Impact of IEEE 1609.4 channel switching on the IEEE 802.11p beaconing performance

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***Abstract*—The IEEE 802.11p Wireless Access in Vehicular Environment (WAVE) protocol can only transmit packets on one channel. To support multi-channel operations, channel switching procedures have been proposed in IEEE 1609.4. This paper provides an analysis of the beaconing performance of IEEE 802.11p when these channel switching procedures are used. To analyse the performance of beaconing, simulation experiments are conducted using the simulation tool OMNeT++. An overview is given of existing solutions which can be applied to minimise the impact of channel switching on IEEE 802.11p performance. An interesting observation is that present solutions focus on optimising for use of the Service Channels, and some even deteriorate the performance of the Control Channel.**

I. Introduction

Communication between vehicles is becoming a reality. These vehicular ad hoc networks (VANETs) are a key topic for research community and industry alike. Vehicular networking enables the support of traffic safety applications designed to decrease the number of accidents on the road, enable traffic management and control applications such as Cooperative Adaptive Cruise Control (CACC) [1] and entertainment or infotainment applications.

In recent years standardisation bodies, academia, and automobile manufacturers have been working together to develop VANET-based communication technologies. The IEEE has defined amendment IEEE 802.11p [2] for vehicular networks, also called Wireless Access in Vehicular Environments (WAVE). WAVE defines the minimum set of specifications that are required to ensure interoperability between wireless devices. This amendment describes the functions and services that allow an IEEE 802.11p-compliant device to communicate directly with another such device [3]. 802.11p specifies the physical and Medium Access Control (MAC) protocol layers for single-channel operations [2]. Therefore IEEE has also specified the IEEE 1609.x family of standards, which defines the functionality of the other WAVE protocol layers. In particular, the IEEE 1609.4 specification [4] is currently a trial-use standard and specifies multi-channel operations on top of IEEE 802.11p. It implements multi-channel operations by dividing the available access time between a Control Channel (CCH) and Service Channels (SCH) into intervals of 50ms. The time division between CCH and SCH specified by IEEE 1609.4 could affect the IEEE 802.11p beaconing performance.

The CCH is used for the periodical dissemination of control information. The procedure used by the CCH for the dissemination of this control information is denoted as beaconing, where short status messages, also referred to as Cooperative Awareness Messages (CAM), are broadcast. Moreover, the CCH is also used for the dissemination of traffic safety related information event messages. The SCHs are used to disseminate non-critical information for infotainment applications.

The information in the beacons is used to build a cooperative awareness in all VANET nodes, from which many applications can draw their inputs. In order to achieve this, each node broadcasts beacons to all the other nodes in range. These beacons contain information such as the GPS (Global Positioning System)-location, speed and acceleration of the vehicle. Since a VANET is dynamically changing, the beacons need to be sent frequently in order to maintain an accurate awareness of the environment. This is necessary because the safety-related applications need real-time information to operate. However, if the channel becomes overloaded the probability of beacon collision increases, reducing the influx of successfully received beacons and increasing delay. In this case queue-buildup may occur. When the buffer in a node is full and one or more new packets need to be queued, several queuing mechanisms can be used to drop and enqueue packets from/into the full buffer.

In this research, two well-known buffer mechanisms are used to drop and enqueue beacons from/into the buffer, namely the Oldest Packet Drop (OPD) and Newest Packet Drop (NPD), see e.g. [5]. With OPD, the oldest beacons in the full queue are dropped, when one or more new beacons arrive. With NPD the newest beacons, which contain the newest information, are dropped from the full queue, when one or more new beacons arrive. This is the tail-drop policy employed in most implementations.

This research investigates (1) the impact of the channel switching procedures on the beaconing performance, and (2) solutions that can minimise this impact.

The main research question in this paper is: How can the impact of channel switching procedures specified in IEEE 1609.4 on IEEE 802.11p beaconing performance be minimised?.

This paper is organised as follows. Sec. II provides an overview of the specifications of IEEE 802.11p and IEEE 1609.4. In Sec. III an overview of the simulation experiments is given in which the impact of the channel switching procedures is evaluated. Sec. IV provides an overview of the solutions that are designed to minimise the impact of the IEEE 1609.4 channel switching procedures on the IEEE 802.11p performance. A discussion is provided in Sec. V. Sec. VI concludes and provides recommendations for future work.

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II. Beaconing and Channel Switching

This section provides an overview of the specifications of IEEE 802.11p and IEEE 1609.4.

A. IEEE 802.11p Beaconing

In 1999, the U.S. Federal Communication Commission allocated 75MHz of Dedicated Short Range Communications (DSRC) spectrum in the frequency band 5.85-5.925 GHz for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [6]. This 75MHz band is divided in seven 10 MHz-wide channels. One channel is the Control Channel (CCH) and the remaining six channels are the Service Channels (SCHs). In Europe a 50 MHz wide spectrum has been allocated for VANETs by the European Telecommunications Standards Institute (ETSI) [7].

