Blind XOR: Low-Overhead Loss Recovery for Vehicular Safety Communications

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***Abstract*—Packet loss in vehicular networks can undermine the effectiveness of communication-based accident prevention systems. Traditionally, retransmission has been used to combat packet loss in communication networks. However, retransmission overhead is known to increase channel congestion in dense wireless vehicular networks, which increases the likelihood of packet loss due to collisions, limiting the loss recovery capacity of the retransmission algorithm. This paper presents a low-overhead retransmission algorithm called blind XOR (BXOR). By XORing multiple packets into a single retransmission, BXOR recovers an increased number of lost packets per retransmission. BXOR keeps the overhead low by not trying to learn the loss status of the receivers via feedback, rather, which packets to XOR are blindly decided by the retransmitter alone. It is mathematically proved that BXOR can outperform existing retransmission methods if the conditional reception probability (CRP) of the XORed packets is greater than 0.5. The performance is maximized by XORing an optimal number of packets, which is a function of the CRP. It is also proved that there is a negative performance if BXOR is exercised for a CRP of less than 0.5. Guided by the analytical results, we propose a practical BXOR protocol, which opportunistically exercises the XOR operation based on the current estimation of the CRP. Simulation experiments confirm that, within a 110-m radius of the original packet transmitter, BXOR can reduce the packet reception failure rate by up to 60% of the rates achievable by previously proposed retransmission algorithms.**

***Index Terms*—Loss recovery, vehicular safety communication.**

I. Introduction

The CONCEPT of motor vehicles interacting with their surroundings using wireless communications is seen as a promising new way to improve road safety and traffic congestion on our increasingly overcrowded roads [1]. For example, by frequently broadcasting their current positions and kinematic data, vehicles can help each other to detect and avoid potential accidents. One of the most challenging issues of such communication system is the possibility of losing safety critical packets. Due to the dynamic nature and the need for fast response, vehicular communication employs a truly distributed medium access control (MAC) protocol, namely, IEEE 802.11p [2], to coordinate access to the shared wireless medium. Without a central controller to schedule transmissions from many vehicles, such wireless information exchange is vulnerable to packet collision, which sharply increases as more vehicles compete for access to the wireless medium during peak hours of traffic in busy highways and intersections [3]. These packet collisions become a major source of packet loss in vehicular communications. Using computer simulations, researchers have confirmed that packet loss can seriously undermine the effectiveness of the much touted communication-based accident prevention technology [4].

For unicast communications, e.g., the traditional client to access point (AP) communication in wireless local area networks, 802.11 can recover from packet loss through an ACK-based retransmission, where the sender retransmits the packet if it does not hear an ACK from the receiver within a timeout interval. However, this technique does not work for broadcast communication because there are no known receivers. For loss recovery in vehicular broadcasts, Xu *et al.* [5] proposed a blind retransmission method, where the sender retransmits (repeats) the same packet multiple k times blindly without knowing the reception status (without waiting for any ACK) of the receivers. This method, which is referred to as simple repetition (SR) in this paper, provides a very practical solution to packet loss in broadcast-based vehicular communication systems. SR was later improved upon by Yang *et al.* [6] by proposing that a receiver that successfully received a packet should be the repeater of the packet instead of the original transmitter. This cooperative repetition (CR) was motivated by the fact that the signal strength attenuates over distance, and hence, CR effectively provides a signal relaying service, thus improving the reception probability of the retransmitted packet in distant nodes.

Ironically, the main drawback of repetition-based schemes, be it SR or CR, is the repetition itself. While each repetition provides an additional opportunity for recovery, it also contributes to channel congestion, which in turn increases the probability of packet loss due to collisions. Indeed, it was found [5] that recovery could be improved only up to a certain limit by increasing the number of repetitions, but any further repetition would be counterproductive. Clearly, to improve loss recovery beyond SR or CR, new techniques are needed that can increase the recovery for each repetition, and therefore, more recovery is possible with less repetition.

Bit-wise exclusive OR (XOR), which is often denoted by the symbol $\oplus$, between two equal-length packets is a promising new network coding concept [7] that can potentially increase the performance of packet retransmissions. The benefit of XOR is best illustrated by the following example. Consider three

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nodes S, R_1, and R_2, which are in the receiving range of two packets a and b, transmitted by another node nearby. S received both packets. R_1 received a but lost b, whereas R_2 received b but lost a. If S repeats $a \oplus b$ (a single retransmission), R_1 can recover b by $a \oplus (a \oplus b)$, and R_2 can recover a by $b \oplus (a \oplus b)$. A single retransmission achieved two recoveries at the same time! Without XOR, S would have to repeat a and b individually, needing at least two retransmissions for the same recovery in the system.

There is a major issue, however, for employing XOR-based repetition in vehicular safety communications—the repeating node needs to have prior knowledge of the packet loss (reception) status at the receivers. In our previous example, if both R_1 and R_2 lost packet a, the XOR operation executed at S would be fruitless. The reception status is usually learned via receiver feedback, e.g., using ACKs. While ACK-based XOR may work for typical wireless networks with a single base station broadcasting to a set of clients, e.g., in WiFi and WiMAX networks [8], it does not scale for vehicular broadcasting with every single vehicle broadcasting frequently and hence expecting a large set of ACKs of its own. An ACK-less XOR, where a retransmitting node makes (blind) XOR decisions without the knowledge of exact reception status of its receivers, would be more appropriate for vehicular broadcasting. However, how to design a blind XOR (BXOR) protocol that does not use receiver feedback, yet guarantees statistically better performance than CR, is a topic that has not been studied thoroughly in the literature.

The main contribution of this paper is to determine feasible applications of BXOR with the objective of improving loss recovery in vehicular networks beyond the existing SR and CR techniques. The specific contributions and outcomes can be summarized as follows.

