Evaluation of the IEEE 802.11p Multi-Channel Operation in Vehicular Networks

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***Abstract*—This paper explores recent improvements in 802.11p multi-channel protocol in vehicular ad-hoc networks. We provide definitions for a vehicular network and explore the operation of 802.11 within a vehicular network. We also study on areas of improvements of this protocol and briefly discuss on advantages and disadvantages of each solution.**

I. INTRODUCTION

Vehicular networks are getting a lot attention these days due to high traffic accidents and the need for drivers and passengers to be more comfortable during their drive. Currently in order for one to get information on cargo tracking, traffic, or accident conditions on the road, one would have to go online with a laptop or other mobile devices. Vehicular networks will provide a much better way of communicating by having the vehicles talk to one another continuously as they are driving on the road. In order to achieve this goal this particular network is going to relay on the IEEE 802.11p multi-channel operation known as WAVE (Wireless Access in Vehicular Networks) [14], [15], [18].

A. What is a Vehicular Network?

Vehicular Ad-Hoc Networks (VANETs) are a special case of mobile ad-hoc networks, where wireless-capable vehicles spontaneously form a network while traveling on the roadway. Vehicular networks can support both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, and are targeted at the delivery of both road safety applications and comfort applications[12]. 802.11p supports both the TCP/UDP/IP protocol stack and a new lightweight WAVEmode short message protocol (WSMP) for the exchange of small packets carrying safety or road messages. There are two physical components to this network; the On-board Unit (OBU) and the Road side Units (RSU).The RSUs are stationary access points set up in strategic locations on the road. These serve as the base stations that serve the OBUs by providing access to this service. The OBUs are devices in transportation vehicle that collect data from the RSU in a single hop transmission, and other vehicles, outside the transmission range of the RSU, in a multi-hop ad-hoc fashion. The RSU continually broadcast the beacon signal in order for the OBUs to synchronize with the RSU and receive system information. The OBUs uses the SCH to communicate with the RSU and other OBUs in range. Figure 1 illustrates the communication between the RSU and the other vehicles on the road. Transmission happens within WBSS (WAVE-mode Basic Service Set) established ad-hoc among the vehicles. A provider initiates the WBSS and a user joins the WBSS without any authentication. In a typical network a user node first gathers necessary network information on the control channel (CCH) through the WAVE service advertisement (WSA). The node initiates a Wave-mode Basic Service Set (WBSS) by periodically broadcasting a WBSS Announcement Message (WAM). These messages contain the operational information of a WBSS including which available service channel (SCH) to use. After this information is exchanged the node may join this WBSS by periodically switching its channel to this SCH [19], [13].

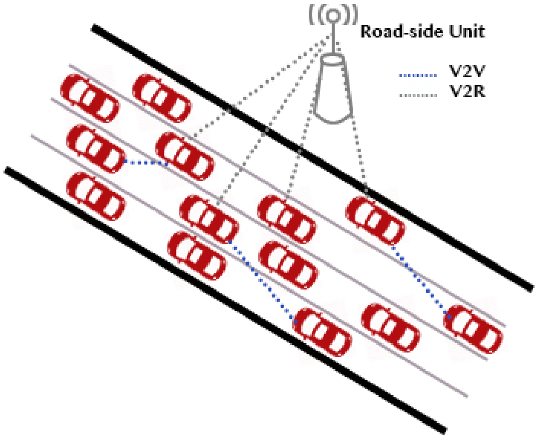

Figure 1. Illustration of vehicular network.

B. How does the 802.11p multi-channel operation work?

The IEEE 802.11p is an amended version of the 802.11a protocol. It uses a multi-channel protocol with a 5.9 GHz Dedicated Short Range Communication (DSRC) in order to communicate with other vehicles on the road or with infrastructure set up along the side the road. The DSRC is split up into 7 channels each with 10MHz and a maximum data rate of 27Mbps. One of these channels is the CCH which provides safety messages as well as coordinate the channel communication among the nodes (cars) in this network. The CCH also further divides its messages into 4 different access categories (AC0 to AC3). AC0 are the least important messages, AC3