The IEEE 802.11p protocol is an amendment of the IEEE 802.11 specification, standardised in 2010 [2]. IEEE 802.11 establishes and maintains the communications in a Basic Service Set (BSS). IEEE 802.11p has been developed to simplify the BSS operations in an ad hoc manner for vehicular usage. The overhead of IEEE 802.11 connection setup, like multiple handshake, is too expensive to be used in VANETs. Therefore IEEE 802.11p introduces Wave BSS (WBSS). A node broadcasts one message, a demand beacon [6]. This demand beacon contains all information needed by receiving nodes to understand what services this node supports and how to configure itself to join the WBSS, such that other nodes can join the WBSS without further actions. Within a WBSS nodes exchange beacons using the Wave Short Message Protocol (WSMP) to create a cooperative awareness. Beacons are small messages, which contain a message as defined by the European ITS VANET Protocol (EIVP), with approximately 400 bytes of information, including security fields [8]. Beacons contain information like position, speed, acceleration and direction of a node. They are sent on a regular interval, e.g. every 100ms, to ensure that all the nodes have an up-to-date cooperative awareness.

IEEE 802.11p uses a Medium Access Control (MAC) protocol based on the Carrier Sense Multiple Access protocol with Collision Avoidance (CSMA/CA) [5]. This means that when a node wants to send a message, the channel has to be idle for a duration of an Arbitration Inter-Frame Spacing (AIFS) period. If the channel is idle it starts transmission. When it finds the channel busy, it chooses a random backoff time from the interval [0, CW] and transmits only when the backoff timer has elapsed. The variable CW represents the size of the Contention Window. When the SCH is used and a node does not receive an acknowledgement for a message, it concludes that the message has collided and is lost, so the value of CW is doubled and it will retry transmission. In the CCH however, beacons are broadcast in the channel and no acknowledgments are sent [5]. This means that the value of CW is never doubled in the CCH.

The IEEE 802.11p protocol specification also supports Quality of Service (QoS) differentiation [2] by using the Enhanced Distributed Channel Access (EDCA) from the IEEE 802.11e standard, see e.g., [5]. EDCA can classify beacons based on four access categories (ACs); background traffic (BK), best effort traffic (BE), voice traffic (VO) and video traffic (VI). Differentiation between the categories is accomplished by choosing different values for the channel access parameters. The default parameter settings used in IEEE 802.11p can be found in Table I.

AC	CWmin	CWmax	AIFSN
VI	3	7	2
VO	3	7	3
BE	7	225	6
BK	15	1023	9

TABLE I
Parameters in EDCA [2]

Voice and video traffic are treated with a higher priority, by using a lower minimum and maximum backoff timer (CW) compared to the other categories. Lower priority traffic has to perform carrier sensing for a longer time, so it can happen that higher priority traffic has already claimed the channel. When using EDCA, for every AC one transmission queue is used. This transmission queue is using the First-in, First-out (FIFO) scheduling mechanism in combination with a tail-drop policy, i.e., NPD queuing mechanism. If there is no room in the queue for a newly arrived packet, this newly arrived packet is dropped [5]. This is a very undesirable situation, since it means that older packets are kept and new packets are dropped. In case of beaconing, the information carried by the newly arrived packets is much more important than the information carried by the older arrived packets. The Oldest Packet Drop (OPD) [5] mechanism addresses this issue by dropping the oldest packet when the queue is full and a new packet arrives.

B. IEEE 1609.4 Multi-Channel Operations

The IEEE 1609.4 specification was first published in 2006 as a trial-use standard. Over a period of two years prototypes were built from the IEEE1609.4 standard and experiments were conducted. Currently, issues found in the trial period are processed and the standard was updated accordingly by the IEEE 1609.4 standardisation committee [9]. The goal of IEEE 1609.4 is to provide multi-channel access to single-radio IEEE 802.11p devices. It describes multi-channel operations as channel switching and routing, and controls the division between the CCH and SCH of IEEE 802.11p. IEEE 1609.4 describes the concept of a time-division protocol, where time is divided in CCH and SCH intervals [4], see Fig. 1 . For safety messages, a messaging rate of 10Hz is sufficient, so the intervals of CCH and SCH are both 50 ms long.

If two or more devices want to exchange data on the same channel, time synchronisation is needed. In IEEE 1609.4 CCH and SCH intervals are synchronised to an external time reference, the Coordinated Universal Time (UTC) [4]. UTC is often provided by the Global Positioning System (GPS). If a device however is not capable of retrieving the UTC, it should get time information from other devices over the air. This is

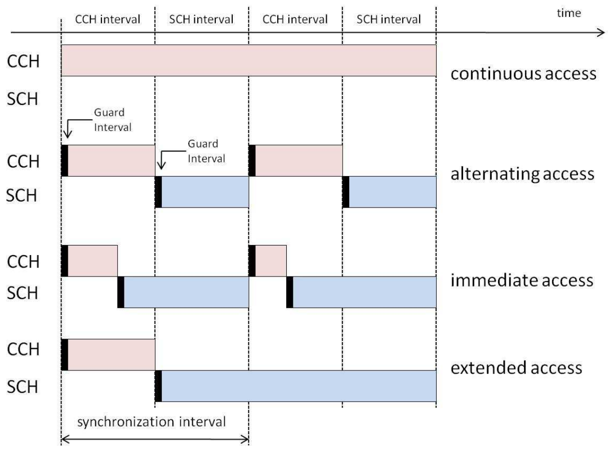

Fig. 1. continuous channel access in IEEE 802.11p, alternating channel access in IEEE 1609.4, and the immediate and extended access schemes [7]

possible by using Wave Time Advertisements frames (WTA), which is available in the IEEE 802.11p specification [2]. WTA frames contain the time of the sending node. The CCH interval starts at a multiple of 100ms after the UTC second boundary.

