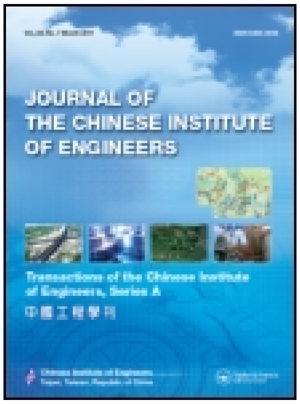
This article was downloaded by: [National Chiao Tung University 國立交通大學]
On: 27 April 2014, At: 17:54
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Journal of the Chinese Institute of Engineers
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tcie20

A cross-layer error correction scheme based on multiple-CRC in OFDM/OFDMA wireless networks

Chia-Yao Chen [a], Wen-Kang Jia [a] & Yaw-Chung Chen [a]
[a] Department of Computer Science and Information Engineering, National Chiao Tung University, Hsinchu, Taiwan 300, ROC

Published online: 13 Nov 2012.

To cite this article: Chia-Yao Chen, Wen-Kang Jia & Yaw-Chung Chen (2013) A cross-layer error correction scheme based on multiple-CRC in OFDM/OFDMA wireless networks, Journal of the Chinese Institute of Engineers, 36:6, 704-714, DOI: 10.1080/02533839.2012.737114

To link to this article: http://dx.doi.org/10.1080/02533839.2012.737114

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

Journal of the Chinese Institute of Engineers, 2013
Vol. 36, No. 6, 704–714, http://dx.doi.org/10.1080/02533839.2012.737114

Taylor & Francis
Taylor & Francis Group

A cross-layer error correction scheme based on multiple-CRC in OFDM/OFDMA wireless networks

Chia-Yao Chen*, Wen-Kang Jia and Yaw-Chung Chen

Department of Computer Science and Information Engineering, National Chiao Tung University, Hsinchu, Taiwan 300, ROC

(*Received 22 November 2011; final version received 28 February 2012*)

The orthogonal frequency division multiplexing access (OFDM/OFDMA) based wireless transmission technology has been widely deployed in recent years. The frame check sequence (FCS) scheme is employed to enhance the reliability of OFDM/OFDMA systems. Since the padding overhead cannot be effectively avoided in OFDM/OFDMA when medium access control frames are encapsulated, we propose a novel cyclic redundancy check based error correction scheme by utilizing the padding space to carry extra segmented FCS information as much as possible; compared with the legacy FCS scheme, our approach greatly enhance the error detection and correction upon the first retransmission (second transmission). A significant performance improvement based on the simulation results is also demonstrated.

Keywords: cyclic redundancy check; error correction; OFDM; OFDMA

1. Introduction

Orthogonal frequency division multiplexing (OFDM-based) wireless networks are widely deployed nowadays. While data transfer occurs under an error-prone wireless environment, data may be corrupted by some inevitable interference (e.g. path loss, fading, shadowing, attenuation factor, etc.; Richard and Prasad 2000, Terry and Heiskala 2002, Msadaa and Filali 2008). In a reliable OFDM-based wireless network, error control schemes must be deployed; two major error control schemes are the automatic repeat request (ARQ) mechanism and the hybrid ARQ (HARQ) mechanism which are adopted in the medium access control (MAC) layer and the physical layer (PHY), respectively.

In the ARQ scheme, the error detection is performed by both sender and receiver to check whether the data frame is corrupted in transmission. Once an error is detected by the receiver, the receiver will notify the sender using an negative acknowledgement (NACK) signal, and the sender will retransmit the data within a certain period. In HARQ, both the error detection and correction scheme are adopted to recover restricted erroneous data. If the receiver fails to recover the corrupted data, a retransmission process such as ARQ will be performed.

Traditionally, error detection and correction schemes are performed independently. The most popular error detection scheme, cyclic redundancy check (CRC), utilize the calculated information appended to a data frame. Due to the limited information carried in the CRC field, the receiver is unable to correct the erroneous frame which will then be dropped automatically. To provide reliable data transfer over an error-prone communication link, the CRC schemes are commonly cooperating with the forward error correction (FEC) and/or ARQ mechanisms. The FEC does not introduce delay, but it leads to lower throughput due to the redundancy (Terry and Heiskala 2002, Msadaa and Filali 2008) in the data frame. On the other hand, the ARQ causes delay, because it uses retransmission to combat the channel errors (Richard and Prasad 2000, Terry and Heiskala 2002, IEEE Std 802.16-2004 2004, Liu and Li 2004, 2005, IEEE Std 802.16e-2005 2005).

Theoretically, an OFDM-based data-burst consisting of a set of OFDM-based symbols will leave certain padding space when MAC frames are stuffed into the data-burst (IEEE Std 802.16-2004 2004, Msadaa and Filali 2008). In addition, the erroneous frame still possesses useful information which can help the receiver figure out the original data frame in case retransmission fails again. As a result, we propose a novel CRC-based error correction scheme in OFDM-based networks. Our scheme can perform multiple checks to precisely specify received data and hence

---

*Corresponding author. Email: ray.cs96g@nctu.edu.tw

reduce the frequency of retransmissions. The key concept of our study is to fully utilize the padding to extend the original CRC information. Besides the original frame check sequence (FCS), we subdivide the entire payload into several independent data blocks whose sub-FCSs will then be calculated. The sub-FCS will be inserted into the original padding position until all padding space is filled up. Through our approach, once an error occurs in a received frame, the receiver can first detect the error by checking the original FCS. If this frame contains extra sub-FCS, the receiver can precisely detect which block is corrupted, so that retransmission cost can be reduced. Further, since the error recovery probability is usually restricted, we can combine two erroneous frames to derive the correct frame based on the corresponding correct sub-block.

