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Performance Evaluation of History-based and Priority-based MAC for Traffic-Differentiated Intra-Vehicular Network

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***Abstract*—The increasing trend of wireless sensor communications in automotive Intra-Vehicular Network (IVN) has imposed a great pressure on wireless link capacity. This is particularly highlighted by a massive number of automotive sensor devices competing for the same transmission channel, which results in significant packet congestion and delay. As an effort to mitigate this situation, this paper presents a comparative performance study of two existing medium access control (MAC) strategies, namely history-based MAC and priority-based MAC, in handling the traffic growth in the IVN. History-based MAC utilizes latest successful transmission parameters for the current transmission attempt whereas Priority-based MAC regulates each node's communication timing. Our numerical simulation results demonstrate a trade-off between these two schemes in terms of packet queuing delay and delivery rate. The Priority-based scheme, in average, suffers from a high transmission delay due to prioritization, but achieves a high packet delivery rate. On the other hand, the History-based scheme attains a low queuing delay at the expense of less successful transmission attempts per unit time.**

***Keywords*-Intra-vehicular Network; MAC strategy; Congestion Problem**

I. Introduction

The concept of Intra-Vehicular Network (IVN) was introduced to facilitate internal communications between car components and central control devices. In this concept, sensor nodes monitor vehicle parts' condition and transmit the acquired data either in time-driven or event-driven fashion. Some examples of transmitted data inside the vehicle are machine heat, indoor temperature, and so on. This underlying data exchange can be facilitated through a number of existing automotive protocols, including Controller Area Network (CAN), FlexRay, and TTEthernet [1], [2]. With a growing number of required sensors in smart vehicles, the main drawback of these protocols is the complex medium installation and maintenance since they rely on the wired connectivity. Therefore, extensive research efforts have been conducted to investigate the possibility of leveraging upon wireless medium in the IVN through the uses of Zigbee [3]–[5] protocols and Ultra-Wideband [6] signalling.

Benefitting from a recent progress in physical and medium access control (MAC) research [7]–[11], wireless intra-vehicular communications have continued to expand into a bigger scope incorporating Internet of Things paradigm in which a large number of sensors communicate with one another to share their information [1], envisioning the development of a smart car and vehicle system [12]. However, as the number of connected nodes increase, the performance of vehicular communication degrades due to packet collisions that result in packets congestion, drops and delay.

One approach that has been considered to mitigate this performance degradation is the IVN topology modification. As reported in [2], network topology has been identified as a contributing factor for a slight performance decrease in the IVN. Furthermore, the authors in [2] attempted to maintain transmission quality by changing star-based network topology [13] into bus-based network topology. However, this modification does not seem to provide the ability to keep up with network growth rate. Another approach that was studied to imporve the IVN performance is the link layer enhancement. More specifically, the authors in [13] has investigated the limitation of an existing MAC/link layer protocol. Their study reported that the original MAC protocol was unable to handle a high traffic load, which leads to increasing packet congestion rate and delay.

Expanding upon the work in [13] and basing our primary setup on the IEEE 802.15.4 standard, in this paper we conduct a comparative performance study between two known MAC strategies, namely History-based and Priority-based MAC to address potential performance degradation in the IVN. The History-based MAC mechanism utilizes parameters of most recent successful transmission, including the Number of Backoff and Backoff Exponent, which are overlooked by the original IEEE 802.15.4 standard, but are considered to be beneficial for future transmission. The Priority-based MAC method attempts to regulate nodes transmission order so that packet congestion can be reduced. In order to facilitate its functionality, this method introduces transmission round and flag to prioritize different network

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traffic types. In this study, we focus our attention on the abilities of the two schemes to sustain reliable data exchange under a mixture of two types of traffic, namely regular/normal and emergency traffic, which reflects practical scenarios of the IVN.

The rest of the paper is organized as follows. Section II-A discusses related works on IVNs. Sections III and IV describe the main ideas of History-based and Priority-based MACs, respectively, applied in the context of IVNs. Section V compares the performance of the two MAC strategies under emulation of a mixture of regular and emergency network traffic. Section VI concludes the paper with a summary of our main findings.

