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Network Coded Repetition: A Method to Recover Lost Packets in Vehicular Communications

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***Abstract*—Rapidly repeating the original packet multiple times has been found to improve the probability of successful reception of a packet in error-prone vehicular communication environment. However, since each repetition increases channel load, performance of repetition-based loss recovery starts to deteriorate with increasing number of vehicles on the road. This paper explores the benefit of Network Coding in improving the performance of repetition-based loss recovery for vehicular safety communications. A simple network coded repetition scheme is proposed, which combines (XORs) packets from close-by neighbours and repeats the XORed packets instead of original packets, thereby creating the possibility of an increased number of packet recovery per repetition. An analytical study is conducted to evaluate the performance of the proposed network coded repetition, which is validated by simulation experiments. Conditions under which network coding can outperform the original repetition scheme are discussed.**

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]. While most of the framework has been defined and the necessary wireless spectrum allocated, there still remains many important issues that must be overcome for vehicular communication to realise its full potential. One such issue is the possibility of losing time-sensitive, critical safety information packets in harsh, congested, and extremely dynamic communication environment. Packet loss in wireless networks is a classical problem, for which there are several classical approaches, e.g., waiting for ACK and retransmit if no ACK is received within a timeout period. However, in vehicular communication, a lost packet must be recovered within time constraints that are much shorter than are needed in traditional mobile computing applications. Unless recovered quickly within the lifetime of the safety information, packet loss can seriously undermine the capability and promise of vehicular communication.

The most widely discussed loss recovery scheme for vehicular safety communication is the repetition-based retransmission scheme proposed in [2]. The basic idea behind the repetition-based loss recovery is that if the sender rapidly repeats (retransmits) a packet several times within a short duration, the nodes that failed to receive the original transmission will now have multiple chances to recover the lost packet in time. All this can be achieved without relying on any ACKs from the receivers. Ironically, the main drawback of repetition-based scheme 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 collision. Not surprisingly, the authors of [2] observed in their simulation experiments that, the recovery performance for a given network condition can be improved only up to a certain limit by increasing the number of repetitions. Any further repetition would be counterproductive.

While it seems logical that there would be an optimum number for repetition where recovery performance would peak, we ask the following question: what if we could somehow increase the performance of each single repetition? We could then achieve overall performance gain despite having to limit the number of repetition. In this paper, we explore whether this can be achieved with network coding, a concept used recently by many researchers to improve bandwidth efficiency in various contexts including multicasting [3] and wireless ad hoc networks [4].

We propose a simple network coded repetition (NCR) scheme, which combines (XORs) packets from close-by neighbours and repeats the XOR-ed packets instead of original packets, thereby creating the possibility of an increased number of packet recovered per repetition. An analytical study is conducted to evaluate the performance of the proposed NCR, which is validated by simulation experiments. We find that, for packet error rate (PER) smaller than a given threshold, NCR is an improvement over the simple repetition (SR), the basic repetition proposed in [2]. For a given reliability target, network coding consumes less bandwidth (less number of repetitions). Alternatively, for the same amount of repetition, network coding improves reliability. The optimum number of repetitions that maximises recovery performance is smaller with network coding than without, and the reliability achieved under optimum repetition is higher with network coding. Consequently, if loss recovery is to operate under optimum repetition, network coding not only improves bandwidth efficiency (less repetitions), but also decreases packet reception failure probability (RFP) at the same time.

