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Decentralized Congestion Control Algorithm for Vehicle to Vehicle Networks Using Oscillating Transmission Power

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Decentralized Congestion Control Algorithm for Vehicle to Vehicle Networks Using Oscillating Transmission Power

By
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Oscillating Transmission Power Decentralized Congestion Control Algorithm for Vehicle to Vehicle Networks

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Declaration of Originality

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Abstract

Wireless access in vehicular environments (WAVE) is a vehicle to vehicle (V2V) communications technology which could help prevent up to 82% of non-impaired accidents, according to the US DOT. A 2013 study by the World Health Organization estimated 2,227 road fatalities in 2009 alone. Currently the channel that is responsible for a vehicle's awareness of others suffers from congestion at moderate loads. In this paper we propose a novel method for adjusting the transmission power in a pattern which alternates between high and low powered transmissions. We modify one commonly used decentralized congestion control (DCC) algorithm, LIMERIC, and compare the power adaptation model against two controls. WAVE supports a 300 meter transmission radius, however, less than 200 vehicles can communicate at the target rate of 10 transmissions per second. We demonstrate that our algorithm reduces the number of packets received by distant vehicles, while maintaining a higher packet rate to the closer vehicles, for which a higher rate is more important.

Dedication

I dedicate this work to my father, who always told me “If it’s worth doing, it’s worth doing right.” You taught me to think for myself and to question everything. It is because of you that I never stop asking why or how the world around us works, and for that I cannot thank you enough.

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I am grateful to have been co-supervised during my Master’s work by Dr. Bob Kent and Dr. Arunita Jaekel in addition to their guidance during my undergraduate degree. I had considered but ultimately decided against doing a Master’s degree, however after one meeting each I was convinced. Thank you both for your invaluable support during my education, and for your confidence in my work over the years.

I’ve had the chance to meet and work with some very talented people over the years and I am grateful to everyone who indulged my inquiries or directly involved me in their own research. Ian, the various resources you offered during coursework and my thesis were invaluable and I would not be in the position I am today without them. Gaurav, your persistence in solving problems and troubleshooting made working with you a very rewarding experience, at the end of the day we always found a solution. I’m hopeful we will have a chance to work together in the future.

To family and friends who have supported my enthusiasm for technology and education, thank you. Lexi Stathis, I am grateful for the encouragement and motivation you have provided me over the length of our friendship.

To my partner Hailey, your support over the last two years has meant more to me than I can describe. Your positive energy is a powerful motivator and we both know I owe a lot to that motivation.

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List of Abbreviations/Symbols

ACK	Acknowledgement Packet
BRR	Beacon Reception Rate
BER	Beacon Error Rate
BSM	Basic Safety Message
C2C	Car to Car (Communication)
CAM	Cooperative Awareness Message
CAN	Controller Area Network
CBR	Channel Busy Ratio
CCA	Clear Channel Assessment
CSMA	Carrier Sense Multiple Access
DCC	Decentralized Congestion Control
DOT	Department of Transportation
DSRC	Direct Short Range Communication
ETSI	European Telecommunications Standards Institute
EV	Ego Vehicle (perspective vehicle in scenario)
GPS	Global Positioning System
ITS	Intelligent Transportation System
LIMERIC	Linear Message Rate Integrated Control
LPPI	Low Powered Packet Interval
LPPC	Low Powered Packet Count
OBU	On Board Unit
PDU	Protocol Data Unit
RSU	Roadside Unit
RV	Remote Vehicle
SUMO	Simulation of Urban Mobility
TTC	Time to Collision
V2V	Vehicle to Vehicle (Communication)
V2I	Vehicle to Infrastructure (Communication)
V2X	Vehicle to Infrastructure/Vehicle (Communication)
WAVE	Wireless Access in Vehicular Environments

Chapter 1 - Introduction

1.1 WAVE Background

Vehicle to Vehicle communication (V2V), Vehicle to Infrastructure (V2I) and its related protocols are rapidly being adopted across North America by government and industry alike. The “p” amendment to the IEEE 802.11 protocol [1] allows for the transmission and receipt of the IEEE 1609 [2] and SAE J2735 [3] PDUs. The SAE J2735 protocol contains a V2X message set as a means of standardizing. Vehicles are equipped with devices known as On Board Units (OBUs) which connect to the vehicle’s Controller Area Network (CAN) [4] bus and enables communication between vehicles. The CAN bus is the internal network of modern vehicles and enables access to the vehicle’s various sensors and controllers. These fields are extremely useful as it allows a more accurate speed than is available from GPS. OBUs currently support GPS technology as the main source of location information, speed and heading, as CAN integration may not be possible in every vehicle.

This protocol stack as it is used by the United States Department of Transportation (US DOT) has been termed Wireless Access in Vehicular Environments or more commonly, WAVE[1]. WAVE encompasses IEEE 802.11p[1] and IEEE 802.11 at the physical layer (ISO 1). The Data link layer (ISO 2) is handled by IEEE 802.2 known as Logical Link Control. At the Network Layer (ISO 3) there is a choice of either using IP with encapsulated TCP/UDP in the Transport Layer (ISO 4), or using the Wave Short Message Protocol (WSMP) family of standards IEEE 1609 to handle both Network and Transport layers. When sending a WSMP packet, the higher layer tends to be an application packet such as the SAE J2735 message set.

In addition to the OBU there exists Road Side Units (RSU) which allow vehicles to communicate with infrastructure such as traffic lights, parking garages, construction zones and toll roads. In practice, vehicles will be alerted to the state of a traffic signal and the expected number of seconds before the state changes. This technology allows drivers to know if they are able to clear the intersection before it turns red, or if they should coast to a stop in order to improve fuel economy and vehicle wear. RSUs can also be used to assist emergency vehicles trying to travel throughout a city. Research on emergency vehicle traffic preemption at traffic lights is a perfect example of how a city's existing infrastructure and services can be improved by supporting V2V [5].

Similar to any new technology, there will be some time before it is common to find a V2V unit in a car. Market penetration is a critical factor in the performance of a V2V device and the features it supports. Messages sent between vehicles such as the Intersection Collision Avoidance message (ICA), Emergency Vehicle Alert (EVA), and other messages[3] sent between vehicles require both parties to be equipped with a V2V unit in order to be useful. Further, infrastructure points which interpret vehicle movement in order to understand the congestion state of a roadway also require vehicles to be equipped.

1.2 Motivation

The Basic Safety Message (BSM) [3] is defined by the SAE J2735 protocol and it is the message that allows vehicle to share information with nearby vehicles. Information contained in this packet includes, but is not limited to, GPS data such as latitude, longitude, speed and heading. Also available in the BSM is data from the CAN bus which is provides networking for the vehicle's 50+ onboard sensors. The type of information available from the vehicle's CAN bus are fields such as speed, RPMs, yaw rate, signal status, brake and accelerator pedal position as well as many others. These packets are processed by On Board Units (OBU) and Roadside Units (RSU) to help avoid collisions and to synchronize traffic signals among other features. Once one vehicle determines there is a high chance for a collision, it opens a direct communication channel with this vehicle in order to negotiate the best way to proceed in avoiding the accident. This feature requires vehicles to have an accurate position for a Remote Vehicle (RV) before it can detect a collision. Therefore, it is important to develop control algorithms that will allow a vehicle to maintain a high awareness level of RVs, without leading to channel congestion.

