Index Coded Repetition-based MAC in Vehicular Ad-Hoc Networks

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Abstract—In this paper we propose a new class of repetition-based MAC protocols for Vehicular Ad-hoc Networks. The design can be used for safety applications and position information dissemination. An erasure broadcast channel is considered in which several vehicles are in a cluster and each vehicle attempts to send its own safety message to all other vehicles. A distributed feedback mechanism has been introduced to propagate the network transmission and reception information throughout the network. Based on the feedback information, a packet coding algorithm, inspired by index coding, is proposed to efficiently reduce the number of transmissions and contentions. Simulations show that the proposed protocol yields a greater average probability of successful transmission.

I. INTRODUCTION

Vehicular ad hoc networks (VANETs) have garnered significant interest, in particular due to their applications in enhancing road safety. Cooperative Collision Avoidance systems prevent multi-vehicle pile-ups by broadcasting safety messages informing nearby vehicles of an impending collision [1]. For such safety applications, the reliability and timeliness of message delivery is paramount, and must be achieved despite the high node mobility and harsh channel conditions of the vehicular environment. Furthermore, the unlimited battery supply of vehicles creates a high interference environment and the lack of RTS/CTS signalling in 802.11 broadcasting causes hidden terminal effects. These factors impose significant challenges on the design of medium access control (MAC) schemes for VANETs.

Various MAC protocols have been devised for VANET. Among these are Time Division Multiple Access (TDMA) slot-reservation schemes such as RR-ALOHA [2] and contention-based techniques such as Fast Collision Resolution [3]. Recently, repetition-based techniques have been proposed in [4], [5] and [6] to address the requirements on delay and transmission reliability, as well as the short useful lifetime of the messages in vehicular safety applications. The use of Optical Orthogonal Codes (OOC) in the repetition patterns proposed in [6] have produced promising results in reducing the interference between nodes. This paper aims to improve upon this OOC-based repetition broadcasting.

The index coding problem has attracted much interest for its application to transmissions over broadcast channels [7], [8]. When information is available to the server about the packets received and those demanded by its clients, the server can combine its packets so that a maximum number of clients' demands are satisfied in each transmission.

We propose an enhancement of repetition-based broadcasting by applying index coding on repetition-based MACs. The required side information about the received packets are transmitted in the header of forward packets. In maximizing the number of informed destination nodes (clients) per transmission, we aim to achieve a higher probability of reception for a fixed number of transmissions on a wireless channel.

The remainder of this paper is structured as follows. In Section II, we review the previous proposed repetition-based MAC schemes for VANETs. Section III deals with our network model and performance metric. In Section IV, we propose our index coded feedback-based scheme. Section V presents the simulation results, and finally in Section VI we conclude the paper.

II. REPETITION-BASED MAC IN VANETs

Repetition-based MAC for safety communications in VANETs was first proposed in [5] and [9] by Xu et al. Each user is assumed to have a safety message that should be received by its neighbours within a certain message lifetime. The message contains the user position and other safety information (braking, collision, etc). A frame of L timeslots (equal to the message lifetime) is allocated to each user to transmit its own message. Within the message lifetime, each user retransmits its message based on a repetition pattern, and in each timeslot the nodes are either transmitting their messages or listening to the channel. The repetition pattern, number of interferers and frame length determine the message loss probability. In Synchronous Fixed Retransmission (SFR), w slots out of L are chosen randomly for repetitions, while in Synchronous p-Persistent Retransmission (SPR) at each timeslot the message will be retransmitted with probability $\frac{w}{L}$ [5], [9]. In both SFR and SPR, the timeslots for different users have been assumed to be synchronous, while Asynchronous Fixed Retransmission (AFR) and Asynchronous p-Persistent Retransmission (APR) have the same retransmission pattern of SFR and SPR but in an asynchronous manner. Of these methods, it was found that SFR had the best performance in terms of message reception probability [5], [9]. The authors

considered a two-ray ground channel model and concluded that for nominal network parameters a loss probability of 0.01 to 0.001 can be achieved. This message loss probability is rather high to be relied upon for critical safety applications. The authors have acknowledged this shortcoming and proposed that this protocol can be used to provide advanced warnings to the driver, instead of applications that react automatically to avoid collisions. Furthermore, the channel model assumption is quite optimistic; in the presence of a more realistic vehicular channel model such as in [10] and [11], the message loss probability would be further degraded.

