# Reliable Network Coded MAC in Vehicular Ad-Hoc Networks

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***Abstract*—We consider the problem of designing cooperative driver assistance and collision warning systems in vehicular networks. In this problem each car has a small size state information message that should be received by its neighbourhood within a short lifetime of $L$ timeslots. Because of the safety nature of the application, communication reliability (success probability) and delay are of critical importance. In a repetition-based MAC scheme, each car retransmits its safety message $w$ times in a time frame of $L$ timeslots. Based on the proposed opportunistic network coding in this paper, given the local feedback information and already heard messages, each node tries to find the best message combining strategy such that the number of nodes that can instantly decode an uncoded packet is maximized. Simulation results show that the proposed scheme outperforms the random linear network coding as well as the uncoded case in terms of message loss probability. Also it results in lower average message reception delay compared to random linear network coding.**

## I. INTRODUCTION

About 160000 road accidents occur every year in Canada, which results in approximately 3000 deaths each year [1]. Transport Canada has estimated that car collisions cost 62.7 billion each year which is about 4.9 percent of Canada's 2004 Gross Domestic Product (GDP) [1]. Most of traffic accidents and car collisions are avoidable using Intelligent Transportation Systems and safety communications. Statistics show that at least 60 percent of chain accidents could be avoided if drivers are informed about an accident and collision at least 500ms beforehand [2]. The driver reaction to the braking light typically ranges from 0.7 to 1.5 second [2], [3] which delays the collision information propagation.

Cooperative driver assistance is one of the recent emerging applications in VANETs. Each vehicle periodically generates a small size safety message less than 200 bytes [4] which contains the state information of the vehicle. The goal of the communication is to provide a reliable up-to-date knowledge about the neighbourhood for each vehicle on the road. Each state message has a typical lifetime of less than 200ms after which it is not useful anymore. Having an up-to-date local map could prevent accidents and collisions by informing vehicles of a sharp velocity change. Also this extra information assists the driver to choose alternative driving strategies such as taking over or turning.

Even though the contention window in IEEE 802.11 broadcast is minimum, the random nature of the back off algorithm does not guarantee a stringent reliability. Once a node gets the channel access, it forces other nodes into the back off state which thereupon results in fairness irregularities. In addition, the lack of RTS/CTS in the broadcast mode results in hidden terminal problem and further collisions. To avoid hidden terminal problem and increase the reliability in broadcast mode, several schemes such as transmitting RTB/CTB and acknowledgement messages [5] have been proposed. However since the small safety message size is comparable to the RTB/CTB and acknowledgement message size, it would not be a reasonable choice in this application.

To address these problems several random repetition-based MAC schemes have been proposed in [6] in which the reliability has been achieved by several retransmissions of the message. Upon generation of a message, it will be randomly and repetitively broadcasted in a time frame of size $L$, which is equal to the message lifetime. Instead of random repetition pattern, a broadcast pattern based on Positive Orthogonal Codes (POCs) have been proposed in [7]. The pairwise correlation property of these codes reduces the total number of collisions, hence results in lower message loss probabilities.

A repetition-based MAC can be visualized as a two-layer design. First layer is the design of the repetition pattern in a time frame. The number of repetitions could be deterministic with $w$ repetitions, or probabilistic such that the expected number of repetitions is $w$. The second layer is the content of each repetition. In the previously proposed MAC schemes, the content of each retransmission is fixed over time and each node only transmits its own message based on the repetition pattern. The main contribution of this paper is to propose a repetition-based MAC scheme in which the content of each retransmission is a combination of a subset of already overheard messages. The proposed combining strategy is a feedback-based network coding algorithm inspired by the index coding problem [8].

It has been shown in [9] that random linear network coding could asymptotically achieve the unicast and multicast capacity in a wireless network with lossy links. In our application the random linear network coding overhead is not negligible compared to the message payload and the presented asymptotic bounds would not hold. Furthermore, the presented results in [9] only consider long term throughput, but unlike

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a data traffic session, here we are interested in safety critical metrics such as message success probability and delay.