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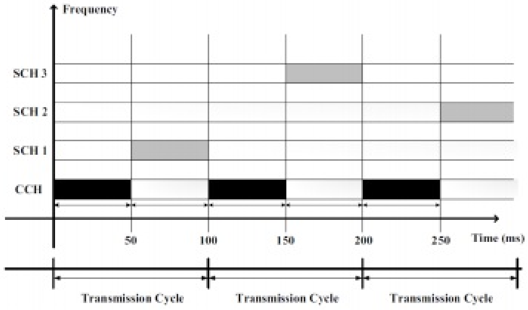

Figure 2. WAVE Channel access scheme.

are the most important messages. The other 6 channels are used by the SSH and are used for non-safety or infotainment messages. Both the CCH and the SCH use a 100 ms time frame (50 ms for the CCH and 50 ms for the SCH) to transmit their respective messages. During the CCH time frame safety messages are exchanged as well as choose the least congested SCH to use during the SCH time frame. Figure 2 illustrates the channel switching between the CCH and the SCH [12], [13].

C. What are the advantages of using the multi-channel operation?

Comparing the 802.11a, which doesnt use the multi-channel operation, to 802.11p, which does, we can see that both the Packet Delivery Ratio (PDR) and throughput are greatly increased in both urban and freeway environments. Figures 3 and 4 depict the advantages of using 802.11p for TCP/UDP protocols and using preemptive and non-preemptive (whether or not an application can take control of when it can send its message). The figure clearly show that the PDR increase to over 80% for both safety and non-safety messages when 802.11p is used.

II. PROBLEM DEFINITION AND SOLUTIONS

This architecture has been studied and proven to be a valid foundation for Vehicular Network. Even with a good solid foundation, there are still some problems that must be addressed with the efficiency of the multi-channel operation and channel allocation [4], [25], [14], [24].
Although the multi-channel operation in 802.11p has its advantages it is not perfect. As the number of nodes (vehicles) increases the amount of received messages for each AC in the CCH decreases mainly due the high collision rate causing an end-to-end delay. Figure 5 shows us the throughput for each channel. As one can see the throughput also decreases for each channel as the number of nodes increases. Clearly there is some work to do on making the channel utilization more efficient [14], [15], [18].

A. Bandwidth Wastage Problem

The multi-channel operation provides some interesting challenges to overcome. One of these challenges is the efficiency of