1) We modeled the performance gain of BXOR with respect to CR as a function of the conditional reception probability (CRP), i.e., the probability that a packet will be received by a nearby node given the same packet has been successfully received by the retransmitting node. We find that BXOR can outperform CR only when CRP is greater than 0.5. BXOR would be counterproductive for CRP smaller than 0.5.
2) We find that the superiority of BXOR over CR is not automatic for CRP > 0.5 but rather dependent on the actual number of packets (code length) that are XORed together. We prove the existence of an optimum code length that maximizes the BXOR performance.
3) Based on our analytical outcomes, we design a practical BXOR protocol that implements a variable code length to ensure that BXOR achieves the optimal performance under all CRP conditions. Using simulations, we quantify the performance gain of BXOR and demonstrate its superiority over both SR and CR under a range of delay constraints. Our simulation experiments show that, within a 110-m radius of the original packet transmitter, BXOR can reduce the packet reception failure rates by 30%–60% of the rates achievable by CR.
4) Our simulations reveal a surprising finding that BXOR still outperforms CR even when the CRP is estimated by the unconditional reception probability (URP). This finding suggests that CRP could be estimated on the fly using readily available URP models, paving the way for more practically realizable BXOR protocols.

The rest of this paper is organized as follows. Section II discusses the related work. Analysis of BXOR is presented in Section III, followed by the implementation issues and solutions in Section IV. Section V presents our simulation experiments and results. This paper is concluded in Section VI.

II. Related Work

Although vehicular communication is based on IEEE 802.11 MAC, the SR scheme can be applied to any MAC protocol. The MAC independence has motivated some researchers [9]–[11] to study improvements of repetition-based recovery in a time-division multiple-access (TDMA)-style MAC protocol, under which the original packets and repetitions are transmitted within synchronized time slots that are assigned to each vehicle according to orthogonal codes. These improvements, however, are specific to TDMA and cannot readily be implemented in carrier-sense multiple-access (CSMA)-based 802.11 MAC, which is the IEEE standard for vehicular communications [2].

The basic XOR technique has been used by several researchers to reduce retransmission overheads in traditional wireless local area networks, where an AP attempts to XOR multiple packets in a single retransmission to save bandwidth. However, in most of these works, the AP relies on some form of feedback from the receivers (clients) to learn the reception status of all packets transmitted by the AP. This knowledge is vital for the retransmitting node to select the optimal coding (XOR) set. For example, in [12] and [13], the receivers are allowed to overhear packets destined for other nodes and buffer them for decoding purposes. The clients then need to send explicit reports to the AP about all such packets that are overheard successfully. The AP uses the normal ACKs sent by the clients together with these additional reports to work out the optimal XOR set. These XOR implementations are different from the proposed BXOR because they all rely on some form of feedback from the receivers to the retransmitter, so the retransmitter has accurate knowledge of the receiver status.

XOR rescue (XORR) [14] is more aligned with BXOR in the sense that it eliminates the extra receiver reports, i.e., the periodic reports that are sent in addition to the normal ACKs, needed in [12] and [13]. It does so by requiring the AP to gradually learn the reception status of each client using a Bayesian learning estimation technique, which only uses the normal ACKs from the clients. In vehicular communication, however, such Bayesian learning algorithms are difficult to implement since the network topology is highly dynamic due to the mobility of vehicles (the links between two nodes could be too short for the Bayesian learning algorithm to converge). Furthermore, XORR does rely on normal ACKs; it is not considered to be BXOR.

The only existing XOR research that would fall in the category of BXOR is the work done by Yang and Guo [15] and subsequently by Wu *et al.* [16]. These authors proposed an XOR protocol for vehicular communications, which do not use

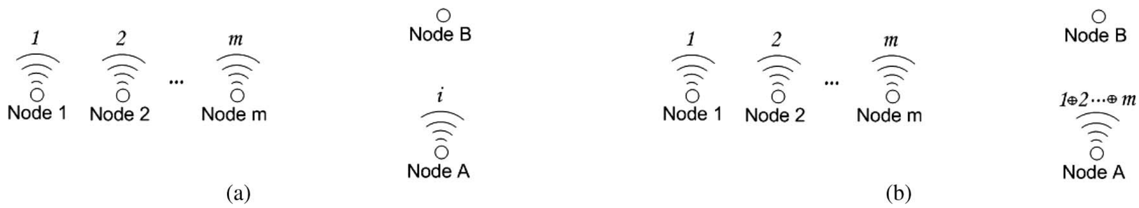

Fig. 1. Network model to study the performance of BXOR. (a) CR: Node A retransmits a packet received from node i, and the retransmission is received by Node B. (b) BXOR: Node A retransmits the XOR of the m packets received from nodes 1 to m, and the retransmission is received by node B.

feedbacks from the receivers. Instead, the retransmitter always XORed two packets and retransmitted a single XORed packet instead of two individual packets. Using simulations, they have shown that such two-packet feedbackless XOR outperforms SR. The decision to combine two packets, instead of three or more, for example, was rather ad hoc, and there were not enough material in [15] and [16] to conclude whether a two-packet BXOR would also outperform CR, which is known to perform better than SR. This paper extends the BXOR research beyond the simple two-packet XOR in significant ways. We provide an analysis of a more general BXOR, which is not limited to two-packet XOR, but rather is allowed to combine an arbitrary number of packets. Our analytical model derives the performance of the general BXOR against the existing CR protocol, making it possible to establish whether and when BXOR could outperform CR. Our analysis reveals that the number of packets that must be XORed to ensure a positive gain from BXOR over the CR is not fixed but depends on the CRP of individual packets. This insight from the analysis is then used to design a BXOR protocol that dynamically decides the number of packets to combine based on the CRP estimates. In our simulations, we compare the proposed dynamic BXOR against SR and CR to demonstrate that BXOR can outperform both.

Some preliminary results of this paper have recently been presented in a conference paper [17]. However, this paper extends the contents of [17] in the following significant ways. First, the proposed BXOR is now compared against CR, which had been shown to perform better than SR. Second, using simulations, we quantify the impact of using a "delay deadline" on the performance gain of the proposed BXOR protocol. This paper allows us to see the tradeoff between retransmission efficiency (RE) and the extra delay introduced due to XOR. Third, we have presented simulation results for the effect of CRP estimation error on the performance gain of the proposed BXOR protocol. Other extensions include more detailed results from the simulation experiments, proof of a new theorem (Theorem 3), a better illustration of the system model, and a presentation of a more comprehensive related work.

III. Performance Analysis of Blind XOR

The primary objective of our analysis is to derive conditions under which BXOR can expect to outperform CR and *vice versa*. The outcome will then enable us to design a practical protocol (see next section) for BXOR-based retransmission.