In order to minimize the message loss probability, [12] and [6] have utilized OOC as the transmission patterns of the users in a frame. Using these codes guarantees that the retransmission patterns of any two users have a correlation of less than λ timeslots. In other words, at most λ repetitions of each two users collide within the frame length. This property has been shown to reduce the message loss probability compared to SFR and SPR.

III. System Model and Performance Metrics

A cluster of N nodes $U = \{u_1, ..., u_N\}$ is considered. Each node has a safety message that should be delivered to all neighbour nodes within the message lifetime. The message lifetime can be determined based on several factors such as the GPS updating period, velocity, etc. Each node uses a repetition-based MAC and a high reception success probability should be achieved. A timeslotted system is assumed and the message transmission duration is one timeslot. The message lifetime is L timeslots and each user's message will be sent repeatedly in w timeslots out of L. The communication is frame-synchronous, meaning that all nodes start their frames simultaneously. Frame-asynchronous cases can also be handled as shown in [13].

We consider an erasure channel in which all the nodes in the transmission range of a sender receive the message with 1-p_e probability. A similar channel model has also been assumed in the context of safety communications in vehicular networks [14], [15]. A more realistic channel model for the vehicle-to-vehicle channel is the Nakagami distribution with properly estimated parameters, which assigns higher reception probabilities for closer points in the range [10], [16], [17]. Since our channel model does not consider higher reception probabilities for closer neighbours, it underestimates the successful message reception probability [15].

Since the optimization of the channel busy time mostly favors non-safety applications, we shall focus instead on the message loss probability, which is safety critical. However, as has been shown in [5] and [9], with a CSMA/CA mechanism the channel busy time could nevertheless be minimized.

The message loss probability is defined as the probability that a vehicle fails to receive the safety message of another vehicle in its communication range within the frame. The delay of a received message is measured from beginning of the transmission frame to the time of successful reception and is in terms of timeslots. The maximum delay is the delay of the last message to be successfully received.

IV. Index coded feedback-based MAC

Towards a highly reliable, fully automatic safety message delivery MAC in a lossy vehicular environment, our proposed scheme tries to minimize the safety message loss probability using a distributed feedback and message combining algorithm. We allow packet combining for each retransmission: when a node has a transmission opportunity it can XOR some of its already-received messages and send the result. In contrast to the previous repetition-based MAC algorithms, a node does not only send repetitions of its own message, but rather can also transmit combinations of its message with other messages that it has overheard. A distributed feedback mechanism is designed to provide reception information for the packet coding algorithm. In the following two sections, we explain the distributed feedback mechanism and packet coding algorithms in detail.

A. Distributed Feedback

During a frame, once a node successfully receives a message from another node, it takes note of this successful reception and passes this information to other nodes. Furthermore, each node should also disseminate its knowledge of successful transmissions between other node pairs.

Each user $u_k (1 \leq k \leq N)$ in the network maintains a binary square feedback matrix F^{u_k} such that:

$$F_{ij}^{u_k} = \left\{ \begin{array}{ll} 1 & \text{if node j has received the message of node i} \\ 0 & \text{otherwise} \end{array} \right.$$

Since every user has its own message, the diagonal elements of the feedback matrix are equal to one. At the beginning of the frame each feedback matrix has only a single element, which is set to one (corresponding to each user's own message). Each node sends the most recent version of its feedback matrix in the packet header along with the known users indices. When a node receives a new message from another node, it takes note of new reception information in the feedback matrix contained in the received message. This is done by changing 0s to 1s for the corresponding entries in its own feedback matrix. As the set of users known to a node increases, the size of the node's stored feedback matrix should also be increased. For example, assume that at a specific timeslot the feedback matrix of the nodes A and B are as the following:

$$F^A = \overbrace{\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}}^{A \quad C} \quad \text{and} \quad F^B = \overbrace{\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}}^{B \quad D} .$$

Now if node A receives the node B message in the next timeslot, it will update its feedback matrix to the following:

$$F^A = \overbrace{\begin{bmatrix} 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}}^{A \quad B \quad C \quad D}$$

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and the set of users known to user A will be {B,C,D}.

In multi-hop scenarios, each vehicle maintains a feedback matrix which only contains information about its neighbours. Vehicles can identify its neighbours using the GPS information contained in the safety messages.

