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# Raptor Code for Wireless Ad Hoc Vehicular Safety Broadcast

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**Abstract**—This paper proposes an implementation of systematic Raptor code in an ad hoc V2V (vehicular-to-vehicular) environment for post-crash safety broadcast. This is to address the latency problem caused by use of repetition code in a high speed vehicular environment for time-sensitive safety applications. The highly dynamic topology and challenging RF behavior of vehicular networks necessitate the use of a robust error control mechanism even with the use of spatial diversity techniques such as STBC-MIMO scheme. A cross-layer simulator model is used to evaluate the delay performance of Raptor codes against a low complexity repetition code. The numerical analysis demonstrates that the end-to-end delay performance is significantly reduced when Raptor codes are used, especially at higher distances from the source node. This is true in the case of single antenna as well as multiple antenna schemes.

**Index Terms**—WAVE, IEEE 802.11p, Raptor code, MIMO.

## I. INTRODUCTION

Wireless Access for Vehicular Environment (WAVE) is a new standard proposed for direct communication between vehicle nodes (V2V) and from vehicle to infrastructure (V2I). The WAVE standard is drafted under two family of standards, namely the IEEE 802.11p for the physical and MAC layers, and IEEE 1609 for higher layers specification. It aims for a fast, secure and reliable communication in a dynamic node density, topology and Doppler shifts.

The intermittent connection of high speed vehicular environment such as motorways entails the need for a robust error control scheme. The broadcast nature for most WAVE applications make fountain codes (also known as rateless codes) suitable for implementation. The lossy vehicular wireless channel for packet transmission is assumed to behave similarly to a binary erasure channel, where rateless codes are known to perform best. In our previous work [1], we considered safety broadcast of post-crash warning messages using the repetition code as this is implied in the standard. However, a repetition code poses a threat to network congestion and an inefficient use of the widely shared WAVE bandwidth.

Fountain codes with their on-the-fly rate adaptivity require no a priori information on channel condition, an otherwise impossible challenge when dealing with vehicular rapidly varying link loss condition. Other benefits of fountain codes are its low complexity design and very low coding overhead requirements. As long as slightly more than the original number of encoded symbols (ESs)

are received, the vehicle server can successfully decode the original source block. This supports a reliable data dissemination which is of high importance in a safety critical application, without the need of a complex routing protocol. Raptor codes, first introduced in [2], are the most successful member of the fountain codes family.

While fountain codes for vehicular communications are a relatively new area of research, we find that most work steers towards an infrastructure-dependent communication for value-added services application. To the best of our knowledge, rateless code evaluation in a VANET safety broadcast application has not been investigated yet.

In this paper, we use an exhaustive numerical approach by means of a detailed physical layer model that among others take into consideration an accurate packet error rate analysis based on the IEEE 802.11p OFDM (Orthogonal Frequency Division Multiplexing) scheme, a novel channel tracking mechanism using a midamble [3], for single antenna and STBC (Space-Time Block Code) multiple antenna schemes. More details can be found in our previous work [1]. We have further extended the model with a newly developed cross layer simulator that takes into account a systematic Raptor encoder/decoder, as well as incorporates the overheads and end-to-end layered architecture communication model.

The rest of the paper is organized as follow. In Section II, we provide a summary of related work in this area. Section III gives a brief overview to systematic Raptor codes. Simulation assumptions, results and discussion are presented in Section IV. Finally, Section V concludes the paper.

## II. RELATED WORK

Raptor codes have been formally adopted as the application layer FEC (forward error correction) scheme in multiple standards such as 3GPP MBMS (Multimedia Broadcast Multicast Service) [4] and the DVB-Handheld standard for IP Datacasting and commercial IPTV services [5]. However, there has been limited work on fountain code for Wireless Access for Vehicular Environment (WAVE).