IEEE 1609.4 defines a Guard interval at the begininng of both the CCH and SCH, see Fig. 1. The Guard interval gives the node time to switch its radio and account for any time differences between the nodes. The value of the guard interval is defined as *SyncTolerance* and *MaxChSwitchTime* [4]. *SyncTolerance* is the expected precision of a node's internal clock compared to the UTC. *MaxChSwitchTime* is the time a node needs to tune its radio to another channel. Typical values for the guard interval are between 4 and 6 ms, resulting in an effective channel availability of 44 to 46 ms per 100 ms interval. During the guard interval nodes are not allowed to send or receive data so all on-going traffic is suspended. Also, a medium busy is declared by the radio to make sure that nodes are not going to transmit simultaneously at the end of a guard interval. When the guard interval is over, all transmissions must first wait for the random backoff. After this the node starts new communication activities on the new channel or resumes any suspended transmissions for this channel.

III. Evaluation of IEEE 802.11p Beaconing under IEEE 1609.4 Channel Switching Constraints

This section provides an overview of the simulation experiments in which the impact of the IEEE 1609.4 channel switching procedures on the beaconing performance is analysed.

A. Simulation Environment

The simulations are executed in OMNeT++[1] in combination with MiXiM[2]. OMNeT++ is an open source discrete event simulation environment which can be used for modelling communication networks. MiXiM is used as an expansion for OMNeT++ to implement wireless and mobile networks. With OMNeT++ and the MiXiM framework the IEEE 802.11p and the IEEE 1609.4 multi-channel operations are implemented.

In the experiments it is assumed that all the nodes are within each others range and their position does not change. All nodes are visible to each other so in this situation no hidden terminals exist. The nodes are uniformly distributed in an area smaller than the communication range. Due to the simplified propagation model, relative position and distances between nodes have no impact. Also it is assumed that the communication channel is a perfect channel, so no bit errors can occur during transmission. This means that packets can only be lost during a collision. This is not how VANETs will operate in the real world, but it gives insight on the beaconing performance when different buffering/queuing-mechanisms and different channel switching methods are used, in other words, it isolates MAC-layer issues.

1) Simulation Scenarios: Two main simulation scenarios/modes are used and analysed in the simulation experiments. The scenario that implements the operation of the CCH as defined in IEEE 802.11p, where a node resides 100% of the time on the CCH for beaconing is denoted as *continuous* scenario. The scenario wherein a node switches every 50 ms between the CCH and the SCH, as specified in IEEE 1609.4, is denoted as *alternating* scenario, as illustreted in Fig. 1.

2) Simulation Parameters: The simulation experiments are performed using the following parameters:

Beacon generation rate: For safety messages it is assumed that 10 messages per second are sufficient to provide a Cooperative Awareness [10]. This generation rate is also sufficient to operate a CACC system [1]. In the continuous scenario the generation of beacons is randomly drawn from a uniform distribution $[0, 100\text{ms}]$. In the alternating scenario beacon generation is restricted to the CCH guard and CCH periods, minus the duration of one transmission. In this case it is drawn randomly from a uniform distribution $[0, T_{cch} - T_s]$. Here T_{cch} stands for the CCH interval time, namely 50 ms. and T_s for the duration of the transmission of a single beacon frame, see [7]. This method is similar to the one used in [11]. It is not necessary to model traffic in the SCH, because they have separate transmission queues [4].

Data rate: A data rate of 3 Mbit/s is used for all nodes, the lowest data rate defined in IEEE 802.11p. Given the critical nature of the communicated information, the most robust modulation is assumed.

EDCA class: EDCA class 0 (Background traffic, see Table I) is used in the simulations. The EDCA 0 class has the largest contention window CWmin, namely 15, see Table II. This gives transmitted beacons the smallest probability of collisions due to simultaneous expiration of backoff counters, see [8].

Scheduling: There exist two popular scheduling mechanisms, namely First-In, First-out (FIFO) and Last-in, Last-out (LIFO). In a FIFO scheduler packets are transmitted in the order as they arrived. On the contrary, with a LIFO scheduler newly arrived packets are transmitted first. From [5] it can be concluded that it does not really make any difference which of the two mentioned scheduling mechanisms (LIFO or FIFO)

[1]http://www.omnetpp.org
[2]http://mixim.sourceforge.net

Parameter	Value
Beacon generation rate	10Hz
Data rate	3Mbit/s
EDCA class	AC0
Beacon size	400 bytes
CWmin	15
Scheduling	FIFO
Simulation time	200s

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Number of nodes	[10, 20, 30, 40, 60, 80, 120, (160, 200 only for continuous mode)]
Queue size	[1, 2, 5]
Buffering method	[NPD, OPD]
Mode	[continuous, alternating]

TABLE III
VARIED PARAMETERS

is used. For this reason a FIFO scheduler is used in the simulations as this is also the standard scheduling mechanism used in EDCA.

Number of nodes: The simulations are performed using a varied number of nodes to simulate different vehicle densities. The number of nodes ranges from 10 to 120 nodes, where 120 nodes is a realistic number of nodes in range during rush hour on a highway. Note that for the continuous scenario 160 and 200 nodes were also considered.

Buffering mechanism: To analyse which buffering mechanism performs best, OPD and NPD, see [5], are compared.