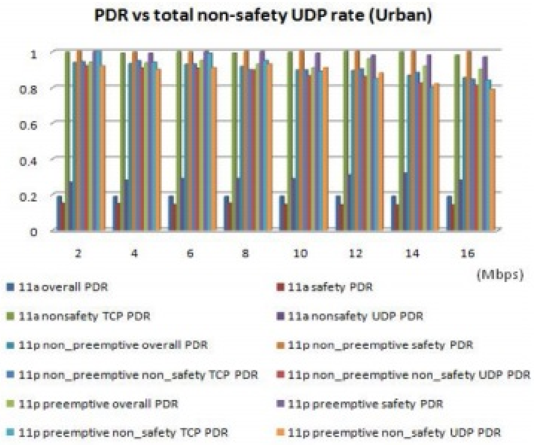

Figure 3. PDR for Urban scenario

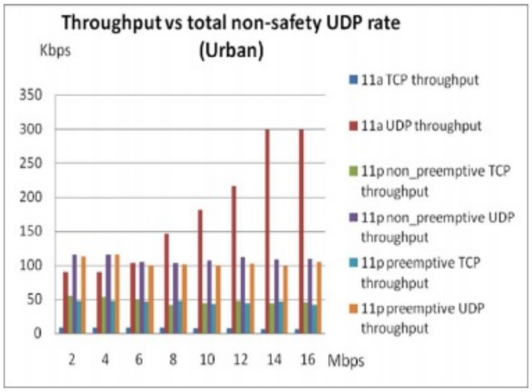

Figure 4. Throughput for Urban Scenario

the CCH and SCH usage. If the control channel packet doesnt require the entire time frame allocated to transmit, it will still stay until the entire time frame because of the equal time allocation of the channels. This causes various problems such as bandwidth wastage by CCH, and when large packets have to be transmitted by SCH, it cannot extend its time frame and use the time wasted by the CCH and thus have to fragment the data and transmit part of the packets in a given time frame and the rest in the next time frame. The receiver waits until the complete packet is received. As such the IEEE 802.11p/1609 draft standards recommend that in such a condition the transmitting node should prevent sending out the packet but instead should send it in the next service frame, although the design avoids bandwidth wastage caused by incomplete packet reception, it results in bandwidth wastage at the end of each service frame due to not using the residual time. Even with the problems of multichannel operations, there have been many solutions put forth to overcome these problems [25], [26]. Considering the problem with SCH utilization mentioned above, the same study also proposed a solution by extending the time the SCH has to transmit a packet and additional protocols to ensure that the CCH can still be used and that the SCH isnt using unnecessary time when it is not needed [25], [26]. Another solution to the SCH utilization problem in multipacket size

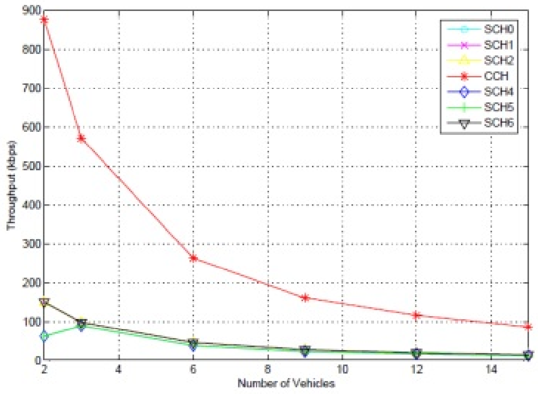

Figure 5. Throughput for Urban Scenario

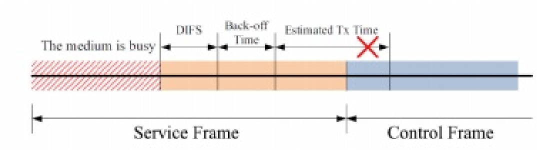

Figure 6. Bandwidth wastage problem

environment is to incorporate a Best-fit scheme where an output queue of different size packets is maintained and instead of fragmenting the data, the channel chooses the smaller packet in the output queue that can be transmitted in the current time frame [25].

B. Extended SCH Protocol

The basic protocol for the extended SCH works by extending the length of the SCH by 3 times, however this causes a couple of problems.

1) If a WSA is not received by a user for some reason the user will not know when to switch to the SCH channel when the provider has and the provider will remain on the whole extended SCH causing considerable wastage on the SCH.
2) If the WBSS has ended and the user is not aware of this then it will remain the extended SCH.

To solve this problem the user will send a WSA acknowledgement (WSAA) when the provider sends its WSA. If the provider doesnt receive the WSAA and user has not confirmed the WSAA was received then the user and provider will stay on the original SCH interval. Only when then WSA and WSAA succeed will both the user and the provider switch to the extended SCH interval. There are still a couple more issues to be addressed before the extended SCH protocol can be used.

1) Need to make the user doesnt leave the SCH before the WBSS has ended.
2) Provider needs to detect its link connectivity.

Because the provider may not have any data frames to send during the SCH the users could drop out before the WBSS has ended. Normally the user leaving the SCH when it has nothing to send is preferable to reduce the wastage of the SCH, however it is not good to drop before the WBSS has ended. To solve this problem the provider will periodically send a unicast keep-alive message to the user to prevent it from leaving the SCH too early. This keep-alive message can help to detect the link connectivity, however if there are no data frames to be sent are only broadcast data frames, then the provider has no base to detect the link connectivity. To solve this problem the provider will send a number of these messages when it wants to detect the connectivity and if none of them get acknowledge then it knows that it can change to the CCH at its next earliest convenience. This protocol is very robust and can provide high throughput even if the network remains in a bad state 60% of the time. However if the network remains in a bad state more the 60% the throughput decreases dramatically. It is worthy to note that this is not likely to happen [26].

