A Cross-Layer Design Combining of AMC with HARQ for DSRC Systems

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Received 12 April 2013; Accepted 30 September 2013

1. Introduction

Vehicular ad hoc networks (VANETs) are a type of mobile ad hoc networks where each vehicle serves as a node interconnected by wireless links. One of the most important features in VANETs is that each vehicle can only move in a predictable manner but at much higher speeds compared with the traditional mobile ad hoc networks (MANETs). The Dedicated Short Range Communication (DSRC) standard [1], which is currently under extensive development by the IEEE 802.11p [2] standardization committee, defines two types of communication in VANETs: vehicle to vehicle (V2V) and vehicle to infrastructure (V2I). An excellent overview on DSRC technology is also given in [3], which first gives a general description of the architecture by introducing the concepts, applications, and characteristics of the technology to be used for V2V and V2I communications. DSRC is committed to support a suite of safety applications such as collision warning, up-to-date traffic information, and active navigation and infotainment. With DSRC, each vehicle on the road is broadcasting routine traffic related messages with the information of position, current time instance, driving direction, speed, acceleration/deceleration, and possible traffic conditions. The frequency spectrum between 5.850 and 5.925 GHz is allocated for DSRC, which will enable vehicles to communicate with the road infrastructure and allows for a large number of ITS applications. This provides an opportunity for automakers, government agencies, and related commercial entities to improve highway safety. However, intervehicle communications must operate effectively within transmit power limits and under received signal strength fluctuations and Doppler spread. DSRC for intervehicle wireless communications can provide numerous safety applications, but these require reliable communications at a reasonable cost.

The DSRC standard employs convolutional codes for Forward Error Correction (FEC). The performance analysis of them has been extensively studied in the literature such as [4–9]. For instance, a feasibility study of delay-critical safety applications over vehicular ad hoc networks based on the emerging DSRC standard is conducted in [4]. Under the current static backoff schemes, the infrastructure data
collection mode of IEEE 802.11p standard does not perform well [5]. The performance of the DSRC system is evaluated under three different channels with convolutional codes, regular LDPC codes, and quasi-cyclic (QC) LDPC codes [6, 7]. It has shown that LDPC codes provide an attractive tradeoff between performance and complexity and should be considered as alternative error correction codes for DSRC systems. Similarly, Amditis and Uzunoglu [8] simulated the physical layer (PHY) of the upcoming vehicular communication standard IEEE 802.11p in V2V situation through two different scenarios under different modulation schemes. In [9], the results of evaluation of the performance of IEEE 802.11p PHY employing turbo coding are presented. In all these results, the LDPC codes are considered the better candidates due to their good performance and low encoding and decoding complexity, which is important to the real time communications in the VANETs.

In wireless communication networks, the demand for high data rates and quality of service (QoS) is growing at a rapid pace. The cross-layer design approaches are likely to provide much better results in practice. The study of [10] tries to achieve links scheduling and power assignment while meeting the data rate and peak power level constraints such that the resulting throughput is maximized. In [11], a cross-layer design along with an optimal resource allocation framework is formulated for wireless fading networks by employing the network coding. However, these cross-layer design methods are notoriously complicated and difficult to translate into practice.

The adaptive modulation and coding (AMC) [12] have been studied extensively and advocated at the physical layer, which can enhance throughput in future wireless data communication system. The automatic repeat request (ARQ) protocol at the data link layer that requests retransmissions for those received packers with error is also very important to throughput enhancement. It has proved that joint AMC-ARQ [13] design outperforms either application of AMC only at physical layer or ARQ only with a fixed modulation and coding scheme. In this paper, we consider the cross-layer design combining AMC and Incremental Redundancy HARQ (IR_HARQ), which is the most efficient ARQ scheme. In physical layer the AMC adjusts the data rates roughly according to the Channel State Information (CSI) by choosing different modulation modes while the data rates are accurately adjusted by HARQ according to the CSI with changing the maximum retransmission number in data link layer. One of the key problems for realizing AMC IR_HARQ is rate-compatible (RC) codes, which consist of a low-rate mother code and several higher rates achieved through compatible puncturing. Hence, the decoder for the lowest rate code is compatible with that for the higher rate codes and no additional complexity is needed. In this work we will employ RC-LDPC codes as the FEC codes for DSRC systems. By taking advantage of the cross-layer design combining AMC and IR_HARQ, the throughput is enhanced with low system complexity.