II. Related Works

A. General Related Work

Several studies have been conducted to investigate and improve the MAC capability of IEEE 802.15.4 in various conditions. For example, the performance of this IEEE standard in a complex vehicular environment has been closely examined in [3] with a focus on propagation simulation and real-life testbed of intra-vehicular sensor nodes. In reference [14], the quality of service (QoS) of this IEEE standard is extensively examined through several experiments with dynamically changing parameters. A key finding of this study is that proper parameters adjustment is required for different environment conditions to achieve desirable performance. The authors in [15] attempted to improve the QoS of IEEE 802.15.4 for time-sensitive transmission by making different queues for different types of delivery. This work has improved the existing first-in first-out (FIFO) queuing by varying MAC parameters for each queue. The results of [15] have inspired the authors in [16] to devise an analytical approach to tune the backoff time using Gaussian distribution. In reference [12], mitigation of packet congestion in the IoT-enabled IVNs was addressed by setting the MAC parameters after each successful transmission. The study was then further investigated in [13], which reveals the limitation of the existing IEEE 802.15.4 standard to handle large intra-vehicular networks.

B. IEEE 802.15.4 CSMA/CA Mechanism

The original IEEE 802.15.4's carrier-sense multiple access with collision avoidance (CSMA/CA) utilizes a basic time unit, namely *Backoff Period* (BP), which is equal to the value of *aUnitBackoffPeriod* or 0.32 ms. In addition to this parameter, the protocol primarily depends on following variables.

1) *Backoff Exponent* (`BE`) that represents backoff delay computation. The delay determines the time before performing any Clear Channel Assessment (CCA) prior to transmission. This value is a random variable, which takes value from 0 to $2^{BE} - 1$.
2) *Contention Window* (`CW`) describes the number of backoff periods. These periods are the duration in which the channel must be sensed unoccupied before evaluating it.
3) *Number of Backoff* (`NB`) determines how many times the algorithm must execute backoff while trying to access the channel. This value is set to 0 (`NB = 0`) before any new transmission attempt.

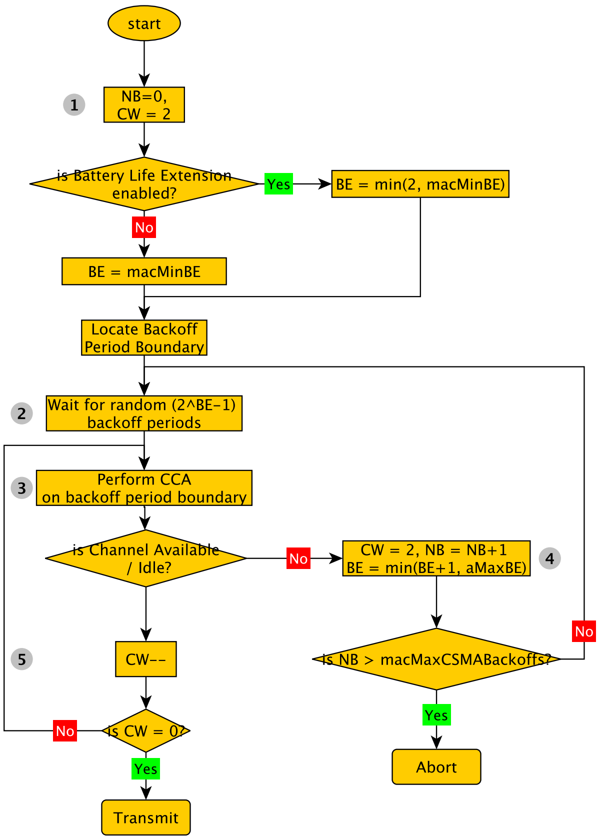

Figure 1: CSMA/CA Algorithm.

Figure 1 depicts the procedures of CSMA/CA mechanism for the IEEE 802.15.4 standard. There are five key steps.