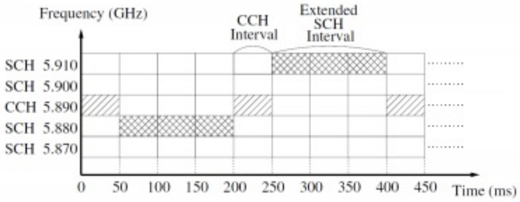

Figure 7. Extended SCH protocol

C. Best Fit Protocol

Alternatively the best fit protocol can be used to reduce the bandwidth wastage of the SCH. A transmitting node may have packets of different sizes in its output queue. Instead of fragmenting a large packet, a transmitting node can choose a smaller packet in the output queue and send it out. In this scheme, the transmitting node first checks whether the ETT of the first packet in the output queue exceeds the residual time of the current service frame. If not, it sends out the packet. Otherwise, it searches its output queue to examine whether there are packets with ETT values that are less than the residual time. If they exist, the transmitting node chooses the packet whose ETT value is closest to the residual time and sends it out, else it does not send out any packet in the residual time. One possible problem with this scheme is that packets of the same flow may become out of order when they arrive at the receiving node. However TCP can reorder received packets to restore the original order, for applications that use UDP and are sensitive to packet reordering their own packet reordering function has to be implemented [25].

D. Effective CCH channel distribution

IEEE 802.11p is a contention based protocol that has low channel utilization under heavy traffic load, because all the channels compete for transmitting in one CCH. We adopt a Distributed Channel Assignment Scheme (DCAS) to increase the successful rate of channel reservation and avoid hidden terminal problem to increase channel utilization. DCAS: The CCH interval is divided into two periods, reservation period and safety period. Vehicles reserve one or more service channels in reservation period and the safety period is used to transmit control messages and safety messages, including acknowledgment of reservation and one-hop neighbors information. Both periods are further partitioned into the same number of slots. But slots in different period have different sizes because reservation messages are smaller than control messages and safety messages. The SCH interval is also divided into several slots for data transmission. Every vehicle maintains two tables. One is neighbor table which records vehicles within two hops in reservation period and safety period. The other is reservation table that records occupied slots of every SCH in data exchange period. When a vehicle newly joins a network, its neighbor table is empty. The vehicle listens to CCH for a whole sync interval to collect information of its two-hop neighbors. Since every vehicle adds its one-hop neighbors map into safety messages, vehicles can collect the information of two-hop neighbors. After collecting information, the vehicle knows the users in every slot in both periods. Therefore, the vehicle randomly chooses idle slots in reservation period and safety period. Because of the same number of slots in both periods, each vehicle will select the same slot number for the reservation period and safety period.

E. Emergency State Transition Mechanism

Delay in the delivery of safety messages is not tolerable, in the current architecture if an emergency situation occurs during the safety interval, the safety message has to wait till the end of current service frame and will be delivered in the next control frame. Emergency State Transmission mechanism protocol is proposed as a remedy to this problem. Emergency state transition mechanism has three states which are normal state, emergency sender state, and emergency receiver state. Normal state is the initial state of a vehicle. In this state, vehicles operate the proposed DCAS scheme. When a vehicle detects emergency events or run into an accident, it will enters the Emergency sender state. It will send safety messages in the reserved slot in safety period to alert other drivers. When a vehicle receives a emergency or safety messages, it will enters the Emergency receiver state and then it broadcasts emergency messages in reservation period and broadcast safety messages in safety period. Vehicles in both emergency sender/receiver states will send safety messages with a flag to indicate that they are in emergency states, where the flag is used to record vehicles identifies. In CCH interval, we reserve the last slot in safety period for vehicle that changes to emergency sender state to transmit emergency message if it had passed its slot. In SCH interval, vehicle cannot communicate with all the other vehicles because they use different service channels. For the reason, vehicle waits for the next sync interval to transmit the emergency message in its own slot in reservation period and safety message in safety period.