Another advantage of the new correction scheme is its backward compatibility with the original correction scheme. If a sender or a receiver does not support the new approach and connect to a device which uses the new correction scheme, the transmission will follow the original correction scheme without any extra cost.

The rest of this article is organized as follows. The conventional ARQ and error detection scheme are explained in Section 2. The OFDM encapsulation and padding are addressed in Section 3. In Section 4, a novel CRC-based error correction scheme is discussed in detail. Section 5 presents extensive simulation results, and conclusions are drawn in Section 6.

2. Conventional AQR and error detection scheme

In conventional ARQ, error-detection information (e.g. parity-check and checksum) is added to the existing data frame to be transmitted together. The error detection scheme directly affects the transmission efficiency in communication networks. In general, the CRC is a powerful class of coding, especially for the detection of random errors and even burst errors in a poor quality communication link. It has been widely used in both wireless and wired networks (ITU-T Recommendation G. 704 1998, Richard and Prasad 2000, Terry and Heiskala 2002, Msadaa and Filali 2008). It is also particularly designed for MAC layer to speedily detect erroneous frames.

In the works of Peterson and Weldon (1996) and Mattes *et al.* (2008), detailed information of CRC is presented. The CRC uses a polynomial-modulo-operation with a generator polynomial $g(x)$, which is a binary polynomial with degree r, to calculate FCS of the binary net data (ND; Mattes *et al.* 2008) with the following equation:

$$fcs(x) = (nd(x) \times x^r) \bmod g(x), \tag{1}$$

where $nd(x)$ and $fcs(x)$ mean the polynomial counterpart of ND and FCS, respectively. The length of FCS is r, which is the degree of $g(x)$. The datagram $\mathrm{T} = [\mathrm{ND, FCS}]$ is transmitted to the receiver, which receives data only if Equation (2) holds. The received data are labelled with apostrophe to denote that data might be corrupted during the transmission.

$$t'(x) \bmod g(x) = ((nd'(x) \times x^r) + fcs'(x)) \bmod g(x) = 0. \tag{2}$$

To calculate the FCS in the sender or to check it in the receiver uses the function of linear feedback shift register or a corresponding table lookup method. If the sender and receiver need to calculate or to check multiple FCS simultaneously, they have to pay more computing cost. Fortunately, the CRC mechanism is usually implemented in a hardware circuit to eliminate the potential computing latency.

When the signal-to-noise ratio (SNR) is relatively high in the OFDM-based wireless link, only a small number of frames may encounter error. Instead of carrying a certain percentage of error correction information, our proposed scheme simplifies the complex error correction (e.g. FEC) to simple error detection. When the SNR is relatively low in the OFDM wireless link, a large number of errors may be present in an erroneous frame because the error correction mechanism is stultified. Instead of discarding the entire frame, the objective of this article is to possibly recover it upon first retransmission by utilizing an extra, segmented CRC checksum.

3. OFDM encapsulation and padding

In this section, we address the problem of data-burst grooming in OFDM-based networks. In OFDM-based networks, frames with the same edge-node destination are assembled into a transmission unit called data bursts (a.k.a. data region; IEEE Std 802.16-2004 2004, IEEE Std 802.16j-2009 2009) which are two-dimensional allocations of a group of contiguous logical sub-channels in a group of contiguous OFDM symbols (or slots). The sub-channel allocation in the OFDM downlink may be performed in either partial usage of sub-channels (PUSC) or full usage of sub-channels (FUSC). For downlink FUSC and downlink optional FUSC using the distributed subcarrier permutation, one slot is a sub-channel by one OFDM symbol. For downlink PUSC using the distributed subcarrier permutation, one slot is a sub-channel by two OFDM symbols. This allocation may be visualized as a rectangle, such as the 4×8 rectangle. MAC frames should be processed and mapped to an OFDM

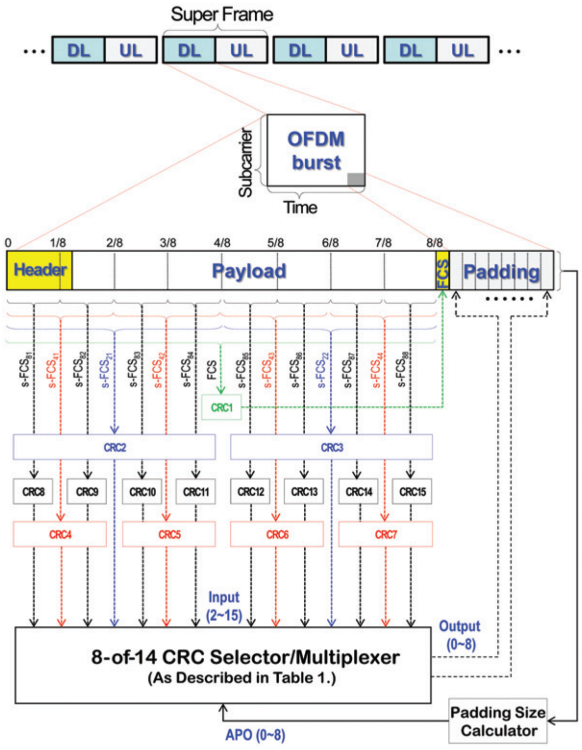


Figure 1. The OFDM frame structure and function diagram of the extra-CRC calculation.

data-burst for downlink and uplink using the appropriate algorithms. Based on the sub-channel allocation mode, data bursts have a minimum length. In other words, this encapsulation process is likely to leave a little surplus of padding space when MAC frames are stuffed into the rectangle (IEEE Std 802.16-2004 2004, IEEE Std 802.16j-2009 2009). The upper half of Figure 1 shows the downlink sub-frame structures.