In [6], the authors analyze the performance of file exchange in I2V environment. The file is partitioned into smaller packets and sent using the unreliable UDP transport with the help of a rateless code at the application layer FEC. This is motivated by the fact that receiving enough encoding symbols is more significant with fountain codes,

than the reliability provided by TCP as used in normal wired file transfer. The authors performed the analysis using a discrete event network simulator without the actual fountain code implemented. However, the generalized assumption that 20% ES overhead is required for successful decoding is not as accurate because this percentage is far above the typical fountain code overhead requirement. Furthermore, no consideration is taken into the received signal strength and the distance of vehicles from the source node as a function of the overhead.

A combination of V2V (vehicle-to-vehicle) and I2V (infrastructure-to-vehicle) communication, also referred to as I2V2V (infrastructure-to-vehicle-to-vehicle) is described in [7], [8] for dissemination of advertisement applications. Paper [8] uses the scenario whereby an infrastructure has a collection of unique P/S (publish and subscribe) advertisements that are available upon request. It focuses more on cooperative communication towards dissemination of the different advertisements when vehicles are no longer within the communication range of the infrastructure. A certification method is used to differentiate the message sets. Meanwhile, paper [7], concentrates on studying the effect of buffer management. Two types of buffer management schemes are proposed, mainly differentiated by how buffer space are freed and allocated when vehicles move from one infrastructure to the next. Both papers also make the use of UDP transport protocol, exploiting the reliability benefit provided by rateless codes.

### III. OVERVIEW OF SYSTEMATIC RAPTOR CODE

The discovery of sparse graph codes with capacity approaching rates has revolutionized digital communication systems. Fountain codes, or rateless codes as the name implies are unlike conventional codes in that the coding rate is not fixed. These codes are able to adapt their code rate on-the-fly regardless of varying or even unknown channel conditions. With fountain codes, the encoder can potentially generate a limitless stream of encoded packets from a finite set of data packets. At the decoder, the original data can be recovered from any sufficiently large set of encoded packets. This makes fountain codes particularly suitable for wireless multicasting and broadcasting applications where users experience different channel characteristics. There are a number of variation of fountain codes namely the Luby Transform (LT) code [9], Online codes[10], and Raptor codes [2].

In this paper, we implemented the systematic Raptor code as proposed in the 3GPP MBMS standard [4]. It is a two-step code process consisting of a high rate precode as outer code and a weakened LT code as inner code which produces the stream for transmission. The outer code provides extra protection to the source symbols by correcting erasures not recovered by the weakened LT code. This concatenated code approach reduces the complexity of the LT-code into linear encoding and decoding times of  $O(\log K)$ , instead of the normal LT code complexity

of  $O(K \log K)$  where  $K$  is the source block length. The precode matrix,  $A$  (of size  $L \times L$ ) in the proposed scheme is a hybrid LDPC-Half systematic  $(L, K)$  linear correction code where  $L = K + S + H$ . The precoding starts with  $K$  source symbols, and adds  $S$  parity symbols induced by an LDPC code dependent only on the value of  $K$  (of size  $S \times K$ ), as well as  $H$  parity symbols from Half precoding using the properties of Gray sequences (of size  $H \times (S + K)$ ). For a given  $K$ , the size of the precode can be determined from the relationships in eq. (1)-(3).

$$X = \min\{x \in \mathbb{N} : x(x-1) > 2K\} \quad (1)$$

$$S = \min\{s \in \mathbb{N}, s' : s' \geq \lceil \frac{K}{100} \rceil + X\} \quad (2)$$

$$H = \min\{h \in \mathbb{N} : \binom{h}{\lceil \frac{h}{2} \rceil} \geq K + S\} \quad (3)$$

