Backoff-Based Coded Random Access for Intelligent Connected Vehicles

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ABSTRACT The rapid growth in the scale of the intelligent connected vehicles (ICVs) brings about the need for novel random access schemes that realize collision avoidance and reliable communication. The coded random access (CRA) scheme utilizes successive interference cancellation (SIC) across slots to enable the extraction of multiple users’ packets from the collision slots and proves to be an efficient solution to collision resolution. In this paper, we propose a random backoff-based CRA scheme to achieve a tradeoff between the access success probability and access delay for CRA. Specifically, we partition the traditional CRA frame into subframes, so that the user access delay is reduced to the same scale of the subframe length. In addition, the backoff operation among subframes is introduced so that access failures originated from the subframe length limit can be reduced with the retransmission in subsequent subframes. In particular, we consider practical Nakagami-m fading channel in the CRA performance analysis and take into account the capture effect in the iterative interference cancellation process. Simulation results show that backoff-based CRA can significantly reduce the average access delay without severe negative effect on the access success probability for moderate system load compared with traditional CRA. Comparisons with the state-of-the-art non-orthogonal random access (NORA) scheme proposed for 5G indicates that backoff-based CRA provides a feasible solution for random access of large-scale ICVs.

INDEX TERMS Coded random access, successive interference cancellation, random backoff.

I. INTRODUCTION Reliable and efficient information exchange lays the foundation for the cooperation of intelligent connected vehicles (ICVs). Novel random access schemes need to be explored for the sake of collision avoidance and reliable communication, especially when the number of intelligent connected vehicles increases drastically. Recently, coded random access (CRA) has received widespread attention as a means of resolving collision in the random access process [1]. CRA is a revolution of the slotted ALOHA random access scheme used in long-term evolution (LTE). Instead of considering the collision slots as waste, CRA utilizes successive interference cancellation (SIC) across multiple slots to extract users’ packets from collision slots.

Typical solutions of CRA include contention resolution diversity slotted Aloha (CRDSA) [2] proposed by Casini and irregular repetition slotted ALOHA (IRSA) [3] proposed by Liva. The CRA scheme works as follows. Users transmit the replicas of the same packet in multiple slots according to predefined access probability distributions and repetition rates. SIC is performed on the receiver side to remove replicas of the recovered packets from collision slots. Successive recovery and removal of replicas enables the iterative peeling of collision slots, and hopefully the reception of all users’ packets. IRSA utilizes a variable and judiciously designed repetition rate and provides throughput gain over CRDSA. Moreover, in [3] Liva identifies the analogy between SIC-based packet reception and iterative message-passing decoding of graph-based codes. The access probability distribution is then optimized using density evolution method [4]. Furthermore, Paolini proposes an extension of IRSA strategy by replacing repetition codes with generic linear block codes [5].
The spatial coupling effect is exploited in [6] to gradually increase the user load in consecutive frames. The high packet recovery rate in the former frames due to light user load benefits the packet reception process in the latter heavy-load frames. Motivated by rateless codes, [7] and [8] introduce a “frameless” version of IRSA, in which the contention period (i.e., frame length) is not predefined but dynamically adapted, to maximize the instantaneous throughput.

A lot of work has been done on the performance analysis of packet loss rate and throughput of CRA given practical frame lengths [3], [5]. The typical performance exhibits a threshold behavior, i.e., all users are reliably resolved if the total number of users is limited under a certain threshold. Many researchers have worked on the promotion of the threshold through packet power variation [9], packet repetition rate optimization [10] and irregular degree distribution design [3], [10] and [11] analyze the delay performance of CRA. The simulation results indicate that the access delay of CRA is closely related to frame length. The delay normalized to the frame length is larger than 1 with more than 90% probability. For the sake of delay reduction, the frame length should be set as small as possible. Moreover, channel fluctuation may lead to transmission failure for certain users in the current frame. Short frame allows the receiver to quickly acknowledge this effect and make corresponding adjustment. However, small frame length increases the occurrence of loops [12], which leads to irresolvable collisions and deteriorates the access probability and throughput performance of CRA.