The rest of the paper is organised as follows. Section II reviews previous work on loss recovery in vehicular communications. The proposed NCR method is introduced in Section III. RFP analysis as a function of PER is presented in Section IV, followed by an extended analysis and simulation for

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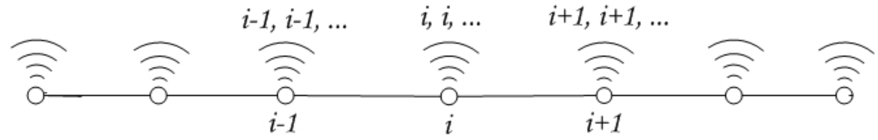
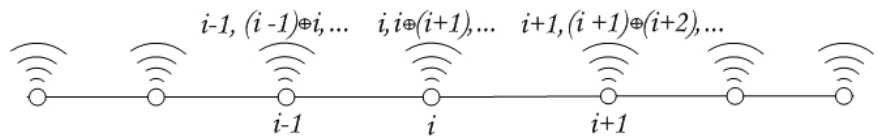


(a) Simple Repetition (SR)



(b) Network Coded Repetition (NCR)

Fig. 1. The two repetition schemes

CSMA networks in Section V. Numerical results are discussed in Section VI. Finally, the paper is concluded in Section VII.

II. Related Work

The idea of repetition based loss recovery can be applied to many MAC protocols such as TDMA, slotted ALOHA and CSMA [2]. Although the de facto MAC protocol of vehicular communication is the CSMA-based IEEE 802.11p [5], the TDMA MAC protocol for vehicular safety communication has been studied in a series of works [6]–[8], in which the simple repetition proposed in [2] is improved by optimizing the time-slot selection for a cluster of vehicles. In this paper, we study a more realistic scenario, in which the vehicle nodes are continuously located in a long straight road so that clustering is not possible and the CSMA protocol is used instead of the TDMA protocol.

Different from the repetition scheme in [2], another "repetition" based protocol has been proposed [9]–[11], in which the packets are repeated by the nodes located at the boundary of the radio range, i.e., instead of repeating its own packets, each node "relays" the packets received from the senders located faraway. It has been shown in [9]–[11] that the "relay-based" repetition can increase the coverage range of packets and significantly improve the reliability for the nodes located faraway from the packet senders. Traditionally, the vehicular safety communication is in the single-hop broadcast mode [1], [12]. The pros and cons of single-hop and relay-based multi-hop communication for vehicular safety is still under discussion [13] and no conclusive decision has been made. In this paper, we follow the traditional single-hop mode of vehicular safety communication, where the packets are not relayed beyond the original transmission range.

The network coding technique was originally proposed for routers to efficiently deliver packets [3], [4]. It was later found that network coding can also improve lost packet recovery for the wireless broadcast communications from access point (AP) to multiple clients [14]. However, the analytical study in [14] is based on the assumption that the AP can obtain the reception status of the broadcast packets by waiting for feedbacks from the receivers. In vehicular communications, such assumption is unrealistic because for vehicles sending broadcast packets, there are no known receivers due to the highly dynamic network topology. In this paper, we analytically study NCR, a network coding based loss recovery scheme not relying on the feedbacks from broadcast packet receivers.

III. Network Coded Repetition

We consider a typical highway traffic scenario of vehicular communication, in which nodes (vehicles) are located along a long straight road. This kind of linear network topology is usually modeled as a straight line on which the nodes are placed following a one-dimensional Poisson process [15], [16]. Each node is a *sender* that periodically transmits broadcast packets (*native packets*) and also a *receiver* that receives the native packets from all the nodes within its communication range. Some of the native packets are lost due to various reasons, e.g., packet collision. To recover the lost native packets, after transmitting a native packet, each node transmits extra k packets (*retransmission packets*). As shown in Fig. 1a, for the simple repetition (SR) scheme proposed in [2], the retransmission packets are exactly the same as the native packets.

In our proposed network coded repetition (NCR), we extend the SR scheme as follows (Fig. 1b). With NCR, instead of repeating its own native packet, each node XORs its native packet with the native packet received from its closest neighbour in a predefined direction, and repeats the XORed packet. By selecting the closest neighbour, we can assume that the probability of not receiving a native packet from the neighbour is negligible (the probability of receiving a packet increases with decreasing distance [12], [17]), which means that there will always be a packet to XOR with.