The rest of the paper is organized as follows. An overview of DSRC system is discussed in Section 2. Section 3 describes the proposed cross-layer design combining methods of AMC and IR_HARQ. The simulation results are presented and discussed in Section 4. Section 5 concludes our work.

2. Overview of DSRC System

DSRC physical layer has the same frame structure, modulation, and training sequences as specified in the IEEE 802.11a standard, and its signal bandwidth is 10 MHz (half the IEEE 802.11a bandwidth). The basic DSRC parameters are shown in Table 1.

The block diagrams of the DSRC transmitter and receiver are shown in Figures 1 and 2, respectively [6, 7]. The input bit stream is first scrambled and then encoded with a convolution code, for which the constraint length is 7 and code rate is 1/2. The interleaving redistributes the bits before transmission, which reduces the effects of burst errors caused by the fading channel. Perfect timing and frequency synchronization is also assumed, and the received signal is transformed to the frequency domain using a Fast Fourier Transform (FFT). The resulting signal is then mapped to bits and deinterleaved. Finally, the soft information is input to channel decoder, and the output bits descrambled. The output of the scrambler is encoded using code rates R = 1/2, 2/3, or 3/4, depending on the desired data rate. The convolution encoder has rate R = 1/2 and constraint length 7 (memory length m = 6), as shown in Figure 3. Higher rates are obtained by puncturing the output bit stream.

3. The Cross-Layer Design Combining AMC and IR_HARQ

3.1. AMC Method Based on LDPC Codes

In this section, we provide the AMC method based on LDPC codes, which have demonstrated impressive error-correcting qualities under BPSK modulation and are also good codes to use in combination with higher-order modulations. Figure 4 shows a rate-adaptive coded modulation communication system.

| Table 1: DSRC physical layer parameters. |
|-----------------|-----------------|
| Modulation      | BPSK, QPSK, 16 QAM, 64 QAM |
| Data rate       | 3, 4.5, 6, 9, 12, 18, 27 Mbps |
| Coding rate     | 1/2, 2/3, 3/4 |
| Number of subcarriers | 52 |
| Subcarrier spacing | 156.25 KHz |
| Number of pilot tones | 4 |
| Guard interval  | 1.6 μsec |
| OFDM symbol duration | 8μsec |
| Signal bandwidth | 10 MHz |
The encoded bits are mapped into M-QAM constellations according to Gray code mappings. For each M-QAM constellation we construct an LDPC code such that the lengths of all codes are integer multiple of M-QAM symbols in the constellation.

Here our objective is to maximize the data rate, while maintaining the required performance. Let $N$ denote the total available number of transmission modes. We assume constant power transmission and separate the total SNR range into $N + 1$, with no overlapping consecutive intervals, with boundary points denoted as $\{y_i\}_{i=0}^{N}$. If the channel estimated SNR is $\gamma$, we have

$$\gamma \in [y_i, y_{i+1}), \quad \text{mode } i \text{ is chosen.}$$

(1)

The boundary point $y_i$ is determined for the instantaneous block error rate (BLER) or bit error rate (BER) is guaranteed to be not greater than target BER$_0$ or BLER$_0$. So the value of $y_i$ is obtained by solving the following equation for each mode:

$$\text{BER}(y_i) = \text{BER}_0$$

(2)

or

$$\text{BLER}(y_i) = \text{BLER}_0$$

(3)

as the functions of the estimated SNR $\gamma$, BER($y_i$), and BLER($y_i$) are the BER and BLER for mode $i$, respectively.

3.2. AMC-HARQ Design. In this section, we develop a cross-layer design, which combines AMC at physical layer with HARQ at data link layer in order to maximize system throughput under performance requirements.

