If STA 2 finds that the first RS block, i.e., the 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 $A-U$, 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 $U_{new}$, are uncorrectable.

8) If $U \cap U_{new} = \emptyset$, STA 2 can reconstruct all the RS blocks in the frame successfully, and hence sends the ACK frame. The process ends here.

9) If $U \cap U_{new} \neq \emptyset$, STA B does not send the ACK, and the process goes to Step 4 above after setting $U = U \cap U_{new}$.

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

IV. IEEE 802.11a PHY PROBLEM AND ENHANCEMENT

The new IEEE 802.11a PHY [2] running at 5 GHz is based on orthogonal frequency division multiplexing (OFDM). The basic principle of OFDM is to divide a high-speed bit stream into a number of low data-rate bit streams, which are used to modulate separate orthogonal sub-carriers in the frequency channel.

A. Eight Transmission Modes of 802.11a PHY

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 the capability to communicate at 6 to 54 Mbps. Forward error correction is performed by bit interleaving and rate-1/2 convolutional coding. The higher code rates of 2/3 and 3/4 are obtained by bit interleaving and rate-1/2 convolutional coding. The 6 to 54 Mbps communication is provided by the IEEE 802.11a PHY.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Modulation</th>
<th>Code Rate $r$</th>
<th>Data Rate (Mbps)</th>
<th>Bps$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BPSK</td>
<td>1/2</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>BPSK</td>
<td>3/4</td>
<td>9</td>
<td>4.5</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>1/2</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>QPSK</td>
<td>3/4</td>
<td>18</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>16-QAM</td>
<td>1/2</td>
<td>24</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>16-QAM</td>
<td>3/4</td>
<td>36</td>
<td>18</td>
</tr>
<tr>
<td>7</td>
<td>64-QAM</td>
<td>2/3</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>8</td>
<td>64-QAM</td>
<td>3/4</td>
<td>54</td>
<td>27</td>
</tr>
</tbody>
</table>

Table I

As listed in Table I, the OFDM system provides a wireless LAN with the capability to communicate at 6 to 54 Mbps. Forward error correction is performed by bit interleaving and rate-1/2 convolutional coding. The higher code rates of 2/3 and 3/4 are obtained by bit interleaving and rate-1/2 convolutional coding.

B. 802.11a PHY PPDU

For transmission, an MPDU is appended to a physical layer convergence procedure (PLCP) preamble and a PLCP header to create a PLCP protocol data unit (PPDU). 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 is shown in Fig. 2; this includes a PLCP preamble, a PLCP header, an MPDU, tail bits, and pad bits.

The PLCP preamble field, with a duration of 16 µsec, is composed of 10 repetitions of a short training sequence (0.8 µsec) and 2 repetitions of a long training sequence (4 µsec). The PLCP header, except the SERVICE field, with a duration of 4 µsec, 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 length a multiple of the OFDM symbol length (in bits). Each OFDM symbol interval is 4 µsec. 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.

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 Mbps, for the SERVICE field. Whether the new

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$^2$ Bps: Bytes per OFDM Symbol of 4 usec.
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.

By using this new format, one can avoid the SERVICE field imposing the limit on 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 new SERVICE field will be as good as the preceding whole frame transmission since the error performance of this backward-compatible with the legacy 802.11a PHY.

Bit is reserved in the current 802.11a PHY, and hence not in the New SERVICE bit in the SIGNAL field. Note that this format/rate of the SERVICE field is used or not is specified in the SIGNAL field, this adaptive usage of the new format is possible.

IV. 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 as that based on a more realistic and complicated channel model, and hence the results presented in this paper can provide guidance for more realistic scenarios.

A. 802.11a PHY Bit Error Probability

The analysis of the 802.11a PHY error performance here is based on those given in [5] and [6] as part of the link adaptation and energy efficiency analysis of the 802.11a WLAN, respectively. The symbol error probability for an $M$-ary QAM with $M = 4, 16, 64$ is given by

$$P_s = 1 - (1 - P_{\text{free}})^2,$$

where the symbol error probability for the $\sqrt{M}$ -ary QAM with average signal-to-noise ratio $E_{\text{av}}/N_0$ per symbol is given by:

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

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

$$P_b^{(M)} = \frac{1}{\log_2 M} \cdot P_s.$$  

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

$$P_{b}^{(2)} = Q\left( \frac{E_{\text{av}}}{2 \cdot N_0} \right).$$

For a rate-$r$ convolutional code, used for the selected PHY mode $m$, the BER after Viterbi decoding is bounded [7] by:

$$P_d^{m} \leq \frac{1}{k'} \sum_{d_{\text{free}}} b_d \cdot P_d,$$

where $k'$ is the numerator of the rate $r = k'/n'$, $d_{\text{free}}$ 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 is chosen by the Viterbi decoder. Note that $m$ is used as an index indicating the PHY mode of operation. When hard-decision decoding is used, $P_d$ is given by:

$$P_d = \left\{ \begin{array}{ll} \sum_{d=-(d+1)/2}^d \binom{d}{k} \rho^k (1 - \rho)^{d-k}, & d = \text{odd}, \\ \sum_{d=-(d+1)/2}^d \binom{d}{k} \rho^k (1 - \rho)^{d-k} + \frac{1}{2} \binom{d}{d/2} \rho^{d/2} (1 - \rho)^{d/2}, & d = \text{even}, \end{array} \right.$$
used for the SERVICE field of the PPDU, can be determined by:

\[
P_{m}^{PLCP} = \begin{cases} 
1-(1-P_{c}^{(24)})(1-P_{c}^{(7)}), & \text{format = old}, \\
P_{c}^{(31)}, & \text{format = new},
\end{cases}
\]

where the probability \(P_{c}^{m}(l)\) of error in a block of length \(l\) bits, assuming random errors with the BER \(P_{b}^{m}\) of PHY mode \(m\) given by (3), is determined by:

\[
P_{c}^{m}(l) = 1 - (1 - P_{b}^{m})^l.
\]

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.

