Raptor Code-enabled Reliable Data Transmission for In-vehicle Power Line Communication Systems with Impulsive Noise

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***Abstract*—With the rapid development of in-vehicle data transmission systems, the power line communication (PLC) technology is considered as a good alternative due to the reduction of cable harness. However, PLC suffers from severe impulse noise which hinders the correct reception of data packets and hence leads to a poor transmission performance. In this paper, we propose a raptor code-enabled data transmission scheme for different traffic classes in in-vehicle PLC systems. Simulation results show that the proposed scheme is suitable for in-vehicle data transmission and can provide good protection against the impulsive noise while a considerable reception overhead is needed.**

***Index Terms*—In-vehicle power line communication (PLC), impulsive noise, raptor code, traffic class.**

I. Introduction

WITH the emerging automated tasks in vehicle domain, the development of in-vehicle communications is increasingly important and subjected to new applications [1]. Although both wired and wireless communications have been largely used for supporting diverse applications, most of the in-vehicle applications with mission-critical nature, such as brake and engine controls, still prefer dedicated wired networks for reliable transmission. According to Ford Motor Company, todays vehicles have more than 2,000 wires, which would measure more than a mile in length [2]. The weight of a wire harness is in the region of 20 to 50 kilograms per car, which makes up the third heaviest and costliest component in a car, right behind the chassis and engine.

Over the past few years, we have witnessed an increasing interest in the use of power line communication (PLC) for home automation systems, automatic meter reading, real-time energy management systems, and many other applications. The use of PLC is promising to in-vehicle applications which features enormous advantages in terms of weight, space and cost since it would remove most part of the wires [3]. Understanding the characteristics of power wires in vehicle as a communication channel has been the drive for many measurement campaigns [4], [5]. The findings show that in-vehicle power lines constitute a harsh and noisy transmission medium with significant impulsive noise, e.g. [6], [7], which can seriously deteriorate the transmission performance. Although traditional forward error correction (FEC) such as Reed Solomon codes and Turbo codes has been considered to be applied in PLC to solve this problem, the challenge is that these methods cannot guarantee a reliable transmission when sever impulsive noise is induced because these codes cannot provide protection across several impulse.

We introduce raptor codes [8] into in-vehicle PLC systems to cope with the side effects caused by impulsive noise. Raptor codes are originated from the family of fountain codes, i.e., the encoder can generate a limitless stream of the encoding packets as desired on-the fly from the source packets of a source block. The decoder is able to recover the source block from any set of encoding packets only with limited increasing of the numbers compared with source packets. Once the decoder gets enough source packets for recovering the source block, the decoder will send feedback to the transmitter so that a new block is transmitted. There are many kinds of fountain codes such as Luby Transform (LT) codes [9], Online codes [10] and Raptor codes. Raptor codes are an enhancement on LT codes which are random bipartite codes where each encoded packet is a linear combination (XOR) of the transmitted packets. Raptor codes can help protect the transmitted data across several impulse, rather than across a single impulse with traditional FEC [11].

In this letter, we propose a raptor code-enabled data transmission scheme for in-vehicle PLC systems considering the effects induced by the impulse noise. The parameters for raptor code are specially designed in order to meet the max end-to-end delay requirement of in-vehicle mission-critical transmission and the parameters characterizing the impulsive noise. Different traffic classes are investigated under this scheme. By designing and employing raptor code-enabled data transmission scheme, a reliable error free transmission can be achieved.

II. The Raptor Code-enabled Data Transmission Scheme for In-vehicle PLC Systems with Impulsive Noise

Table I shows the max end-to-end delay and service rate for two in-vehicle traffic classes, one of which is the control data and the other is safety data. Different traffic classes have different requirements. The end-to-end delay is a crucial parameter when designing the raptor code-enabled data

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TABLE I
MAX END-TO-END DELAY AND SERVICE RATE FOR DIFFERENT TRAFFIC CLASSES [12]

Traffic Class	Max End-to-End Delay	Service Rate
Control Data	2.5 ms	10-100 ms
Safety Data	45 ms	0.05-1 ms

transmission scheme because the total time of all the data transmitted should not exceed the max end-to-end delay. After a time within the service rate, new data is transmitted.