Based on the joint consideration of the aforementioned problems, we propose a random backoff-based CRA scheme to achieve a tradeoff between the access success probability and the access delay. Specifically, we partition the traditional CRA frame into subframes, so that the access delay of the user is reduced to the same scale of the subframe length. In addition, the backoff operation among subframes is introduced, so that access failures due to loops in each subframe can be reduced with the retransmissions in subsequent subframes. Moreover, we consider Nakagami-m fading channel to represent realistic vehicular communication scenarios and take into account the capture effect [13], [14] in the CRA performance analysis. Simulation results show that backoff-based CRA can significantly reduce the average access delay without severe negative effect on the access success probability for moderate system load. Furthermore, the result of backoff-based CRA is compared with the state-of-the-art random access scheme proposed for 5G, i.e., the non-orthogonal random access (NORA) scheme. It is shown that backoff-based CRA can double the throughput compared with NORA with acceptable delay increase, which indicates that backoff-based CRA provides a feasible solution for random access of large-scale ICVs.

II. SYSTEM MODEL

A. NETWORK MODEL

We consider a network of intelligent connected vehicles which consists of \( N + 1 \) nodes. We focus on the scenario in which \( N \) sensing nodes periodically report situation messages to the sink node, so that the sink node can perform best route calculation or report road conditions. A simple illustration of the network is given in Fig. 1. The transmit power is assumed to be \( P_0 \) for all sensing nodes. Since the nodes are close to each other, we ignore the effect of path loss in the message transmission. We consider a Nakagami-\( m \) fading channel and assume independent and identically distributed (i.i.d.) fading between different nodes.

We assume that time is divided into frames. The nodes are frame synchronized, which is achieved using Global Positioning System (GPS) that provides an unified time reference for all nodes [12]. Each sensing node reports one message per frame. The frame structure is given in Fig. 2. Each frame is further divided into \( K \) subframes. Each subframe consists of one notification beacon and \( K \) data slots. The frame structure fits with LTE and 5G structures in that notification beacon fits in with physical broadcast channel (PBCH) while data slots can be arranged in physical uplink shared channel (PUSCH). In the notification beacon, the sink node broadcast CRA configuration information, such as the message repetition degree distribution, the backoff window, etc. Upon receiving the CRA configuration information, the sensing nodes which decides to report the situation information in the current subframe would generate \( l \) message replicas and transmit them over \( l \) slots chosen uniformly at random among the \( K \) available data slots. The length of the data slot is \( T_0 \). The repetition rate \( l \) is drawn randomly from the message repetition degree distribution, which is same for all nodes.

1LTE random access (RA) procedure consists of the exchange of four messages: preamble, response, initial layer 3 message (Msg3) and contention resolution. The NORA scheme combines LTE RA scheme with successive interference cancellation to alleviate collisions. Specifically, NORA facilitates the simultaneous transmission of Msg3 of collided UEs instead of conducting retransmission of preambles. NORA has shown significant advantage over LTE RA scheme and has attracted extensive research interest [15]–[18].

2We ignore the impact of vehicle mobility in that the relative movement between vehicles is marginal for scenarios of route calculation or road condition reporting.

3Nakagami-\( m \) channel model is most commonly used to model small-scale fading in vehicular communication in that it reflects a realistic driving environment [19], [20].
FIGURE 2. Frame structure of the backoff-based CRA scheme. Each frame is divided into $K_s$ subframes, which consists of notification beacon and data slots.

The situation information reporting operation of sensing nodes are dispersed over the frame according to a certain traffic model. According to [21], we use uniform traffic model and beta traffic model to characterize stable and bursty scenarios respectively. For the uniform model, the probability that a sensing node starts its reporting operation in the $i$-th subframe, denoted as $p_i$, is given as

$$p_i = \frac{1}{K_s}, \quad 1 \leq i \leq K_s$$

For the beta model, $p_i$ is given as

$$p_i = \int_{i-1}^{i} \frac{1}{K_s i^\alpha (K_s-i)^\beta} \text{Beta}(\alpha, \beta) \, dt, \quad \alpha = 3, \beta = 4, \quad 1 \leq i \leq K_s$$

in which $\text{Beta}(\alpha, \beta)$ is the beta function.