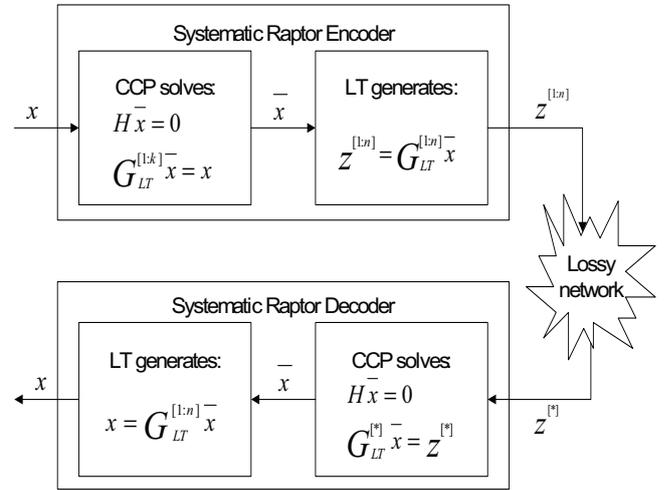


Fig. 1. Systematic Raptor block diagram

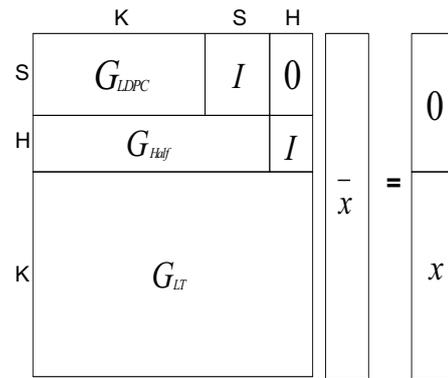


Fig. 2. Code constraint processor (CCP) operation

A crucial assumption in systematic Raptor design is that the linear system processed by the encoder has full rank  $L$  over  $GF2$  (Galois Field 2). This is possible by accordingly

pre-designing the first  $K$  rows of the LT generator matrix for each block length  $K$ . These are the rows that will eventually produce the systematic symbols. This means that the first  $K$  symbols of the encoded symbols are similar to the source symbols and the remaining symbols are the repair symbols. For that purpose, the encoder and the decoder are equipped with a special pseudorandom number generator. Its output depends on the two long pre-calculated arrays  $V0$  and  $V1$  (refer to [4] for the array values). These arrays serve as a kind of database to form the called *source triples*, and fed to the pseudorandom number generator. Source triples are read from the arrays according to the current encoded symbols identifier (ESI), subsequently numbered according to the position of a processed encoded symbol within the LT encoded stream. The source block sizes may range from  $K_{min} = 4$  to  $K_{max} = 8192$  source symbols.

This precode matrix  $A$  need only to be calculated once for the number of the source symbols ( $K$ ) used and then stored for future reference. The systematic Raptor encoder and decoder block diagram is as shown in Figure 1 where  $H$  refers to the parity check matrix consisting of  $G_{LDPC}$  and  $G_{Half}$ . The code constraint processor (CCP) in other words is an efficient way to perform operation of a binary inverse matrix. Two methods to go through this is by using the Gaussian elimination procedure or by using iterative belief propagation. The Gaussian elimination method is usually used for smaller block lengths  $K$ , while belief propagation method is used for larger  $K$  values. In the 3GPP MBMS specification, an enhanced Gaussian elimination is proposed. Similarly, in our scenario where a very short  $K$  value of 8 is used, we utilized the Gaussian elimination method. Figure 2 depicts the structure of the precode  $A$  matrix,  $x[0], \dots, x[K-1]$  denoted as the  $K$  source symbols and  $\bar{x}[0], \dots, \bar{x}[L-1]$  denoted as the  $L$  intermediate symbols.

#### IV. NUMERICAL ANALYSIS

We consider an application layer FEC (forward error correction) coding algorithm as explained in Section III. The application layer procedure starts with partitioning of the data block into  $K$  smaller size packets, also known as the source symbols (SSs). This data is then encoded using the systematic Raptor code which is referred to as the encoded symbols (ESs). In this paper, the safety application considered is the hazardous location notification, with a source block size of 512 bytes that is partitioned into  $K = 8$  SSs of 64 bytes payload each ( $N_{payload}$ ). The transport protocol for both Raptor code and repetition code simulation is the UDP (user datagram protocol).