1.3 Problem Statement

The IEEE 1609 standard defines the transmit rate for the BSM packets to be 10Hz with a transmit radius defined by the FCC as 300m [6]. At this standard transmit rate, it is estimated that at 200 vehicles the channel for BSMs is 100% utilized [7]. This figure assumes perfectly scheduled back-to-back packets, therefore the real limit is much lower due to the fact that collision detection is handled by the Carrier Sense Multiple Access (CSMA) algorithm. In a congested network one observes a high frequency of packet collisions [8] and an overall degradation of vehicle awareness. A higher frequency of collisions leads to a more variable packet rate meaning a vehicle could theoretically be unable to transmit successfully if it has a high rate of collisions. A total lack of awareness means the V2V system will not be able to provide accurate and timely collision warnings. The CSMA mechanism as defined in IEEE 802.11p has been shown to be unable to provide adequate sharing of the medium at a high level of channel congestion [8].

Vehicles send their messages after sensing the channel is clear, meaning there is no fairness in which vehicles get to send and how often. Consider the situation where one vehicle probes but finds the channel busy “most of the time.” Other vehicles have no way of knowing that this vehicle is struggling to keep an appropriate transmit rate and there is no bandwidth or time to allow for this sort of communication[9]. This decentralized behaviour of the vehicles suggest that a Decentralized Congestion Control (DCC) algorithm is required to reduce congestion without adding more communication overhead. Further, there are a number of papers [9] that discuss an increase in performance upon using DCC Algorithms, the Packet Error Ratio (PER) was reduced [7] and the global fairness [10,11] of channel sharing was increased.

The situation is further complicated by the inability to verify that RVs are receiving the Ego Vehicle's (EV)'s messages. In standard IEEE 802.11 packets are received by the destined party who then acknowledges their receipt by sending a response known as an acknowledgment or ACK packet back to the sender. The extra traffic is acceptable in a situation where each packet is destined for only one receiver because this scenario only generates one ACK packet. In the case of V2V communications it is not possible to have every vehicle send ACKs to every other vehicle's beacons due to what is termed ACK Explosion [9]. For example, if an ego vehicle (EV) has 100 RVs in range, and if that EV was transmitting BSMs at 10 Hz, then in one second the EV would provoke 1000 ACK packets. In the case of a congested network, the extra packets would only further increase congestion within the network.

Our goal is to reduce the number of packets received by vehicles which are at a greater distance while maintaining a high awareness level to nearby vehicles to which our position is most relevant.

1.4 Solution Outline

The proposed solution involves alternating the power level of outgoing packets in an oscillating fashion. Using a static ratio between high and low powered packets, we will attempt to send packets less often to more distant vehicles. The intended behaviour is that the distant vehicles, which do not need updates as frequently, will receive less packets while maintaining high awareness levels in the immediate area where it is a priority. Figure 1 gives a visual example of how the two transmission powers would affect different areas.

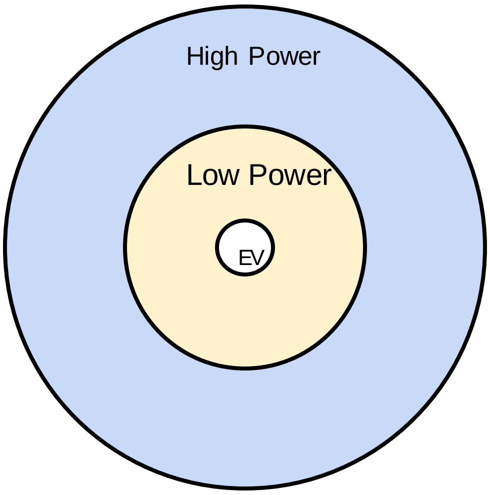

Fig. 1: Example of Packet Distance Relative to Power

The desired outcome is that remote vehicles (RV) vehicles that are farther away from the EV (Ego Vehicle) are able to observe slowed or stopped traffic at a distance. Also those RVs farther away only see a fraction of the EVs packets, reducing the channel congestion at the RVs location. As the RV gets closer it is able to see all packets from the EV restoring full awareness. This is an acceptable loss of accuracy given that the vehicles further away are less important than closer vehicles as far as the EV is concerned [12].

Simulations using SUMO [13] and OMNet++ [14] have been performed using an existing DCC algorithm (LIMERIC) which will be modified to support the oscillating transmit power level behavior as described above. Two controls have been tested in this experiment against the modified algorithm. A version of the oscillating power model was also tested on its own without the rate control algorithm, instead transmitting at 10 Hz. In the first control all vehicles will transmit at 10 Hz in order to emulate the current network conditions before any congestion control is added. The second control will be the unmodified algorithm LIMERIC [8] in order to show how the modifications effected the algorithm. The BER and Beacon Reception Rate (BRR) will be be measured and compared between the four cases. Our main goal is to increase the BRR as it is more important than BER[9] which can still stay high even with significant improvements to BRR.

Our hypothesis is that the described transmission model above will have the effect of providing more timely updates to nearby vehicles, while reducing the number of packets received by distant vehicles.

1.5 Thesis Organization

The rest of this thesis is organized as follows. Chapter 2 discusses the relevant background knowledge and previous research in this area. Chapter 3 describes our proposed DCC approach with the results analyzed in Chapter 4. Chapter 5 we conclude by discussing the meaning of the results obtained and how they relate to future research.

Chapter 2 - Background

2.1 Vehicle to Vehicle Messages

While there are a number of messages defined by the SAE J2735 protocol, the one packet sent most often is the Basic Safety Message (BSM), which has a rate of up to 10 Hz. The packet contains information about the transmitting vehicle, such as position, velocity, heading and data from the vehicle's sensors where available. The BSM allows infrastructure and other vehicles to become aware of the transmitter and react accordingly. A single channel defined in the IEEE 1609 as the target for all BSM packets.

One example of how the BSM information is used is to prevent collisions between two vehicles. As two vehicles receive each other's BSM packets, algorithms are used to determine if there is a collision imminent. The time to collision (TTC) is calculated to determine if the driver should be informed or if the collision will be avoided on its own. In the event that the TTC is sufficiently large, there is a high probability that, in that time, one or both vehicles will alter their course naturally. Once the TTC crosses below some threshold value, the driver is alerted of the dangerous situation and (where applicable) is given directions in order to avoid the accident.

2.2 Terminology

Although primarily in this paper V2V is the primary term used to describe the technology in question, many acronyms exist in this area of research with slightly different usages. In this section, we will define some of the important terminology used in the rest of the thesis.

- **Direct Short Range Communication or (DSRC)** refers generically to the usage of a short range radio technology in the Industrial, Scientific and Medical(ISM) Band.