Propagation model: To focus on MAC-layer behaviour, a Unit Disc propagation model is used, and all nodes are in range, meaning there is no attenuation.

The freshness of a received beacon depends on several components, such as queuing delay, contention delay and transmission delay. In these experiments all generated beacons have the same length, so the transmission delay becomes a constant. Because of the fact that all nodes in a VANET are relatively close to each other, the propagation delay is negligible. Parameters not listed in Table II or III can be found in the IEEE 802.11p [2] or IEEE 1609.4 [4] specifications.

B. Performance Metrics

To analyse the beaconing performance, multiple performance metrics can be used. The following subsections describe the performance metrics used in this research.

1) Reception Probability: This metric indicates the probability that a beacon, once transmitted, is successfully received. As more nodes in the system exist, the more beacons are broadcast on the CCH channel per second. As the load on the channel increases, the collision and dropping probabilities increase. The reception probability is calculated by measuring the total number of received beacons and dividing it by the total number of generated beacons.

2) End-to-end delay (freshness): As the load on the channel increases, the channel becomes more congested and so the contention delay increases. It is important that the end-to-end delay of beacons is not too high in order to make sure that nodes receive fresh information. To compute the delay of beacons, the sending node adds a timestamp to the beacon when it begins contention for this beacon. In the experiments, all nodes use the same clock, so their timers are perfectly synchronised. In this way the receiving node can subtract the timestamp of the received beacon from the time of reception in order to compute the beacon end-to-end delay or freshness. The average end-to-end delay is calculated by summing up the end-to-end delays of all beacons received by all nodes and dividing it by the total number of received beacons.

C. Simulation Results and Analysis

In this section the results of the simulation experiments are reported. The simulation experiments are performed using the method of independent replications. No results are collected during the warmup-period. The calculated 95% confidence intervals are smaller than 5% of the shown calculated mean values, and are omitted from the plots for readability.

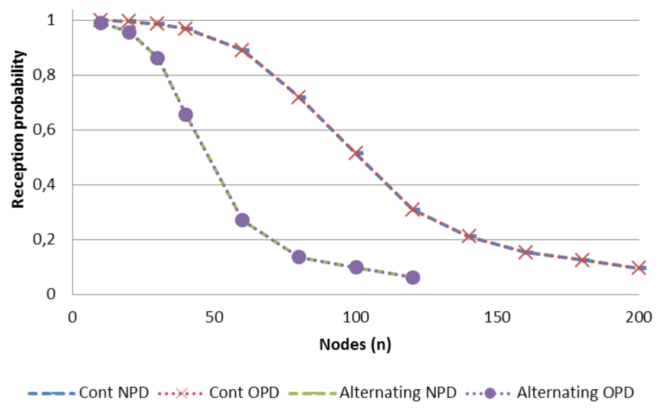

Fig. 2. Reception Probability for continuous and alternating scenarios, with OPD and NPD for queue length of 1

1) Reception Probability: As discussed earlier, the load on the channel increases as the number of nodes increases. This results in more collisions and increased dropping probability.

In Fig. 2, the reception probability is plotted against the number of nodes for a queue length of 1, when (1) both the buffering mechanisms, OPD and NPD and (2) both continuous and alternating scenarios are used. It can be seen that there is no difference in reception probability for the two studied dropping mechanisms, OPD and NPD, because the lines overlap. An explanation for this result is that the circumstances in the simulations with respect to the channel load are equal; all frames suffer from the same collision probability and queue drop as other frames, no matter how old the frame is. Also, the dropping of frames due to a full queue was only observed for the alternating scenario with a queue size of 1. This resulted in at most 6% loss for 120 nodes.

On the other hand, the use of the continuous or alternating scenario has a significant impact on the reception probability. It

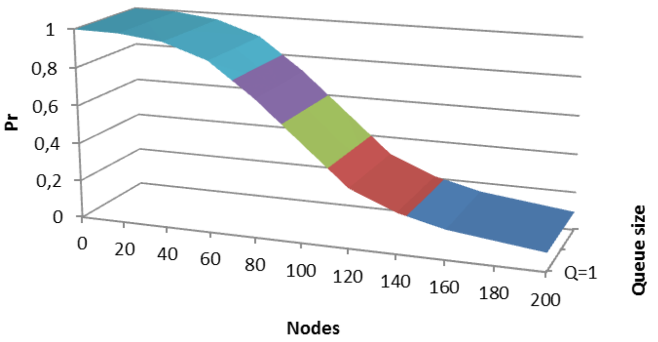

Fig. 3. Reception Probability for continuous scenario, with NPD and varied queue length and number of nodes

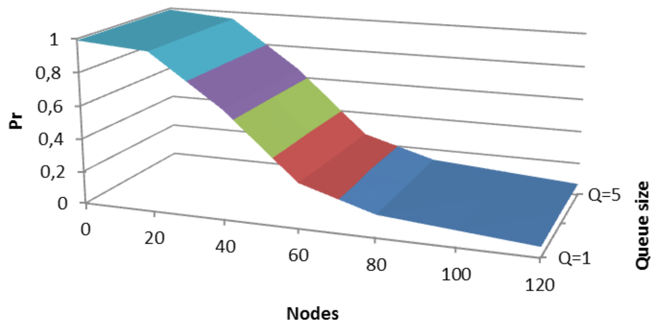

Fig. 4. Reception Probability for alternating scenario, with NPD and varied queue length and number of nodes

was shown in [12] that CACC (an application with particularly steep requirements) becomes less effective with reduced influx of fresh beacons into the Cooperative Awareness, where 8 Hz seems to be the minimum rate at which beacons must be received in order to keep acceleration over- and undershoot acceptable [12].