1) **Parameter Initialization:** The algorithm starts with parameter initialization related to channel assessment, comprising the parameters `NB`, `CW`, and `BE`. For the first transmission initiated by a node, these parameters are set to default values, i.e., $\mathtt{NB} = 0$, $\mathtt{BE} = \mathtt{macMinBE}$, $\mathtt{CW} = 2$). Parameter `macMinBE` stands for the minimum value of *Backoff Exponent* (`BE`).
2) **Backoff Counter Decrement:** The algorithm then counts down the random backoff period that is generated randomly within $[0, 2^{\mathtt{BE}}-1]$ range. The `BE` value is decremented irrespective whether the channel is busy or idle.
3) **Channel Sensing:** This third step is carried out whenever the delay timer expires. This step checks the

channel activity in the backoff period boundary. If the channel is currently inaccessible, then step 4 is executed. Otherwise, the procedure continues to step 5.

4) **Busy Channel:** An extra channel verification is performed within a $\min(\texttt{BE} + 1, \texttt{macMaxBE})$ random backoff period. This step only runs whenever $\texttt{NB} \leq$ `macMaxCSMABackoff`.
5) **Available Channel:** If two consecutive assessments find the available channel twice, then the CSMA will notify the MAC layer and transmission may take place. Otherwise, one more CCA request will be scheduled.

III. History-based MAC

In order to mitigate packet collision and congestion, the MAC mechanism must be able to assess channel efficiently before frame retransmission attempts exceed the maximum allowable round.

The CCA dictates that successful transmission from a particular user is only possible if the wireless channel is clear, i.e., no existing transmission from other users is detected. Based on the IEEE 802.15.4 standard, for each attempt to assess the channel clearance, a variable named `NB` (the number of backoffs) is incremented. This value must be lower than the maximum backoff number (denoted by `MacMaxCSMABackoff`) or otherwise the CCA will fail.

A main drawback of this original IEEE 802.15.4 standard is that each channel assessment attempt utilizes predetermined fixed-valued parameters, including the number of backoffs `NB` and the backoff exponent `BE`, for any transmission session. Any indication of busy channels during the CCA process will increase the values of both `NB` and `BE`. Remark that a larger value of `BE` corresponds to a longer random backoff delay. In other words, several backoff steps may be required before obtaining a suitable backoff period.

A History-based MAC mechanism that was proposed in [12] aims to improve the original MAC mechanism of IEEE 802.15.4 by minimizing the required effort to assess the channel. This work discovered that the original standard is unable to handle a large number of transmissions within the network. In contrast, History-based MAC was proved able to serve more nodes than the original standard. The approach behind is the utilization of `NB` and `BE` from the last successful transmission. This is intuitively reasonable given the fact that the physical surrounding conditions will not change drastically in the IVN context. In such a case, the nodes are expected to have a quicker channel assessment.

History-based MAC works in a similar way to the original IEEE 802.15.4 MAC scheme except the parameter initialization step. If the initial channel assessment is successful, then the corresponding values of `NB` and `BE` are recognized as `SNB`, denoting a saved `NB`, and `SBE`, representing a saved `BE`. The values of `SNB` and `SBE` will then be referenced in the next channel assessment.

IV. Priority-based MAC

The original IEEE 802.15.4 MAC and History-based MAC may still encounter a high number of packet queue drops as a consequence of rapid packet interval to local buffer time. Packets arrive on each device's local buffer and wait for transmission time that can take too long. Meanwhile, the nodes inside the network compete to obtain the channel for a transmission purpose. Remark that transmission can only occurs after CCA reports two consecutive channel idle times. In order to achieve the idle check, a node may suffer a backoff period that is constrained by the backoff boundary. If a node fails to obtain channel access, then it has to retry until the requirement is fulfilled. The IEEE 802.15.4 standard permits up to three maximum frame retries. If packet retransmission attempts exceed this number, then the first packet in the queue must be dropped.

In the IVN real implementation, the network nodes may not have to emit packet at any unpredictable times since different types of sensing devices may have different purposes. Sensors such as distance/proximity and anti-theft send packets when desired events occur. Therefore, these sensing devices can stay in the sleep-mode when idle. Meanwhile, other types of sensor may generate packets more frequently to provide real-time information such as heat and velocity. In other words, these devices emit periodical packets. Priority-based MAC is developed based on this observation. The strategy attempts to allocate transmission time for each transmitting node exclusively. The process will provide equal chance to each node to send packets without any interference from other nodes. During active transmission mode, each node will transmit packets in turn according to its assigned round. Otherwise, the node will remain idle. If a node has urgent information that requires immediate transmission, then it is allowed to exit idle state and begin transmission procedures.