- **Vehicle to Vehicle Communications (V2V)** and sometimes Car2Car(C2C) is similarly used to refer generically to a radio based technology that allows two vehicles to exchange communications.
- Modern cities use **Intelligent Transportation Systems (ITS)** to monitor and control traffic using historical or realtime statistics wherever possible. ITS controls infrastructure such as traffic lights and their timing, bi-directional lanes, ETA signs on highways and many other assets. For example, the city of Toronto has a center lane on some streets which can change directions depending on the traffic conditions.
- **Vehicle to Infrastructure (V2I) Communication** is another integral part of improving awareness and safety on our roadways. While a great deal of focus is put on Vehicle to Vehicle communications, an important set of features is made available by V2I. Integration of ITS with V2I leads to advanced applications, one example being adaptive traffic lights to allow priority to emergency vehicles and clear the intersection before they arrive.
- **WAVE** refers to the specific stack of protocols used in the current US DOT efforts as described above. In Europe, a similar V2V technology is being standardized by the European Telecommunications Standards Institute (ETSI), which has a similar message to the BSM.
- The **Cooperative Awareness Message(CAM)**, contains location, class and identifying information about the vehicle that transmitted it. The CAM is sent in a frequency from 1 to 10 Hz in a single hop and is the ETSI equivalent of the BSM.
- The **Basic Safety Message (BSM)** is a broadcast packet transmitted regularly at a regular interval, and it can be classified as a beacon style transmission. Where a broadcast packet is a packet destined for everyone to receive, a beacon is a continuous broadcast. The data contained in a V2V beacon is time-sensitive, as packets become less relevant as new packets are received [9]. This is because as a new packet is received from some vehicle, it is assumed to be the latest position of that vehicle.

In every BSM is what is referred to as a “blob” of data, meaning that the bytes are all packed together as they exist every time in a known fixed size. The fields selected for this part of the packet were those required to provide positional awareness to the RV. The fields can be categorized as position, motion, control and size and allow any vehicle to calculate the possible current position in the duration between beacons. The 38 byte blob is shown below in **Figure 2** as it appears in the Society of Auto Engineers (SAE) DSRC Implementation Guide[15]

```
msgCnt      MsgCount,               1 byte
id          TemporaryID,            4 bytes
secMark     DSecond,                2 bytes
lat         Latitude,               4 bytes
long        Longitude,              4 bytes
elev        Elevation,              2 bytes
accuracy    PositionalAccuracy,   4 bytes
speed       TransmissionAndSpeed, 2 bytes
heading     Heading,                2 byte
angle       SteeringWheelAngle      1 byte
accelSet    AccelerationSet4Way, accel set (four way) 7 bytes
brakes      BrakeSystemStatus,      2 bytes
size        VehicleSize,            3 bytes
```

Fig. 2: BSM Blob Definition [15]

2.3 Fundamental Concepts

In certain scenarios, it is clear that some RVs on specific roadways will be visible (but not relevant) to the EV. The most common example of this is highways that run through or along a city centre without there being an exit. In this circumstance the highway traffic and city traffic don’t need to be aware of each other (because they will never interact), but each is contributing to the channel load of the other. This visibility of undesired/unnecessary packets can cause problems, as highway vehicles may experience a degradation of awareness when driving past city centers. This problem can be framed as the pollution of a network’s medium by irrelevant packets.

The hidden node problem is a well-known scenario in wireless communications which results in a packet collision. The scenario involves two transmitters which are not in reception range of each other, and one receiver in the middle.

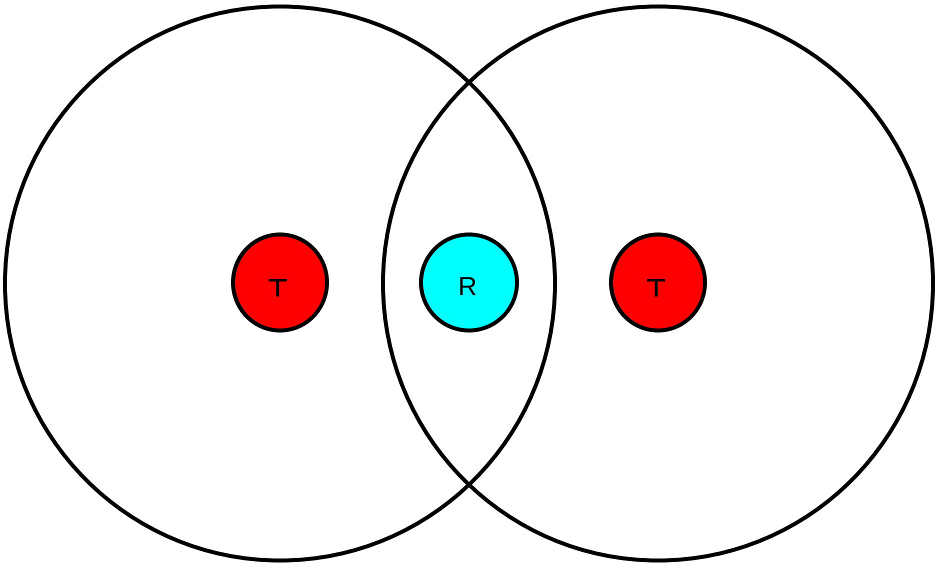

Fig. 3: Visualization of the Hidden Node Problem

The receiver is able to hear both transmitters but if one is transmitting while the other senses for an open channel, it will view the channel as free even if the other is currently transmitting. As soon as the second transmitter begins to emit its packet, a collision occurs. The receiver is receiving energy from both transmitters simultaneously causing the rest of the packet to be received with errors. Given the nature of roadways being long queues, this situation occurs often in practice [16].

2.4 Performance Metrics

In general, a congestion control algorithm attempts to moderate the flow of data. In the case of networking, the goal is often to increase the throughput of a network. The details of these sorts of algorithms tend to be specific to the nature of what is being communicated, and over what medium.

The **fairness** of a DCC algorithm is an important factor that describes how well distributed a resource is. In the case of V2V communications, fair use of the channel may be that everyone is transmitting at the same rate, or perhaps that everyone is using a percentage of the medium relative to the number of vehicles in it’s own immediate area. Fairness in DCC comes with many challenges however, such as the fact that an EV has a difficult or impossible time of discovering a RV’s congestion unless it shares it. For example, if the EV were to know the channel utilization rate for some RV it could choose to influence it one way or the other in order to provide optimal sharing or fairness.

The **Beacon Error Rate** is often used to evaluate the performance of DCC algorithms[9]. Packet errors can happen for many reasons, most notably by packet collisions and signal degradation. A packet error is considered to occur when a packet is received by a radio that detects incorrect bits in the received message. If there is an error detected, the packet is unable to be passed to higher layers and is consequently dropped. A high error rate in a network means that packets are being sent and received, but many packets aren’t being used. Error rates should be kept as low as possible in order to avoid wasting precious MAC resources.

The **Beacon Reception Rate** can be considered a measure of awareness in terms of DCC analysis. It can be calculated as the number of packets received from a specific vehicle in a defined interval or the sum of beacons received from all vehicles per interval [9]. This interval is generally taken as one second in DSRC, as it is how rates are defined in the IEEE 802.11p standard. A high reception rate means more awareness in the case of a single RV’s rate as it appears to the EV. More packets per second mean less time between packets and therefore a more accurate position. **Inter-packet delay** is sometimes observed directly [9], independently of the beacon receive rate.

Channel Access Delay is defined as the duration an EV waits, in order to gain access to a channel in order to transmit. A higher delay means an EV had to wait longer before transmitting a packet. A long delay between the time the packet was created and the time it was sent decreases the relevancy of the beacon as it grows more inaccurate over time in the case where the EV is moving. The source of delay could be anything from a congested network or possibly an uneven distribution of medium access across all vehicles.