The proposed algorithm here is in the same line of our previous work in [10]. Here, we consider a more realistic vehicle-to-vehicle channel model and assume the perfect feedback is provided. Furthermore, we study the random linear network coding performance in our application. We show through simulations that given perfect feedback, the proposed opportunistic network coding has superior performance in terms of average delay and message loss probability.

We should emphasize that the goal of our paper is not to study the network coding algorithm, but rather to investigate the reliability gain that we can achieve by using network coding in repetition-based MAC schemes through simulations.

The rest of the paper is organized as follows. The network topology, performance metric and MAC are presented in Section II. The proposed message coding scheme is explained in Section III. In Section IV, we present the simulation results and finally Section V concludes the paper.

## II. SYSTEM MODEL AND PERFORMANCE METRICS

We consider a cluster of $n$ vehicles with each vehicle equipped with a GPS device that provides access to a global clock with sub micro second accuracy. With coordination, a common time reference point is chosen and nodes will be synchronized. As a matter of fact in the standard draft specification of IEEE1609.3 and IEEE1609.4 [11], [12] the synchronization assumption is made to support synchronized channel switching between the control channel and service channel. So without any reservation we assume that the time is slotted and a time frame consists of $L$ timeslots. We also assume that the frames of different users are synchronized. At the start of each time frame, each node has a safety message consisting of its state information such as GPS location, velocity and acceleration. Each node transmits $w$ repetitions of its message based on a repetition pattern.

Our metrics of interest are the message success probability and average delay. Message success probability is the average probability that a node receives the safety message of another node within the time frame. Average delay is the average delay that it takes that a node receives another node's safety message. The average delay is over successful message receptions within the time frame.

An erasure channel is assumed such that an uncollided transmission is received from node i with probability 1- $p_e^i$ where $p_e^i$ depends on the distance from node $i$ as well as the stochastic channel model. The erasure channel has also been previously assumed in the context of safety communications in vehicular networks [2], [13]. It has been shown that Nakagami distribution with properly estimated parameters would be a more realistic channel model for vehicle-to-vehicle communications [14]). Our simulation follows a realistic Nakagami channel model with the parameters chosen from the IEEE 802.11p standard.

## III. OPPORTUNISTIC MESSAGE CODING

The proposed opportunistic scheme aims to minimize the safety message loss probability and reception delay in a lossy vehicular environment. We propose to allow packet combining in each retransmission. In contrast to previous repetition-based MAC algorithms, a node does not merely repeat its own message. Instead, it may transmit combinations of its message with other messages that it has overheard.

Specifically, a node's transmission opportunity can be used to send the result of an XOR operation on some of its previously-received messages. The reception information of the nodes is represented in terms of a binary square matrix as follows:

$$F_{ij} = \begin{cases} 1 & \text{if node } j \text{ has received the message of node } i \\ 0 & \text{otherwise.} \end{cases}$$

Depending on which nodes have received the transmitted message successfully, the feedback matrix will be updated accordingly in all nodes after each retransmission. Based on this updated feedback matrix, each node knows which packets have been received by the other nodes, and this information can be exploited in an efficient message combining strategy.

For example, after updating its feedback matrix, node A has scheduled a retransmission. Node A's feedback matrix is:

$$F = \begin{array}{c} \overbrace{\begin{array}{cccc} A & B & C & D \end{array}} \\ \begin{bmatrix} 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \end{array}$$

In previous repetition-based MAC schemes, node A would send its own message ($P_A$) and nodes B and D would each have an opportunity to receive this new message from node A. However, node A also has messages from nodes B and C, $P_B$ and $P_C$, respectively. If node A transmits $P_A \oplus P_B$ (bitwise XOR), not only will nodes B and D have a chance to receive $P_A$, but node C will also have the chance to receive $P_B$. This example reveals that packet combining can increase the number of potential message receptions per transmission.