F. Variable CCH Interval (VCI)

In a Contention based mechanism, the current WAVE MAC is intuitively questioned on its capability of supporting either delay- or throughput- sensitive applications. In a congested vehicular traffic condition, the limited length of CCH is unable to provide sufficient bandwidth to deliver a large amount of safety packets and control packets. On the other hand, if the node density is sparse, the occasional transmission on the CCH channel will waste the channel resource, whereas some large bandwidth consuming applications, such as video download and map update, cannot obtain sufficient bandwidth resources on the SCHs. In this protocol The CCH interval is further divided into safety interval and WAVE service announcement (WSA) interval. The optimal CCH interval is derived to improve the saturation throughput of SCHs while ensuring the transmissions of safety information and private service advertisements on CCH. The CCH interval is further divided into the safety interval and the WSA interval. A new CCH interval begins from the safety interval, during which WAVE nodes transmit safety information and broadcast the VCI packets. During the WSA interval, service providers broadcast WSA packets and piggyback with service information and the identities of SCHs to be used. Nodes that need the service can optionally respond to the WSA packet with an acknowledgement (ACK). Furthermore, a service user can initiatively send a request for service (RFS) packet to make an agreement with a service provider. After the end of the CCH interval, nodes tune to certain SCHs to transmit service packets. VCI scheme can adjust the ratio between the CCH interval and the SCH interval according to the network condition, at the beginning of the CCH interval, the RSU broadcasts a VCI packet containing the length of the CCH interval to the nodes under its radio coverage range. Furthermore, a sufficient length of CCH interval should ensure successful transmission of safety packets, as well as WSA packets under the coverage range of the RSU. The optimized CCH interval is calculated by RSUs, which need to collect the current vehicular environment, including the number of nodes within their coverage range. However, the CCH intervals announced by different RSUs may be variable. In this case, nodes that receive different values of CCH interval should adopt the longest CCH interval to ensure the transmission of safety information.On the other hand, when a node tends to communicate with another node within a neighbor RSU that has a different CCH interval, this pair of nodes should select the longer CCH interval. Moreover, when no RSU can be detected, nodes within one hop will choose a leader to perform the VCI packet broadcast. The smallest ID mechanism is a simple but effective leader selection strategy. Alternatively, only the nodes that act as service providers can broadcast the VCI packet. As the WSA packets broadcasted by service providers during the WSA interval contain the basic service

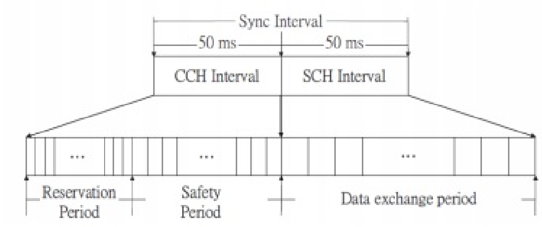

Figure 8. Distributed Channel Assignment Scheme

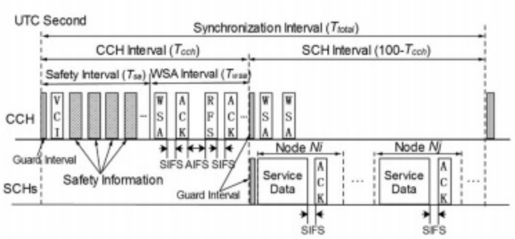

Figure 9. Variable CCH interval

```
Result: CCH Interval
// Executed by nodes at the beginning of the CCH interval
//$CIcurr$: CCH interval of the current-synchronizing cycle
//$CIprev$: CCH interval of the previous synchronizing cycle
//$CIwsa_f$ : CCH interval announced in the WSA/RFS/ frame
//$CIvci_f$ : The CCH interval announced in the VCI frame
//Set the default CCH interval
if $CIprev! = 0$ then
    $CIcurr = CIprev$
end
else
    $CIcurr = 50ms$
end
// Update the CCH interval when receiving the VCI frame
if receive a VCI frame then
    if it is the first time receiving a VCI frame then
        Update the $CIcurr$
        else if $CIcurr < CIvci\_f$ then
            $CIcurr = CIvci\_f$
        end
    end
end
// Update CCH interval when receiving the WSA/RFS/ACKframe
if receive a WSA/RFS/ACK frame then
    if have not yet received a VCI frame then
        Update the $CIcurr$
        else if the WSA/RFS/ACK frame is from the node will connect to then
            // Under different RSUs
            if $CIcurr < CIwsa\_f$ then
                $CIcurr = CIwsa\_f$
            end
        end
    end
end
```

set identity (BSSID) information the service provider with the smallest BSSID will transmit the VCI packet[24].