A single-hop safety message is assumed in the scenario to eliminate the need for complex routing analysis. Since the communication is of broadcast nature, DCF (Distributed Coordination Function) MAC is only used for idle channel sensing. No retransmission mechanism implies that the contention slot will be a random number between 0 to the minimum contention window,  $CW_{min}$ . In our

simulation, we consider  $CW_{min}$  value of 31. Other MAC parameters such as SIFS (short inter-frame spacing), DIFS (DCF inter-frame spacing), and  $T_{slot}$  (slot time) follow the draft IEEE 802.11p standard in [11].

TABLE I  
SIMULATION PARAMETERS

Parameter	Value
Transmit power, $P_T$	15 dBm
Receiver Sensitivity, $RX_{sens}$	-89.76 dBm
Communication range, $CR$ (Free Space Model)	700 m
Bandwidth, $B$	10 MHz
Noise figure, $NF$	10 dB
Noise power, $k \cdot T \cdot B \cdot NF$	-94 dBm
Data rate, $R$	6 Mbps
Basic rate, $R_0$	3 Mbps
Antenna height, $h_t = h_r$	1.5 m
channel frequency, $f_c$	5.9 GHz

The end-to-end delay calculation takes into consideration Raptor code encoding and decoding processing delays, additional ESs overheads ( $\epsilon$ ) required to successfully decode the packet, and other delays from layered architecture headers and IEEE 802.11p DCF MAC scheme. The no interference scenario delay calculation is as shown in eq. (4)-(5), where PLCP preamble and header is represented by 5 OFDM symbols; upper layer headers sizes,  $N_{layer\ headers}$  are 8 bytes for UDP, 20 bytes for IP and 34 bytes for MAC; number of coded bits per OFDM symbol,  $N_{DBPS}$  for 6 Mbps QPSK 1/2 mode is 48; and  $T_s$  is the OFDM symbol duration.

$$T_{DATA} = T_{PLCP\ preamble} + T_{PLCP\ header} + \left\lceil \frac{N_{layer\ headers} + N_{payload}}{N_{DBPS}} \right\rceil \cdot T_s \quad (4)$$

$$T_{safety} = (DIFS + \frac{CW \cdot T_{slot}}{2} + T_{DATA} + SIFS) \cdot K \cdot (1 + \epsilon) \quad (5)$$

The developed physical layer simulator block diagram for an multiple antenna system is an extension from previous work in [12]. With plenty of space availability on vehicles, antennas can be placed sufficiently apart so that the transmission paths experienced by each transmit or receive antennas are fairly decorrelated. However, due to the nature of the rapidly varying scatterers and Doppler shift caused by the moving vehicle, the conventional assumption of an independent and identically distributed channel can no longer be made [13]. Therefore, to simulate a time evolution of the channel, we apply the Clarke's model as presented in [14]. Each of the channel taps are derived from a standard time-varying Rayleigh process that can be adapted to specific maximum vehicular speeds as shown in eq. (6):

$$h(t) = \sum_{n=1}^L A_n \cdot \exp(j(\phi_n - 2\pi f_d t \cdot \cos(\alpha_n))) \quad (6)$$

where phase  $\phi_n$ , and arrival azimuth  $\alpha_n$ , is uniformly distributed over  $(\pi, -\pi)$ ,  $A_n$  is unit value fading amplitude,  $f_d$  is the maximum Doppler frequency, and  $L$  is the number of multipath components. This Rayleigh channel is multiplied with an 8-tap exponentially decaying power delay profile from the ETSI Channel B model [15] with 100 ns mean rms delay spread. This delay spread is in agreement with highway measurements as reported in [16].