In our proposed algorithm, a sender has some previously received packets from other nodes. The sender also has side information about the received and needed packets of its neighbours. The sender tries to find the best combination of packets to maximize the number of received messages in its next transmission. It can be shown that this problem is NP-hard; we provide a heuristic for this problem. Unlike the index coding problem in [8], here the sender has only one transmission opportunity and tries to maximize the number of received messages with its single transmission.

We modify a heuristic solution for index coding [15] to solve this problem. Let us assume that $R(u_s)$ is the set of messages received by the sender $u_s$, and that $N(u_s)$ is the set of messages that are still needed (not yet received). $U_{u_s}$ denotes the set of users that are known to the sender (users already present in the feedback matrix of the sender). For each

$u_i \in U_{u_s}$, $N(u_i)$ and $R(u_i)$ are the set of needed messages and the set of received messages for that user, respectively.

A known user with $m$ *needed* messages can be decomposed into $m$ virtual users, each of which needs one of the $m$ messages. Each virtual user has the same set of *received* messages as the original user. The new set of users is called $\acute{U}$. A graph $G(\acute{U}, E)$ is constructed by connecting pairs of vertices corresponding to distinct users $\acute{u_i}, \acute{u_j} \in \acute{U}$ if one of the following rules holds:

- $N(\acute{u_i}) \in R(\acute{u_j})$ *and* $N(\acute{u_j}) \in R(\acute{u_i})$ *and* $N(\acute{u_i}), N(\acute{u_j}) \in R(u_s)$ (1)
- $N(\acute{u_i}) = N(\acute{u_j})$ *and* $N(\acute{u_i}), N(\acute{u_j}) \in R(u_s)$

Continuing with the example from the previous section, node A's expanded feedback matrix with virtual users is:

$$F' = \overbrace{\begin{bmatrix} 0 & X & 1 & 0 & X \\ 1 & 1 & 0 & 1 & 1 \\ X & 0 & 1 & X & 0 \end{bmatrix}}^{\begin{array}{ccccc} B1 & B2 & C1 & D1 & D2 \end{array}}$$

where $X$'s represent "don't cares" resulting from virtual user decomposition, and A's own column is omitted. The virtual user associated with each column is denoted above the matrix. For example, node B has been decomposed into virtual users B1 and B2.

Since the sender can only combine messages that it has, an inspection of the two rules presented in (1) shows that only the entries in $R(u_s)$ need to be considered. Here, since $u_s = A$, we may safely ignore the fourth row in the matrix $F$. Furthermore, we can also ignore any virtual users that need a message which is not in $R(u_s)$, and hence the column for virtual user C2 is omitted in $F'$.

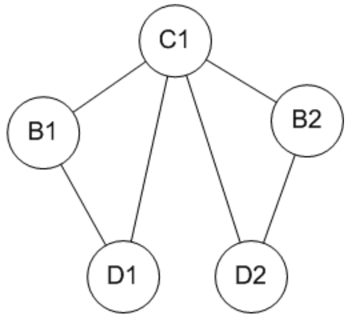

Fig. 1. Graph $G(\acute{U}, E)$ for node A, with two cliques of size three.

The corresponding graph $G(\acute{U}, E)$ is shown in Figure 1. The users corresponding to the vertices of each clique of this graph can receive their needed messages with a single transmission. The transmitted message is the XOR of the messages needed by each user in the clique. Whereas the index coding problem reduces to the clique partition problem, here we require the maximum clique of the graph. This maximum clique corresponds to maximum number of users that may receive one of their needed messages with a single transmission by the sender.

A fast heuristic is used to find the maximum clique. We assume that the maximum clique contains the highest degree vertex in the graph. Next, a greedy algorithm chooses the maximum degree vertex in the potential set of clique vertices to join the current clique at each step. Simulation results shows that this simple algorithm performs well enough (especially in lower loads) in our application. When a node has a transmission opportunity, if the clique size is larger than the number of nodes that have not received its message, it will transmit a combination of the needed messages in the clique. Otherwise (coding has no benefit), it will transmit its own message.