Furthermore, the modulation and coding schemes (MCS) are critical factors that affect the growth of padding overhead. For example, IEEE 802.16 WiMAX systems support various MCS. In the downlink, BPSK, 16QAM and 64QAM are mandatory for both fixed and mobile WiMAX; 64QAM is optional in the uplink. FEC coding using convolution codes is mandatory. Convolution codes are combined with an outer Reed–Solomon code in the downlink for OFDM-PHY. The standard optionally supports turbo codes and low-density parity check codes with a variety of code rates as well. A total of 52 combinations of MCS are defined in WiMAX as burst profiles. Different modulation and coding combination will decide the efficiency of the data-burst.

In the OFDM-based system, the overall factor of padding overhead in a data-burst varies depending on the type of sub-frame, MCS, resource allocation scheme, frame length distributions, etc., regardless of whether they are variable-length or fixed-length frames. In general, the fewer the OFDM symbols within a burst, the more significant the padding overhead. According to some studies (Hoymann *et al.* 2003, 2004, Msadaa and Filali 2008), the overhead to payload ratios may be more than 30% depending on the frame length distribution, modulation rate, coding rate and burst length. In a simulation environment, the maximum possible padding overhead may reach 4.3%, assuming a frame length of 1518 byte with 64QAM 3/4 modulation and coding rate. Excessive padding usually results in inefficiency and high data-burst blocking probability.

Several methods have been proposed to reduce the padding overhead in OFDM-based systems (Hoymann *et al.* 2003, 2004). Unlike previous approaches, our proposed method does not attempt to reduce padding overhead, instead it tries to utilize the padding overhead to create a robust OFDM-based error detection/correction scheme, and to achieve a high efficiency OFDM-based transmission system so that the retransmission rate can be significantly reduced in an poor radio quality environment.

4. Padding based extra-CRC error correction scheme

In this section, the error correction scheme for base station (BS) side and mobile station (MS) side is described in detail. The scheme is built on previous work (Chen *et al.* 2011).

4.1. *Base station*

While the BS calculates the FCS to construct a frame, BS simultaneously needs to calculate 14 extra sub-FCSs (Figure 1), where the s-FCS$_{21}$ denotes the FCS of the first half ND and the s-FCS$_{88}$ the FCS of the last eighth ND. The length of every s-FCS is equal to the FCS, and when the FCS calculation is completed, the calculation of every s-FCS will also be done.

Before a frame is transmitted, the BS needs to decide the padding length (PL) and padding content. Unlike the original padding method, the s-FCSs are used as the padding content. As presented in Table 1, based on the average padding overhead (APO), a BS can choose the padding content immediately, and the APO P_o can be calculated using the following equation:

$$p_o = \left\lfloor \frac{PL}{r} \right\rfloor . \qquad (3)$$

Table 1. Padding method.

APO	Padding content
0	CRC_1[a]
1	CRC_2
2	CRC_2,CRC_3
3	CRC_4,CRC_5,CRC_3
4	CRC_4,CRC_5,CRC_6,CRC_7
5	CRC_8,CRC_9,CRC_5,CRC_6,CRC_7
6	CRC_8,CRC_9,CRC_{10},CRC_{11},CRC_6,CRC_7
7	CRC_8,CRC_9,CRC_{10},CRC_{11},CRC_{12},CRC_{13},CRC_7
≧8	CRC_8,CRC_9,CRC_{10},CRC_{11},CRC_{12},CRC_{13}, CRC_{14},CRC_{15}

Note: [a]The CRC_1 is assumed to be mandatory requirement.

In Equation (3), r is the length of FCS. If APO is larger than 8, this frame will have padding for 8 s-FCSs and the normal padding content and be treated as a frame with 8 s-FCSs padding.

4.2. *Mobile station*

When a frame arrives, the MS verifies the FCS and all s-FCSs simultaneously. If the frame has passed the FCS check, the received ND has no corruption. Otherwise, if FCS checks fail but all s-FCSs have passed the check, that means only FCS is corrupted but ND is correct. In these two situations, there is no need to retransmit the frame. Only if the FCS check and any s-FCS check have failed, must the frame be retransmitted, and the MS has to record the correct data blocks which passed the s-FCS check. The detailed procedure at the receiver is illustrated in Figure 2. The second transmission uses the same check procedure. When any s-FCS check fails in the second transmission, the MS can use the 'correct data block information' of the two transmissions to correct the ND.

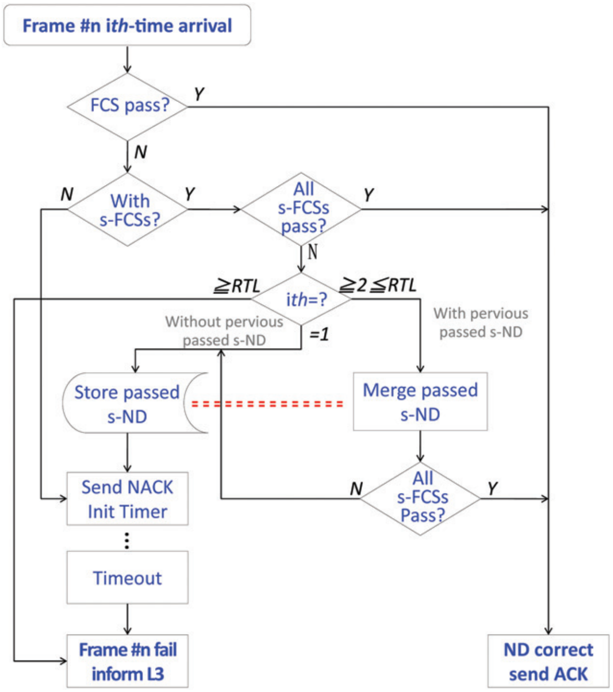


Figure 2. The flowchart of frame error correction.