In the alternating scenario, the reception probability is lower than in the continuous scenario, starting from a topology with 10 nodes. This observation was expected and is due to the fact that the effective load on the channel significantly increases when the alternating scenario is used, since a node has to transmit the same number of beacons in less than halve the time compared to the continuous scenario. This results in a reception probability which appears to decrease twice as fast for the alternating scenario. Or in other words, alternating between CCH and SCH dramatically reduces scalability of a beaconing system when compared to continuous access.

Figures 3 and 4 show the reception probabilities for all number of nodes and queue sizes for the continuous and alternating scenario respectively. From these figures, it can be concluded that the queue size has a negligible effect on the reception probability. A node sends only 10 beacons per second. As long as the channel is not saturated a node can transmit its beacon before arrival of the next, so the buffer hardly contains more than one beacon. As mentioned above, frames were only sporadically dropped in the alternating scenario for a queue size of 1 with large number of nodes. Therefore, the buffer size and its effect on the dropping of frames does not affect the reception probability, the impact for Q=1 is barely visible in Fig. 4.

2) End-to-end delay (freshness): Fig. 5 plots the average end-to-end delay against the number of nodes, for a queue size of 1 and when (1) both the buffering mechanisms, OPD and NPD and (2) both continuous and alternating scenarios are used. As expected, the average beacon end-to-end delay increases as the number of nodes increases. In the alternating scenario, the average end-to-end delay increases much faster than in the continuous scenario. This is because in the alternating scenario nodes have to send the same number of beacons in less than halve the time, resulting in a much larger congestion of the channel. Also, it can happen that a beacon arrives in the

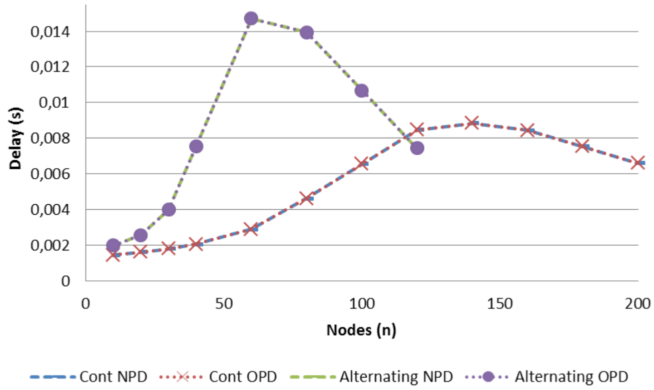

Fig. 5. Freshness: the average end-to-end delay for queue length 1

queue and has to wait for the next service interval to finally be transmitted.

Again the buffer mechanism, OPD or NPD, does not have a significant impact on the average beacon end-to-end delay.

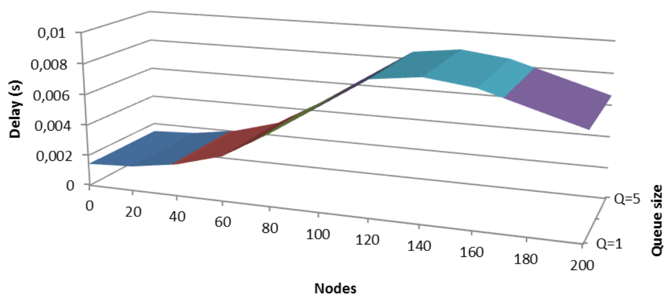

Fig. 6. Freshness: the average end-to-end delay for the continuous scenario with NPD, varied queue size and number of nodes

Surprisingly, for the alternating scenario the end-to-end delay decreases as the number of nodes is greater than 60. The delay is even lower for the alternating scenario compared to the continuous scenario when more than 120 nodes are using the channel. This effect can be explained if the results are compared to the results presented in Fig. 2. Only packets that are received successfully have an end-to-end delay. This means that, due to the congestion of the channel, only the beacons with a small end-to-end delay will complete transmission. The result is a decrease of end-to-end delay, but fewer beacons complete transmission. The same effect also occurs for alternating mode, as seen in Fig. 5, but at a much larger value of n. This means the saturation point of the channel is shifted. The continuous scenario uses the available channel resources more efficiently and therefore congestion occurs later.

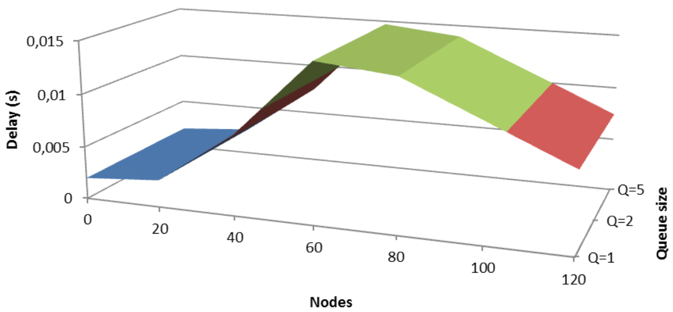

Fig. 7. Freshness: the average end-to-end delay for the alternating scenario with NPD, varied queue size and number of nodes

In Figures 7 and 6 the total delay for continuous and alternating mode is shown with a varied number of nodes and queue lengths respectively. Again, it can clearly be seen that the queue length has little influence on the delay.