**B. BACKOFF-BASED CRA PROCEDURE**

The CRA procedure in each subframe is the same as that proposed in [1]. Here we give an example of CRA in which four nodes reports situation message to the sink node in a subframe of five data slots. As shown in Fig. 3, Node 1 and Node 4 choose a repetition rate $l = 3$, while Node 2 and Node 3 choose a repetition rate $l = 2$. The message sent by the sensing node includes preamble, node identity, situation information and replica pointer. Preamble is used for channel estimation. Node identity is used for the identification of different sensing nodes at the sink node. Replica pointer contains the data slot indices of the other replicas sent by one sensing node.

The sink node utilizes SIC across multiple slots to separate collided messages. For simplicity, here we assume the collision model to illustrate the sink node operation. Specifically, the message in singleton slots (slots that only one node transmits its message) can be decoded correctly while the messages in collision slots (slots that more than one node transmits its message) are irrecoverable. As shown in Fig. 3, Node 4’s message is decoded in Slot 5, enabling the reception of Node 2’s message in Slot 3 by subtracting the replica of Node 4’s message. In the same way, the reception of Node 2’s message enables the removal of its replica from Slot 2, which leads to the reception of Node 1’s message. Subtracting Node 1’s message from Slot 1 enables the reception of Node 3’s message. Utilizing the analogy of SIC-based reception and belief propagation (BP) decoding of erasure codes [3], we can visualize the aforementioned decoding process using the bipartite graph depicted in Fig. 4. Each square corresponds to a slot (referred to as check node (CN) in the bipartite graph) while each circle refers to a node’s message (referred to as variable node (VN) in the bipartite graph) we aim to solve. An edge between a square and circle indicates that the node transmits one of its message replicas in that slot.

In the back-off based CRA scheme, we further consider the retransmission of the sensing node’s message in the following subframes if its message are not successfully received by the sink node in the current subframe. Specifically, in the notification beacon of each subframe, the sink node broadcast the
list of the sensing nodes with successful situation information transmission. Upon the reception of the list, the sensing nodes whose situation information is not received by the sink node will reattempt to report the situation information.

III. ANALYTICAL MODEL FOR BACKOFF-BASED CRA

A. DEGREE DISTRIBUTION

In the bipartite graph, the number of edges connected to a VN is referred to as the VN degree, \( \Psi(z) = \sum_{n=0}^{N_l} \Psi_n z^n \) denotes the probability generating function of the VN degree, where \( \Psi_n \) denotes the probability that a sensing node repeats its message \( l \) times within a subframe. \( \{\Psi_n\} \) is referred to as the VN degree distribution, which is determined solely by the access strategy of the sensing node. \( L (L < K) \) denotes the maximum repetition rate for practical considerations.

The number of edges connected to a CN is referred to as the CN degree. Without loss of generality, we conduct the analysis of the CN degree distribution in the \( i \)-th subframe. \( \Xi(z) = \sum_{n=0}^{N_v} \Xi_n z^n \) denotes the probability generating function of the CN degree, in which \( \Xi_n \) denotes the probability that a slot contains messages of \( n \) sensing nodes and \( N_l \) denotes the number of sensing nodes that transmit messages to the sink node in the \( i \)-th subframe. \( \{\Xi_n\} \) is referred to as CN degree distribution, which is determined by the VN degree distribution \( \{\Psi_n\} \), the number of sensing nodes in the subframe \( N_l \) and the number of slots in the subframe \( K \).

Let \( \nu = \sum_{l=1}^{L} \Psi_l \) denote the average message repetition rate. In the \( i \)-th subframe, the probability that a sensing node sends its message in a given slot is \( \frac{n}{K} \), thus \( \Xi_n \) is given as

\[
\Xi_n = \binom{N_v}{n} \left( \frac{\nu}{K} \right)^n \left( 1 - \frac{\nu}{K} \right)^{N_v - n}, \quad 0 \leq n \leq N_l. \tag{3}
\]

Then we consider the degree distribution from the edge perspective. Let \( \phi_l \) denote the probability that an edge is connected to a VN of degree \( l \) and \( \rho_n \) as the probability that an edge is connected to a CN of degree \( n \). We have

\[
\phi_l = \frac{l \Psi_l}{\sum_{l=1}^{L} l \Psi_l} = \frac{\nu}{\nu}, \quad 1 \leq l \leq L. \tag{4}
\]