The detailed steps of the priority-based MAC mechanism are depicted in Figure 2 and explained as follows.

1) **Parameter Initialization:** Priority-based MAC starts by initializing the values of relevant parameters, such as transmission round, flag, and node id. The parameters of round and node id will play a vital role in determining the node's turn to begin the underlying MAC mechanism since the procedure runs in a distributed environment. Time synchronization is also required prior to data collection since all nodes will determine their transmission round independently.
2) **Transmission Round Check:** Since all the nodes have been synchronized before collecting data, then a simple modulus operation is used to mark which node's turn in each round. Once the result of the modulus operation equals to the corresponding node id, the transmission flag is set to true. It then follows that the algorithm proceeds to step 4, otherwise it

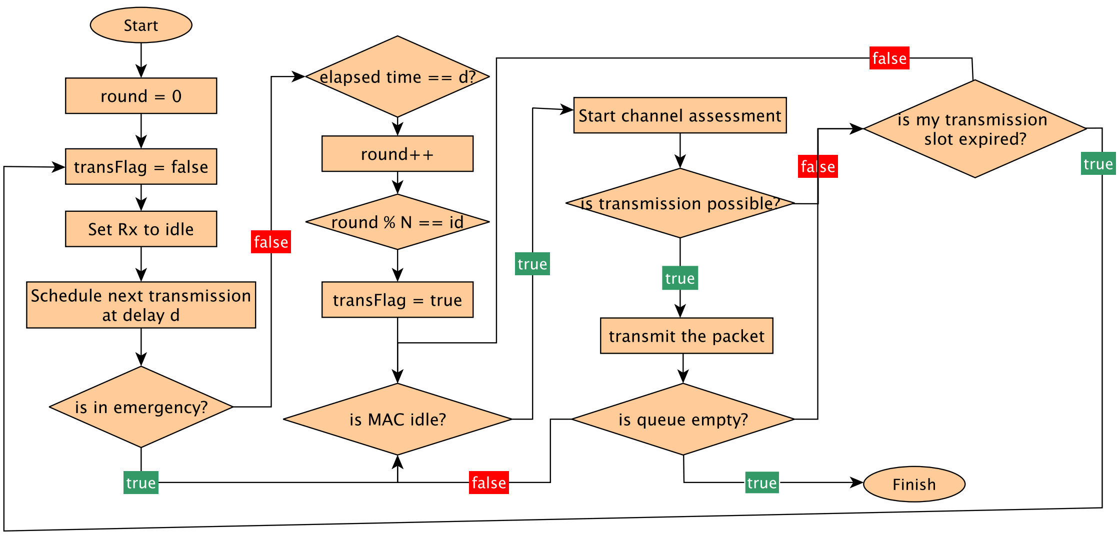

Figure 2: A flow-chart of the Priority-based MAC scheme.

executes step 3.

3) **Idle State** A node entering idle state will have its receiver to be idle and wait for its turn. While it is in this state, the transmission flag is set to false and the algorithm proceeds to step 2.
4) **Transmission State** After the node transmits an outgoing packet, it will check the queue condition and whether its transmission round expires. If there is sufficient time to assess the channel and there exist packets left in the queue, then the node is allowed to perform CCA and transmission.

V. Performance Analysis

In the following we compare the performance of History-based and Priority-based MAC under typical traffic scenarios encountered in the IVN. We first explain the simulation setup used to evaluate the network performance. We then discuss the results of the simulation to gain further insights.