From the simulation experiments, it can be concluded that in general the continuous scenario performs better than the alternating scenario for both Reception Probability and End-to-end delay.

IV. Minimising IEEE 1609.4 Channel Switching Impact

As clearly visible in the simulation experiment results, using the channel switching specified in IEEE 1609.4 has a negative impact on the IEEE 802.11p beaconing performance. The reception probability decreases and the average end-to-end delay increases. In order to increase the performance under channel switching, several solutions have been proposed in literature. This section gives an overview of such solutions.

It is important to notice that to the best knowledge of the authors of this paper, no solutions could be found that focus on minimising the impact of the IEEE 1609.4 channel switching on the CCH performance, all methods focus on optimising for the SCH.

For example, studies in e.g., [7], [3], [13], [14], consider that the standardised IEEE 1609.4 channel switching scheme causes a bandwidth wastage problem for the SCH. The argumentation is the following. When a packet transmission is going to take place at the end of the SCH interval and the estimated transmission time for this packet exceeds the residual time of the current interval, then the IEEE 1609.4 standard recommends that the transmitting node should prevent sending out this packet during the current interval but instead should send it during the next interval, leaving the end of every synchronisation interval underutilised.

In order to decrease the impact of the bandwidth wastage problem on the SCH, several alternative schemes have been researched, which will be briefly described in the following subsections.

A. Immediate and Extended Access

Two different channel switching schemes have been proposed in [7] to minimise the SCH bandwidth wastage problem. These scheme are the Immediate Access and the Extended Access, see Fig. 1. These schemes improve the performance of bandwidth-demanding non-safety applications in the SCH at the cost of the CCH.

When the Immediate Access scheme is used, the node does not have to wait until the CCH interval is over. It can switch to the SCH once the CCH has completed its transmissions and can stay there until the synchronisation interval is over.

The Extended Access scheme allows transmissions on the SCH without waiting for the CCH. This sacrifices CCH performance for the SCH. These schemes do not focus on minimising the impact of channel switching on the IEEE 802.11p beaconing (i.e., CCH) performance.

B. Fragmentation Scheme

The Fragmentation scheme [14] is designed to decrease the impact of the bandwidth wastage problem on SCH. This is accomplished by using packet fragmentation in order to utilise the residual time at the end of the SCH interval (i.e., service frame). The original packet that needs to be transmitted at the end of the service frame is fragmented in such way that the estimated transmission time of the first fragment is equal to the residual time of the current service frame. In this way there will be no unused time and bandwidth in a service frame. Thus mitigating the bandwidth wastage problem, at the expense of an extra header for the fragmented packet.

This scheme works for large packets (such as TCP) but is of little use when applying it to the messaging nature of beaconing, as the messages already are relatively small and exhibit some degree of robustness because reception of a beacon does not depend on reception of previous or subsequent beacons, a dependency which exists when fragmenting packets. Furthermore, given the stochastic nature of CSMA/CA channel access, it is not guaranteed this node can also use the residual time of the current service frame.

C. Best-fit Scheme

The best-fit scheme [14] utilises the remaining bandwidth by sending packets which fit in the remaining time of the service interval. In particular, the transmitting node checks the estimated transmission time for each packet that needs to be transmitted and is placed at the head of the transmission queue. If the estimated transmission time is less than the residual time in the service frame, it sends out the packet.

Otherwise, the scheme checks within the transmission queue whether there are packets whose estimated transmission time is less than the residual time. If there are such packets the scheme selects the packet whose estimated time is closest to the residual time and sends out that packet. This scheme performs better than the fragmentation scheme only if packets with different sizes are present in the queue [3]. This scheme does not minimise the impact of channel switching on the CCH performance. Moreover, this scheme is not standardised and it is hard to implement. First of all, nodes need to know the size of all the packets stored in the transmission queue in order to reshuffle the packets. Secondly, this scheme assumes a diversity of packet sizes. This may be the case in SCH packets, but beacons on the CCH are all of equivalent size. Third, it is difficult for a node to determine *a priori* the actual duration of contention plus transmission, because of the frequent changes in the channel congestion and the stochastic nature of backoff.

D. Exploitable node-assisted WBSS Broadcasting Mechanism

In [3] the Exploitable Node-Assisted WBSS Broadcast Mechanism is presented. Due to the CSMA/CA feature used in IEEE 802.11p, nodes cannot send packets if other nodes are sending packets at the same time and in the same channel. A so-called exploitable node is a node that is in SCH and is informed that another node is sending data to a Road Side Unit (RSU). The exploitable nodes can broadcast the WBSS to newly arriving vehicles, so these new vehicles can join the WBSS faster. When all idle nodes are broadcasting the WBSS simultaneously, most of the packets will collide. To prevent this from happening, a priority control is used. The WBSS coverage of a RSU is divided into a near and a far part, as illustrated in Fig. 8. Node C and D are within the near area of the RSU so they have a higher priority. Also the RSSI (Received Signal Strength Indication) and transmission power can be used to measure the distance between the RSU and the vehicles. Based on this distance a priority class from EDCA will be chosen. Vehicles that are closer to the RSU, and within the near area, will use a higher EDCA priority class than vehicles in the far area. Lower priority traffic has to perform carrier sensing for a longer time, so it can happen that higher priority traffic has already claimed the channel.