5. Performance evaluation

The worst case of this proposed scheme is that every frame is transmitted without any padding. In this situation, the receiver cannot get any extra information which can be used to correct the corrupted data. The best case for this scheme is that every frame transmission carries at least eight padding contents. Since the receiver can recognize the most precise position of the error bit, so it has the highest probability to recover the corrupted data if the next arrival fails. In this section, these two extreme conditions will be discussed in detail. Without loss of generality, the results of other possible transfer conditions will lie in between these two extreme conditions. Before evaluating the performance of the proposed scheme, some background conditions must be decided.

5.1. *Radio propagation and interference model*

In a practical network, the signal quality from a sender to a receiver is attenuated by different factors such as transmission power, shadowing, fading and path loss. For a wireless system, these factors along with the interference at the receivers are critical components of any model. In this section, the radio and interference models used in this study are described.

The radio propagation model used in this study only considers attenuation caused by path loss due to the signal propagation over distance. The fading and shadowing effects are not considered here. The model based on the Stanford University Interim path-loss model as recommended by the 802.16 task group (IEEE 802.16a-03/01 2003) is used. In this model, some assumptions on sender power and antenna gains can be used to determine the received signal power at MS and the SNR. By mapping SNR of the receiver to one of the thresholds specified in IEEE Std 802.16e-2005 (2005), the MCS to be used between the

Table 2. MSC and SNR thresholds.

MSC	Threshold α (dB)
BPSK 1/2	6
BPSK 3/4	9
16QAM 1/2	11.5
16QAM 3/4	15
64QAM 1/2	17
64QAM 2/3	19
64QAM 3/4	21

communicating nodes can be determined. The SNR at the receiver is calculated using

$$\mathrm{SNR}_{[\mathrm{dB}]} = 10\log_{10}\left(\frac{\tilde{p}_{MS}}{BW\cdot N_0}\right), \tag{4}$$

where BW is the effective channel bandwidth in Hz, N_o the thermal noise density and $\tilde{p}_{MS}$ the received signal power at MS, which is defined by

$$\tilde{p}_{MS} = \frac{G_{BS}G_{MS}P_{BS}}{L(BS, MS)}, \tag{5}$$

where P_{BS} is the transmission power of the BS; G_{BS} and G_{MS} the antenna gains at the BS and MS, respectively and $L(BS, MS)$ the path loss from the BS to MS. Given the SNR of MS, the BS can determine the MCS based on Table 2. Specifically, the BS will use the highest MCS whose minimum required SNR is smaller than $\mathrm{SNR}_{[\mathrm{dB}]}$.

The distance between BS and MS depends on its signal power and its noise (Hoymann 2005), and it can be calculated

$$d = \frac{\lambda \times 10\left(\left(p_t[\mathrm{dBm}] - \mathrm{SNR}_{[\mathrm{dB}]} - N_{[\mathrm{dBm}]}\right)/20\right)}{4\pi}. \tag{6}$$

In Equation (6), λ denotes the wavelength, p_t the transmit power and N the noise.

5.2. *Padding length*

The PL can be calculated from the burst size and the data size. If D denotes the datagram size of a transmitted frame (includes frame header), the frame size of OFDM burst will be no smaller than D, because the burst size includes the data size and the PL (Figure 1). The PL can be denoted as follows:

$$PL = \begin{cases} \left\lceil(\theta \times Ns) \times Sc \times \frac{(M\times Cr)}{8}\right\rceil - D & \text{if}\left\lceil(\theta \times Ns) \times Sc \times \frac{(M\times Cr)}{8}\right\rceil > D \\ 0 & \text{if}\left\lceil(\theta \times Ns) \times Sc \times \frac{(M\times Cr)}{8}\right\rceil = D \end{cases}, \tag{7}$$

where θ is the number of data subcarriers, Ns the number of symbols in a frame, Sc the number of subcarriers, M the M-QAM alphabet size and Cr the code rate of the modulation. Figure 3 describes the PL in different modulation orders, when packets within any length distributions are encapsulated in fitted OFDM bursts. All types of frames must carry various variable-length paddings, and high-order modulation will have longer PL than low-order modulation. In Figure 3, the average PLs in BPSK/QPSK, 16QAM and 64QAM are 4–8, 8–15 and 15–22 bytes, respectively.

5.3. *Packet error rate*

The bit error probability (BEP) can be evaluated for various modulation types using the SNR. In the case of multilevel-QAM, the BEP P_b can be approximated as follows:

$$P_b \cong \frac{4}{\log_2 M}\left[1 - \frac{1}{\sqrt{M}}\right]Q\left(\sqrt{\left[\frac{3}{M-1}\right]\frac{E_b}{N_0}}\right). \tag{8}$$

In Equation (8), M is M-QAM alphabet size. Packet error rate (PER) of the Tth transmission, which uses the original CRC scheme, can be calculated as

$$PER = \left[1 - (1 - P_b)^{m+r}\right]^T. \tag{9}$$

In Equation (9), m is the length of ND and r the length of FCS. $(m + r)$ denotes the total length of the frame. In the proposed scheme, since the double checking procedure can correct the corrupted FCS, the PER of the Tth transmission can be calculated with the following equation:

$$PER = [1 - (1 - P_b)^m]^T \times \left[1 - (1 - P_b)^{\frac{m}{p_o}}\right]^{T-1}, \tag{10}$$

where p_o is the APO of the same data block in two consecutive transmissions. For instance, if the first two transmission frames all carry eight padding contents, the d in the second transmission is 1/8.