A direct measure of how occupied a channel is can be calculated as the **Channel Busy Ratio** (CBR). The CBR is calculated by checking the Clear Channel Assessment (CCA) on the channel, which determines if the channel is currently not in use. The ratio of busy to non-busy measurements taken over some interval is considered to be the Channel Busy Ratio. The CBR is frequently used as an input parameter to DCC algorithms which adapt parameters based on network utilization [9].

2.5 Current Problems and Solutions

2.5.1 Rate Reduction

One common method for reducing packet congestion involves **reducing the rate** at which packets are sent. With the standard defining a rate of 10 packets per second, some algorithms reduce this number either to a fixed rate [17] when a high level of congestion is detected, or calculate a new rate based on an input parameter which describes the current congestion level [18,11,19]. The reduction of transmit rate means that an EV is receiving updates from some RV with larger gaps between messages, known as the inter-packet delay (IPD). This extra time means that the EV's awareness of the RV is reduced. Consider some RV which creates a message and sends it. Since the position and other values in the packet are taken when the packet was generated, they are less likely to be accurate the further time progresses. For example, if a vehicle travelling at 100km/h sends a packet and 100ms elapses, that vehicle has moved approximately 2.8m. In the case of a reduced transmission rate, this elapsed period would be greater, leading to less accurate representation of the RV.

2.5.2 Power Adaptation

Other algorithms adapt the **transmit power level** and/or the **receive power sensitivity** [20]. This means that a packet sent with a lower power will not travel as far as a packet sent with a higher power. This helps to reduce congestion by reducing the number of cars the EV is transmitting to. Similarly, adjusting the receive sensitivity to make it less sensitive means packets with less energy will not be processed. Ignoring these packets makes the radio interpret the channel as free, enabling it to transmit or switch channels. Generally the power is adapted relative to some calculation of congestion, however one paper was discovered which chose a transmit power by selecting one randomly from a known probability distribution [21].

2.5.3 State Based Approaches

In algorithms that assign static parameters to states, it is sometimes observed that state changes are happening at a very high frequency. States are defined based on some criteria (often channel utilization or number of observed vehicles) and are assigned individual behaviours through static parameters [17]. This hopping from one state to another is sometimes attributed to the significant difference between static parameters. The behaviour observed suggests that the sudden change in radio behaviour associated with a shift in state can cause other vehicles to observe a suddenly lower CBR which causes the second vehicle to change state. For this reason, algorithms which adapt their control parameters slowly appear to have better system-wide stability [20, 7].

2.5.4 The Scale of Simulations

A challenge involved in DCC research using simulations is apparent when one considers the scale of vehicles required. A normal V2V simulation which incorporates moving vehicles as well as radio simulation, would likely use a fraction of the agents as you might see in a DCC simulator. In order to see heavy congestion of the channel it is necessary to have many agents who will all be interacting with each other, creating a complexity we are familiar with from the ACK implosion problem. The computational requirements on the simulator drastically increase the resources required for larger simulations when testing DCC algorithms [9].

2.6 Literature Review

Among the algorithms that adapt rate in order to reduce network congestion stands the Linear MEssage Rate congestIon Control algorithm (LIMERIC) [7, 18]. LIMERIC adapts the rate of the vehicle's transmission from iteration to iteration, attempting to share the channel evenly between all vehicles. The authors have proven convergence of their algorithm in a noiseless environment and also used a gain saturation technique to handle very large vehicle densities. The authors note that their linear approach allows them to avoid the problems that often come with binary control, such as frequently bouncing between states. LIMERIC has been proven to be very effective at controlling congestion [18] but does (as with all rate control algorithms) increase the IPD of vehicles. This indicates that the time between two packets from one RV increases as the rate decreases. Further, the simplicity of the derived update function used by LIMERIC means it is easy to implement and adapt in order to study the effects of other DCC techniques.

While LIMERIC used channel utilization as its input parameter, BRAEVE [22] found that estimating the number of vehicles provided smoother convergence, as vehicles were reacting to each other's presence rather than to their rate changes.

The same researchers as in [7] further modified LIMERIC to enable estimation of the error an RV has in the EV position, creating EMBARC. In other words, it helps choose when to send beacons by estimating when RVs need an update in order to accurately represent the EV's position. Position and kinematic information is obtained from the GPS sensor and used to calculate the Suspected Tracking Error (STE) across neighbours. LIMERIC runs asynchronously from STE, and both modules propose a time that they think the next packet should be emitted at. Whichever time is reached first is what triggers a transmission. This transmission ultimately changes the system, causing both components of the system to pick two new packet times and so on. The update interval is held at a minimum of 100ms, as to not violate the max 10 Hz transmit rate. In a highway simulation EMBARC was compared to LIMERIC as well as the original STE tracking algorithm from which EMBARC was derived (IVTRC) and a 10 Hz control. BRAVE was shown to outperform the other algorithms in terms of packet error ratio, inter-packet delay and tracking error in almost all cases.

The creators of the Successive Rate and Power Adaptation (SuRPA) [23] devised an algorithm that would control for the collision rate of packets. After devising an algorithm based on the binary search technique, simulations were performed comparing their technique to the ETSI-DCC, as well as the TRC and TPC sub-modules separately. Researchers used the mobility simulator SUMO integrated with the network simulator NS3 in order to observe the performance of their algorithm. SuRPA first attempts to modify the transmit rate given the current channel conditions in order to reduce the collision rate to an acceptable limit (5% in this paper). If the adaption of rate isn't enough to reduce collisions on it's own, the transmit power is then reduced in order to control the number of vehicles affected by a given packet. The researchers showed that with up to 100 vehicles (the max number of vehicles considered in the simulations) a transmit rate of 10 Hz was easily maintained by the algorithm. Power adaptation was seen to come into effect starting at approximately 65 vehicles. With these very promising results, it would be interesting to see the algorithm operating with a higher number of neighbouring vehicles.

The European counterpart of WAVE, which is being developed by ETSI, has a similar message to the BSM known as the CAM. This CAM message is sent at a rate from 1 to 10 Hz and causes similar congestion problems to the BSM. To solve this problem ETSI created a DCC algorithm [24] which adapted several behaviours of the protocol. Transmit power level, beacon rate, data rate are adapted along with the sensitivity if the Clear Channel Assessment (CCA) and packet prioritization. The parameters are controlled by a state machine with the following states: relaxed, active, and restrictive. State is decided by the

Channel Load (CL) and each state has a fixed set of parameters for the different modules controlled by the DCC algorithm.

Using simulations, researchers in [25] looked at the performance of each of the ETSI DCC controls individually in order to understand how they each affected various metrics. Packet Delivery Ratio, Update Delay and Channel Load (averaged over all nodes) were recorded at distances from 20m to 400m. The researchers observed the combined DCC algorithm performed worse than its components working on their own. This was attributed to the idea that the combined algorithm inherited the weaknesses of each individual component. The power control module had the lowest Packet Delivery Ratio due to the fact that a lower transmit power reduces the range a packet can be heard. The researchers further criticized the update delay caused by the Transmit Rate Control mechanism at high channel loads. They noted that it increased to the point that it would be unable to provide fast enough updates for many of the safety applications that require them. Further problems of rapid state shifting were also observed as vehicles changed states (10 times per minute in some cases). These state changes were attributed to the significant difference between the parameters associated with each state. Other research such as [26,27] has also confirmed the weaknesses of the combined and separate ETSI-DCC controls.