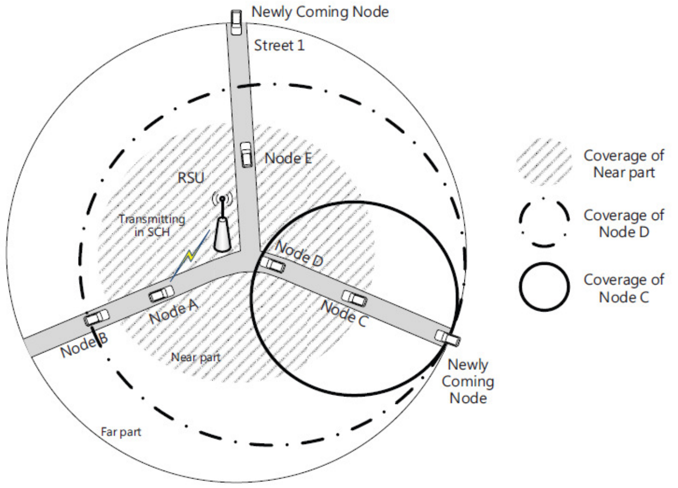

Fig. 8. Broadcast coverage of the nodes in the near area [3]

This scheme does not minimise the impact of channel switching on beaconing performance. Furthermore, it is not standardised and its complexity is high. The Exploitable node-assisted WBSS Broadcasting mechanism makes it possible for newly arriving vehicles to connect faster to a RSU. The RSU has to send fewer administrative packets and can send more useful packets. However, it comes with the cost that nodes need to calculate their relative location to the RSU. Additionally, in order to make full use of the Exploitable Node-Assisted WBSS Broadcast Mechanism all vehicles should support this mechanism.

E. Adaptive Independent Channel Switching Mechanism

While the number of nodes increases, more packets are generated and the channel could become congested. This means that the queuing and contention delay of packets increases, as the channel gets more congested. Simulation experiments in [13] indicated that for a contention window greater than 64 and a number of nodes greater then 20, the transmission times for the nodes to complete their transmissions exceeds 50 ms. This means that the CCH interval defined in IEEE 1609.4 is too short in this situation.

In [13] a channel switching mechanism addressing this issue is presented, namely the Adaptive Independent Channel Switching Mechanism (AICSM). In the AICSM all nodes can independently change their average switching time, based on the vehicle density. As soon as a node finishes its CCH transmissions and its average switching time has elapsed, it changes to the SCH. The AICSM is illustrated in Fig. 9.

In this switching scheme, the SCH performance is significantly improved, at the cost of CCH performance, for several reasons. The SCH interval will often be longer than the 50 ms specified in IEEE 1609.4. This means that more packets can be sent during the SCH transmission time, because some nodes will switch faster to the SCH than others. Also, this results in fewer collisions between packets at the start of the SCH, because the nodes switch independently of each other.

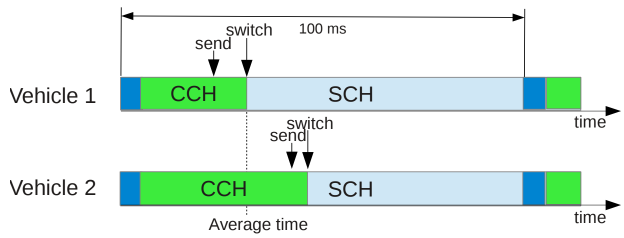

Fig. 9. The Adaptive Independent Channel Switching Mechanism [13]

This scheme does not minimise the impact of channel switching for the CCH. Moreover, this solution is not standardised. Because of the fact that nodes can independently of each other implement an adaptive independent channel switching mechanism, it is very scalable. A significant drawback is that not all nodes reside on the CCH at the same time. For instance, Vehicle 1 in Fig. 9 will miss the beacon transmitted by Vehicle 2, because it is switched to the SCH when Vehicle 2 is sending its beacon.

V. Discussion

It is interesting to note that all above-mentioned mechanisms increase SCH performance, and with exception of the Fragmentation and Best-fit scheme do so at the cost of CCH performance. In the light of beaconing performance, this can have catastrophic impact on the quality of the cooperative awareness. It should be stressed that a node not only has to transmit its own beacon, but should also be able to receive beacons sent by *all* nearby others for the concept of cooperative awareness to work, hence the synchronised "common" CCH. Accurate information on the dynamics of the vehicle in front is imperative for e.g. a collision-avoidance or a cooperative driving application to work. This fact renders Immediate Access, Extended Access, and AICSM useless in the dynamic VANET, where receiving up-to-date beacons is vital.

The problem of multi-channel access with a single-radio device while still maintaining high availability of the CCH does not exist in a dual-radio setup, where one radio is continuously tuned to the CCH and the other can be used for the SCH. Although problems with increased cost and adjacent channel interference exist [15], it is advisable to explore other solutions than alternating between channels in a time-division manner because this severely limits the capacity of a system which already is capacity-limited in dense traffic. The use of dual-radio devices is considered by ETSI [16].