In order to guarantee a reliable transmission for PLC systems, raptor codes are taken into account. As mentioned in section I, raptor codes is a kind of fountain codes which are an enhancement on LT codes. The coding and decoding part of raptor code are all based on packets which can be bits of any length, denoted as L. Raptor codes differ from LT codes because of the different degree distribution and the high-performance pre-code process. Raptor codes can be categorized as systematic and non-systematic, which we mainly focus on systematic raptor codes, i.e., the source packets are among the encoding packets that can be generated.

At the transmitter, there are N_B blocks to be transmitted and each block consists of k packets. In each block, the k packets are encoded as n packets and then transmitted. Therefore, the number of redundant packets in a block is $n-k$. For systematic raptor encoder, the encoding process is shown in Fig. 1 where each circle represents a packet of L bits. The k source packets are first pre-coded as s intermediate packets using a hybrid LDPC-Half systematic linear correction code. The LDPC code here is not the traditional error correcting code and is detailed in [13]. Then the s intermediate packets are encoded as r redundant packets by a weakened LT code. Soliton distribution is employed in the weakened LT code scheme. The total encoded packets is composed of the original k source packets and r redundant packets. A generation matrix can be created which encodes the k source packets into n packets. In systematic raptor decoder, following the known relationships amongst the intermediate packets and the source packets, the reverse of the generation matrix can be calculated by Gaussian elimination [13] so the original k source packets can be decoded. The pre-code can provide protection to the source packets by correcting erasures not recovered by the weakened LT code. The weakened LT code can guarantee the complexity of $O(\log k)$, which is better than the normal LT code complexity of $O(k \log k)$. So this concatenated code can provide both high protection and low complexity. The reception overhead is denoted as ε, which satisfies $r = k\varepsilon$. Decoding is successful with a probability equal to $(1-\delta)$ where δ is upper-bounded by 2^r [8]. This suggests that the decoding probability can be larger when larger k and ε is used. However, too large ε can decrease transmission efficiency. Typically, ε is about 10%.

Raptor codes cannot be adopted in PLC systems directly since the parameters for raptor codes are severely limited by the statistical character of impulsive noise. A single impulse noise can be characterized as

$$\mathrm{n}_s(t) = Ae^{-bt}\sin(\omega_p t), \quad 0 \le t \le d, \tag{1}$$

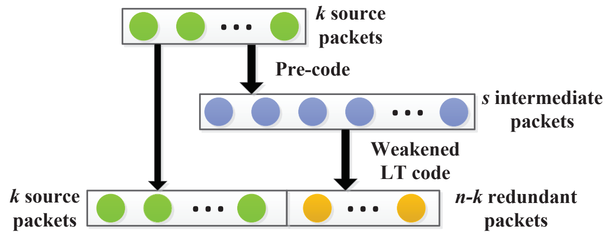

Fig. 1. Configuration of the encoder of systematic raptor codes.

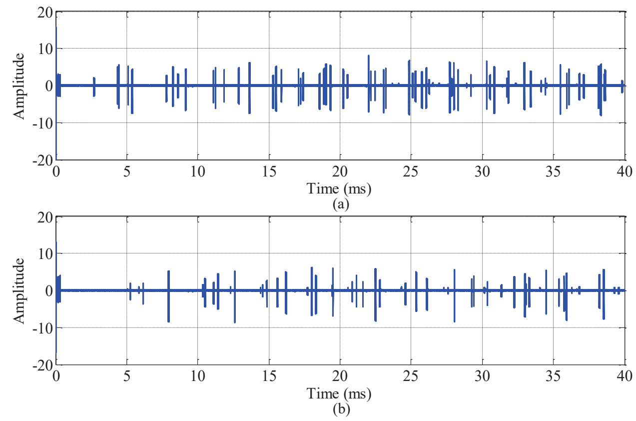

Fig. 2. The regeneration of impulse noise in two example vehicles (a) and (b) from the observed data in [6].

where A is the peak amplitude of the impulse which is modeled as Gaussian distribution with mean value of $\bar{A}$ and variance of σ, b is the speed the impulse fading away, ω_p is the frequency and d is the duration of the impulse.