Chapter 3 - Proposed DCC Power Algorithm

In order to provide acceptable awareness to surrounding vehicles, it is reasonable to prioritize vehicles that are closer. Closer vehicles are more likely to interact sooner with the EV than those farther away, and therefore do not require as accurate of a position for the EV. In order to achieve this behaviour, we exploit the relationship between the transmit power of a packet and the distance it can be received at. A packet transmitted with a higher power can be received farther away than one sent with less power. With this algorithm we are able to maintain two separate transmit rates such that vehicles at close range see all packets at their full rate and those farther away see only those packets sent at a higher transmission power.

The proposed method is different from other algorithms that attempt to set the transmit power relative to some parameter which represents the level of congestion [20,12]. The novel element is the intentional switching between two drastically different transmit powers in order to target two groups separately.

Firstly, we select two transmission powers Tx_N and Tx_F as the near and far powers respectively measured in mW. Next we define two transmission rates, R_n and R_f as the near and far rates respectively. These variables should be selected such that $Tx_n < Tx_f$ and $R_n > R_f$ as a higher power and lower rate is desired for further vehicles. These rates are used by the algorithm to determine which packets are sent with a higher power level in order to maintain the two perceived rates to RVs.

The two rates are combined to calculate the number of low powered packets that should be sent between high powered packets in order to maintain the desired rates. This low powered packet interval (LPPI) is calculated as $LPPI = (R_n / R_f) - 1$ low powered packets per high powered packet. Next, we define the algorithm more formally using pseudocode to describe functions and a flowchart to describe how they work together. LPPC is the Low Powered Packet Count and Tx_c represents the current transmit power.

```
initialize()
    set_rate (Rn, Rf)
    LPPC = LPPI

set_rate (Rn, Rf)
    LPPI = max((Rn/Rf) - 1, 0)

iterate()
    if( LPPC >= LPPI)
      Txc = Txf
      LPPC = 0
    else( LPPC >= LPPI)
      Txc = Txn
      LPPC += 1
```

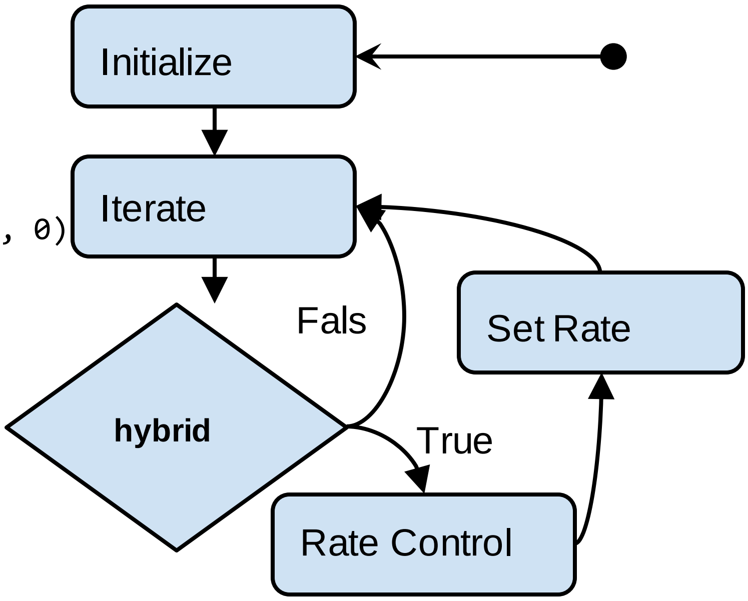

Fig. 4: Pseudocode and Flowchart of Proposed Algorithm

For example, if we had 10 and 2 as our near and far rates respectively, we would have an LPI of 4. This means we would send one high powered packet then four at low power, repeating this process. **Figure 5** below shows the pattern described in this example with the targeted vehicle distances on the x-axis. In practice these distances would not be exact, but would depend on atmospheric conditions as well as the unique configuration of each radio. Therefore Tx_N and Tx_F would have to be tuned according to these and other variables which control the transmission range.

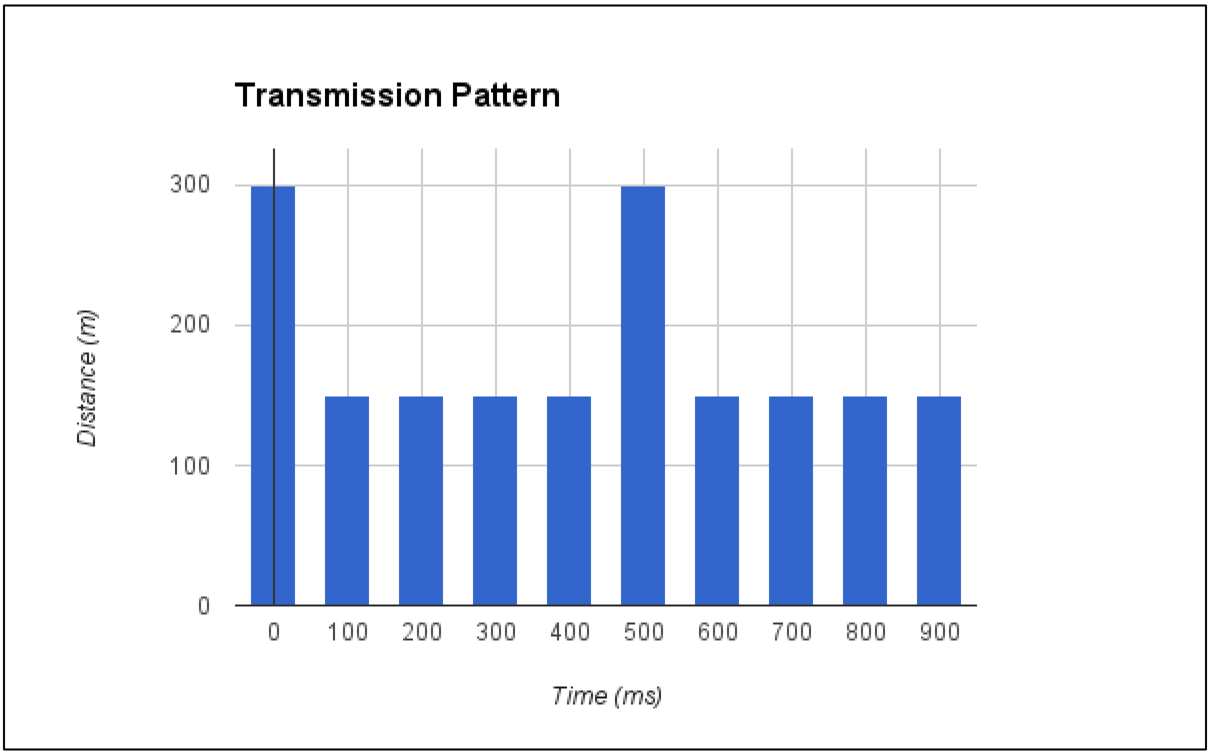

Fig. 5: Desired Transmission Pattern

While the transmission rates are set explicitly in the provided example, it would be possible to use a rate control algorithm in order to provide further congestion control in the case that the power adaption alone does not sufficiently reduce congestion. This method is explored in chapter four by using LIMERIC to adjust the rate according to the level of congestion according to the CBR.