The reason of selecting the closest neighbor from a *predefined direction* is to guarantee that each native packet is encoded in *two* coded retransmissions. For example, in Fig. 1b, the predefined direction is *rightwards* so that each native packet (i)[1] will be encoded in its own coded retransmission $(i \oplus (i+1))$ and the coded retransmission of its left side

[1] We use (i) to denote the native packet from node i

neighbor $((i-1) \oplus i)$. Note that the predefined direction being rightwards or leftwards is not an issue as long as all nodes follow the same direction (for leftwards direction, native packet (i) will be encoded in its own coded retransmission $(i \oplus (i-1))$ and the coded retransmission of its right side neighbor $((i+1) \oplus i)$).

Under NCR, a native packet is not only retransmitted by its original sender but also by the sender's closest neighbour. The retransmission packets are sent in the coded (XOR-ed) form so that the number of retransmissions is the same as the SR scheme. The coded retransmission packets are repeated for k times. For a given node i, there are $2k$ retransmission packets containing the content of its native packet: node $i-1$ transmitting k retransmission packets $((i-1) \oplus i)$ and node i transmitting k retransmission packets $(i \oplus (i+1))$.

In the following section, we analyze and compare the RFP of NCR and SR as a function of PER.

IV. Reception Failure Probability Analysis

In previous works, RFP has been used as a key metric to measure the performance of error recovery in vehicular communications [2], [7], [8]. It is defined as the probability that a native packet is lost and *not recovered* by the retransmissions. In this section, we analytically derive the RFP as a function of PER for SR and NCR. We use the following definitions:

- *Packet Error Rate* (PER) E_i: the probability of losing a packet sent from node i. The packet could be either native packet or retransmission packet.
- γ_i: probability that native packet (i) can be recovered by coded retransmission $((i-1) \oplus i)$.
- δ_i: probability that native packet (i) can be recovered by coded retransmission $(i \oplus (i+1))$.
- η_i: probability that the coded retransmission $((i-1) \oplus i)$ can be decoded.
- θ_i: probability that the coded retransmission $(i \oplus (i+1))$ can be decoded.

We first derive the RFP of SR (ϵ_r). Because the native packet of node i is transmitted $k+1$ times, the RFP is the probability of not receiving any of the $k+1$ transmissions:

$$\epsilon_r = E_i^{k+1} \tag{1}$$

Now we derive the RFP of NCR (ϵ_c). The native packet (i) is transmitted once, and coded retransmissions $((i-1) \oplus i)$ and $(i \oplus (i+1))$ are transmitted k times. So RFP is the probability that:

- Packet (i) is not received, and
- Packet (i) can not be recovered by coded retransmission $((i-1) \oplus i)$, and
- Packet (i) can not be recovered by coded retransmission $(i \oplus (i+1))$.

$$\epsilon_c = E_i(1-\gamma_i)(1-\delta_i) \tag{2}$$

γ_i and δ_i are derived as follows:

The coded retransmission $((i-1) \oplus i)$ is transmitted k times by node $i-1$, so γ_i equals to the probability of receiving at least one out of k coded retransmissions $((i-1) \oplus i)$ sent by node $i-1$ and the coded retransmission $((i-1) \oplus i)$ can be decoded:

$$\gamma_i = (1 - E_{i-1}^k)\eta_i \tag{3}$$

Native packet $(i-1)$ is needed to decode (i) from $((i-1) \oplus i)$, so the η_i is the probability of receiving native packet $(i-1)$, or native packet $(i-1)$ can be recovered by the coded retransmission $((i-2) \oplus (i-1))$ sent by node $i-2$:

$$\eta_i = (1 - E_{i-1}) + E_{i-1}\gamma_{i-1} \tag{4}$$

Then we can get:

$$\gamma_i = (1 - E_{i-1}^k)(1 - E_{i-1} + E_{i-1}\gamma_{i-1}) \tag{5}$$

Equation (5) shows that γ_i depends on γ_{i-1}, which depends on γ_{i-2}, which depends on γ_{i-3}... To simplify the iterated relationship, we make the assumption that the difference between γ_i and γ_{i-1} is small and they can be regarded equal when calculating γ_i from E_{i-1}. By replacing γ_{i-1} with γ_i, (5) becomes a linear formula of γ_i which can be solved as:

$$\gamma_i = \frac{(1 - E_{i-1}^k)(1 - E_{i-1})}{1 - (1 - E_{i-1}^k)E_{i-1}} \tag{6}$$