The system model is shown in Fig. 1. If received successfully, native (original transmitted) packets from nodes 1 to m are retransmitted or repeated (relayed) by node A. Both A and B are within the transmission range of nodes 1 to m, and B is within the range of A's retransmissions. How A's retransmissions recover lost native packets for B is the focus of our analysis.[1] In CR, A's retransmission contains only one native packet. In BXOR, A combines (XORs) m number of native packets into a single retransmission. The variable m is a performance parameter to be optimized later in the section.

One way to compare the performance of different retransmission methods is to measure the average number of recovery per retransmission. Thus, the relative performance of BXOR with regard to CR can be defined as gain G

$$G = \frac{\mu_c}{\mu_b} \tag{1}$$

where μ_c and μ_b denote the average numbers of recovery achieved by BXOR and CR, respectively. Clearly, BXOR outperforms CR if and only if G is greater than 1. G being smaller than 1 would mean that BXOR would perform worse than CR. In our system model, we consider the loss recovery only in node B. There are only two possible outcomes when B receives a retransmission from A: 1) This retransmission can recover a lost packet for B, or 2) this retransmission is useless (cannot recover any lost packet for B). Therefore, μ_b and μ_c are simply probabilities for B to recover a lost packet when it receives a retransmission from A. These probabilities can be derived as follows.

For CR, let us assume that B has received a retransmission from A that contains native packet i (A successfully received i but has no knowledge whether B receives it or not). The probability that this retransmission helps B to recover i is the probability that B did not receive i. Therefore, we obtain

$$\mu_b = 1 - p_i \tag{2}$$

where p_i is the probability that node B receives native packet i given that node A also receives the same. We will refer to p_i as CRP, which can be denoted as $P(B_i|A_i)$.

For BXOR, node A will retransmit the XOR of the m native packets. When B receives this retransmission, a packet will be recovered if and only if B loses one of the m native packets but receives the rest of the $m-1$ packets. We can, therefore, derive μ_c as

$$\mu_c = \sum_{i=1}^{m} \left[(1-p_i) \prod_{j=1}^{m, j\neq i} p_j \right]. \tag{3}$$

[1] Without loss of generality, we consider a single node B to analyze the effect of retransmissions from A. More nodes can be easily accommodated once the results are obtained for one node.

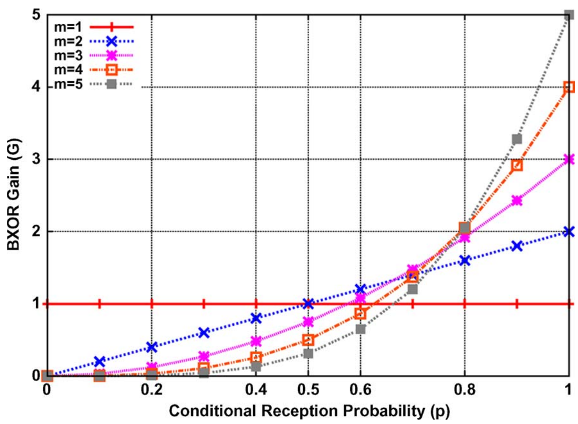

Fig. 2. Coding gain achieved by XORing different numbers of packets.

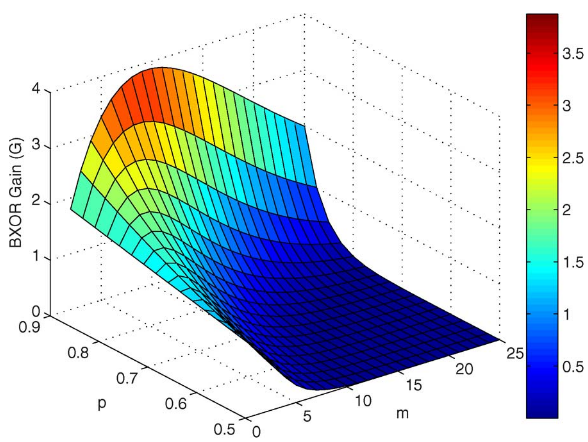

Fig. 3. Coding gain achieved when $p > 0.5$.

If the differences in p_i values are negligible,[2] then we obtain

$$G = \frac{m(1-p)p^{m-1}}{1-p} = mp^{m-1}. \tag{4}$$

According to (4), the relative performance of BXOR with regard to CR is a function of both m (number of packets XORed) and p (CRP). Figs. 2 and 3 plot this function, which reveal three important results proved in the following theorems.

Theorem 1: BXOR cannot outperform CR if $p < 0.5$.

Proof: Equation (4) shows that the gain is a function of m and p: $G(m, p)$.

We first prove that $G(m,p) < G(m, 0.5)$ if $p < 0.5$. Taking the partial derivative over p

$$\frac{\partial G}{\partial p} = m(m-1)p^{m-2} > 0.$$

Equation (5) shows that given m, $G(m,p)$ is an increasing function of p. When $p < 0.5$, we have

$$G(m,p) < G(m, 0.5).$$

[2]We will show in the next section how this can be achieved in a practical protocol that implements BXOR.

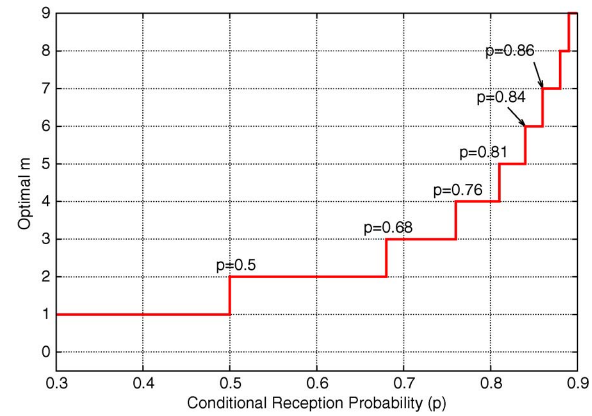

Fig. 4. Optimal m for different CRPs.

Next, we prove that $G(m, 0.5) \leq 1$ if $m \geq 2$. Taking the partial derivative over m

$$\frac{\partial G}{\partial m} = p^{m-1}(1 + m \ln p).$$

When $m \geq 2$ and $p \leq 0.5$, we can get

$$\frac{\partial G}{\partial m} = p^{m-1}(1 + m \ln p) < p^{m-1}(1 + 2 \ln p)$$
$$< p^{m-1}(1 + 2 \ln 0.5) < 0.$$

Equation (5) shows that given p $(p < 0.5)$, $G(m,p)$ is a decreasing function of m.