The algorithm for alternating the power level calculates LPI according to the target rates. The first packet transmitted is a high powered packet followed by LPI low powered packets. The algorithm counts the number of low powered packets (LPPC) and resets the counter after each high powered packet is emitted.

The LPI must be recalculated every time the input rates are changed in the event that rate control is also implemented. In the case that a new LPI is recalculated such that LPPC < LPPI, the next packet sent would be a high powered packet. In the opposite case the interval is expanded and more low powered packets are sent until LPPC > LPPI and a high powered packet is sent.

Chapter 4 - Results

4.1 Simulation

In order to simulate the V2V network as well as the mobility of vehicles, a simulation using the Vehicles in Network Simulation (VEINS) framework [28] was used. VEINS connects a widely used network simulation tool OMNeT++ [14] and the traffic/mobility simulator SUMO [13]. VEINS contains a basic implementation of the IEEE 802.11p and IEEE 1604 protocols in order to facilitate the testing of V2V networks. This implementation was modified to include the proposed algorithm, as well as support for the LIMERIC algorithm. While some statistics were available through OMNeT++ already, the implementation was modified to make a record of every packet received. Several fields were collected per packet in a trace file:

- creation time
- time the packet was received
- sender ID
- receiver ID
- distance the packet traveled
- transmit power
- number of vehicles observed in the last 2 seconds (by the receiver)

In SUMO three simulations were created which consisted of two opposing lanes of traffic. In order to observe the performance of each algorithm at varying vehicle densities, two simulations with six and twelve lanes of 80km/h traffic were created. A final simulation with twelve lanes and vehicles driving 50km/h was also created and was intended to stress the network the most. The length of the roadway was 900m (chosen to be three times the transmission range) and vehicles were added at a constant rate according to lane availability. This means the simulator would place a vehicle any time there was space, leaving a 2m following distance. Each vehicle maintained a constant speed throughout the simulation ensuring that every instance of the simulation had the exact same mobility component.

4.2 Simulation Results

The results which appear in the rest of this paper were obtained by running the simulation for 10 seconds for each DCC mechanism: a 10 Hz control, LIMERIC, Oscilating Power method and a Hybrid LIMERIC-Oscilating Power adaptation.

Static rates of 2 and 10 were used for the far and near target rates respectively, while transmit powers were set to 2 mW and 8 mW for near and far respectively.

The desired effect of our algorithm, and the reason we chose to prioritize the near and far groups of vehicles differently, is to **sacrifice awareness** for vehicles at a distance. Using Weka [29] two visualizations were constructed using color coded points. The scatter graphs below show for each vehicle the distances at which they received packets.

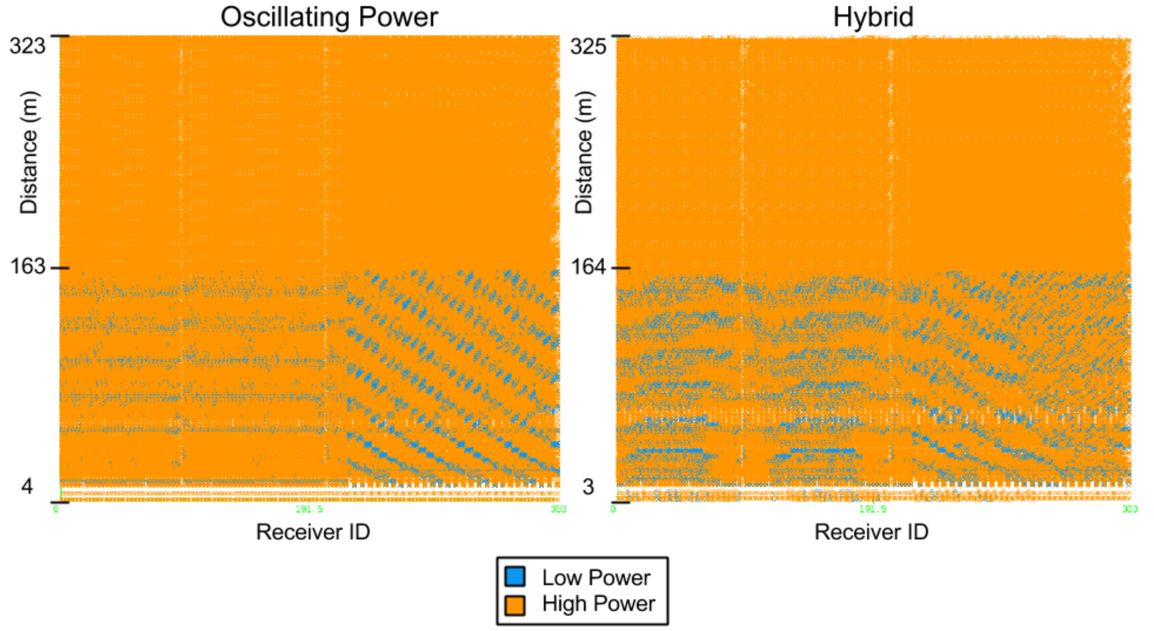

Fig. 6: Low Power Range Demonstration 6 Lanes

The colouring of the points makes it simple to show that packets sent at a higher power travelled the full transmission range, whereas the packets sent with a reduced power level travelled nearly half as far.

At the end of each simulation, scalar values from each vehicle were totaled to produce the figures below.

4.2 Sent and Received Beacons

In **Figure 7** the number of sent beacons for the OSC Power method had exactly the same number of packets sent as the reference in each scenario. We expected this result because the mobility simulator is deterministic in terms of providing the same mobility simulation each time for each DCC method. Further, the OSC Power method sends at the same 10 Hz rate as the control. Across all simulations the Hybrid method was able to send more packets than LIMERIC alone. This is a great result as it means that local vehicles (inside the range for low powered packets) would have a received more packets in the same interval. Furthermore when looking at the two methods that did not use an input parameter (10Hz and OSC Power) we see a significant increase in sent packets as the number of vehicles increase. This same difference in the other models was not observed as they were balancing to achieve the same network throughput given the current channel congestion.

Observing the change in the number of received packets according to **Figure 8**, we see that the LIMERIC and OSC Power methods on their own received more packets than when both mechanisms were in place. This makes sense as the rate control and power oscillation are happening simultaneously and combining their effect.The number of received packets increased with the density of vehicles in the simulation.