A. *Simulation Design*

Simulation was designed carefully in order to provide fair comparison in terms of packet arrival rate at the buffer of each device and packet transmission timing for the two schemes. Recall that the History-based MAC scheme does not have explicit pre-allocated time for node transmission, which may lead to a high congestion rate. On the other hand, the Priority-based MAC scheme manages timing allocation for all the nodes and allows only one node transmitting at a given time slot. Two different communication patterns are introduced to emulate a variety of network traffic behaviors in the IVN. The first pattern is regular/periodic phase pattern that represents timely packet emittance. The second pattern is the random phase pattern to demonstrate emergency situation where packets arrive randomly at the buffer and transmission may occur soon afterwards. Consequently, any communication occurs in this period will rely on the channel capacity to serve on-going transmission.

In one simulation timeframe which lasts s, there are n sessions. Each session i runs $\frac{n}{s}$ simulation time. Furthermore, each session consists of two different phases, namely regular and emergency phases, which are denoted by green and red lines, respectively, cf. Figure 3. In order to flexibly change the duration of these phases, variable α is introduced to capture the fraction of time for the emergency phase. Therefore, the regular phase will take place in $(1-\alpha) \times \frac{s}{n}$ time whereas the emergency phase will occupy $\alpha \times \frac{s}{n}$ fraction of time for each session.

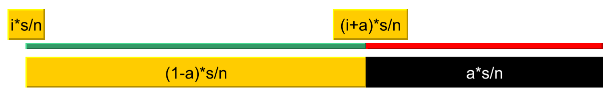

Figure 3: Each session is divided into 2 phases

During the emergency period, relevant nodes will have packets in the transmission buffer at any random time. At this stage, there is no scheduling mechanism. In other words, transmitting nodes will compete with one another to use the wireless medium. In contrast to this period, the regular period is governed by the interval regularity of packet arrivals at the local buffer.

B. *Results*

In Figure 4, we plot the simulation results of queuing delay against the number of nodes. As a performance indicator, queuing delay is calculated by subtracting enqueue time with dequeue time. According to Figure 4, Priority-based MAC suffers from a large delay while History-based MAC has favorable performance. Due to time-slotting in the Priority-based mechanism, each node must wait until its transmission

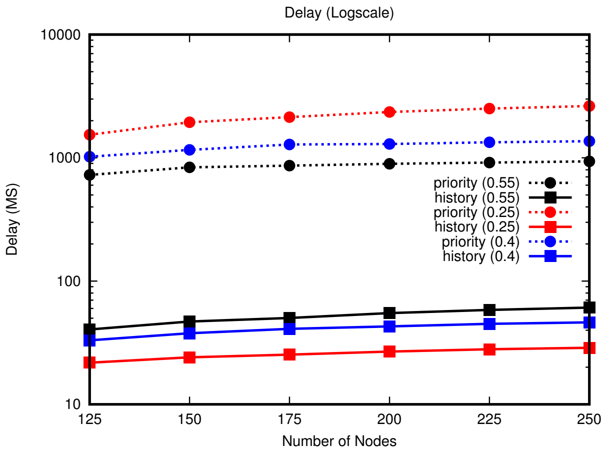

Figure 4: Queuing delay versus the number of nodes.

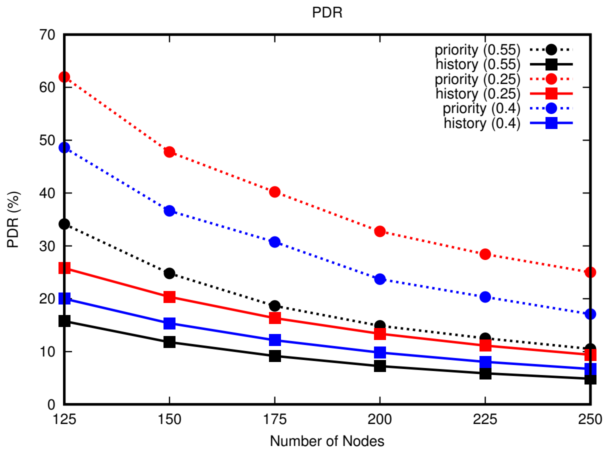

Figure 5: Packet delivery ratio (PDR) versus the number of nodes.

turn. By increasing the number of nodes, the waiting period, in average, will be longer. In the IEEE 802.15.4 standard, the MAC layer must ensure that the channel is idle prior to packet transmission. Packets transmitted using the history-based MAC scheme concede less channel assessment time due to the absence of time-slotting mechanism. However, the long channel availability inspection may result in undesirable packet drops.