Since only finite delays and buffer sizes can be afforded in practice, the maximum number of ARQ retransmissions has to be bounded. We denote the maximum number of retransmissions allowed per block by $N_{\text{max}}$. Note that a block is dropped if it is received incorrectly after a maximum number of $N_{\text{max}} + 1$ transmissions, that is, after $N_{\text{max}}$ retransmissions. Let BLER denote the average block error rate and $\text{BLER} = p$. The average number of transmissions per block is computed as

$$\bar{N}(p, N_{\text{max}}) = 1 + p + p^2 + \cdots + p^{N_{\text{max}}}.$$

(4)

When mode $i$ is used, each transmitted symbol will carry $R_i = R_i \log_2 M_i$ information bits for mode adhering to a $M_i$-QAM constellation and a code with rate $R_i$. Define $P_i(i)$ as the probability that the mode $i$ will be chosen. Therefore, the average spectral efficiency achieved at physical layer without considering possible retransmission is

$$\bar{S}_{e,\text{phy}} = \frac{1}{N} \sum_{i=1}^{N} R_i P_i(i).$$

(5)

When HARQ is implemented, each block, and thus each information bit, is equivalently transmitted $\bar{N}(p, N_{\text{max}})$ times. Hence, the overall average spectral efficiency, as a function of $N_{\text{max}}$, is given by

$$\bar{S}_{e,\text{link}} = \frac{\bar{S}_{e,\text{phy}}}{\bar{N}(p, N_{\text{max}})} = \frac{1}{\bar{N}(p, N_{\text{max}})} \sum_{i=1}^{N} R_i P_i(i).$$

(6)

For a certain channel and modulation mode, the average spectral efficiency $\bar{S}_{e,\text{link}}$ at data link layer by changing the maximum number of retransmissions $N_{\text{max}}$. The system model and layer structure of our cross-layer design are shown in Figures 5 and 6, respectively. Let $I$ denote the total number of AMC available modes. For each mode we define the maximum number of retransmissions for IR_HARQ as $N_{\text{max}}$. If $N_{\text{max}}$ is $I$, under $i$th AMC mode, the total available number of transmission modes of this system is $N’ = f_1 + f_2 + \cdots + f_i$. We assume that the instantaneous BLER is guaranteed to be not greater than target BLER$_0$ at
Figure 5: Cross-layer combining AMC with HARQ transmission system.

Figure 6: Cross-layer structure combining AMC with HARQ.

physical layer. The BLER is not greater than \( BLER_0^{N+1} \) at data link layer. So we obtain

\[
BLER_0^{N+1} \leq BLER_{\text{link}}.
\]

From (7), we have

\[
BLER_0 \leq BLER_{\text{link}}^{(1/(N+1))}.
\]

The whole SNR range is divided into \( N + 1 \) intervals, with thresholds \( \gamma_i \), \( i = 0, 1, \ldots, N \). The instantaneous channel signal to noise ratio SNR is \( \gamma \). When \( \gamma \in [\gamma_i, \gamma_{i+1}) \), mode \( i \) is chosen. The threshold \( \gamma_i \) is determined according to (3). In (3) the target BLER_0 at physical layer is determined according to (8).

By always selecting the acceptable code producing the highest spectral efficiency for a given channel estimated SNR value, we will maximize the spectral efficiency of the overall system, while the BER or BLER requirement is still maintained.

4. Performances

4.1. Extraction of the LLR of QAM Modulation. In LDPC coded QAM system, the calculation of the Log-Likelihood Ratio (LLR) on the coded bits is an important function of practical wireless receivers. In this section, the exact bit LLR for the M-QAM signal is presented [14].

As an example let us consider a 16-QAM transmitted symbol sequence \( s_k = s_{ik} + j s_{Qk} \), with \( s_{ik}, s_{Qk} \in \{\pm 1, \pm 3\} \).

According to the mapping rule \( s_k = M(u_{k1}, u_{k2}, u_{k3}, u_{k4}) \), each modulation symbol is obtained from the information bits \( u_{kj}, j = 1, \ldots, 4 \). Without loss of generality, we assume \( s_{ik} = M_f(u_{k1}, u_{k3}) \) and \( s_{Qk} = M_q(u_{k2}, u_{k4}) \). An example of Gray code mapping is given in Figure 7.

Let \( X_k \) denote the baseband received signal sample corresponding to symbol \( s_k \):

\[
X_k = x_{ik} + j x_{Qk} = a \sqrt{E}\overline{S}_k + n_k.
\]

In (9), \( a \in \mathbb{R}^+ \), \( E \) represents the received signal symbol energy and \( n_k = n_{ik} + j n_{Qk} \) is additive white complex noise, with \( n_{ik} \) and \( n_{Qk} \) being independent Gaussian processes with zero mean and variance \( \sigma^2 = N_0/2 \).