5.4. *Actual transmitted data*

The actual transmitted data (ATD) is the data size which includes the total frame size and retransmitted frame size. If L is the total data size to be transmitted,

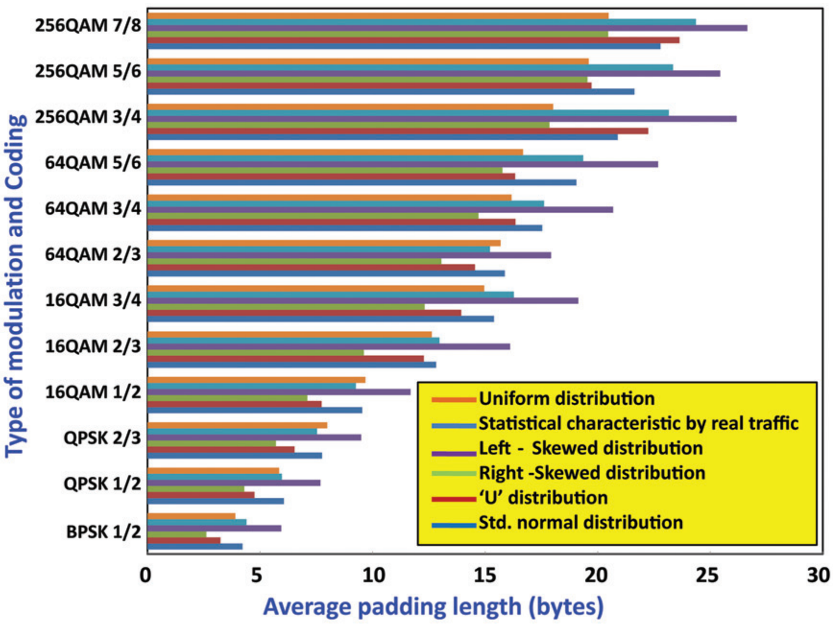


Figure 3. Modulation order versus padding size.

the ATD will be no less than L. When the transmission uses the original CRC scheme, the ATD can be denoted as follows:

$$\mathrm{ATD} = \frac{L}{(1 - P_b)^{m+r}}. \qquad (11)$$

As in the above, the ATD of the transmission in our proposed scheme can be calculated with the following equation:

$$\mathrm{ATD} = \frac{L\left(1 + (1 - P_b)^{\frac{m}{po}} - (1 - P_b)^{\left(1+\frac{1}{po}\right)m}\right)}{(1 - p_b)^m + (1 - P_b)^{\frac{m}{po}} - (1 - P_b)^{\left(1+\frac{1}{po}\right)m}}. \qquad (12)$$

5.5. *Simulation scenarios*

For evaluating the performance of the proposed error correction scheme, the parameters of the wireless network used to calculate factors, as discussed above, are summarized in Table 3. In this article, we assume that both BS and MS always use the lower modulation rate for achieving larger coverage. The deployment of BS considered in this article includes hexagonal cells regrouped into clusters in which frequency channels are unique. Each cell coverage area is assumed to have no any uncovered hole.

Table 3. Parameters.

Parameter	Value
Transmission power of BS	30 dBm
Sub-channel bandwidth	20 MHz
Channel frequency	5.47 GHz
Thermal noise	−10,097 dBm
CRC type	CRC-16
Length of FCS	16 bits
Length of ND	1024 bits

Figure 4 shows the PERs in first, second and third transmissions in the overhead with different average paddings. The APO 'zero' means the transmission uses the original CRC scheme without padding in any s-FCS. The PERs of all transmissions decline with the increase of APO. In Figure 4, the PER of the transmission with high padding overhead is smaller than that with low padding overhead and the same BER. When a frame can carry as many as possible s-FCSs, the new method will feature better performance. In some harsh environments, the BEP will be unusually high, resulting in transmissions which use the original CRC scheme being non-forwardable. But using the new method, the frame can be forwarded in the same condition. For example, when BEP is 10^{-3}, the PERs of frames which use both CRC schemes are 64.1% and 63.52%, this means both frames have a high probability of retransmission. After first

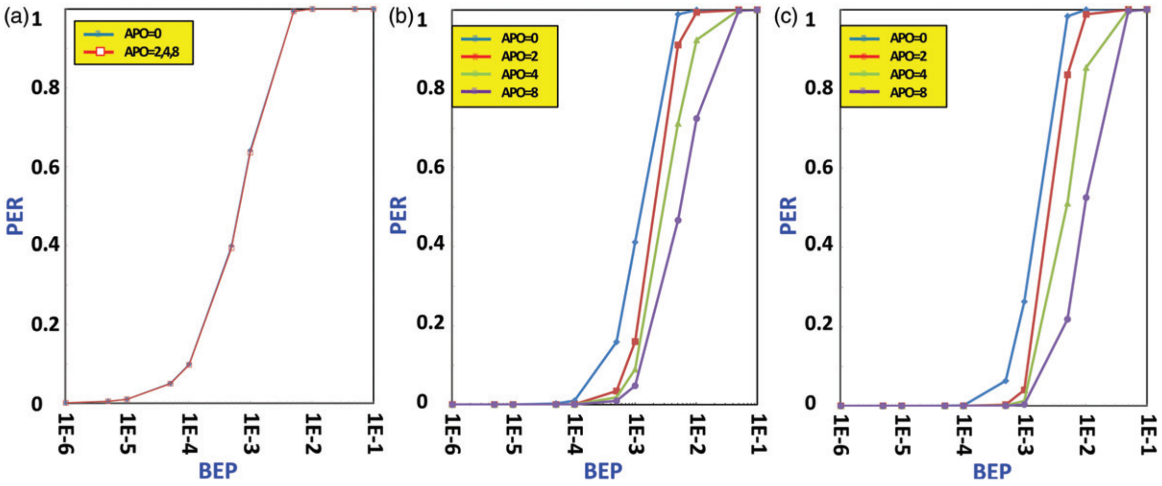


Figure 4. PER upon: (a) first transmission; (b) second transmission (first retransmission); and (c) third transmission (second retransmission).

retransmission, the PER of the frame that uses the original CRC scheme is 41.09%. When the frame uses the new CRC scheme, during first retransmission, the PER is smaller than 15.98% (APO = 2, PER = 15.98%; APO = 4, PER =8.99%; APO = 8, PER = 4.78%). After two retransmissions, the PER of the frame which uses the original CRC scheme is 26.34%. When the frame uses the new CRC scheme, during first retransmission, the PER is smaller than 4.02% (APO = 2, PER = 4.02%; APO = 4, PER = 1.27%; APO = 8, PER = 0.36%). Therefore, in high BEP environment, our novel CRC-based error correction scheme can effectively reduce the number of frame retransmissions.