The presented feedback mechanism increases the message size. For a matrix F^{u_k} of size N, the amount of overhead is $N^2 - N + N\lceil \log N \rceil$ bits: the $N^2 - N$ term is the size of the feedback bit matrix included in the message, with the well-known diagonal elements omitted, and the $N\lceil \log N \rceil$ term is the number of bits required to transmit the identifiers for all known users. Users can obtain unique identifiers through a process similar to the OOC code distribution protocol mentioned in [6] and described in [13]. To account for this overhead and have a fair comparison we compare our proposed MAC with L timeslots in a frame with a repetition-based MAC without feedback and $L^* = \lceil L(\frac{S_M + S_F}{S_M}) \rceil$ timeslots in a frame. S_M is the safety message size and S_F is the maximum feedback overhead length.

B. Index Coding Algorithm

Based on the updated feedback matrix, at each timeslot, each node has the knowledge (possibly incomplete) of all the receptions. Returning to our previous example, assume that node A, after updating its feedback matrix, has scheduled a retransmission. In the previous repetition-based MAC schemes node A will send its own message (P_A) and nodes B and D will have the chance to receive a new message from node A. Could node A instead send some combination of its received messages to increase the number of newly-informed nodes? Node A has the messages of nodes B and C as well. If node A sends $P_A \oplus P_B$ (bitwise XOR), then in addition to nodes B and D, which will have the chance to receive P_A, node C also will have the chance to receive P_B. This example shows that by intelligently combining messages together, one can increase the number of message receptions.

Here, a sender has some packets and also some side information about which packets have been received and which ones are still needed by its neighbours. The sender finds the best packet combining strategy to maximize the number of received messages in one transmission. It is possible to show that this problem is NP-hard. In the sequel, we provide a heuristic for this problem. In contrast to the index coding problem in [8], [18], here the sender has only one broadcast opportunity and wants to maximize the number of received messages with its transmission.

We modify a heuristic solution for index coding [19] to solve our problem. Let us assume $R(u_s)$ and $N(u_s)$ are the set of messages received by the sender and the set of messages that are still needed (not yet received), respectively. U_{u_s} is the set of users that are known to the sender (users already present in the feedback matrix of the sender). $N(u_i)$ and $R(u_i)$ ($u_i \in U_{u_s}$) are respectively the set of needed and received messages of each known user to the sender. We represent a known user with m needed messages as m virtual users, each with one needed message. Each virtual user has the same set

of received messages as the original user. We call the new set of users $\acute{U}$. Now a graph $G(V, E)$ can be constructed such that the vertices represent the users of $\acute{U}$. We connect two 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 $N(\acute{u_i}), N(\acute{u_j}) \in R(u_s)$

To illustrate, let us continue with the example from the previous section. Node A's expanded feedback matrix with virtual users is:

$$F'^A = \begin{array}{c} \begin{array}{ccccc} B1 & B2 & C1 & D1 & D2 \end{array} \\ \left[\begin{array}{ccccc} 0 & X & 1 & 0 & X \\ 1 & 1 & 0 & 1 & 1 \\ X & 0 & 1 & X & 0 \end{array} \right] \end{array}$$

where "Don't cares" from virtual user decomposition are expressed with Xs, and A's own column is omitted. The virtual users are denoted above the matrix. For example, node B has been decomposed into virtual users B1 and B2, etc. An inspection of the two rules presented in (1) shows that only those entries in $R(u_s)$ are important, since the sender can only perform coding with messages in its memory. Here, since $u_s = A$, we may safely ignore the fourth row in the matrix F^A. Moreover, we can also ignore any virtual users that need a message which is not in $R(u_s)$. This is why C2 does not appear in F'^A.
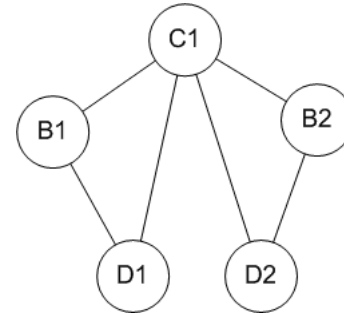

Fig. 1. Graph $G(V, E)$ for node A, with two cliques of size three.