Our simulation randomly sets packet arrival up to 30 ms during the emergency phase while the Priority strategy provides 60 ms tolerance time for each node to transmit the remaining packets in the buffer. Therefore, there will be more packets coming than departing. This condition must be avoided in History-based MAC since the packets keep coming and channel assessment must be able to keep in pace.Due to the condition that all nodes may attempt to transmit, the competition among nodes increases as the size of network grows. Priority-based MAC, on the other hand, is able to determine which node transmits first according to the transmission round calculation. As long as a node has its transmission round, it can exhaust its turn to transmit packet. Therefore, packet transmission may take place immediately for that node, and the queue in its buffer may be quickly emptied during this duration.

In the network simulation, packet drop occurs whenever the corresponding packet stays too long in the queue or the queue is full. The MAC mechanism regulates how long a packet stays in queue with a variable called retransmission attempt. When CCA occurs several times, the process may exceed the maximum allowed number of retransmission attempt. An effective way of measuring the severity of packet drops is using the packet delivery ratio (PDR).

Figure 5 illustrates the PDR of the two MAC schemes. It can be seen that History-based MAC has a lowest PDR due to its rapid transmission attempts. This scheme continuously assesses the channel during packet arrival. After one node successfully obtains a clear channel, other nodes will compete to do so. Due to the absence of exclusive time transmission, frequent packet drops may continue to occur.

Table I: PDR Result for History-based MAC.

Number of Nodes	PDR (%)		
	$\alpha = 0.25$	$\alpha = 0.4$	$\alpha = 0.55$
125	25.78	20	15.75
150	20.34	15.35	11.77
175	16.32	12.14	9.16
200	13.36	9.8	7.23
225	11.12	8.05	5.87
250	9.38	6.71	4.86

Table II: PDR Result for Priority-based MAC

Number of Nodes	PDR (%)		
	$\alpha = 0.25$	$\alpha = 0.4$	$\alpha = 0.55$
125	61.97	48.6	34.13
150	47.78	36.62	24.79
175	40.22	30.73	18.62
200	32.75	23.7	14.87
225	28.42	20.33	12.5
250	25	17.09	10.5

In our simulation we allocate 50 sessions in each scenario. During this period, if the network contains more transmitting nodes, then the competition will be more intense. For example, if $s = 600$ seconds, $\alpha = 0.4$, and the number of nodes is 200, then each session lasts for 120 seconds, which consists of 72 seconds for the regular phase and 48 seconds for the emergency period. During this emergency period of 48 seconds, 200 nodes must compete with one another to get transmission allocation. Since packets arrive in a random fashion, CCA timing plays an important role for the History-based approach. Parameters such as `NB`, and `BE` will determine packet transmission time for the corresponding node.

Tables I and II list the PDR values for both History-based and Priority-based MAC, respectively. According to the tables, History-based MAC with $\alpha = 0.55$ exhibits the most inferior PDR performance. This condition is expected to worsen as the number of nodes increase. The best result for History-based MAC is obtained when $\alpha = 0.25$ on a network with 125 nodes. In this case, the PDR value of History-based MAC reaches 25.78%. In contrast to this strategy, Priority-based MAC can achieve 61.9% with the same configuration.

VI. Conclusion

We have compared the performance of two MAC strategies, namely History-based and Priority-based MAC, and studied their feasibility as the main MAC scheme for the IVN. History-based MAC uses the most-recent parameters of successful transmission to determine parameters for the next transmission. Priority-based MAC regulates nodes transmission timing by introducing transmission round and flag. Numerical simulation have been used to show the performance of the two schemes in terms of queueing delay and PDR using a fair packet arrival setup. The results have demonstrated that the Priority-based method produces a higher PDR rate, but with a higher queuing delay than the History-based scheme. Further observation has revealed the trade-off in implementing the two schemes in the IVN, suggesting that further research is necessary to reap most of the benefits from combining the two schemes.

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