The impulsive noise comprised of many impulses can be described as follows:

$$\mathrm{n}(t) = \sum_i n_s(t-t_i) = A\sum_i e^{-b(t-t_i)}\sin[\omega_p(t-t_i)], \tag{2}$$

where t_i denotes the time when the impulses occur. Poisson process is employed to calculate t_i [14]. In Fig. 2, we regenerate the impulsive noise of two example vehicles from the observed data in [6], and it has been shown by [6] and [7] that Poisson process is a perfect model in calculating the inter-arrival time of the in-vehicle impulse noise. It is a frequently applied model to calculate the occurrence of sporadic events. The mean inter-arrival time is described by $1/\lambda$ where λ is the mean number of events in a specialized time period. Figure 3 illustrates the impulsive noise over a period of 5 ms with $\bar{A}$ of 5 and $1/\lambda$ of 300 s. Each impulse is damped sine shaped. The impulse noise is considered as an additive noise in the time domain.

Based on the description above, parameters of raptor codes must be carefully designed for reliable transmission due to the max end-to-end delay and the statistical character of impulsive noise. The number of the redundant packets r only depends on the packet error rate denoted as p and the number of source packets k. In order to achieve a reliable error-free transmission, for all the N_B block transmitted, r must satisfy

$$r > kp/(1-p). \tag{3}$$

The parameters of the impulse noise $1/\lambda$, $\bar{A}$ and d can significantly affect the packet error rate p, leading to the

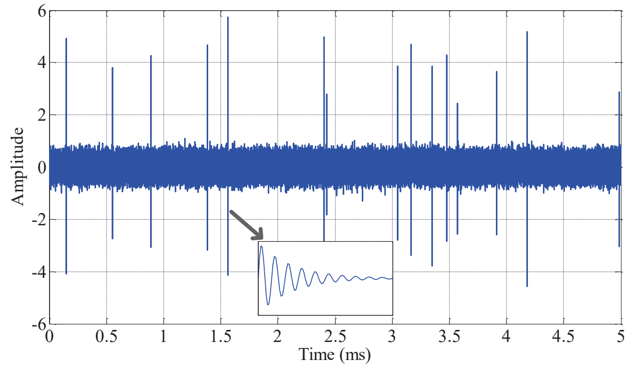

Fig. 3. The impulsive noise over a time period of 5 ms with $\bar{A}$ of 5 and $1/\lambda$ of 300 s.

change of r and k.

The mean inter-arrival time $1/\lambda$ is an important parameter for designing the packet length L. For a considerable reception overhead ε, L should satisfy

$$L < (1/\lambda) \cdot \sqrt{m} \cdot R/a, \tag{4}$$

where a is the coefficient, R denotes the baud rate and m QAM is used for OFDM subcarriers. Equation (4) shows that the value of L is limited by $1/\lambda$, this is because when $1/\lambda$ is fixed, larger L can cause higher packet error rate p and a higher ε has to be taken account. So for a proper value of ε, the value of L must be limited.

For different traffic classes, raptor codes should be designed differently because of the different max end-to-end delay. In order to meet the demand on delay, we have

$$(k + r) \cdot L < delay \cdot \sqrt{m} \cdot R. \tag{5}$$

The raptor codes scheme for different traffic classes should satisfy equation (3)-(5). In the simulation we found that the packet error rate p ranges from 1%-30% and a is about 2-8 when different $1/\lambda$, $\bar{A}$, d and different delay are used. Based on the value of p, a and equation (3)-(5), we can achieve a considerable setting of the parameters of raptor codes which is shown in section III.

III. Performance Evaluation

In the network model, the data baud rate R is 3 Mbps, OFDM modulation with subcarriers of 1024 is realized. In each subcarrier, QPSK is selected as modulation formats. Besides the impulsive noise, additive white Gaussian noise with signal to noise ratio of 10 dB is also added. The impulse response for direct connections in [15] is employed as the transfer channel. A fine channel estimation and equalization is realized at the receiver.