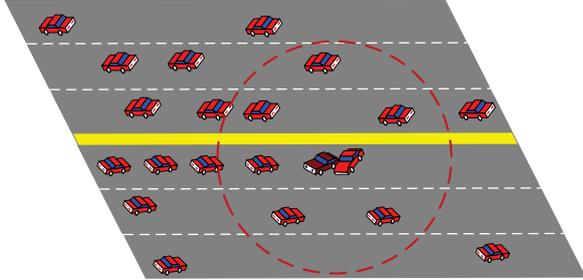


Fig. 3. Post-crash warning on motorways

Figure 3 shows a post-crash warning application on a bidirectional motorway. Simulation is performed based on two different average speeds values. This average speed values,  $v$  is used for the maximum Doppler shift,  $f_d$  calculation in eq. 6 given by  $f_d = \frac{vf}{c}$ , i.e.  $v$  is maximum vehicular speed in m/s,  $f$  is the IEEE 802.11p channel frequency set at 5.9GHz,  $c = 3 \times 10^8$ m/s. A high traffic density motorway, where cars are spaced closer together is represented by low average speed of 50 km/h scenario. The opposite goes for low density traffic. In the latter scenario, we assume a higher average speed of 100 km/h. Figure 4 shows that due to the small size ESs and efficient midamble channel estimation, the different average speed do not place a significant impact on the packet error performance. We shall consider our future analysis on the end-to-end delay performance using the low average speed value i.e. 50 km/h.

The channel erasure probability used in the simulation are based on the PER (packet error rate) curves shown in Figure 4. The SNR values are translated to distance in Figure 5 using a Free Space path loss model. Simulation parameters used are as depicted in Table I

The end-to-end delay analysis in Figure 6 shows that Raptor codes always outperforms repetition codes. At 600 m distance from the source node, Raptor codes reduced the end-to-end delay performance by 53% in SISO scheme, and 32% in STBC 2x2 scheme. Meanwhile for STBC 4x4 scheme, the end-to-end delay is reduced by 38% at 1000m distance. This analysis also show that the combination of Raptor codes and spatial diversity provided by multiple antenna schemes have provided a communication range extension. For example, at 6ms delay, the communication range is extended by ~30% with STBC 2x2 and ~100% with STBC 4x4 in comparison to the Raptor code with

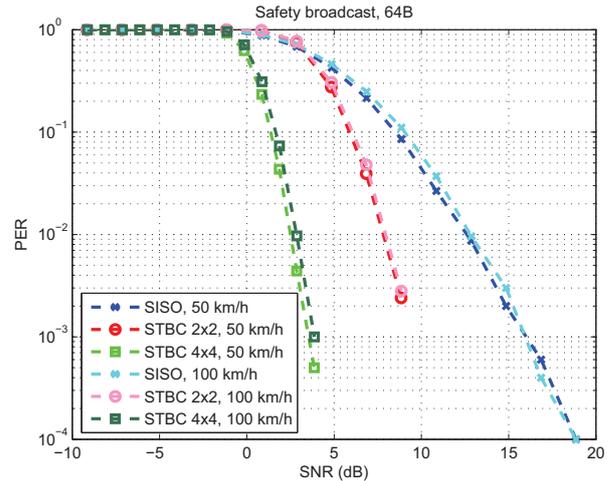


Fig. 4. Safety broadcast: packet error performance

SISO. Raptor codes with a STBC 4x4 configuration show an advantage over repetition code at farther distances from the source node i.e above 800m. As summarized in [17], most safety message allows an upper limit latency of 100ms. Even the most stringent delay requirement for pre-crash sensing application has a maximum allowable latency of 50ms. As shown in Figure 6, the end-to-end delay performance for all cases fall below this range.