The coded retransmission $(i \oplus (i+1))$ is transmitted k times by node i, so δ_i equals to the probability of receiving at least one out of k coded retransmissions $(i \oplus (i+1))$ sent by node i and the coded retransmission $(i \oplus (i+1))$ can be decoded:

$$\delta_i = (1 - E_i^k)\theta_i \tag{7}$$

Native packet $(i+1)$ is needed to decode $(i \oplus (i+1))$, so the θ_i is the probability of receiving native packet $(i+1)$ or native packet $(i+1)$ can be recovered by the coded retransmission $((i+1) \oplus (i+2))$ sent by node $i+1$:

$$\theta_i = (1 - E_{i+1}) + E_{i+1}\delta_{i+1} \tag{8}$$

Then we can get:

$$\delta_i = (1 - E_i^k)(1 - E_{i+1} + E_{i+1}\delta_{i+1}) \tag{9}$$

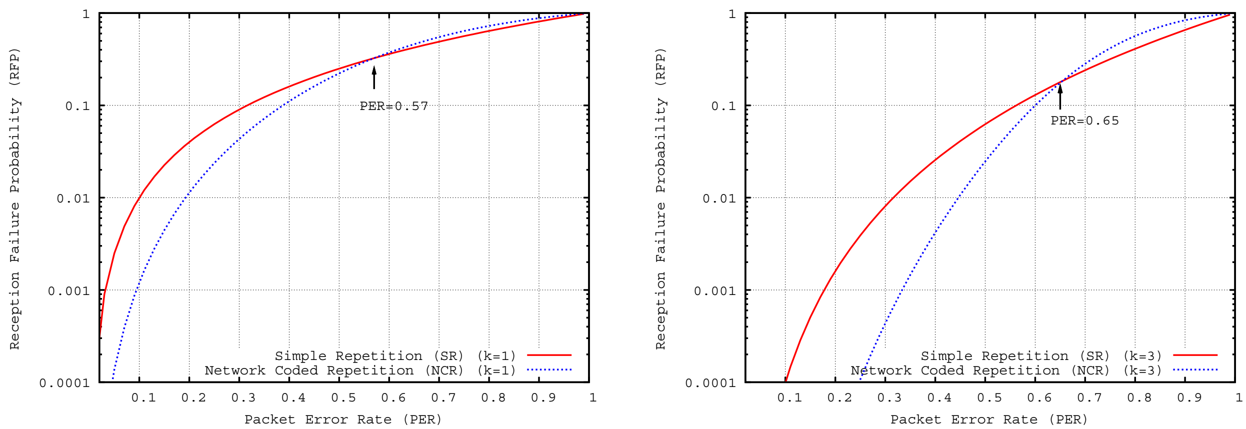
Again we make the assumption that δ_{i+1} can be replaced by δ_i in (9), δ_i can be solved as:

$$\delta_i = \frac{(1 - E_i^k)(1 - E_{i+1})}{1 - (1 - E_i^k)E_{i+1}} \tag{10}$$

With (2), (6) and (10), ϵ_c can be expressed as a function of k and PER: E_i, E_{i-1} and E_{i+1}:

$$\epsilon_c = E_i\Big[1 - \frac{(1 - E_{i-1}^k)(1 - E_{i-1})}{1 - (1 - E_{i-1}^k)E_{i-1}}\Big]\Big[1 - \frac{(1 - E_i^k)(1 - E_{i+1})}{1 - (1 - E_i^k)E_{i+1}}\Big] \tag{11}$$

To compare ϵ_c with ϵ_r, we assume that both E_{i-1} and E_{i+1} equals to E_i. This assumption is also based on the fact that PER depends on the distance between sender and receiver. Since nodes $i-1$ and $i+1$ are closest neighbors of node i, the difference of PER of these three nodes are small. Based