Therefore, when $m \geq 2$ and $p \leq 0.5$, we have

$$G(m,p) < G(m, 0.5) < G(2, 0.5) = 1. \quad \blacksquare$$

This theorem says that, given that A does not have knowledge of B's reception status, if CRP is less than 0.5, XOR cannot improve upon CR no matter how many packets are XORed.

Theorem 2: If $p > 0.5$, G is maximized for $m = -1/\ln p$.

Proof: By solving the equation

$$\frac{\partial G}{\partial m} = p^{m-1}(1 + m \ln p) = 0$$

we can get $m = -1/\ln p$. ■

Since m is actually an integer, it would be more practical to consider the closest integer to $-1/\ln p$ if the optimum m is to be used in any given implementation. Because $|\ln p|$ decreases with p, the optimal value $round(-1/\ln p)$ increases monotonically with p. The optimal m as a function of p is shown in Fig. 4. It can be observed that a certain CRP range can be mapped to a given optimal m. For example, when CRP is between [0.5, 0.68], $m_{\mathrm{opt}} = 2$, and when CRP is between [0.68, 0.76], $m_{\mathrm{opt}} = 3$.

Theorem 3: If $p > 0.5$ and $2 \leq m \leq (-1/\ln p)$, then G is larger than 1 and increases with m.

Proof: Since $m \leq (-1/\ln p)$, we can get

$$\frac{\partial G}{\partial m} = p^{m-1}(1 + m \ln p) > p^{m-1}\left(1 + \frac{-1}{\ln p}\ln p\right) = 0.$$

Therefore, when $m \geq 2$, for given p, G monotonically increases with m, i.e.,

$$G(m,p) > G(2,p).$$

Because $(\partial G/\partial p) > 0$, $G(2,p) > G(2,0.5)$ when $p > 0.5$. Therefore, we can get

$$G(m,p) > G(2,p) > G(0.5,2) = 1. \qquad \blacksquare$$

Theorem 3 confirms that for large m_{opt} ($m_{\text{opt}} \gg 2$), some gain can still be expected for BXOR even if it is not desirable to accumulate all of the m_{opt} packets before a retransmission takes place. As will be highlighted in the following section, this result is particularly useful when the retransmission delay is a major design constraint, which is indeed the case for vehicular safety communications.

In this section, we have derived conditions under which BXOR can be expected to outperform CR. There are several issues that must be addressed to implement BXOR in a practical system. The following section examines these issues and presents a protocol for implementing BXOR.

IV. Implementation of Blind XOR

To implement BXOR, we need to address three key issues: 1) CRP estimation; 2) CRP consistency; and 3) XOR delay.

A. CRP Estimation

From the preceding analysis, it is clear that a node interested in using BXOR for retransmission would need to estimate CRP. More precisely, given that a native packet i is received by node A, we need to estimate the probability of node B receiving the same packet $P(B_i|A_i)$. Without this estimation capability, the retransmission cannot be guaranteed to outperform CR or to maximize the gain (by choosing the optimal m). Unfortunately, how to estimate $P(B_i|A_i)$ is still not known. However, some of the analytical models proposed for vehicular communication, such as [18]–[20], could be used to calculate the URP, i.e., given a native packet i, the probability of node B receiving the packet $P(B_i)$ irrespective of whether A has received it or not. These models use the node positions, which are available in vehicular communications, as well as the node density (for computing the collision probability). The node density could be estimated by counting the number of broadcast packets received by a vehicular node or by using more sophisticated methods, such as those proposed in [21]. The question follows: Can we use URP to estimate CRP?

If the packet receptions of nodes A and B are independent (uncorrelated), from the probability theory, we know that the conditional and unconditional probabilities are the same, that is

$$P(B_i|A_i) = \frac{P(A_i)P(B_i)}{P(A_i)} = P(B_i). \tag{5}$$

However, if the packet reception is dependent (correlated), CRP $(P(B_i|A_i))$ is greater than URP $(P(B_i))$ [22], [23]. In other words, if URP is used to approximate CRP, then we are likely to underestimate the real value of the CRP. According to the analytical result shown in Fig. 4, the underestimation of CRP may underestimate m_{opt}. However, since it may not be desirable to always XOR an optimal number of native packets due to delay constraints, the underestimation of m_{opt} may not be a serious issue. Once we have the simulation results, we will revisit this issue in Section V.

B. CRP Consistency

For mathematical tractability, the analysis in the previous section assumes that the CRPs of all XORed packets are the same. There are two problems with this assumption, and in this section, we propose practical solutions for both of them. First, in reality, $p_i \neq p_j$ due to different distances of i and j from A. To address this issue, we propose that a retransmitting node A sorts all receiving native packets according to their distances from A and distributes these packets into separate XOR buffers or bins so that the CRPs in any given bin are all consistent (has a small variance). The retransmitting node will combine (XOR) packets only from the same buffer.

The second problem is that there may be many nodes within the retransmission range of A, and they may be at different distances from A. For example, both B and C can be within the retransmission range of A, but the p_i for B $(P(B_i|A_i))$ can be different from the p_i of C $(P(C_i|A_i))$. We propose to use a reduced range for the XOR retransmissions to address this particular issue, so all the nodes that receive an XOR retransmission from a given node are all within a small distance from each other. We will demonstrate the effectiveness of our proposal through simulations in Section V, which confirms that the CRP consistency improves with power reduction of retransmitted packets.

C. XOR Delay

Any XOR-based method, blind or not, has the drawback of introducing some additional delay before a retransmission can take place. For example, if two packets are to be XORed, node A cannot immediately retransmit a native packet upon its successful reception. It would have to wait for one more native packet to arrive (with the compatible CRP in this case, so it is placed in the same CRP bin). This delay issue may become a problem if A chases a large m_{opt}. The simplest way to treat this issue is to use a variable $d_{\max}$ to limit the maximum delay in the XOR process. If $d_{\max}$ expires, then Node A will have to end the waiting and retransmit either an XORed packet (if two or more packets were already accumulated) or a single packet otherwise. The performance of BXOR under different values of $d_{\max}$ is explored in Section V.