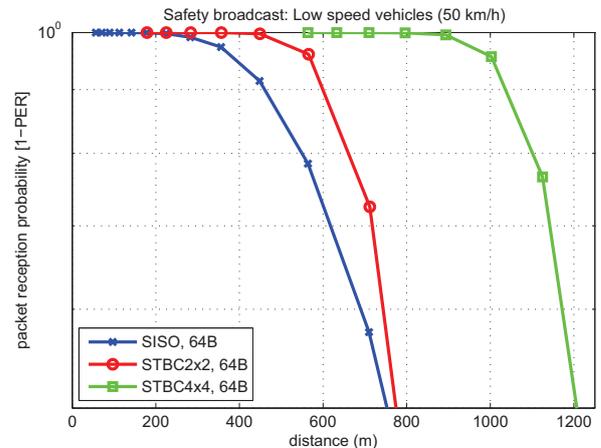


Fig. 5. Probability of success vs. distance from source node

## V. CONCLUSIONS

In this work, a combination of the performance evaluation of systematic Raptor codes against repetition codes with multiple antenna against single antenna schemes for ad hoc vehicular safety broadcast messages have been presented. To the best of our knowledge, this is the first paper to evaluate a rateless code in a VANET safety broadcast application. This preliminary results are a motivation towards the consideration of rateless code for safety broadcast. It is shown that the Raptor code improves of

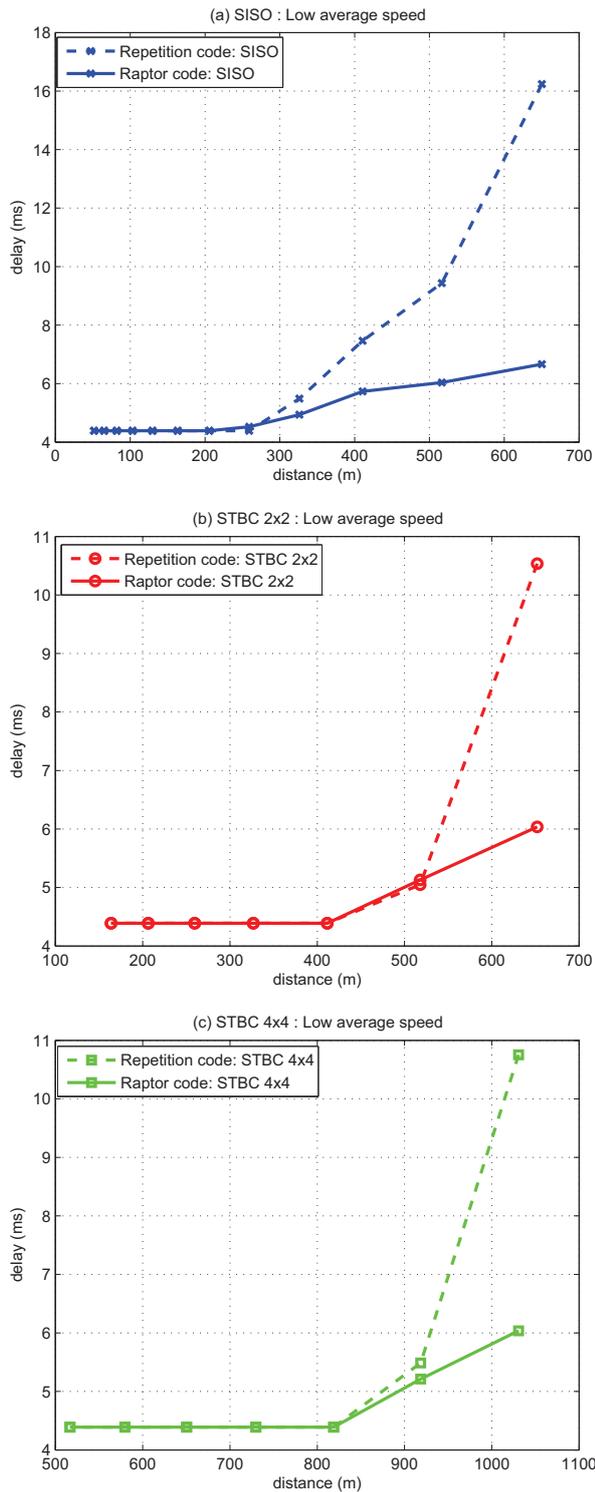


Fig. 6. Safety broadcast: End-to-end delay performance in low average speed traffic

up to 53% of end-to-end delay performance and fall below the 100ms latency requirement specified for most WAVE safety applications. However, in this analysis we have not considered interference from other transmissions by surrounding vehicles. This will be analyzed future in our upcoming work. Future work will also consider analysis of infotainment in an infrastructure-based networks.

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