(a) k=1 (b) k=3

Fig. 2. Reception failure probability as a function of packet error rate

on this assumption, Equation (11) becomes a function of E_i and k:

$$\epsilon_c = E_i\Big[1 - \frac{(1-E_i^k)(1-E_i)}{1-(1-E_i^k)E_i}\Big]\Big[1 - \frac{(1-E_i^k)(1-E_i)}{1-(1-E_i^k)E_i}\Big] \tag{12}$$

RESULTS:
The RFP for different E_i are plotted in Fig. 2, which shows the first important result of this paper: *improvement in RFP achieved by NCR over SR is more significant for smaller PER, decreases with increasing PER, and finally becomes negative beyond a threshold PER.*

It can be observed from Fig. 2 that, for $k = 1$, NCR performs better than SR as long as PER is less than 0.57, but for $k = 3$, NCR remains a better recovery strategy for PER less than 0.65. Therefore, a second result we obtain is: *with increasing repetition, NCR remains a better strategy for a wider range of PER* .

Although the above results are significant, they consider the performance only as a function of PER, which actually depends on other factors, such as node density and the distance between sender and receiver, in a practical vehicular wireless network. In the following section, we extend the RFP analysis to accommodate these practical details, particularly the packet collision behaviour observed in a CSMA MAC protocol expected to be used in vehicular communications (IEEE 802.11p).

V. Analysis for CSMA Networks

In [18], an analytical model of non-persistent slotted CSMA protocol is proposed for a network in which node positions are Poisson distributed in a 2-dimension plain. This model was later simplified in [16] for vehicular networks (one-dimension node distribution along a highway). In this model, MAC collision determines whether a packet is lost or received: within the communication range, a packet will be received with probability 1 if no collision happens and it will be lost with probability 1 if it is subject to a collision. The

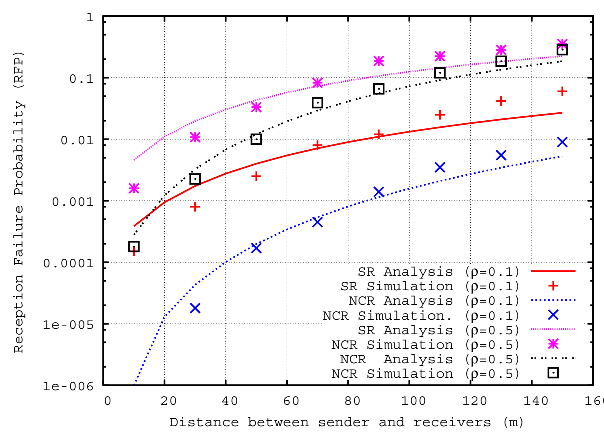


Fig. 3. Simulation results when k=1

probability of collision is affected by node density and the distance between sender and receiver. In this paper, we use this model to first derive the PER for a given density, and then use it to derive the RFP. Using x to denote the distance between sender and receiver, the PER can be derived as:

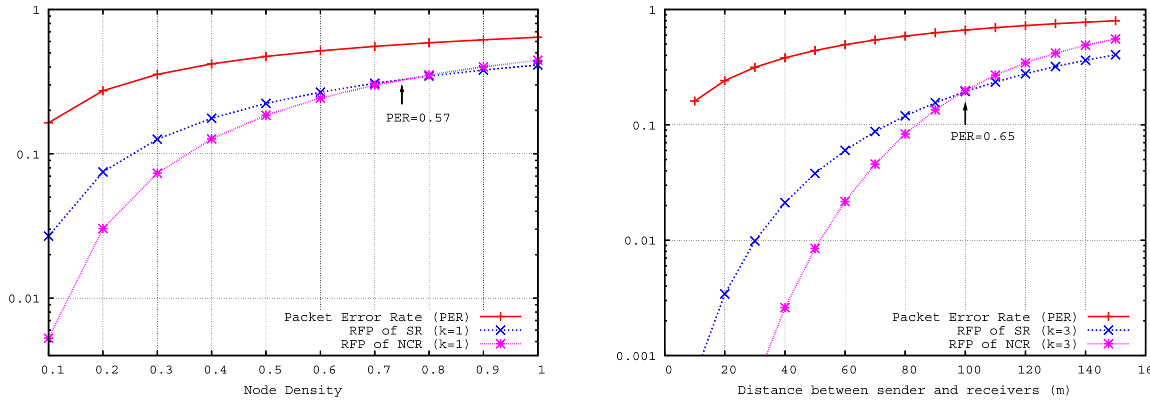
$$E(x) = 1-(1-q)e^{-2\rho q R}e^{-2\rho q \tau x} \tag{13}$$