A number of 1000 blocks are transmitted both for control data (a) and safety data (b) using the proposed raptor code-enabled data transmission scheme. In this case, the parameters of the impulse noise d is set as 1 s, $\bar{A}$ is set as 5 and $1/\lambda$ is 300 s. The impulses are with $\bar{A}$ of 5, d of 2 s, ω_p of 10 MHz , σ of 1 and b of $4/d$. For control data with max end-to end delay of 2.5 ms, smaller packet length L and block size k are necessary due to the low end-to-end delay. In the simulation, L is set as 19 bytes and k is 70. 24-bits cyclic redundancy check

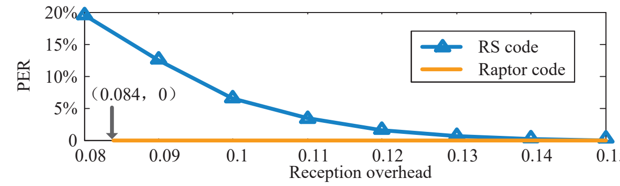

Fig. 4. PER versus reception overhead using raptor code and RS code.

(CRC) is used for packet checking. The minimum reception overhead needed is about 1.17%. For safety data with much longer delay of 45 ms, L and k can be larger. In this case, L is set as 50 bytes and k is 300, where 32-bits CRC is used and the minimum overhead required is 2.1%.With the help of the specially designed raptor code, a reliable transmission can be guaranteed both for control data and safety data with a considerable amount of overhead required when the impulsive noise exists. Raptor code can help solve the side effects caused by impulsive noise both for control data and safety data.

We compared our raptor codes scheme to Reed-Solomon (RS) code trying to prove its superiority. We simulated 1000 blocks with L of 50 bytes and k of 200. d is set as 2 s, $\bar{A}$ is 5 and $1/\lambda$ is 300 s. Figure 4 illustrates the packet error rate (PER) versus reception overhead when both codes are used. For raptor code, the minimum reception overhead required for reliable transmission is 0.084. As for RS code, a (200, 230, 50 bytes) code is required whose overhead is 0.15. The overhead of RS code is much larger than that of raptor code. Raptor code outperforms RS code in terms of reception overhead.

We analyzed the lowest reception overhead ε needed in the circumstance of different noise parameters on the premise of reliable transmission when control data is selected as the traffic class which is illustrated in Fig. 5. In other words, all blocks simulated are decoded successfully and the data is correctly transmitted in this case.

Figure 5 (a) shows the reception overhead ε as a function of the impulse noise duration d. Four cases with different packet length L and block size k are simulated. $\bar{A}$ is set as 5 and $1/\lambda$ is 300 s. It can be seen from the figure that the reception overhead gets higher when the noise duration is longer. Lower reception overhead is achieved when using smaller L and larger k which means that lower packet error rate is achieved in this case. Besides, when the noise duration increases, the slope of the curves also increase which means that longer duration induces severer influence.

Figure 5 (b) shows the reception overhead ε as a function of the mean value of the noise amplitude $\bar{A}$. $1/\lambda$ is 300 s and d is 2 s. We can see that higher noise amplitude causes higher reception overhead. Smaller packet length L and larger block size k outperforms the other three cases. We also found that when the noise is 7 times the amplitude of the signal transmitted, reception overhead can reach up to 20% which significantly reduces the transmission efficiency.

Figure 5 (c) shows the reception overhead ε as a function of the mean inter-arrival time $1/\lambda$. $\bar{A}$ is 5 and d is 1 s. We found that the reception overhead decreases when increasing the mean inter-arrival time $1/\lambda$. Lower reception overhead is also achieved when smaller packet length L and larger block size k are used. Furthermore, we found that the reception