G. CCH Ensurance

One of the main reasons for having a vehicular network is to reduce the number of accidents on the road so it is essential to ensure that the CCH messages arrive at the intended target. There have been a number of protocols designed for this assurance. In order to ensure the message arrival the network must control the congestion of the channel. To control the channel congestion the mechanism responsible for broadcasting the network such as an RSU or another vehicle will listen to the network and estimate the number of neighboring nodes and adjust its transmission power and frequency. It will adjust transmission power for sparse traffic and adjust frequency for more dense traffic. This method reduces the number of frames that are sent over the air. The problem with this is that due to the ever changing nature of a vehicular environment and the time needed for the node to estimate and adjust the signal could make the adjustment unnecessary. In other words a vehicle could move beyond the point in which the message was adjusted for. In order to mitigate the above scenario a Piggybacked Acknowledgment protocol (PACK) has been designed. The basic concept behind this protocol is to calculate the performance of the network by piggybacking ACK information from nearby vehicles. It then calculates a failure score based upon how many positive ACK and negative ACK and the total number of feedback messages it collected from other vehicles. The score provides an accurate account of the broadcast reception ratio and provides a quicker analysis of the network and faster adjustment of the transmission signal. The CCH messages can further be ensured by sending multiple transmissions within the same broadcast time frame. Given that most messages sent over the CCH are only about 50 Bytes a node can send over another message without degrading the communication quality. This process is known as the ECHO protocol. The ECHO protocol works as follows:

1) If the message is a routine message and is not a duplicate message it has heard before it will send this message along with its own message in the same timeframe.
2) If the message was generated by an event such as a car accident and the message was sent in the last 100 ms then the message the message will be sent regardless if it has already transmitted this message before.

The goal of the above scenario is to ensure that safety messages arrive at their destination. The disadvantage of this of course is that overhead is increased and could slow the network traffic down [16].

H. Choosing Least Interfered SCH

WAVE suggests each provider to choose the least interfered SCH for delivery in its WBSS (Wave-mode Basic Service Set), but doesnt specify how performing this choice, it only suggests to measure the congestion level of the SCHs by monitoring WSAs received on the CCH from providers in visibility, this provides the vehicle with the SCH information of all the one-hop neighbor providers but can be aware of potentially interfering 2-hop neighbors due to lack of visibility. CRaSCH(Cooperative Reservation of SCH) , its a gossip-based reservation mechanism that relies on co-operation among nearby providers. Two types:

1) *Pro-active-Gossiping*: Every provider advertises in enhanced WSA frames the information about its own SCH and the SCHs reserved by nearby providers whose WSAs have been heard.The Channel Gossip field only accounts for 1-byte overhead, i.e., 2 bits for the Gossip-Type subfield and 6 bits for the SCHBitmap. The first subfield refers to the WSA frame type (WSA or CCW, as clarified in the following); the second subfield indicates the current occupancy status of every SCH, as perceived by the provider sending the WSA. Specifically, a bit 1 in position i, i = 1, . . . , 6, of the bitmap signals a busy status for the i-th service channel, while a bit zero means that the channel is not in use by any provider.

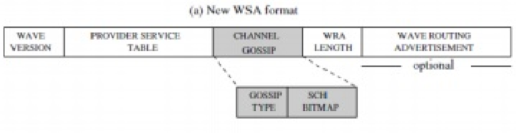

Figure 10. New WSA

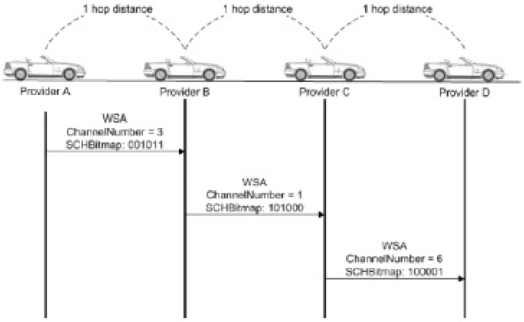

Figure 11. Pro-active Gossiping

2) *Reactive-Gossiping*: In addition to the Proactive gossiping, here when the provider reacts to a detected SCHoverlapping event by sending a collision warning frame, which triggers the SCH change by one (or more) providers. Here we use CCW(Channel Collision Warning) instead of WSA; CCH is an enhancement to the enhanced version of WSA used in the proactive gossiping. It has a 3-bit long UnsafeSCHid and a 6-byte long OwnerId subfields. The first one contains the identifier of the SCH that has been selected by two or more providers; the second subfield refers to the MAC address of the provider that has been considered by the gossip provider as the owner of the advertised SCH1. The owner is the provider which has been heard by the gossip provider as the first sender of the WSA frame reserving the channel.