V. Simulation and Results

We have conducted simulation experiments to quantify the performance of the proposed dynamic BXOR protocol under different delay constraints and further compare its performance against existing repetition-based protocols SR and CR. While

TABLE I
QUALNET PARAMETERS

Category	Parameter	Value
PHY	Frequency	5.9GHz
	Channel bandwidth	10MHz
	Data rate	6Mbps
	Modulation	QPSK
	Coding rate	1/2
	Data bits per OFDM symbol	48
	Radio sensitivity	-85dBm
MAC	Slot time	16μs
	SIFS	32μs

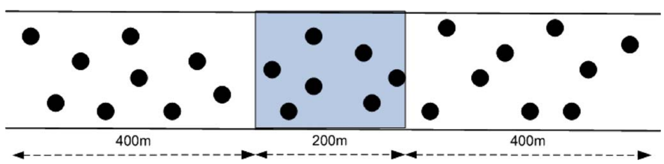

Fig. 5. Typical section of a six-lane road.

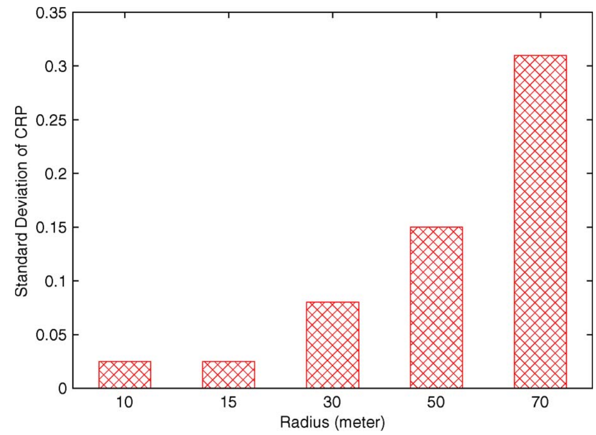

Fig. 6. Standard deviation of CRP with different radius.

the design of the proposed BXOR protocol is guided by the insights obtained from a simple analytical model, we include many practical details of wireless communications in our simulations to obtain a more realistic assessment of the protocol performance. Another objective of the simulation is to investigate the effectiveness of using URP, which is more readily available, as an estimate for the CRP, which is difficult to derive.

A. Simulation Setup

In this section, we explain the software tool, the simulation framework, and the communication parameters used in our simulation experiments. We used a commercial simulator called Qualnet 3.9.5 [24], which has extensively been used by the networking research community for simulating complex communication protocols involving both wired and wireless components. This tool has built-in support for simulating many standard protocols at various layers of the communication stack. We have configured the PHY and MAC layer parameters according to the IEEE 802.11p standard [2], which is expected to support vehicular communications in the future. The values of the parameters are listed in Table I. We select the Rayleigh fading model to calculate the signal to noise and interference ratio (SNIR) of each packet received at each node. The SNIR value is then used by the Qualnet built-in SNIR bit error rate model to determine if a packet is successfully received.

We simulate a typical highway traffic scenario over a 20 m $\times$ 1000 m area that represents a segment of a six-lane road (as shown in Fig. 5). Two hundred nodes are randomly positioned in the six lanes with uniform distribution. Each node starts periodically transmitting a 300-byte broadcast packet every 100 ms at a random time uniformly distributed within the first 100 ms of the simulation. The transmission power is 13 dBm; therefore, the theoretical transmission range is 150 m, which is the required transmission range for the cooperative collision warning application [1]. In the simulations, all the nodes perform loss recovery by sending retransmission packets. The retransmission packets could get lost due to the hidden terminal effect, which is not considered in the analytical abstraction in Section III. Therefore, we can study the performance of BXOR in a more realistic scenario.

All the nodes in the network keep the trace of both native and retransmission packets received from other nodes. After each simulation, these traces are used to calculate RE and reception failure probability (RFP). RE is defined as the average number of native packets recovered per retransmission packet received. RFP, which is widely used as the metric to measure the reliability of vehicular safety communications [3], [5], [6], is defined as the probability that a native packet is lost and not recovered by the retransmission packets.

To avoid the neighbor count edge effect [25], i.e., the nodes located at both ends of the 1-km road have less potential hidden terminals than other nodes have, only the traces from the nodes located in the central 200-m area (the shaded area in Fig. 5) are collected to calculate RE and RFP. The simulation time is set to 10 s, and each simulation is repeated 30 times with different random seeds, generating different node positions and transmitting starting times. The relative statistical errors (defined as the ratio of the half-width of 95% confidence interval and the mean value [26]) of both RE and RFP are below 10%, which confirms that the sample set from 30 simulation runs can provide statistically significant data to evaluate the loss recovery performance in terms of RE and RFP.

B. CRP and URP Measurements

Before running the simulations with error recovery, one simulation experiment was conducted without implementing any retransmissions. The purpose is to measure the CRPs in the network to explore the opportunities for BXOR (BXOR opportunity depends on CRP) and verify the validity of some of the implementation choices presented in the previous section (e.g., CRP consistency and CRP estimation using URP).

First, we explore the effectiveness of our proposed method of using a reduced range for XOR retransmissions to address the CRP consistency issue (see Section IV-B). In our simulations, every node retransmits using the proposed BXOR protocol, but let us examine the CRPs around one specific node to see how the retransmission range affects the CRP consistency. For example, let us select the center node and call it node A. Fig. 6 plots the standard deviation of CRP for all the nodes that are

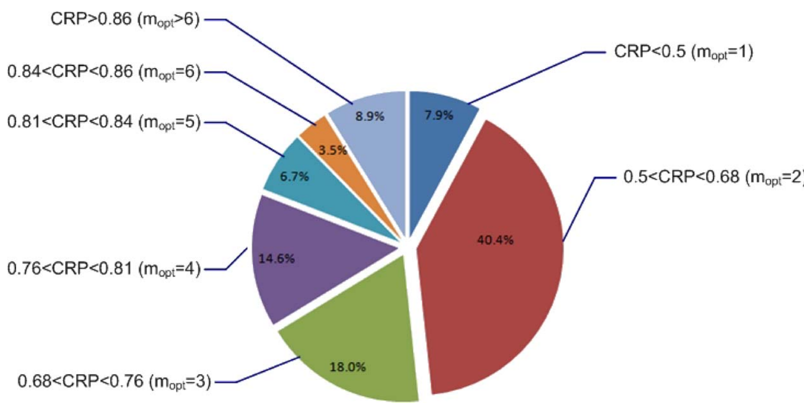

Fig. 7. CRP distribution.

within a given radius around node A. We can see that the standard deviation drops as we reduce the radius, confirming that by reducing the retransmission range we can effectively address the issue of CRP inconsistency. In our simulation of BXOR later in the section, we use −3 dBm to transmit the XORed packets so that the retransmission range is about 15 m, which gives a small CRP standard deviation of 0.025 (see Fig. 6). The 15-m retransmission range might seem small, but it actually covers approximately 30 m of simulated highway, which includes six vehicles on average. Note that the transmission range of native broadcast packets still remains at 150 m, which is necessary for vehicular safety communications.