The performance of the proposed coding scheme will be compared to random linear network coding in Section IV. In the next part we explain and discuss the application of random linear network coding in our application.

### *A. Random Linear Network Coding*

The random linear coding algorithm is simple: each node enqueues all the received messages and when it has a transmission opportunity based on its retransmission pattern, it broadcasts a random linear combination of all the already received messages in its queue with the coefficients in GF(q). After each message reception, a node tries to do the Gaussian elimination on all the received coded messages in the queue to find the newly decodable messages. Utilizing random linear network coding scheme introduces overhead to each message. In random linear network coding, higher number of neighbours and larger Galois field size results in higher message overhead. Considering a fixed message lifetime, frame size and data rate, higher message overhead results in a smaller number of timeslots in a frame, which for a fixed number of repetitions results in more collisions. On the other hand, by taking advantage of network coding schemes higher information entropy can be achieved and the probability of an innovative retransmission (a transmission that potentially satisfies more users need) will be higher than blindly repeating the same message. To have a fair comparison and to consider the coding overhead the frame size for random linear network coding has been scaled down to $L^* = \lfloor L \frac{M}{M + nlog(q)} \rfloor$; in which $M$ is the message size and $n$ is the number of active users in that time frame.

## IV. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed opportunistic network coding algorithm through simulations.

We have used the Nakagami channel model for the vehicle-to-vehicle communication link. The distribution of the signal amplitude $X$ based on this channel model is:

$$f_X(x) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^m} e^{-\frac{mx^2}{\Omega}}$$
$$m \geq \frac{1}{2}, \ \Omega \geq 0$$

in which $\Omega$ is the average received power and $m$ is the fading figure.

TABLE I
PHYSICAL AND MAC LAYER PARAMETERS

| | |
|---|---|
| Data Rate | 1Mbps |
| Message Lifetime | 100ms |
| Slot Duration | 1ms |
| Message Size | 100B |
| Transmit Power | 10dBm |
| Reception Threshold | -90dBm |
| Frequency | 5.9GHz |
| Gt | 4dB |
| Gr | 4dB |

In [14] the fading figure parameter $m$ has been estimated based on empirical measurements for a vehicle-to-vehicle link in a highway:

$$m = \begin{cases} 3 & d < 50m \\ 1.5 & 50m < d < 150m \\ 1 & 150m < d \end{cases}$$

in which $d$ is the distance between the sender and the receiver.

This estimation of $m$ with the physical and MAC layer parameters listed in TABLE I have been used in our simulations. Considering the antenna gains, the Effective Isotropic Radiated Power (EIRP) will be less than 20dBm, which is the maximum allowed EIRP by the IEEE802.11p standard.

We consider a three-lane highway of length 1000m. Every 30 meter there is a car randomly placed in one of the lanes. At each time frame each vehicle transmits a safety message with probability $\mu_p$. For nominal vehicle velocities the movement during a time frame is negligible. For example for a speed of 20m/s and a frame size of 100ms the vehicle movement in a time frame is 2m. So we do not consider the mobility in our simulations as it is not a defining factor in the algorithm performance. However the effect of mobility has been considered indirectly through the use of Nakagami channel.

The POCs have been used to specify the repetition pattern. The POCs have been generated by using the proposed algorithm in [7]. The simulations have been done for three different MAC schemes: 1) POC MAC without network coding 2) POC MAC with random linear network coding and 3) POC MAC with the proposed opportunistic network coding. We have used $GF(2^8)$ in our simulations.