Figure 5 shows the PER of the original error correction scheme in various locations. According to Figure 3, the APO of BPSK, 16QAM and 64QAM are 2, 4 and 8, respectively. There is 73.94% of the area in which the PER is higher than 90% in first transmission. The area in which PER is lower than 20% is only 5.32%, and lower than 50% is 12.34%. Although retransmission can reduce the PER, the effect is limited. As shown in Figure 5(b) and (c), after second transmission, the area with PER lower than 20% is increased by only 5.87%, and lower than 50% is increased by 5.92%. After third transmission, the area with PER lower than 20% is 14.68% and lower than 50% is 20.88%.

Figure 6 shows the PERs of the novel error correction scheme at different positions. In Figure 6(a), the result of the proposed scheme is similar to the original scheme in first transmission. If the frame must be retransmitted, the new scheme has better error correction capacity than the original CRC scheme. As shown in Figure 6(b), the area with PER lower than 20% is 18.41% and lower than 50% area is more than 26%. The result of the new scheme in retransmission is better than the original CRC scheme on the third transmission. The comparisons of several PERs versus coverage are summarized in Table 4.

Figure 7 shows the relationship between goodput and SNR of MS with different MCS. The total transmitted data size divided by ATD equals the goodput. In good transmission conditions, the performances of the original and the proposed schemes are almost the same. But under poor transmission conditions, the proposed scheme features better goodput. In Figure 7, the proposed error correction scheme features significant performance improvement for all modulations. Higher M-QAM alphabet size experiences better enhancement. In 64QAM, the performance has been enhanced 1–2 dB, 16QAM has 1 dB enhancement and BPSK has 0.5 dB.

Figure 8 shows goodput at different positions. Figure 8(a) shows the result of the original error correction scheme, and the area in which the goodput is higher than 80% is 5.32% and higher than 60% is 10.23%. The proposed error correction scheme features significant improvement in performance. In Figure 8(b), the area in which goodput is higher than 80% rises to 6.54%, and higher than 60% rises to 14.05%. The comparison table of goodput is summed up in Table 5.

The relationship between latency and SNR in different MCS is shown in Figure 9, in which the frame size is 5 ms, downlink-to-uplink bandwidth ratio is 3:1, and code rate is 1/2. Our novel error correction scheme can significantly reduce the latency for all

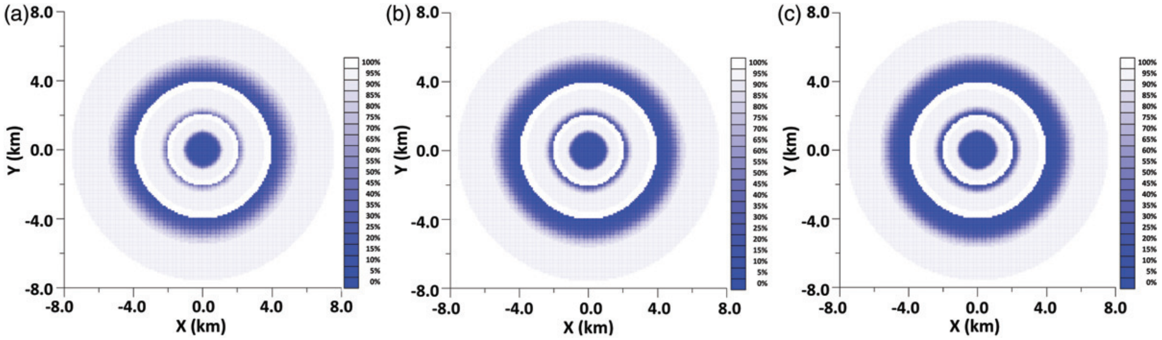


Figure 5. PER of original scheme at different positions upon: (a) first transmission; (b) second transmission; and (c) third transmission.

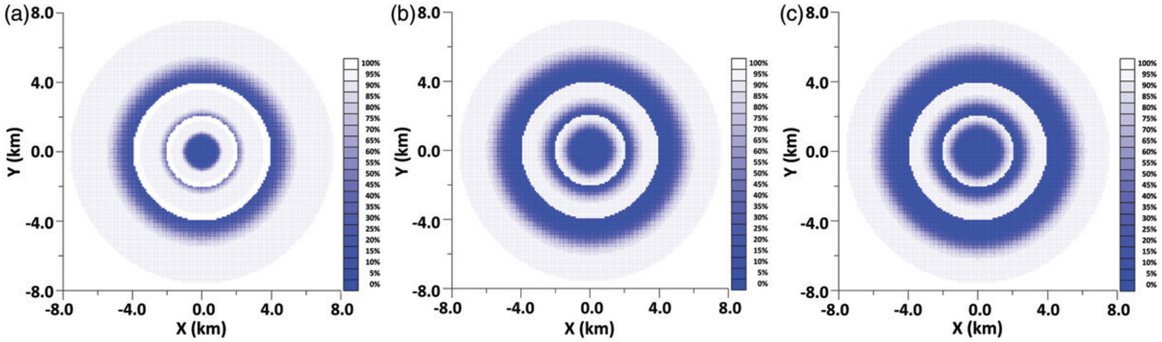


Figure 6. PER of novel scheme at different positions upon: (a) first transmission; (b) second transmission; and (c) third transmission.