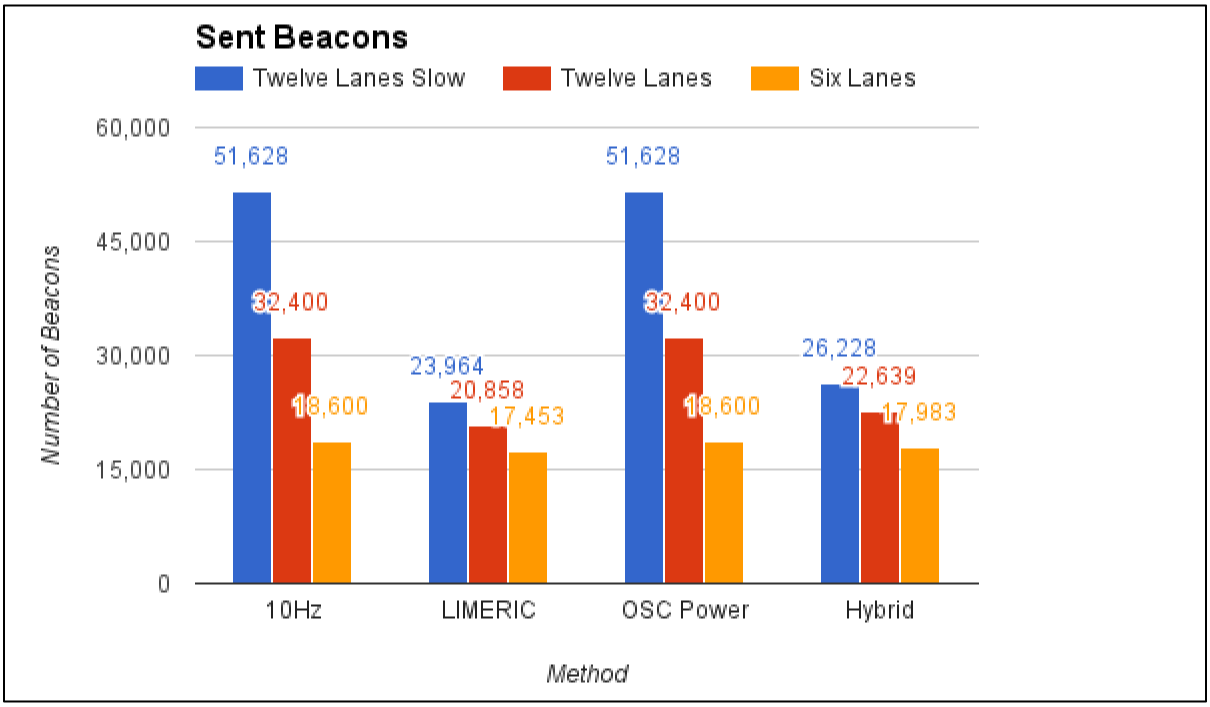

Fig. 7: Sent Broadcast Packets per Algorithm

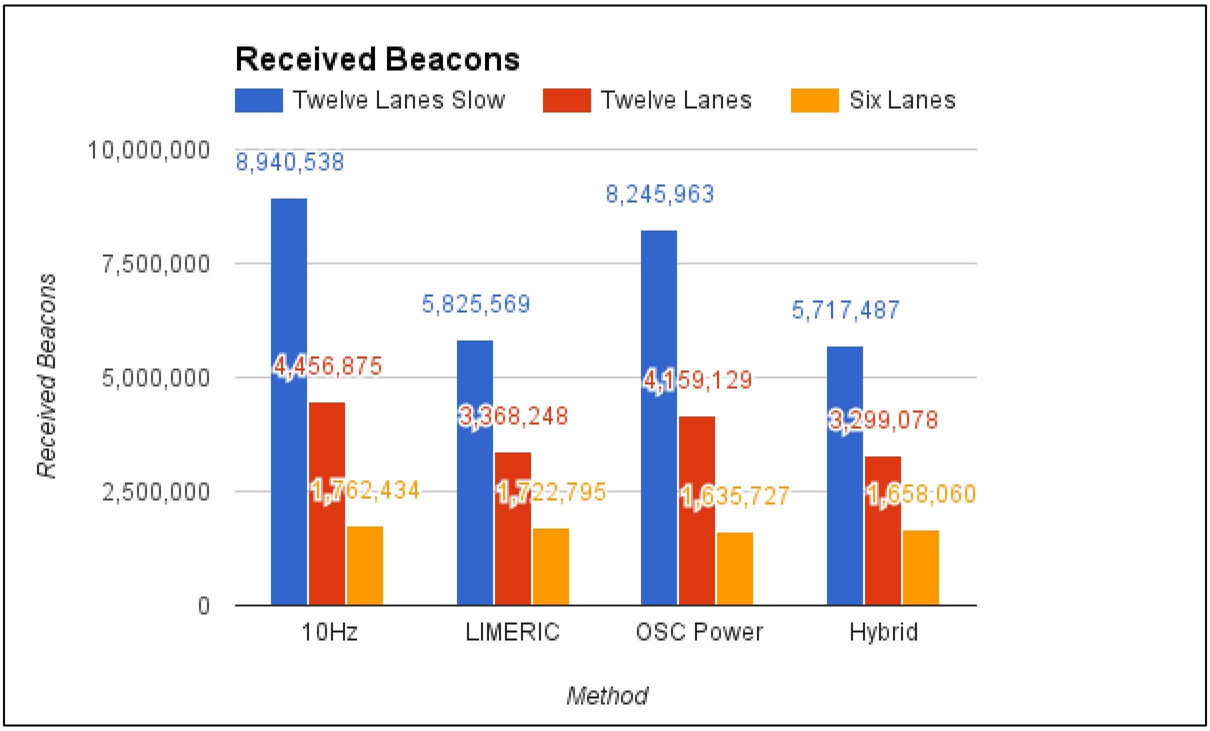

Fig. 8: Received Beacon Packets per Algorithm

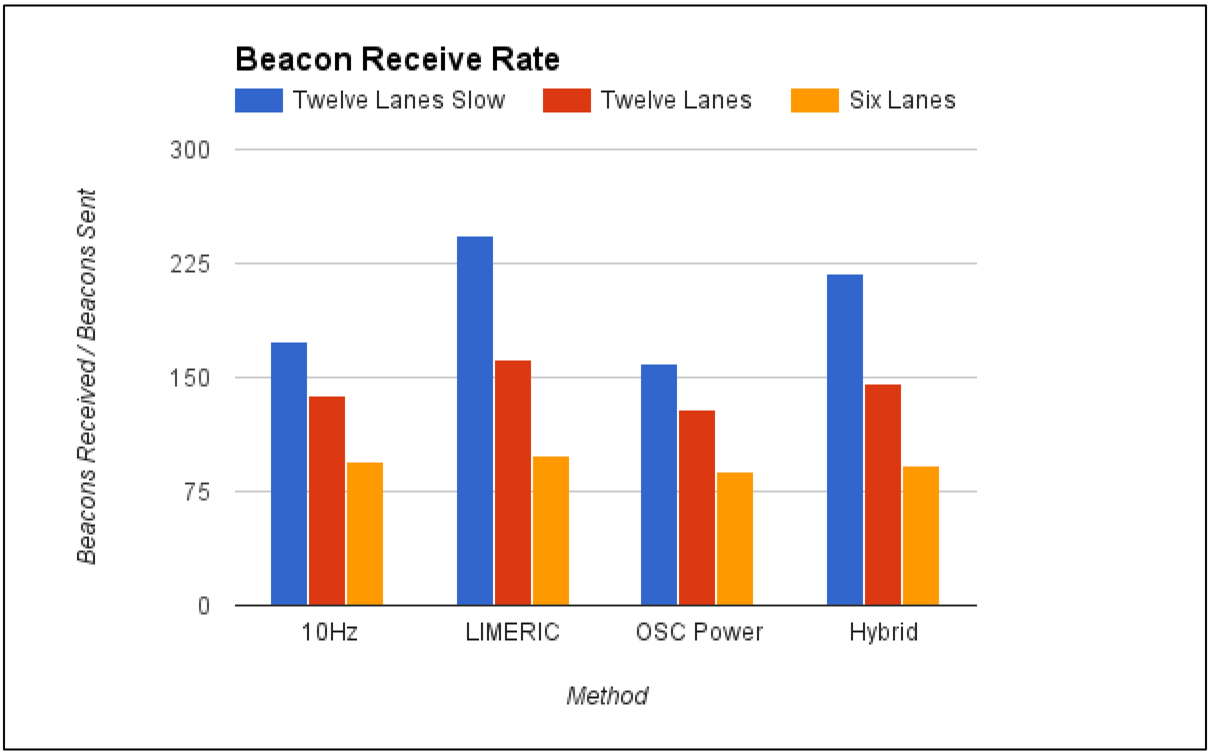

Fig. 9: Beacon Receive Rate

Comparing the sent to received ratio in **Figure 9**, we can see it relates closely to the number of vehicles affected by the transmission pattern. LIMERIC was able to reach more vehicles than the control due to its more efficient use of the medium. LIMERIC also had a higher received to sent ratio of packets due to the nature of the reduction of packets to distant vehicles introduced with the OSC Power and Hybrid methods.