Since \( \sum_{n=1}^{N_l} n \Xi_n = \mathbb{E}[\Xi_n] = \frac{\nu N_l}{K} \), we have

\[
\rho_n = \frac{n \Xi_n}{\sum_{n=1}^{N_l} n \Xi_n} = \frac{\nu K \Xi_n}{\nu N_l}, \quad 1 \leq n \leq N_l. \tag{5}
\]

B. MESSAGE DECODING PROBABILITY WITHIN A SUBFRAME

Then we analyze the message decoding probability \( p_{d,i} \) in the \( i \)-th subframe. Under the assumption of the absence of loops, we are able to apply the and-or tree evaluation [4] technique to analyze the performance of CRA [3]. The message updates between the VN and the CN are depicted in Fig. 5.

Let \( q_j \) denote the probability that a message is unknown in the \( j \)-th iteration and \( p_j \) denote the probability that a message is not decoded in a slot in the \( j \)-th iteration. Consider a degree-\( n \) CN, the probability that a sending node’s message is successfully decoded is given by

\[
\sum_{n=0}^{N_l} w_{n,s} \left( \frac{n-1}{s} \right) (1 - q_{j-1})^n q_{j-1}^{n-1-s}, \quad \text{where} \quad w_{n,s} \text{ denotes the capture probability, i.e., the probability that a message can be successfully decoded in a degree \( n \) slot when } s (0 \leq s \leq n-1) \text{ colliding messages have been removed, and } q_{j-1} \text{ denotes the probability that a message is unknown during the } (j-1)\text{-th iteration. Averaged over the CN degree distribution from the edge perspective, we have}
\]

\[
p_j = 1 - \sum_{n=1}^{N_l} \rho_n \sum_{s=0}^{n-1} w_{n,s} \left( \frac{n-1}{s} \right) (1 - q_{j-1})^n q_{j-1}^{n-1-s}, \tag{6}
\]

where \( \left( \frac{n-1}{s} \right) = \frac{(n-1)!}{(n-s)!}, \) and the capture probability \( w_{n,s} \) under Nakagami-\( m \) fading channel is given as [19]

\[
w_{n,s} = \frac{n-s}{\Gamma(m)\Gamma(m(n-s)-m)} 

\times \sum_{k=0}^{\infty} \frac{(-1)^k \Gamma(m(n-s)+k)\theta^{m(n-s)-m+k}}{k!(m(n-s)-m+k)!}, \tag{7}
\]

\[
\text{where } m \text{ is the shaping parameter of Nakagami-} m \text{ fading channel and } \theta \text{ is the signal-to-interference-ratio (SIR) threshold for the successful decoding of the message}.
\]

In a similar manner, consider a degree-\( l \) VN, an edge is revealed whenever at least one of the other \( l-1 \) edges have been revealed. Averaged over the VN degree distribution from the edge perspective, we have

\[
q_j = \sum_{l=1}^{L} \phi_l q_{j-1}^{l-1}. \tag{8}
\]

The initial condition is set as \( q_0 = 1, \) i.e., all messages are unknown at the beginning of the process.

Assuming a maximum of \( I_{\text{max}} \) iterations with each frame, the probability of successfully decoding a sensing node’s message within the \( i \)-th frame is expressed as

\[
p_{d,i} = 1 - \sum_{l=1}^{L} \Psi_l (p_{l,\text{max}})^l. \tag{9}
\]

\[4\]For simplicity, we omit the impact of noise in the analysis as in literatures [19], [22], [23].
C. RANDOM BACK-OFF AMONG SUBFRAMES

Let \( N_i[v] \) represent the number of sensing nodes which attempt the \( v \)-th message transmission in the \( i \)-th subframe. We have \( N_i = \sum_{v=1}^{V} N_i[v] \), where \( V \) is the maximum number of message transmission attempts within one frame. The number of sensing nodes which conduct their first message transmission attempt in the \( i \)-th subframe is given by

\[
N_i[1] = N_i p_i, \tag{10}
\]

where \( p_i \) is given in (1) for stable scenarios and in (2) for bursty scenarios.