Second, we study the CRP distribution to work out how often BXOR can outperform CR (recall that, according to Theorems 1 and 3, BXOR can outperform CR if and only if CRP is greater than 0.5). From the simulation, the CRP distribution is obtained as follows. Each time a node receives a native packet, we compute the CRP for one of the nodes within 15-m radius of the receiving node. This gives us one CRP sample. From all the samples collected in the simulation, we compute the distribution shown in Fig. 7. Fig. 7 shows that 92.1% of the time, the CRP would be greater than 0.5. Therefore, BXOR can be applied most of the time. Another important result revealed by Fig. 7 is that the percentage of CRP samples corresponding to a larger m_{opt} (for example, larger than 4) is small (19.1%). This means that if the retransmissions are always XORed with optimum number of packets to maximize the gain, the vast majority of retransmissions would have to XOR only a small number of packets (helps avoiding large XOR delay).

Third, we measure the difference between CRP $(P(B_i|A_i))$ with URP $(P(B_i))$, which is shown in Fig. 8. We observe a very interesting result. We find that, up to 0.78, URP can be used to estimate CRP with fairly small error. URP would underestimate CRP significantly only beyond 0.78. From Fig. 4, we obtain that for CRP larger than 0.78, m_{opt} is greater or equal to 4. Therefore, estimating CRP using URP will only affect (underestimate m_{opt}) a small percentage of the XORed packets, and the vast majority of them, which are smaller than four packets, will not be affected. As data are collected from simulation experiments, a more quantitative analysis of the effect of the CRP estimation error will be discussed later in this section.

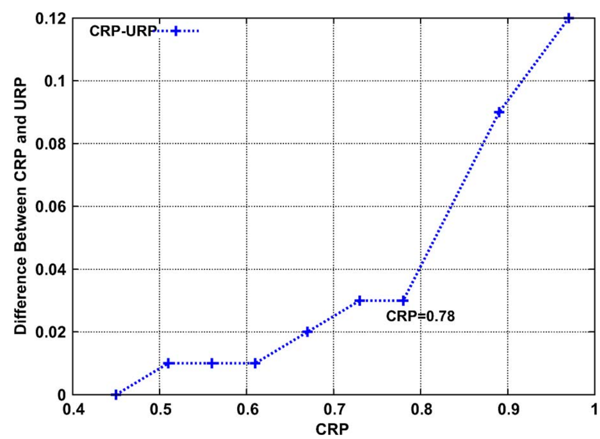

Fig. 8. Difference between CRP and URP.

We store all the measured samples of CRP and URP in two separate databases. For each node, these databases store a CRP (or URP) value corresponding to every other node in the network. For example, for node i, the stored value p_j would represent the CRP (or URP) for a received native packet transmitted by node j. As such, these databases are basically $N \times N$ matrices, where N is the number of nodes in the network. We use these databases for estimating the CRP values during the BXOR simulations presented in the next section.

C. Simulation Results With Retransmissions

We have implemented BXOR, SR, and CR protocols in our simulation. BXOR was implemented following the protocol proposed in the previous section. In this implementation, BXOR first waits until m_{opt} packets are accumulated in the buffer, or the first packet in the buffer has waited for $d_{\max}$ seconds (whichever happens first), and then takes these packets out of the buffer and XORs them together. SR is implemented according to [5], where each node simply repeats a native packet k times. The transmission time of the k repetition is randomly distributed between 0 and 100 ms.[3] CR is implemented according to [6], where each node buffers all the received

[3]This interval was chosen to uniformly distribute the additional transmission load over the entire packet generation interval.

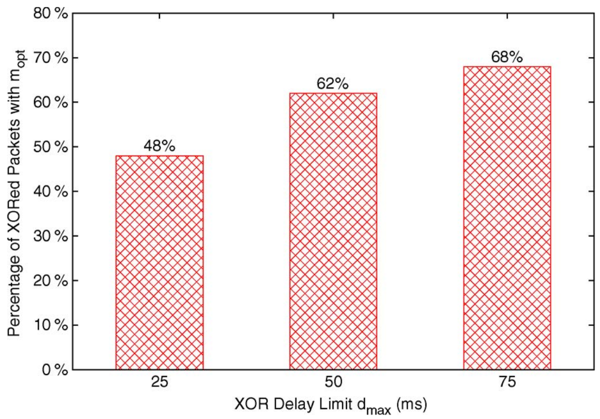

Fig. 9. Percentage of XORed retransmissions with optimal m ($m = m_{\text{opt}}$).

native packets whose lifetime (100 ms) has not expired. When transmitting its own native packet, it sorts the packets in the buffer according to their distances from itself and selects the three packets with largest distances and piggybacks them with its own native packet.

For the CRP estimation in the BXOR protocol, we used the CRP (or URP) databases derived in the previous simulation (see previous section). Each time a native packet is received by a node i from node j, the corresponding value from the database is used to estimate the CRP for that packet. The estimated CRP is then used to sort the arriving packets into different BXOR buffers. For example, as explained in Section III, if the CRP is between [0.68, 0.76], then the packet will be put in the BXOR buffer, which attempts to XOR three packets together ($m_{\text{opt}} = 3$ in this case). Initially, we use the CRP database to achieve a more accurate estimation for CRP. Later, we use the URP database to investigate the impact of CRP estimation error on BXOR performance.