Let \( \Lambda(u_k) \) indicate the LLR of bit \( u_k \) given \( X_k \), and in the case of equiprobable symbols

\[
\Lambda(u_k) = \log \frac{P(X_k|u_k = 1)}{P(X_k|u_k = 0)} = \log \frac{P[X_k|u_k = 1]}{P[X_k|u_k = 0]}. \tag{10}
\]

Define by \( S(u_{kj} = 1) = \{q : s^{(q)} = M(\ldots, u_{kj} = 1, \ldots)\} \) and \( S(u_{kj} = 0) = \{q : s^{(q)} = M(\ldots, u_{kj} = 0, \ldots)\} \) the subsets of symbol indexes corresponding to \( u_{kj} = 1 \) and \( u_{kj} = 0 \) respectively, then

\[
P[X_k|u_{kj} = 1] = \sum_{q \in S(u_k = 1)} p(X_k|s^{(q')}),
\]

\[
P[X_k|u_{kj} = 0] = \sum_{q \in S(u_k = 0)} p(X_k|s^{(q')}). \tag{11}
\]
Figures 8 and 9 show the symbol set partitioning for the bits $u_{k,i}$, $i = 1, \ldots, 4$, respectively. From the assumption on the noise $n_k$, we have

$$p\left(X_k \mid s^{(q)}\right) = \frac{1}{\pi N_0} \exp\left(-\frac{\|X_k - a \cdot \sqrt{E_s} s^{(q)}\|^2}{N_0}\right).$$

(12)

Therefore, straightforward calculation gives

$$\Lambda(u_{k1}) = \log \frac{e^{-(X_k - a_1 \cdot \sqrt{E_s})^2/2\sigma^2} + e^{-(X_k + a_1 \cdot \sqrt{E_s})^2/2\sigma^2}}{e^{-(X_k - a_3 \cdot \sqrt{E_s})^2/2\sigma^2} + e^{-(X_k + a_3 \cdot \sqrt{E_s})^2/2\sigma^2}},$$

$$\Lambda(u_{k2}) = \log \frac{e^{-(X_k - a_1 \cdot \sqrt{E_s})^2/2\sigma^2} + e^{-(X_k + a_1 \cdot \sqrt{E_s})^2/2\sigma^2}}{e^{-(X_k - a_3 \cdot \sqrt{E_s})^2/2\sigma^2} + e^{-(X_k + a_3 \cdot \sqrt{E_s})^2/2\sigma^2}},$$
Table 2: Transmission modes in the AMC system under AWGN channel.

| Model | MCS1   | MCS2   | MCS3   | MCS4   | MCS5   | MCS6   |
|-------|--------|--------|--------|--------|--------|--------|
| Modulation        | 4QAM   | 4QAM   | 16QAM  | 16QAM  | 64QAM  | 64QAM  |
| Coding rate           | 1/2    | 2/3    | 2/3    | 3/4    | 3/4    | 5/6    |
| Spectral efficiency   | 1.00   | 1.33   | 2.67   | 3.00   | 4.50   | 5.00   |
| SNR thresholds        | 1.8    | 3.4    | 9.4    | 10.6   | 15.6   | 16.7   |

Table 3: Transmission modes cross-layer combining AMC with HARQ (the maximum number of retransmissions $N^{max}$ is fixed).

| Model | MCS1   | MCS2   | MCS3   |
|-------|--------|--------|--------|
| Modulation        | 4QAM   | 16QAM  | 64QAM  |
| Coding rate           | 5/6~1/2| 5/6~1/2| 5/6~1/2|
| Spectral efficiency   | 1.6667~1.00 | 3.333~2 | 5~3    |
| Thresholds SNR under AWGN channel | 4.8 | 10.9 | 16 |

Table 4: Transmission modes cross-layer combining AMC with HARQ under AWGN channel (the maximum number of retransmissions $N^{max}$ is changeable).

| Model | MCS1   | MCS2   | MCS3   |
|-------|--------|--------|--------|
| Modulation        | 4QAM   | 16QAM  | 64QAM  |
| Coding rate           | 5/6~1/2| 5/6~1/2| 5/6~1/2|
| Spectral efficiency   | 1.6667~1.00 | 3.333~2 | 5~3    |
| Maximum number of retransmissions | 4 | 3 | 2 | 4 | 3 | 2 |
| SNR thresholds        | 3.6    | 4.9    | 5.95   | 10     | 11     | 12.5   | 15.1   | 16.1   | 17.4   |

The similar conclusion can be obtained for any other MQAM schemes in DSRC standard.