The symbols in (13) are defined as:

- R: Transmission range.
- τ: Number of time slots to transmit a packet (transmission delay).
- ρ: Node density (number of nodes per meter).
- λ: Native packet generation rate (number of packets per slot).
- k: number of retransmissions per native packet.
- q: Probability that a node starts transmitting in a given time slot.

The probability q can be calculated by numerically solving the following formula [18]:

$$q = \frac{e^{-2q'\rho R}}{\tau + 1 - \tau e^{-2q'\rho R}} \tag{14}$$



(a) k=1, d=150m (b) ρ=1.0, k=3

Fig. 4. The effect of distance and density

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Transmission range	150m
Bit rate	6MBps
Slot length	16μs
Packet size	300 bytes
Packet generation rate	10 packets per second

where q' is the probability that a node intends to transmit in a given time slot, which can be expressed as:

$$q' = \frac{1+k}{1/\lambda - (k+1)\tau} \tag{15}$$

With (13), we can derive ϵ_r and ϵ_c by replacing E_i, E_{i-1} and E_{i+1} with $E(x)$, $E(x+\Delta)$ and $E(x-\Delta)$ in (1) and (11), where Δ is the average distance between two adjacent nodes: $\frac{1}{\rho}$. Thus, we have derived the RFP of SR and NCR as functions of distance x.

To validate the analysis, a set of simulation experiments are conducted using a commercial software called Qualnet [19]. We modified the CSMA MAC protocol module in Qualnet 3.9.5 to the non-persistent slotted CSMA protocol, where the time slots of all the nodes are perfectly synchronized (in vehicular communication, such synchronisation can be achieved through high-precision GPS clocks). For the physical layer, we selected the 'abstract PHY' option, which simulates an 'ideal radio channel', where collision is the only source of packet loss. Other parameters used in the simulation are listed in Table I.

Two different node densities, $\rho = 0.1$ and $\rho = 0.5$, are simulated, which represent low and high density scenarios for a typical 6-lane highway (for $\rho = 0.1$ and $\rho = 0.5$, the inter-vehicle distance in a given lane is 60m and 12m, respectively). Simulation results for a single repetition ($k = 1$) are shown in Fig. 3 and compared with the values obtained from the analysis. We can see that RFP increases with distance for both densities, but RFP is lower when node density is low. These results are in line with intuition, as both density and distance affects the probability of collision. The important thing here is to note that the simulation results matched closely with the analytical ones, confirming the validity of the analytical model used in this section to derive the RFP for CSMA-based vehicular networks.

VI. NUMERICAL RESULTS AND DISCUSSION

In this section, we discuss the numerical results in a CSMA network with the parameters listed in Table I.

A. The effect of distance and density

Since PER increases with vehicle density and the distance between sender and receiver, we can expect that, for a given density there is a distance threshold beyond which NCR becomes counterproductive and similarly for a given distance, there is a density threshold. We explore these expected results in Fig. 4. Note that the density threshold for which NCR becomes counterproductive is unrealistically high ($rho = 0.75$ or one vehicle every 8 meters).