The sensing nodes with message transmission failure in the current subframe will perform random backoff and retransmit their message in the following subframes. The number of sensing nodes that attempts its \( v \)-th message transmission in the \( i \)-th frame originates from the sensing nodes whose \( (v-1) \)-th message transmission failed in the \( i' \)-th frame (denoted as \( N_{i',F}[v-1] \)). Among these failed sensing nodes, \( p_{v,i} \) of them end up attempting the \( v \)-th message transmission in the \( i \)-th frame after the random backoff process. Since these sensing nodes perform uniform backoff within the backoff window \( W_{BO} \) (length broadcast by the sink node in the notification beacon), the value of \( p_{v,i} \) is \( \frac{1}{W_{BO}} \). Then, we have

\[
N_i[v] = \sum_{i'=i_{\min}}^{i_{\max}} p_{v,i} N_{i',F}[v-1], \tag{11}
\]

where

\[
i_{\min} = i - \left( \frac{W_{BO}}{(N + 1)T_0} \right), \tag{12}
\]

\[
i_{\max} = i - 1, \tag{13}
\]

\[
N_{i',F}[v-1] = N_{i}[v-1] \cdot (1 - p_{d,i'}). \tag{14}
\]

IV. PERFORMANCE EVALUATION

For practical application scenarios of intelligent connected vehicles such as situation cognition, we focus on the event that all sensing nodes successfully report their messages to the sink node. The definitions and expressions of the noteworthy performance metrics are given as follows.

A. PERFORMANCE METRICS

1) NUMBER OF SUCCESSFUL SENSING NODES

The number of successful sensing nodes, sometimes also referred to as throughput [15], is defined as the total number of sensing nodes that successfully reports their messages to the sink node within a frame, given as

\[
S = \sum_{i=1}^{K_i} N_i \cdot p_{d,i}. \tag{15}
\]

2) AVERAGE SUCCESS PROBABILITY

The average success probability \( p_s \) is defined as the probability that one sensing node successfully reports its messages to the sink node within a frame, which is expressed as the ratio of the total number of successful sensing nodes within \( K_s \) subframes and the total number of sensing nodes in the network, given as

\[
p_s = \frac{\sum_{i=1}^{K_s} N_i \cdot p_{d,i}}{N}. \tag{16}
\]

3) AVERAGE DELAY

The average delay of the successful sensing nodes \( D_s \) is defined as the average number of slots between the slot in which the sensing node first transmits its message and the slot in which its message is successfully decoded.

\[
D_s = \frac{\sum_{i=1}^{K_s} \sum_{v=1}^{V} \sum_{b=1}^{N_{i,b}[v]} ((v-1)T_s + T_{i,b})}{\sum_{i=1}^{K_s} \sum_{v=1}^{V} N_{i,S}[v]}, \tag{17}
\]

in which \( T_{i,b} \) denotes the time between the first slot that the \( b \)-th sensing node first transmits its message and the slot in which its message is successfully decoded in the \( i \)-th subframe, \( T_s = (K + 1)T_0 \) is the length of the subframe, and \( N_{i,S}[v] \) denotes the number of sensing nodes whose \( v \)-th message transmission in the whole frame succeed in the \( i \)-th subframe.

B. NUMERICAL RESULTS

The parameter configurations for CRA performance evaluation are specified in Table 1. We analyze the throughput, average success probability, and average delay performance of the backoff-based CRA scheme. Moreover, we compare CRA with the state-of-the-art NORA [15] scheme to show its superiority.

Fig. 6 and Fig. 7 depict the throughput and average success probability of backoff-based CRA (denoted as “CRA w BO” in the figure) respectively given \( K_s = 2 \) and \( K_s = 5 \) under uniform traffic model, which corresponds to stable scenarios. The results for CRA without backoff (denoted as “CRA wo BO” in the figure) are also given for comparison. Moreover, results for CRA with \( K_s = 1 \), which is equivalent to traditional CRA scheme proposed in [3], and NORA are considered. It is shown that CRA can support at least 160 sensing nodes with guaranteed reliability, which doubles the value 80 supported by NORA. However, CRA with \( K_s = 2 \) and \( K_s = 5 \) exhibit performance loss compared with the case of \( K_s = 1 \). Moreover, the advantage of the backoff scheme is not clearly manifested.