Using the two rules, the corresponding graph $G(V, E)$ is generated and is shown in Fig. 1. The users corresponding to the vertices of each clique of this graph can receive their needed messages with a single broadcast. The transmitted message is the XOR of all the needed messages of the clique users. Contrary to the index coding problem where we solve the clique partition problem, here we should find the maximum clique of the graph which shows the maximum number of users that can receive their needed message with a single broadcast. The maximum clique problem is NP-hard and many algorithms have been proposed during the last decades. [20] and [21] are among the most recent efficient algorithms, using the branch and bound algorithm together with vertex colouring. The colouring scheme helps to find a better upper

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bound of the maximum clique size and accelerate the pruning step.

For practical values of message size and channel rate, the timeslot duration is on the order of a few milliseconds or less. In the worst case, the sender should find the best message combination within a timeslot. For a fast algorithm and a nominal computer system finding the maximum clique for a sparse random graph with 100 vertices takes more than 10ms on average [20]. Therefore, instead of finding the maximum clique, we use a simple, fast, sub-optimal algorithm. We simply assume the maximum clique contains the highest degree vertex in the graph. Then, we use a greedy algorithm that, at each step, chooses the maximum degree vertex in the potential set of clique vertices to join the current clique. Simulation results shows that this simple algorithm performs well enough in our application. Even for the index coding problem, it has been shown that if we partition the graph to 3-vertex and 2-vertex cliques, it still performs well in terms of minimum number of transmissions [19].

V. SIMULATION RESULTS

In this section, we evaluate the proposed index coded scheme on top of the OOC MAC protocol in comparing it with two other repetition-based MAC protocols: SFR MAC ([5], [9]) and OOC-based MAC ([12], [6]). A binary erasure channel is assumed for modeling the wireless link. The communication range is limited to a nominal value of 300m [5]. Each pair of vehicles within the maximum range can successfully receive each other's messages with probability $1 - p_e$. Based on a 3-lane highway and minimum distance of 30m between vehicles in each lane (including the length of the vehicle), a maximum of 30 vehicles can fit within the maximum communication range. We considered a cluster of 15 vehicles. The simulations have been done for 128 timeslot frames and high ($p_e = 0.5$) and low ($p_e = 0.2$) error probabilities.

Fig. 2 shows the loss probability averaged over all vehicles versus the number of repetitions each vehicle makes within a transmission frame, where $p_e = 0.2$, for the three schemes. The OOC codes have been generated based on the presented algorithm in [6]. For higher values of w, more repetitions create more opportunities for updating the feedback matrices. This allows each vehicle to gain a more complete picture of the transmissions and receptions of their neighbours, which leads to more effective packet coding. As we can see in Fig. 2, for $w = 12$ the loss probability of our scheme is almost one order of magnitude smaller than the loss probability of the OOC-based MAC.

For higher channel error $p_e = 0.5$, as shown in Fig. 3, OOC's performance degrades and its loss probability approaches that of SFR. The channel loss decreases the number of successfully received repetitions within a transmission frame. For lower numbers of repetitions, the random transmission patterns used in SFR become similar to OOC transmission patterns. However, even for such a lossy channel, our scheme still provides a loss probability of 10^{-3} for $w = 12$ which
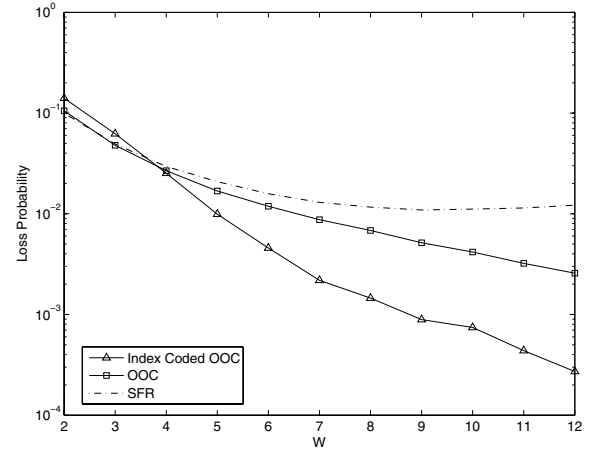

Fig. 2. Message loss probability versus number of retransmissions. L=128, p_e=0.2 and N=15