First, we investigate how frequently the parameter $d_{\max}$, i.e., the XOR delay limit, prevents BXOR from using the optimum number of native packets (to maximize gain). Fig. 9 shows the percentage of XORed retransmissions that used the optimal number of packets as a function of $d_{\max}$. As expected intuitively, this percentage drops with decreasing $d_{\max}$. It is, however, interesting to note that the drop is not drastic. For example, when we decrease $d_{\max}$ from 75 to 50 ms (a reduction of 33%), the percentage of optimal retransmissions drops only from 68 to 62 (a drop of less than 10%). Even with a sharp reduction of $d_{\max}$ to only 25 ms, BXOR still uses optimal XOR nearly 50% of the time. This outcome is consistent with our earlier observation that for the vast majority of CRPs, the optimal m is small (see Fig. 7), which allows BXOR to accumulate enough packets within the delay deadline.

Second, in Fig. 10, we show the distribution of the number of packets XORed, i.e., the percentage of retransmissions with $m = 1, 2, 3$ and so on.[4] As expected (see Fig. 7), we find that the vast majority of packets has $m \leq 4$. One effect of increasing $d_{\max}$ from 25 to 75 ms is that the frequency of $m = 4$ increases, whereas the opposite trend is observed for $m = 1$. The decreasing frequency of $m = 1$ means that a longer delay deadline causes less BXOR opportunities to be missed. The quantitative effect of this on the RE (average number of recovery per retransmission) is captured in Fig. 11. We can see that although the efficiency slightly decreases due to the reduction of $d_{\max}$, BXOR still outperforms both SR and CR. As expected, CR performs better than SR.

Third, we investigate the performance of BXOR in terms of RFP. Fig. 12 compares the RFP of BXOR with those of SR and CR. We can see that BXOR outperforms not only SR but also CR for all distances up to 150 m. As expected, RFP of BXOR can further be reduced by setting a larger $d_{\max}$ (50 ms achieves a lower RFP than 25 ms). For $d_{\max} = 50$ ms, BXOR significantly outperforms CR. For example, at a distance of 110 m, the RFP of BXOR is 0.16, which is 70% of the RFP of CR (0.23). For a 10-m distance, CR achieves a RFP of 0.085, whereas the RFP of BXOR is 60% lower (0.035).

Finally, we turn our attention to an important performance parameter, i.e., retransmission delay. In particular, we want to find out whether the reliability improvement of BXOR is at the cost of increasing the packet delay. We define the retransmission delay as the time elapsed from the moment a native packet is generated until it is recovered by a retransmission packet. The average retransmission delay of all the recovered packets is shown in Fig. 13. As expected, the delay for BXOR increases with $d_{\max}$, but it is worth noting that the average delay can be significantly less than $d_{\max}$. For example, the average delay for $d_{\max} = 75$ is only 45 ms! This is because the XOR assembly of m_{opt} packets can sometimes complete before the $d_{\max}$ timer expires (retransmission happens before $d_{\max}$). We can see that in terms of average retransmission delay, BXOR outperforms CR for $d_{\max}$ up to 50 ms, and it is only slightly worse off for 75 ms.[5] The results in Fig. 12 and 13, therefore, confirm that compared to the CR scheme in [6], BXOR can significantly improve the reliability of vehicular safety communication without increasing the communication delay.

Up until now, the CRP estimation for BXOR has been accomplished using the data stored in the CRP database (see the previous section about the CRP and URP databases). While this provides a very accurate estimation of CRP in our simulation experiments, as mentioned earlier, it is difficult to estimate CRP on the fly due to lack of appropriate estimation models. However, as we mentioned in Section IV-A, URP could be more easily estimated using some of the models published in the literature. Therefore, in practical deployments of BXOR, one may consider using URP to estimate CRP. However, approximating CRP with URP may lead to CRP estimation errors, which may affect the performance of BXOR. To quantify the effect of this estimation error, we run another set of simulation, but this time CRP is estimated using the data in the URP database. The result is shown in Fig. 14. It is rather surprising to see that the effect is almost nonexistent for small $d_{\max}$ (for 25 ms, two curves

[4]Note that different BXOR buffers have different m_{opt} values, but due to delay constraints, $m = 3$ (for example) would not necessarily mean that the packet is coming from the buffer with $m_{\text{opt}} = 3$. As such, the numbers in Fig. 10 would not necessarily match those in Fig. 9.

[5]Waiting to piggyback retransmission with regular transmission is the source of delay in CR. For SR, delay is incurred due to distributing the k repetitions randomly over the 100-ms interval.

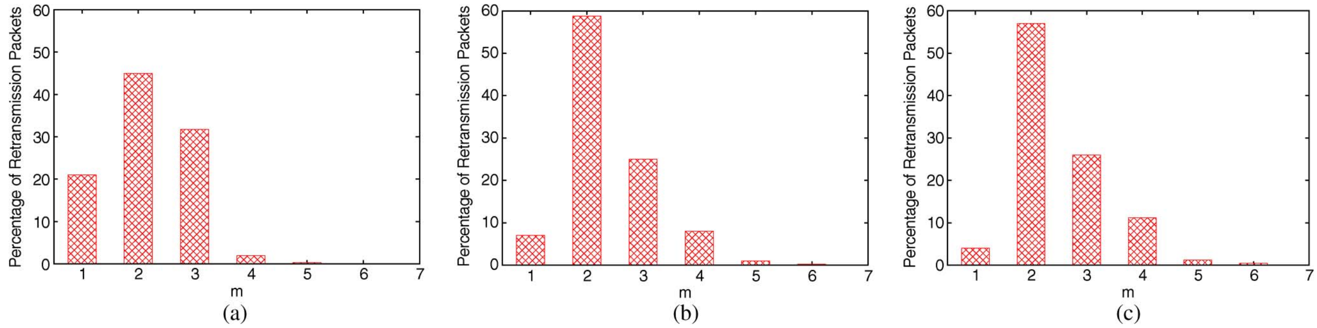

Fig. 10. Percentage of retransmission packets sent with different m ($m \leq m_{\text{opt}}$ because of the delay limit $d_{\max}$). (a) $d_{\max} = 25$ ms. (b) $d_{\max} = 50$ ms. (c) $d_{\max} = 75$ ms.