| Notation | Meaning | Value |
|----------|---------|-------|
| \( N \) | Number of sensing nodes | 10-200 |
| \( K_s \) | Number of subframes in a frame | 1.25 |
| \( K \) | Number of data slots in a subframe | 200/K_s |
| \( P_0 \) | Transmit power of the sensing nodes | 1 |
| \( \Psi(x) \) | Probability generating function of the VN degree | \( 0.86x^3 + 0.14x^8 \) |
| \( L \) | Maximum message repetition rate | 8 |
| \( T_0 \) | Time length of a data slot | 5ms |
| \( \theta \) | SIR threshold for message decoding | 3dB |
| \( m \) | Shaping parameter of Nakagami-\( m \) fading channel | 1.5 |
To further demonstrate the effect of the backoff scheme, we provide the result of the failure probability, given as $1 - p_s$, in Fig. 8. It is shown that when the total number of sensing nodes in the network is less than the throughput, CRA w BO exhibits evident reduction of failure probability compared with CRA wo BO for a given $K_s$. For $K_s = 2$, the failure probability of CRA w BO is obviously lower than CRA wo BO given $N < 170$. Similarly, the failure probability of CRA w BO is lower than CRA wo BO given $N < 160$ for $K_s = 5$. In particular, CRA w BO can reduce the failure probability by one order of magnitude for $N < 120$. The reason is that the introduction of the backoff mechanism allows the message retransmission of failed sensing nodes in subsequent subframes. When the number of sensing nodes does not exceed the throughput, the backoff mechanism can effectively resolve the message transmission failure of individual nodes caused by channel fluctuation. However, when the number of sensing nodes approaches or exceeds the throughput, the message transmission failure mainly results from unresolved collisions of sensing nodes, which is exacerbated with the introduction of the backoff operation.

Similar conclusions can be obtained for bursty scenarios. Fig. 9 and Fig. 10 depicts the throughput and average success probability of CRA under beta traffic model respectively. For $K_s = 2$, both the CRA w BO and CRA wo BO schemes can guarantee successful access if the total number of sensing nodes $N$ is lower than 130. When $N$ is between 130 and 155, the CRA w BO scheme exhibits clear performance superiority over the CRA wo BO scheme in terms of throughput and access success probability. However, the CRA w BO scheme shows significant performance loss when $U$ exceeds 155, which most likely results from the retransmission accumulation of failed sensing nodes. The corresponding values for the $n_F = 5$ case are 90 and 135, respectively. Moreover, the throughput performance of the $K_s = 2$ case is superior to the $K_s = 5$ case. It is also worth noting that when $N > 190$, CRA wo BO with $K_s = 2$ and $K_s = 5$ shows performance advantage over traditional CRA, which results from the bursty attempt of sensing nodes that leads to increased successful message transmissions in a subset of subframes within the whole frame.

It is noteworthy that the performance gain of CRA over NORA in terms of throughput and average success probability comes at the expense of average delay. Fig. 11 depicts the average delay for uniform traffic model. It is shown that the delay of CRA significantly exceeds that of NORA, which validates the rationality of the introduction of subframe and the backoff mechanism in this paper. As manifested in Fig. 11, the average delay of the $K_s = 2$ case is reduced by nearly 50% compared to the traditional CRA case whereas the average delay of the $K_s = 5$ case is reduced by 80%. Moreover, the introduction of the backoff operation among subframes does not result in evident delay increase yet brings about noticable throughput gain when the number of
sensing nodes in the network is moderate. Similar results can be obtained for bursty scenarios.

V. CONCLUSION

In this paper, we propose a random backoff-based CRA scheme to achieve a tradeoff between the access success probability and the access delay for CRA. Simulation results have shown that backoff-based CRA can significantly reduce the average access delay without severe negative effect on the access success probability for moderate system load. Furthermore, the results of backoff-based CRA are compared with the state-of-the-art random access scheme proposed for 5G, i.e., the NORA scheme. It is shown that backoff-based CRA can double the throughput compared with NORA with acceptable delay increase, which indicates that backoff-based CRA provides a feasible solution for the random access of large-scale ICVs.

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