4.2. Simulation Results. To evaluate the performance of our algorithm, we have performed the simulations under AWGN channel. The transmission modes of AMC system are listed in Table 2 in ascending order of rate. The (2304, 1920) LDPC code with rate 5/6 is employed as a mother code, from which (2304, 1728) code with 3/4 rate, (2304, 1536) code with 2/3 rate, and (2304, 1152) code with 1/2 rate [15] can be obtained by puncturing. Decoded with Belief Propagation (BP) algorithm [16], is set to be the maximum number of iterations equal to 50. BER and BLER performances of modulation modes in Table 2 under AWGN channel and Rayleigh channel are shown in Figure 10. Let the constrained performance in physical layer be $\text{BER}_0 = 10^{-3}$, from which we can determine the thresholds $\gamma_i$ with (2).

The transmission modes of AMC-HARQ system with fixed maximum number of retransmissions based on RC-LDPC codes are listed in Table 3. We still use (2304, 1920) RC-LDPC codes with 5/6 rate as FEC, from which LDPC codes with 1/2, 2/3, 3/4, and 4/5 rate can be obtained by puncturing. Therefore, the maximum number of retransmissions of ARQ is 4. The BLER for 5/6 rate LDPC code as well as its punctured codes under AWGN channel is shown in Figure 11. Let the constrained performance in data link layer be $\text{BLER}_0 = 10^{-2}$. From (8) the performance target BLER in physical layer is $\text{BLER}_0 \leq 0.001^{1/5} = 0.2512$. Let 4/5 rate punctured code as criterion thresholds $\gamma_i$ can be determined according to (3), which is shown in Table 3.
The transmission modes of AMC-HARQ system with changeable maximum number of retransmissions based on RC-LDPC codes are listed in Table 4. RC-LDPC codes (2304, 1920) [15] with 5/6 rate also are employed as FEC. The number of modulation modes is MCS1, MCS2, and MCS3. We consider three values for the maximum numbers of retransmissions $N_{\text{max}} = 2$, 3, and 4 for each modulation mode. Given the performance constraint at the data link layer is $\text{BLER}_0 = 10^{-2}$, we can get the performance target BLER in physical layer for each mode and the thresholds $\gamma_i$ can be obtained according to (3), which are shown in Table 4. The simulations are performed for comparing the throughput of three systems under AWGN channel. We assume perfect channel estimation so that the receiver can obtain the exact quality SNR, and the feedback channel is error-free. The stopping-waiting IR HARQ protocols are adopted. The maximum iterative decoding numbers of LDPC codes are 50. The results are shown in Figure 12, from which we can know that AMC-HARQ system with changeable maximum number of retransmissions outperforms the other two systems. We replace the LDPC codes by rate compatible convolutional codes (CC) and turbo codes (TC) in [2] and the simulation results are shown in Figure 13. The proposed AMC-HARQ system based on LDPC codes illustrates the best performance.

5. Conclusions

In this paper, we developed a cross-layer design, which combines adaptive modulation and coding at the physical layer with IR-HARQ at the data link layer in order to maximize system spectral efficiency under prescribed performance constraints. In physical layer the AMC adjusts the data rates roughly according to the CSI by choosing different modulation modes. In data link layer HARQ adjusts the data rate accurately according to the CSI by changing the maximum retransmission number. Numerical results demonstrated the rate improvement of our cross-layer design over AMC alone, as well as AMC-HARQ with fixed maximum number of retransmissions. In our proposed scheme, we employed RC-LDPC as channel codes due to their decoder for the lowest code rate being compatible with the ones for higher code rates. Our new method can improve the performance and no additional complexity is needed. All of our simulations are conducted under AWGN channel, and in the future,
we intend to perform further experiments under a more realistic channel model for the DSRC system.

Acknowledgments

The work is supported by the NSFC (Grant nos. 61032003, 61271172, and 61071000), RFDP (Grant nos. 2012018510025 and 2012018510030), NCET (Grant no. NCET-09-0266), and SRF for ROCS, SEM.

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