Table 4. PER versus coverage.

	Coverage					
	Original scheme			Proposed scheme		
PER (%)	First Ts (%)	Second TS (%)	Third TS (%)	First Ts (%)	Second TS (%)	third TS (%)
0–20	5.32	11.19	14.68	5.32	18.41	24.46
20–50	7.02	7.07	6.2	7.23	8.36	8.32
50–100	87.66	81.74	79.12	87.45	73.23	67.22

Notes: First TS, first transmission; second TS, second transmission; third TS, third transmission.

modulation in a harsh radio quality environment. When SNR is 23 dB using 64QAM, 17 dB using 16QAM, and 10 dB using BPSK, the latency is reduced by more than 2.8, 2.5 and 3.2 ms, respectively.

According to the discussion above, our proposed CRC-based error correction scheme is suitable for the poor wireless environment, because in that situation our proposed scheme can reduce the retransmission times, have better goodput and lower latency than the original CRC scheme. All transmissions must be padded with as many s-FCSs as possible, so as to improve the transmission performance by reducing retransmissions.

6. Conclusions

In this article, we investigated the current CRC detection scheme and demonstrated the CRC-based error correction scheme based upon CRC error

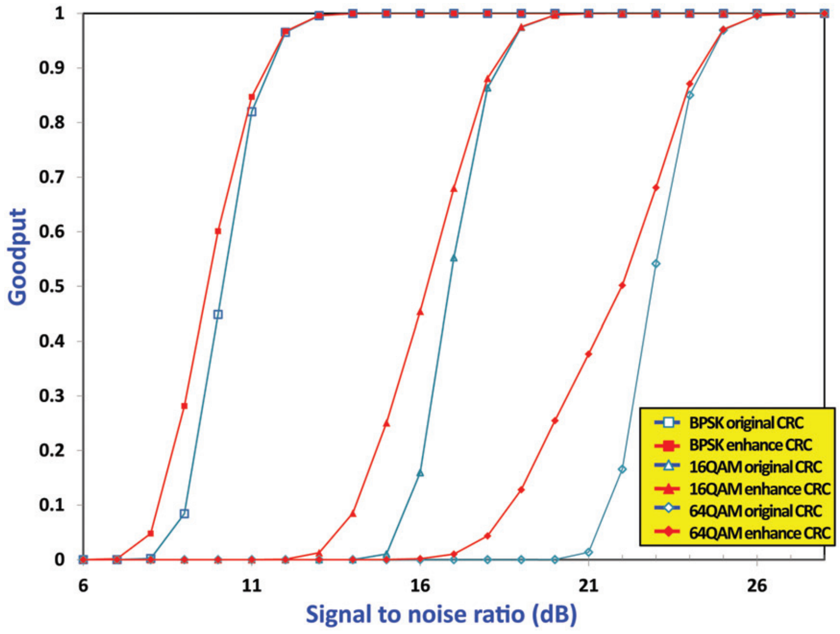


Figure 7. Goodput versus SNR of MS.

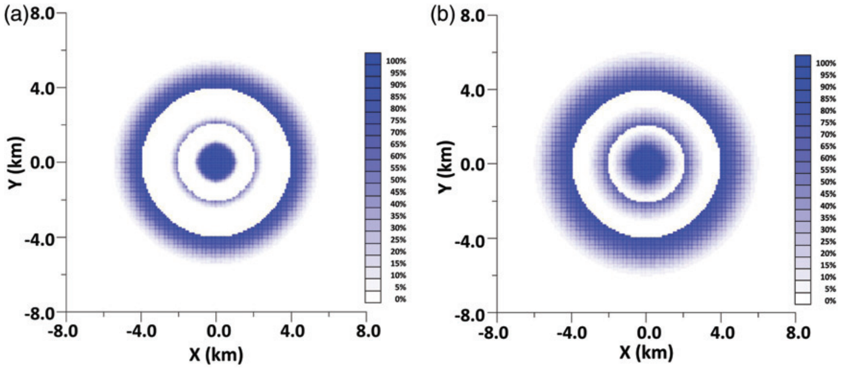


Figure 8. Goodput at different positions upon: (a) original error correction and (b) novel error correction schemes.

Table 5. Goodput versus coverage.

	Coverage	
Goodput (%)	Original scheme (%)	Novel scheme (%)
100–80	5.32	6.54
80–60	4.91	7.51
60–40	4.98	9.23
40–20	6.01	11.25
20–0	78.78	65.47

detection in OFDM/orthogonal frequency division multiplexing access networks. A detailed design for setting up the process was provided and performance evaluation was presented.

Compared with the original CRC scheme in a high SNR (low BEP) radio quality environment, our approach slightly improves error detecting capacity. As expected, our approach reduces the regular coding overhead compared with FEC due to an obvious performance improvement in throughput. In a low SNR (high BER) radio quality environment, our scheme obtains a significant improvement in both error detection and correction upon the first retransmission (second transmission). There is a very low

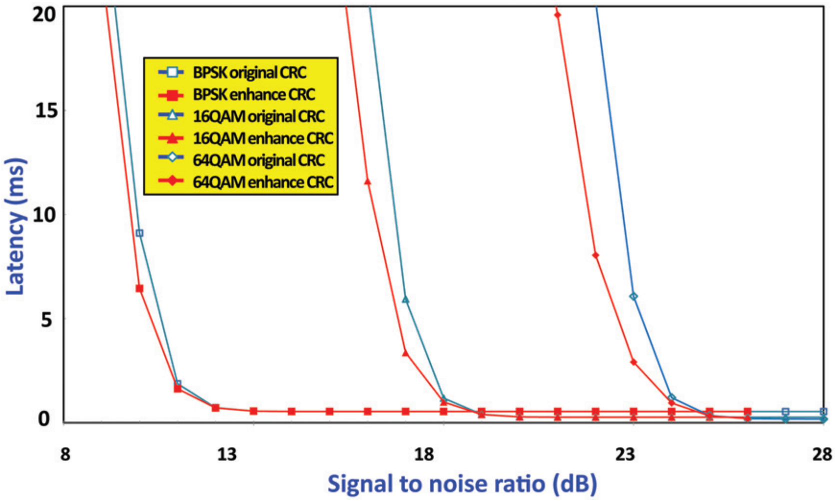


Figure 9. Latency versus SNR.

probability of second retransmission (third transmission) required even under very poor radio conditions. Thus, our approach obviously improves the throughput of OFDM-based systems.