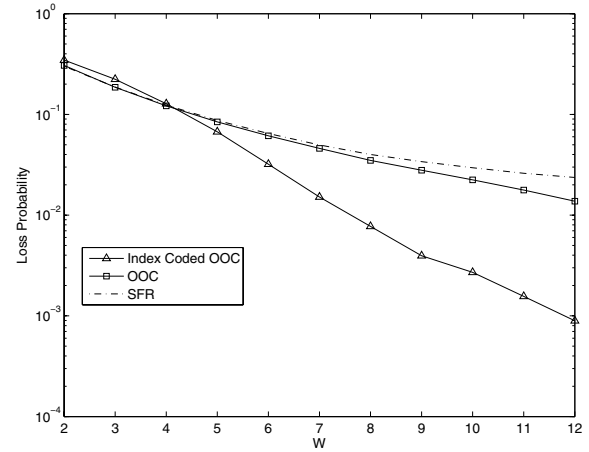Fig. 3. Message loss probability versus number of retransmissions. L=128, p_e=0.5 and N=15

indicates the enhanced reliability of the proposed MAC for safety applications.

Fig. 4 and 5 show the average delays of received messages, averaged over all vehicles in the cluster, for the three MAC schemes with low and high channel error rates, respectively. We see that the proposed index coded scheme suffers a slight penalty in terms of average delay. For the low channel error rate, this difference is negligible. Even when the channel error rate is high as in Fig. 5, the difference in the average delay is at most 5 timeslots.

The maximum delays of received messages, averaged over all vehicles, for the three MAC schemes are compared in Fig. 6 and 7, for $p_e = 0.2$ and $p_e = 0.5$ respectively. For smaller values of w, the incomplete feedback information leads to a less efficient packet coding which results in slightly higher maximum delay for our MAC. For higher values of w, more successfully received repetitions allow feedback information to be effectively disseminated throughout the network. Thus, each vehicle is able to perform message coding efficiently, which
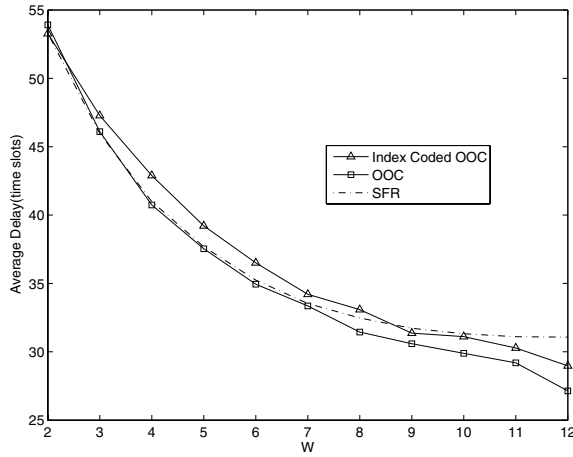
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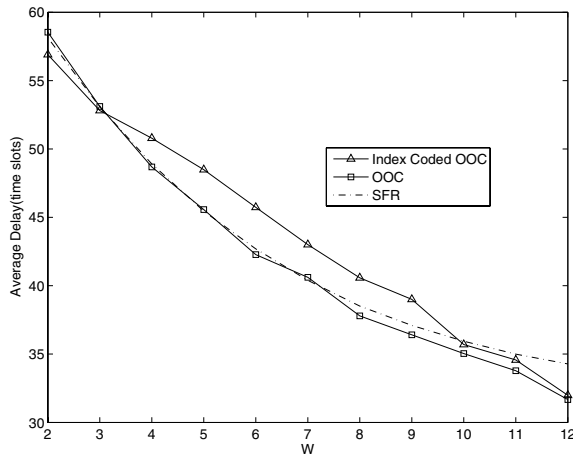Fig. 4. Average delay versus number of retransmissions. L=128, p_e=0.2 and N=15

Fig. 6. Maximum delay versus number of retransmissions. L=128, p_e=0.2 and N=15

Fig. 5. Average delay versus number of retransmissions. L=128, p_e=0.5 and N=15

Fig. 7. Maximum delay versus number of retransmissions. L=128, p_e=0.5 and N=15

allows for more messages to be delivered in each timeslot. This effectively lowers the maximum message delivery delay.

Fig. 8 and 9 show the average size of the message header used for feedback versus the number of retransmissions performed by each vehicle in a frame when $p_e = 0.2$ and $p_e = 0.5$, respectively. We can see that a greater number of retransmissions made by each vehicle in a frame allows each vehicle to gather more feedback information about the network. Consequently, this increases the average amount of feedback information included in the transmitted messages.