In order to ensure the CCW frame to seize the channel before any other transmission, CRaSCH assigns it a higher priority than the WSA frame, but lower than the safety messages carried over the same CCH[12].

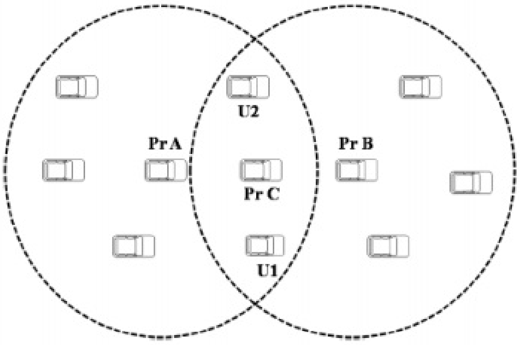

Figure 12. Proactive Gossiping-fail

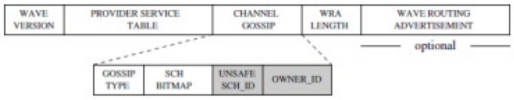

Figure 13. CCW format

I. RAMC Protocol

Increasing the infrastructure of the vehicular network by putting multiple radios in an RSU both the CCH and SCH can operate in parallel and not sequentially. One of the radios will be dedicated to the CCH and the other radios will be used by the SCH. This allows a vehicle to operate on the service channels all the time and still receive safety messages sent over the CCH. This protocol is known as RSU-Assisted Multi-channel Coordination (RAMC). RAMC works as follows: Both channels are divided up into a contention free period (CFP) and a contention period (CP). During the CFP vehicles are individually polled and when pulled the vehicle can transmit its safety message while the other vehicles must remain silent. During the CP messages are exchanged using the distributed coordination function. Furthermore each channel has a period of time allocated for sync intervals. During the sync intervals all vehicles must send at least one safety message, the RSU will consolidate and broadcast the safety messages to all in range. Figure 14 shows the design of the CCH and SCH as described by the RAMC protocol. The broadcast is also divided into 3 different spatial regions; service, polling, and beacon. In the service area vehicles can operate in both the CCH and SCH. In the polling region vehicles can only operate in the CCH and are polled as mentioned above. Vehicles in the beacon region must stay silent during the CFP and transmit its safety message during the CP. Figure 15 shows how the space is divided up during the RSU broadcast. This protocol allows the average delivery ratio of safety messages stay above 90% and average time delay to be no more than 8ms no matter if the traffic is sparse or dense. This protocol also allows the share usage of non-safety messages to be between 80 and 90 percent even under heavy traffic conditions. The disadvantage of implementing

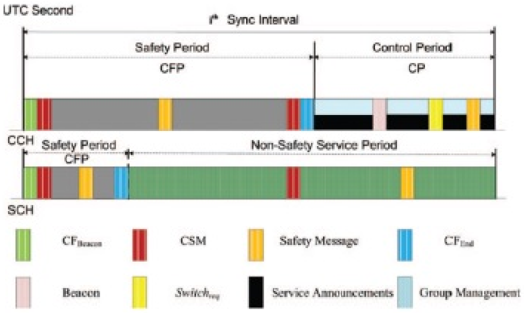

Figure 14. RAMC protocol

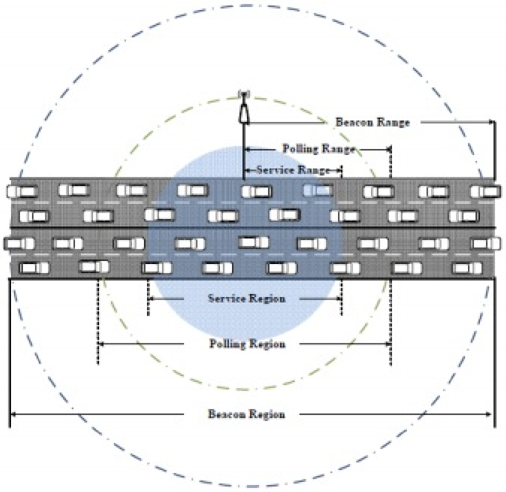

Figure 15. Spatial Division

the RAMC protocol is that it will require more hardware to be implemented and increase cost of construction. It is worthy to note that this is only a one-time cost [17].