VI. Conclusion and Future Work

This paper provides an analysis of the beaconing performance of IEEE 802.11p when using the channel switching procedures proposed in IEEE 1609.4. Both the continuous scenario and alternating scenario are evaluated in OMNeT++, using a varied number of nodes, queue lengths and buffering mechanisms. Also an overview is given of solutions that improve the performance under the 1609.4 channel switching procedures. Most solutions in literature are designed to minimise the impact of the channel switching procedures mainly on SCH performance, some with detrimental effects on the CCH. This is not favourable in a VANET, where an up-to-date cooperative awareness is a valuable asset for both safety and efficiency applications.

A recommendation for future work is to focus on specifying a scheme that could minimise the impact of the channel switching and improve the beaconing (i.e., CCH) performance, if needed at the cost of SCH, or to use multi-channel radios. This seems more in line with meeting scalability and dependability requirements of the applications which increase traffic performance and safety, and require a good cooperative awareness to do so.

References

[1] J. Ploeg, B. Scheepers, E. van Nunen, N. van de Wouw, and H. Nijmeijer, "Design and Experimental Evaluation of Cooperative Adaptive Cruise Control," in *Intelligent Transportation Systems (ITSC), 2011 14th International IEEE Conference on*, oct. 2011, pp. 260 –265.

[2] "Amendment 6: Wireless Access in Vehicular Environments," *IEEE Std 802.11p-2010*, pp. 1 –51, 15 2010.

[3] C.-M. Huang, C.-C. Yang, and H.-D. Huang, "An Effective Channel Utilization Scheme for IEEE 1609.4 Protocol," in *Ubiquitous Information Technologies Applications, 2009. ICUT '09. Proceedings of the 4th International Conference on*, dec. 2009, pp. 1 –6.

[4] "IEEE Draft Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-Channel Operation," *IEEE P1609.4/D9, August 2010*, pp. 1 –61, 2010.

[5] E. M. van Eenennaam, L. Hendriks, G. Karagiannis, and G. J. Heijenk, "Oldest packet drop (OPD): a buffering mechanism for beaconing in IEEE 802.11p VANETs," in *Third IEEE Vehicular Networking Conference, VNC 2011, Amsterdam, The Netherlands*. IEEE Communications Society, November 2011, pp. 252–259.

[6] D. Jiang and L. Delgrossi, "IEEE 802.11p: Towards an international standard for wireless access in vehicular environments," in *Vehicular Technology Conference, 2008. VTC Spring 2008. IEEE*, 11-14 2008, pp. 2036 –2040.

[7] C. Campolo, A. Molinaro, and A. Vinel, "Understanding the performance of short-lived control broadcast packets in 802.11p/WAVE vehicular networks," in *Vehicular Networking Conference (VNC), 2011 IEEE*, nov. 2011, pp. 102 –108.

[8] R. Reinders, E. M. van Eenennaam, G. Karagiannis, and G. J. Heijenk, "Contention window analysis for beaconing in VANETs," in *Seventh IEEE International Wireless Communications and Mobile Computing conference, IWCMC 2011, Istanbul, Turkey*. IEEE Computer Society, July 2011.

[9] Q. Chen, D. Jiang, and L. Delgrossi, "IEEE 1609.4 DSRC multi-channel operations and its implications on vehicle safety communications," in *Vehicular Networking Conference (VNC)*, oct. 2009, pp. 1 –8.

[10] E. M. van Eenennaam, W. Klein Wolterink, G. Karagiannis, and G. J. Heijenk, "Exploring the Solution Space of Beaconing in VANETs," *IEEE Vehicular Networking Conference, VNC, Tokyo, Japan*, Oct 2009.

[11] C. Campolo, A. Vinel, A. Molinaro, and Y. Koucheryavy, "Modeling broadcasting in IEEE 802.11p/WAVE vehicular networks," *Communications Letters, IEEE*, vol. 15, no. 2, pp. 199 –201, february 2011.

[12] C. Lei, E. M. van Eenennaam, W. Klein Wolterink, J. Ploeg, G. Karagiannis, and G. Heijenk, "Evaluation of CACC string stability using SUMO, Simulink, and OMNeT++," *EURASIP Journal on Wireless Communications and Networking*, 2012.

[13] L. Zhang, Y. Liu, Z. Wang, J. Guo, Y. Huo, Y. Yao, C. Hu, and Y. Sun, "Evaluating and improving the performance of IEEE 802.11p/1609.4 networks with single channel devices," in *Communication Technology (ICCT), 2011 IEEE 13th International Conference on*, sept. 2011, pp. 877 –881.

[14] S.-Y. Wang, H.-L. Chao, K.-C. Liu, T.-W. He, C.-C. Lin, and C.-L. Chou, "Evaluating and improving the TCP/UDP performances of IEEE 802.11(p)/1609 networks," in *Computers and Communications, 2008. ISCC 2008. IEEE Symposium on*, july 2008, pp. 163 –168.

[15] R. Lasowski, C. Scheuermann, F. Gschwandtner, and C. Linnhoff-Popien, "Evaluation of adjacent channel interference in single radio vehicular ad-hoc networks," *Intelligent Vehicular Communications System workshop, co-located with CCNC 2011, Las Vegas, USA*, pp. 267–271, 2011.

[16] "ETSI ES 202 663 V1.1.0 Intelligent Transport Systems (ITS); European Profile Standard for the Physical and Medium Access Control Layer of Intelligent Transport Systems Operating in the 5 GHz Frequency Band," European Telecommunications Standards Instititute, Tech. Rep., 2010.