VI. CONCLUSION

We presented a new class of repetition-based MAC protocols for reliable safety message dissemination in VANETs. A distributed feedback mechanism is proposed, which provides side information for a message combining algorithm. Simulations show that this scheme greatly outperforms the previous repetition-based MACs in terms of message loss probability while having comparable delay performance.
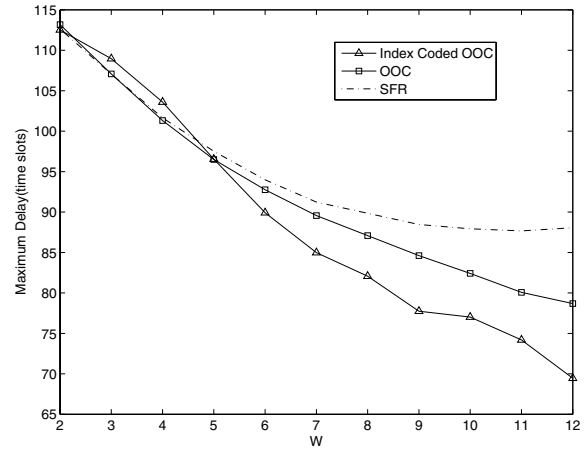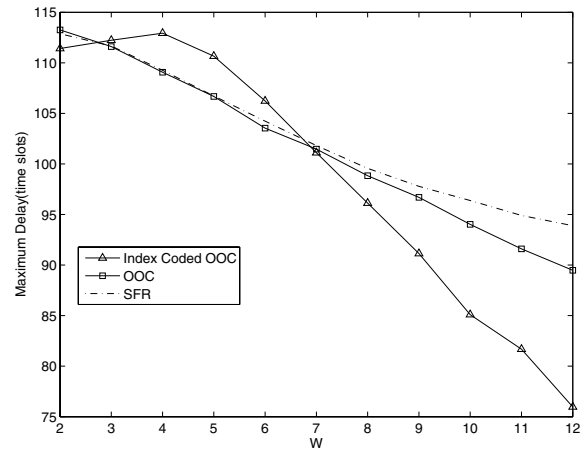
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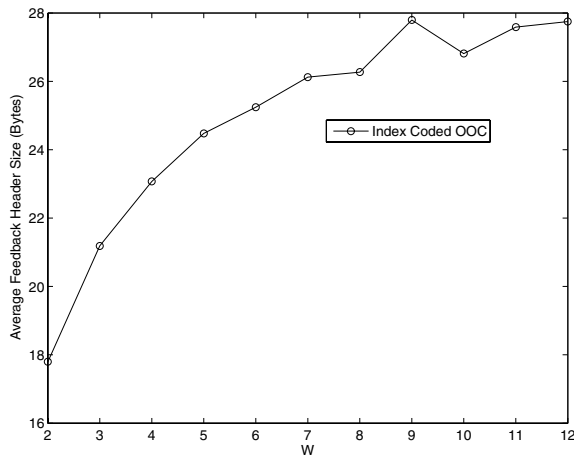
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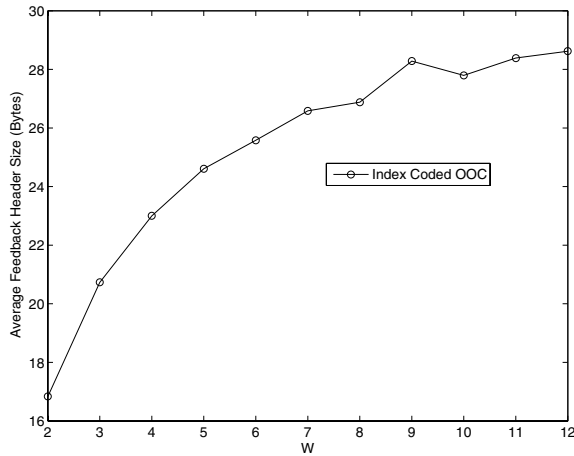Fig. 8. Average feedback header size versus number of retransmissions. L=128, p_e=0.2 and N=15

Fig. 9. Average feedback header size versus number of retransmissions. L=128, p_e=0.5 and N=15

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