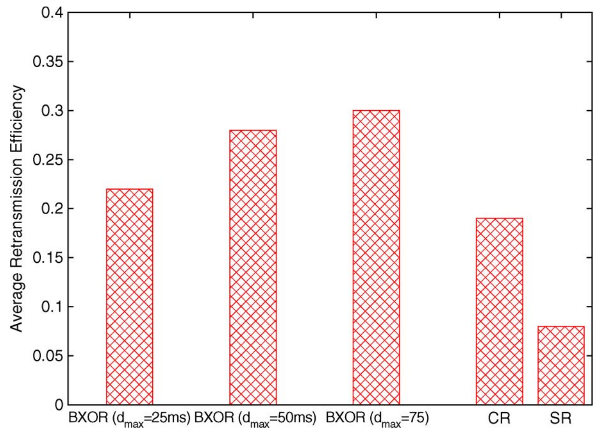

Fig. 11. RE of different schemes.

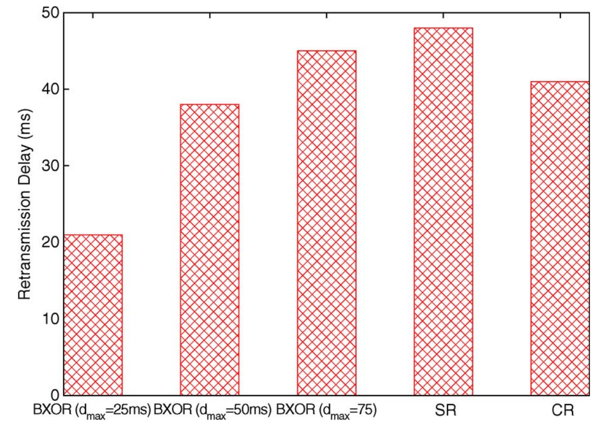

Fig. 13. Delay of different retransmission schemes.

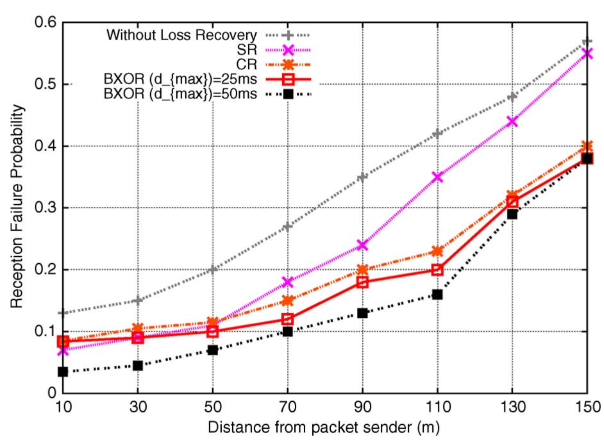

Fig. 12. Reliability achieved by different retransmission schemes.

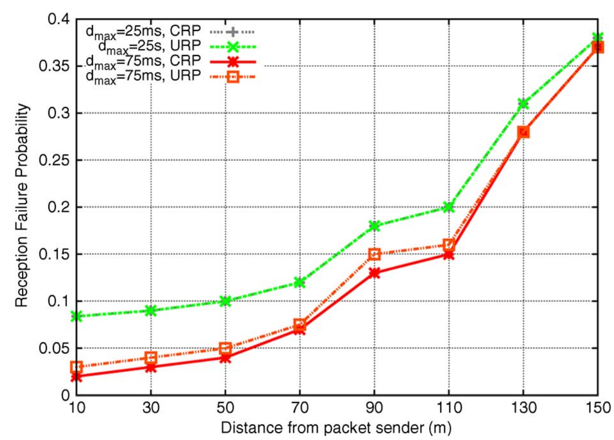

Fig. 14. Effect of estimating CRP with URP.

are overlapped). This can be explained by the fact that for a very small $d_{\max}$, BXOR can hardly utilize m_{opt} packets. Since the estimation error caused by the use of URP basically refers to the underestimation of m_{opt}, it does not really affect the performance of BXOR. The effect would be more pronounced for larger $d_{\max}$ values, because that is when BXOR would be able to utilize m_{opt} packets often. Indeed, we can see that the effect of the estimation error becomes noticeable for a $d_{\max}$ of 75 ms (two curves are no longer overlapped). The difference, however, is not large, particularly at longer distances. These simulation results therefore suggest that use of URP may be a viable option to estimate CRP on the fly, paving the way for more practically realizable BXOR.

VI. Conclusion and Future Works

We have analytically studied BXOR, i.e., an XOR-based loss recovery scheme for vehicular safety communications, which is accomplished without the knowledge of receiver status. We have found that BXOR can outperform existing retransmission methods if the CRP is greater than 0.5. The gain can be maximized by XORing an optimal number of packets. There is no benefit, and in fact, there may be a negative effect if BXOR is exercised for CRP less than 0.5. Guided by the analytical results, we have provided a solution for implementing BXOR in vehicular networks. By implementing BXOR in simulation experiments, we have shown that BXOR can achieve higher communication reliability compared with previous loss recovery schemes without increasing the communication delay. With our current design of BXOR, the reliability improvement is more prominent closer to the transmitting node. This outcome is still useful as the closer the vehicles are, the more reliable communication is required to avoid vehicle collisions. Further improvement of the proposed BXOR to alleviate failure at longer distances would be a challenging and interesting problem that we leave for future research.

Our BXOR protocol depends on estimating the CRP for every received native packets, which may hinder immediate deployment of the proposed protocol due to lack of CRP estimation models in the literature. Clearly, accurate CRP estimations would be useful future work in this regard. However, we have found that URP could be used as a viable estimation for CRP, because the estimation error affects the BXOR performance only in some specific cases. Since there are models available in the literature to estimate URP, these models could be used to deploy BXOR in the interim until more accurate CRP estimation models are discovered.

Traditional XOR-based schemes rely on explicit feedbacks to learn the reception status, whereas the BXOR, as studied in this paper, takes the approach of using purely probabilistic estimation of reception status with no overhead of explicit feedbacks. It is yet not known that if an XOR-based loss recovery with part explicit feedbacks and part probabilistic estimation would further improve the communication reliability of vehicular networks. It would be an interesting future work to study the possibility of combining the two approaches, i.e., feedback and probabilistic estimation, for the purpose of achieving a better balance between the accuracy of reception status and the feedback overhead.

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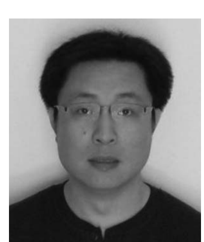

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