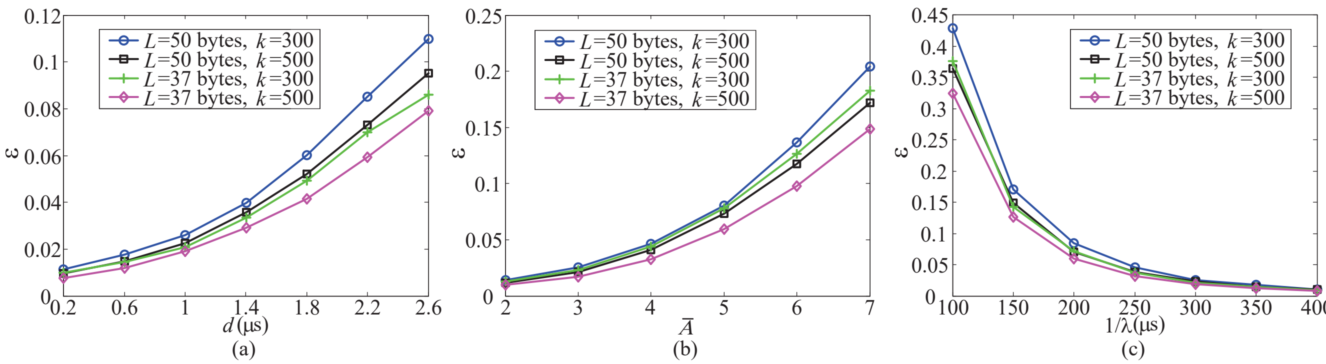

Fig. 5. The reception overhead ε as a function of the noise duration d (a), the noise amplitude $\bar{A}$ (b) and the mean inter-arrival time $1/\lambda$ (c).

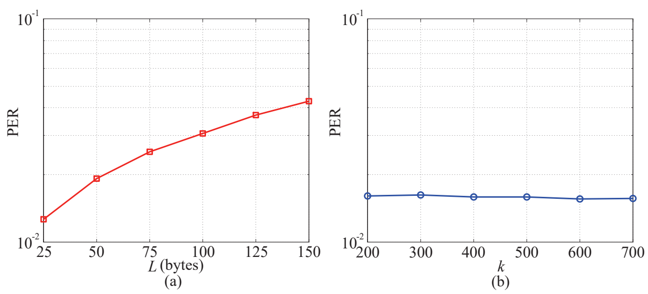

Fig. 6. PER versus the symbol length L (a) and the block size k (b).

overhead is more vulnerable to $1/\lambda$ than d and $\bar{A}$. When $1/\lambda$ decrease to 100 s, the reception overhead can be high up to 40%. The mean inter-arrival time $1/\lambda$ is the key parameter when designing the reception overhead of raptor code.

We calculate the PER with different block size k and packet length L to find out why the case of lower reception overhead always occurs with smaller L and larger k. Figure 6 (a) shows the PER a function of the packet length L. We can see from the figure that PER increases when L increase. Since smaller L means less error probability within a packet, smaller L helps decrease the packet error rate and hence the redundant packets needed in this case is also lower. As shown in Fig. 6 (b), little change of PER when different k are considered, so PER is not the reason for the larger k needed. In the raptor decoding part, larger block size k help the raptor code work more efficient, so thats why the case of smaller L and larger k always achieves the lowest reception overhead in the 3 figures. When designing the parameters of raptor code for different traffic classes, a relative smaller L and larger k should be chosen on the premise of different end-to-end delay to guarantee a lower reception overhead needed. However, L should not be too small because too small can decrease the transmission efficiency when the data bits added for CRC is fixed.

The proposed raptor code scheme can be well used in the circumstance of the real impulsive noise shown in Fig. 2. For vehicle (a), when L is 50 bytes and k is 500, the minimum reception overhead needed is 8.7%. For vehicle (b) with weaker impulsive noise, the minimum overhead needed is 5.5%. Raptor codes can be well adopted for real in-vehicle power lines to solve the side effects caused by impulsive noise.

IV. Conclusion

In this paper, we have proposed a raptor code-enabled data transmission scheme for in-vehicle PLC systems which can be used for different traffic classes. For control data and safety data, the parameters of raptor code are specially designed and simulated and a reliable error-free transmission is achieved. In the simulation, we found that the mean inter-arrival time $1/\lambda$ is the key parameter when designing the reception overhead of raptor code compared with the others. We further noticed that smaller packet length L and larger block size k help to achieve a lower reception overhead in the data transmission. And we prove that raptor code outperforms RS code in terms of reception overhead in our system researched.

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