For \((n,k)\) RS code, the error probability of an RS code block is given [7] by:

\[
P_{RS}(n) = \sum_{i=0}^{l} \binom{n}{i} (P_{c}^{m})^i (1-P_{c}^{m})^{n-i},
\]

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

\[
P_{s}^{m} = P_{c}^{m}(8).
\]

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

\[
P_{e,RS}^{m}(N) = 1 - (1 - P_{c}^{m}(24))(1-P_{c}^{m}(48))(1-P_{c}^{m}(224))^N, \tag{4}
\]

where the numbers 48 and 224 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 with PHY mode \(m\) with 208-byte frame body can be approximated as:

\[
P_{e,nonRS}^{m}(N) = 1 - (1 - P_{c}^{m}(24))(1-P_{c}^{m}(7+8 \cdot (36+208 N))). \tag{5}
\]

Note that number 36 represents the number of octets in 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:

\[
P_{\text{ret}}^{m}(R) = (P_{c}^{m})^{R-1}(1-P_{c}^{m}).
\]

Accordingly, the probability that the frame is not successfully transmitted within \(R\) transmissions is given by:

\[
P_{\text{error}}^{m}(R) = 1 - \sum_{i=1}^{R} P_{\text{ret}}^{m}(i) = (P_{c}^{m})^R. \tag{6}
\]

When the retransmission-combining scheme is used, the receiver needs to receive the RS blocks that were never correctly decoded in 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 retransmission-combining is used, can be derived by considering the following facts: 1) there can be \(R'\) \((R-R')\) frame receptions without (with) uncorrectable error in the headers, where \(1 \leq R' \leq R\); 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:

\[
P_{\text{comb}}^{\text{ret}}(R) = \sum_{R'=0}^{R} \left(R'-1\right) \left(1-P_{\text{ret}}^{m}\right)^{R'}. \tag{7}
\]

\[
= \sum_{R'=0}^{R} \sum_{i=1}^{R'} \sum_{j=1}^{e_{R'}} \sum_{k=1}^{e_{R'-1}} \ldots \sum_{m=1}^{e_{R'-2}} \prod_{l=1}^{R'} P_{e}^{m}(e_{l} | e_{l-1}),
\]

where \(e_{l}\) is the number of the RS blocks that were never correctly received after the \(i\)-th frame transmission without uncorrectable header error being 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 \(P_{\text{error}}^{m}\) is given by:

\[
P_{\text{error}}^{m}(R) = 1 - (1 - P_{c}^{m}(48))(1-P_{c}^{m}(224)).
\]

and the probability \(P_{e}^{m}(i | j)\) that \(i\) out of \(j\) RS blocks for the frame body in an RS-coded frame has uncorrectable errors is given by:

\[
P_{e}^{m}(i | j) = \left(\binom{j}{i} P_{e}^{m}(224)\right)^i (1-P_{e}^{m}(224))^j. \tag{8}
\]

Finally, the probability that the frame is not successfully transmitted within \(R\) transmissions is obtained from:

\[
P_{\text{error}}^{m}(R) = 1 - \sum_{i=1}^{R} P_{\text{comb}}^{\text{ret}}(i). \tag{9}
\]

V. PERFORMANCE EVALUATION

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.

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 \(N = 10\), i.e., a 2080 byte long MSDU. The following three cases are shown:

1) “no” : the error probability when the FEC is not used (5).
2) “old” : the error probability when the FEC is used with the current 802.11a SERVICE field format using (4).
3) “new” : the error probability when the FEC is used with the proposed new SERVICE field format using (4).
We first observe that with 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.

As the new SERVICE field format relies on the performance of the 6 Mbps transmission rate, it does not improve the performance at all in the case of the 6 Mbps 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 sufficient 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 in certain circumstances.

Fig. 5 shows the probability that the frame is not successfully transmitted without and with retransmission-combining, i.e., $P_{\text{error}}(R)$ and $P_{\text{error}}^{\text{comb}}(R)$ in (6) and (7), respectively. As the maximum number of retransmissions $(R-1)$ increases, the improvement using retransmission combining becomes greater as it increases the chances of utilizing combining using more versions of the same frame. The proposed retransmission-combining provides error performance enhancement at the cost of more memory needed to buffer the partially-corrected frames.

VI. CONCLUSION

In this paper, we evaluated the performance of the optional MAC-level FEC of the emerging IEEE 802.11e standard. A novel retransmission-combining technique was proposed to enhance the performance of the MAC-level FEC scheme. We also identified a 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, was proposed to resolve the problem. Finally, we evaluated the error performance of the MAC-level FEC, and its enhanced performance via retransmission-combining and new 802.11a PHY frame format, based on mathematical analysis. The new SERVICE field format is currently being proposed to the IEEE 802.11 Working Group.

ACKNOWLEDGMENT

The author would like to thank Yingwei Chen and Dave Bryan at Philips Research USA for their discussion and valuable comments to the earlier version of the paper.

REFERENCES