Two sets of simulations for low load ($\mu_p = 0.2$) and higher loads ($\mu_p = 0.4$ and $\mu_p = 0.6$) have been performed. The loss probability and the average delay have been averaged over all the vehicles. As we can see in Figure 2, in low load both coding algorithms have much lower loss probability compared to the uncoded scheme. The opportunistic coding performs slightly better than the random linear network coding. For $\mu_p = 0.2$, opportunistic network coding has the best average delay performance, which is closely followed by the uncoded scheme (Figure 3). Although the average delay of the uncoded scheme is close to the opportunistic coding case, we should take into account that the average delay has been measured based on the number of successfully received messages which is much less for the uncoded scheme. The poor delay performance of random linear network coding is related to the fact that it does not guarantee instant decodability and a node should collect enough coded messages to decode new messages. For higher loads ($\mu_p = 0.4$ and $\mu_p = 0.6$), since the coded packets consist of a larger number of original messages, the random linear network coding loss probability gets worse (Figure 4). In this case, a node would need more coded messages in order to decode the original messages. In high load, the opportunistic coding still has the best performance in terms of message loss probability and again has a better average delay performance compared to random linear network coding (Figures 5 and 6).

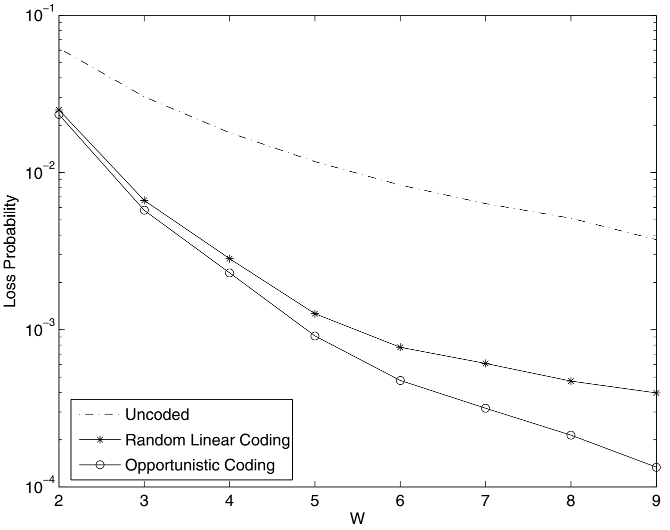

Fig. 2. Loss Probability vs. Number of repetition($\mu_p = 0.2$)

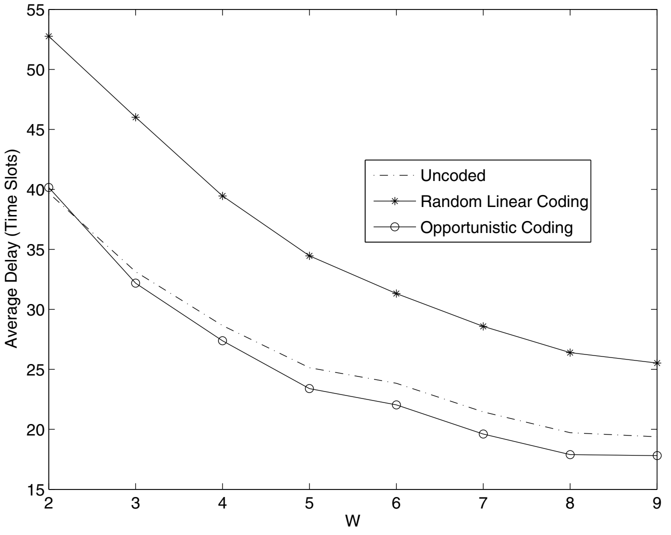

Fig. 3. Average Delay vs. Number of repetition($\mu_p = 0.2$)

## V. CONCLUSION

We proposed an opportunistic network coding algorithm for safety message dissemination in vehicular networks. The