In principle, our CRC-based error correction scheme is backward compatible with the legacy CRC error detection scheme in OFDM-based networks. Unlike the FEC scheme, our scheme neither increases the hardware complexity much in the MAC layer, nor occupies any extra bandwidth to carry the extra segmented CRC information.

Furthermore, the improvement of a CRC-based error correction scheme not only can improve the performance of reliable wireless transmissions such as Wi-Fi, WiMAX, MMDS, DAB, DVB-x, 3GPP, 3GPP2 and LTE, but also can be applied to several wired transmissions such as xDSL, xPON, HiperLAN/2 and MoCA. Our approach allows wireless transmission in very poor radio conditions in which even FEC functions poorly; moreover, through our approach, the throughputs for all kind of modulation and/or coding rate can be improved.

However, we have not yet performed a comparison of our scheme with FEC and HARQ. Besides, alternative retransmission mechanisms such as Go-back-N retransmission and selective retransmission can further be combined with our scheme so as to further improve the performance. All the above issues will be addressed in future works.

We believe that only few simple design revisions could make a big improvement for the error detection, error correction and throughput in OFDM-based networks. Our study would be most useful for extremely poor radio condition environments. The result of this study can prove that the method, which separates payload to segments and uses low CRC order generator to compute the short FCSs individually, can reach better error correction efficiency than the original method, which uses whole payload and high CRC order generator to compute a single FCS directly.

Nomenclature

BW	effective channel bandwidth
Cr	code rate of the modulation
D	datagram size of a transmitted frame
G_{BS}	antenna gains at the BS
G_{MS}	antenna gains at the MS
$L(BS, MS)$	path loss from the BS to MS
M	M-QAM alphabet size
N	noise
N_o	thermal noise density
Ns	number of symbols in a frame
P_b	bit error probability
P_{BS}	transmission power of the BS
$\tilde{p}_{MS}$	received signal power at MS
P_o	average padding overhead
p_t	transmit power
r	length of FCS
Sc	number of subcarriers
θ	number of data subcarriers
λ	wavelength

References

Chen, C.Y., *et al*., 2011. A redundancy-free reliable multicast in wireless multi-hop relay networks. *In*: *proceedings of*

2011 international wireless communications and mobile computing conference (IWCMC 2011), 5–8 July 2011, Istanbul. Turkey: IEEE, 1063–1068.

Hoymann, C., 2005. Analysis and performance evaluation of the OFDM based metropolitan area network IEEE 802.16. *Computer networks*, 49 (3), 341–363.

Hoymann, C., Puttner, M., and Forkel, I., 2003. The HIPERMAN standard: a performance analysis. *In: proceedings of IST mobile and wireless communication summit 2003*, 15–18 June 2003, Aveiro. Portugal: Instituto De Telecomunicacoes (IT), 827–831.

Hoymann, C., Puttner, M., and Forkel, I., 2004. Initial performance evaluation and analysis of the global OFDM metropolitan area network standard IEEE 802.16. *In: proceedings of European wireless conference 2004*, 24–27 February 2004, Barcelona. Spain: IEEE, 228–234.

IEEE 802.16a-03/01, 2003. IEEE 802.16 Broadband Wireless Access Working Group, 2003. *Channel models for fixed wireless applications*, June 2003.

IEEE Std 802.16-2004, 2004. *IEEE Standard for local and metropolitan area networks Part 16: air interface for fixed broadband wireless access systems*, October 2004.

IEEE Std 802.16e-2005, 2005. *IEEE Standard for Local and metropolitan area networks–Part 16: Air Interface for Fixed Broadband Wireless Access Systems–Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands*, February 2006.

IEEE Std 802.16j-2009, 2009. *IEEE Standard for local and metropolitan area networks Part 16: air interface for broadband wireless access systems, Amendment 1: Multiple Relay Specification*, June 2009.

ITU-T Recommendation G. 704, 1998. *Synchronous frame structures used at 1544, 6312, 2048, 8448 and 44736 kbit/s hierarchical levels*, October 1998.

Liu, J. and Li, J., 2004. Parameter estimation and error reduction for OFDM-based WLANs. *IEEE transactions on mobile computing*, 3 (2), 152–163.

Liu, H. and Li, G., 2005. *OFDM-based broadband wireless networks: design and optimization*. Hoboken, NJ: John Wiley & Sons.

Mattes, T., *et al*., 2008. Safety proof of combinations of CRC for industrial. *Journal of applied computer science*, 16 (1), 15–32.

Msadaa, I.C. and Filali, F., 2008. On the performance bounds of OFDM-Based 802.16 broadband wireless networks, *In: proceedings of IEEE wireless communications and networking conference 2008* (WCNC 2008), 31 March–3 April 2008, Las Vegas, NA, IEEE, 1459–1464.

Peterson, W. and Weldon, E.J., 1996. *Error correcting codes*. Cambridge, MA: MIT Press.

Richard, V.N. and Prasad, R., 2000. *OFDM for wireless multimedia communications*. Norwood, MA: Artech House.

Terry, J. and Heiskala, J., 2002. *OFDM wireless LANs: a theoretical and practical guide*. Indianapolis, IN: Sams.