J. Fixed Back-off Window

In wireless medium access control (MAC) protocols such as CSMA/CA, a window based backoff mechanism is used such that a node willing to transmit will sense the medium first, and if the medium is not free it will choose a backoff time uniformly at random from the interval [0,CW +1] where the initial CW value equals CW_{min}. The interval size will grow (doubled) if the subsequent transmission attempt fails until CW value equals CW_{max}. Different Arbitration Inter Frame Space (AIFS) and Contention Window (CW) values are chosen for different application categories (ACs). There are four available data traffic categories with different priorities: background traffic (BK), best effort traffic (BE), voice traffic (VO) and video traffic (VI). It can be seen clearly that voice and video traffics can be served with higher priority by picking lower backoff window size and shorter inter-frame space time. As a result, the throughput of these types of traffic can be increased by choosing small backoff window which reduces the waiting time to be served. However, sometimes the number of concurrent transmitting vehicles is large in vehicular networking environment, and hence making nodes highly aggressive will lead to low throughput due to the high probability of collision. Fixing protocol parameters usually leads to undesired performance, especially when the number of transmitting vehicles is large and backoff window size is small Solution: modifying the original IEEE 802.11p MAC protocol in such a manner that each transmitting vehicle could adjust its backoff window size in order to achieve higher throughput based on channel feedbacks. For this the 802.11p has to be modeled as a p-persistent CSMA. The main difference between the p-persistent CSMA and the original IEEE 802.11p protocol is the selection of the backoff interval. Instead of using the window based backoff mechanism, the

```
while $v$ is in  do
    if $v$ receives base stations broadcast containing the
    number of concurrent transmitting vehicles $M$ then
        Calculate $popt$
        Set $CWmin = CWmax = CW$
    else
        Use previous $CW$
    end
end
end
```

backoff interval of p-persistent CSMA is determined by the transmission probability p such that a station chooses to transmit with probability p and stays idle with probability 1 p in each subsequent time slot when the medium is sensed busy Two types of algorithms: Centralized Enhancement Algorithm Virtual Transmission Time (VT) is made up of idle times, collision times and successful transmission time. In order to achieve higher throughput, the time between two subsequent successful transmissions (VT) has to be minimized. One main assumption of this algorithm is that the base station knows the number of concurrent transmitting vehicles in the communication range and will update this information to all the transmitting vehicles by broadcasting periodically, once the vehicle receives the broadcast, it will be able to calculate the optimal transmission probability using Where L=packet size, D=length of the DIFS in terms of number of slots, M= number of vehicles, p=transmission probability of a node. The centralized algorithm is then given as For CEA implementation, certain types of road sensors or monitoring system are required to obtain the number of vehicles within the communication range. A beacon based mechanism can also be used such that each vehicle will broadcast its existence to the base station who can in turn count the total number of transmitting nodes.

K. Distributed Enhancement Algorithm

The distributed enhancement algorithm is based on the observation that when more nodes are contending for the channel, the ratio of channel busy time increases. During an observation interval, a station simply keeps counting the amount of time a channel is busy and updates the proportion of busy time at the end of observation interval. i, the station compares the current busy proportion with the previous one and computes the difference.

III. SUMMARY

This paper explored the various solutions to the 802.11p multi-channel processing as it pertained in vehicular networks. We saw various solutions to improve the channel utilization for both CCH and SCH, being able to ensure safety messages arrive at their destination, and being able to choose the least congested channel for non-safety messages. We saw the potential advantages and disadvantages of each solution. As vehicular networks become more prevalent in the real world we will be able to see if the solutions described above will be feasible for now we can only speculate as to the potential for the improvement on the 802.11p multi-channel operation.

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