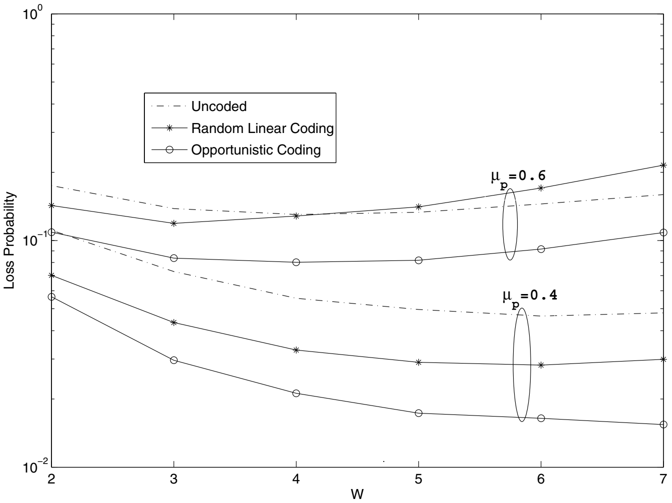

Fig. 4. Loss Probability vs. Number of repetition($\mu_p = 0.4, 0.6$)

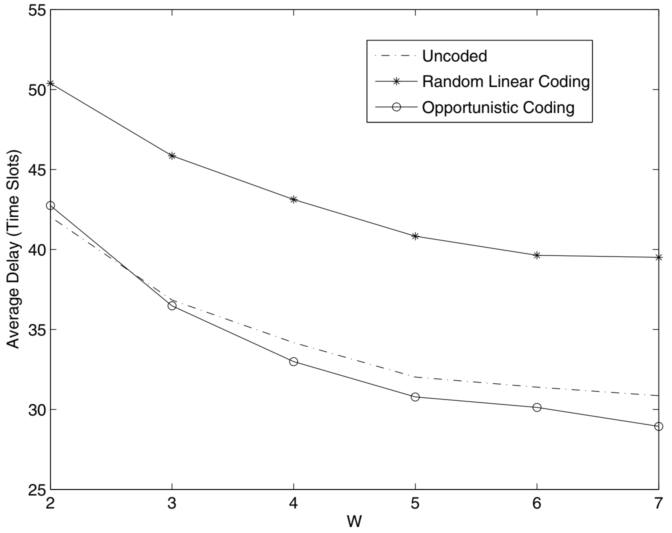

Fig. 5. Average Delay vs. Number of repetition($\mu_p = 0.4$)

presented algorithm specifies the repetitions content in a repetition-based MAC scheme. The network coding algorithm tries to choose the best subset of already received packets based on the provided feedback information. The selection objective is to maximize the number of users that can immediately decode an original packet. The proposed scheme provides relaying opportunity and results in lower message loss probability as well as lower average delay. Based on our simulation results, the loss probability of the MAC scheme with opportunistic network coding is better (noticeably for lower loads) than the one without coding. Also compared to the random linear network coding, the proposed algorithm results in lower average delay. This proves the applicability of the proposed coding scheme for reliable and low delay delivery of the safety messages in vehicular networks.

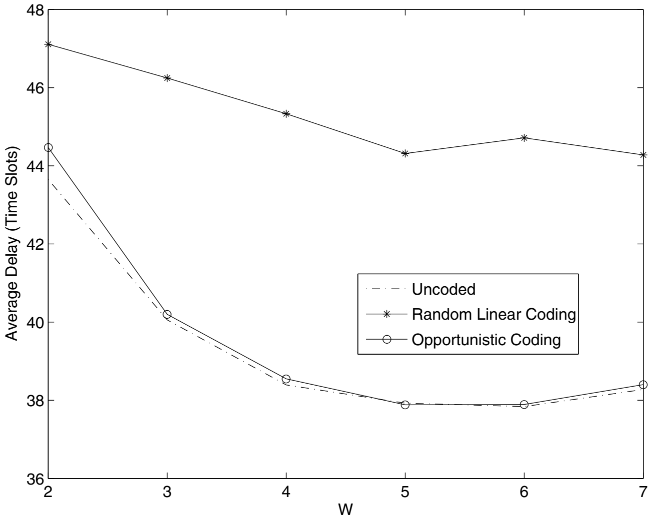

Fig. 6. Average Delay vs. Number of repetition($\mu_p = 0.6$)

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