B. Optimal Repetition

Fig. 5 shows the effect of k on the RFP at a particular distance ($x = 100m$). It confirms that, like the SR, NCR also has an optimum repetition at which the RFP is minimised. However, the important result is that, *NCR not only needs a smaller number of repetitions to minimise RFP, the minimum RFP achieved under NCR is significantly lower than that with SR*. Therefore, if the recovery schemes are optimised, NCR not only reduces the bandwidth overhead of error recovery (less number of repetitions), but also increases the packet reception reliability in vehicular networks.

Note, that Fig. 5 shows results for only at a distance of 100m. Although there would be an optimum k for every distance, the actual value of the optimum k and the corresponding RFP would be different at different distances. How to select the optimum k for a given transmission range therefore becomes an issue, which can be resolved by averaging the RFP observed at all distances within the transmission range for a given k:

$$\bar{\epsilon}_r = \frac{1}{R}\int_0^R \epsilon_r(x)dx \tag{16}$$

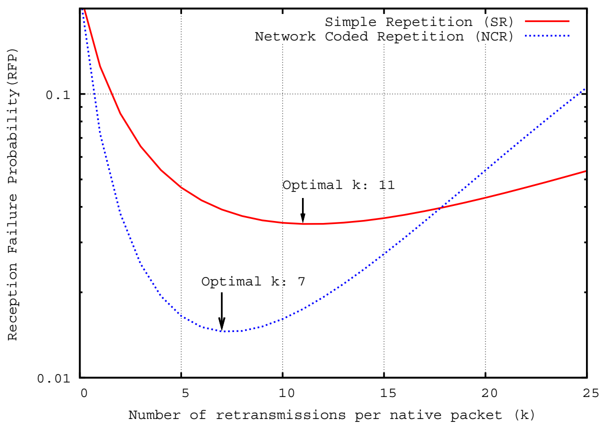


Fig. 5. RFP as a function of k (ρ=0.5, x=100m)

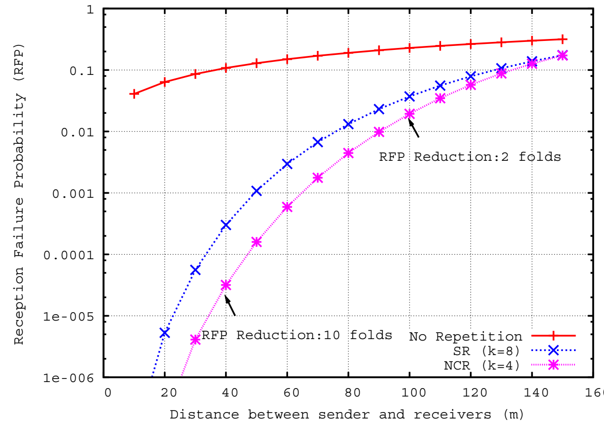


Fig. 6. RFP when ρ=0.5 and optimal k for each repetition scheme

$$\bar{\epsilon}_c = \frac{1}{R}\int_0^R \epsilon_c(x)dx \tag{17}$$

By comparing the average RFPs of a given network achieved by different k values, the optimum k, k_{opt}, can be derived as the k for which average RFP is minimised. For the parameter values of Table I, k_{opt} was found to be 8 and 4 for SR and NCR, respectively. RFP as a function of distance for the two schemes under their own k_{opt} values are presented in Fig. 6. We can see that although NCR employs only half as much repetitions, it actually reduces RFP by many folds (e.g., more than 10 folds at a distance less than 40m).

VII. Conclusion and Future Works

We have explored whether network coding can further improve the performance of the widely discussed repetition-based error recovery protocol in vehicular safety communications. We have proposed a simple NCR protocol and studied its performance analytically. The analytical model is validated by simulation. It has been shown that, for an error rate smaller than a threshold, the proposed NCR protocol can outperform the SR scheme. When the number of repetitions is optimised for maximum recovery, NCR not only requires less number of repetitions, but also reduces the RFP significantly. The numerical results in this paper are derived for linear network topology which represents the typical high way traffic scenario. The performance evaluation of NCR in city-like environments (short road segments with intersections) requires further study in future works.

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