4.3 Beacon Error Rates

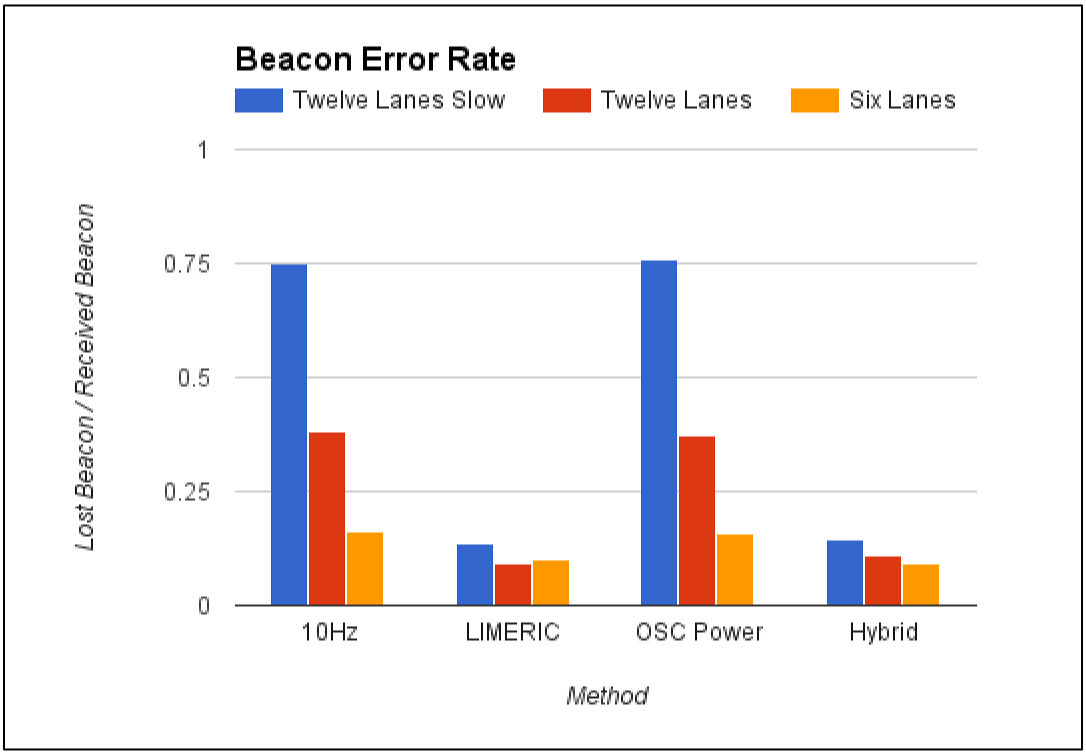

Fig.10: Packet Errors per Received Packet

The OSC Power method wasn't able to reduce the number of packet errors by a significant amount on its own. According to **Figure 10,** in the case of BER, the hybrid method performed well compared to the control and Power OSC methods but had more error than LIMERIC on its own. When calculating the BER we see that the OSC Power method had a higher ratio of errors to received packets than the control. This supports the suggestion that combined algorithms can suffer from the weaknesses of both strategies[18]. Further, it is important to note that across vehicle densities, error rates for 10Hz and OSC Power both increase significantly where the Limeric and Hybrid methods maintain somewhat stable error levels. The high error levels represent a waste of resources and represent the failure of the existing 10Hz method at high loads.

4.4 Utilization

The average channel utilization was reduced more with the hybrid than with LIMERIC or the OSC Power method on their own. It is possible that the higher channel utilization in the OSC Power method is what leads to the increased errors. The busy times shown below are averages of all vehicle’s observed busy times across the simulation. Percentages above 100% indicate heavy overlapping transmissions. Again in these statistics we see the pattern of consistency from LIMERIC and the Hybrid.

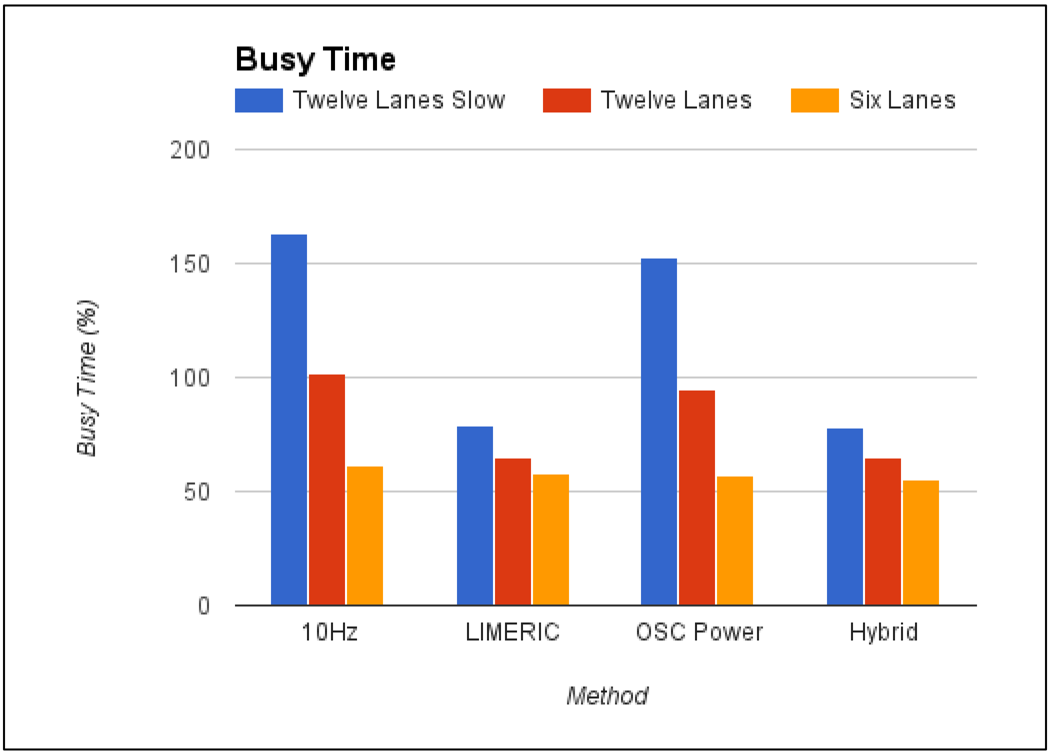

Fig. 11: Channel Activity

Next, we begin our analysis of the trace files of times,IDs, distance travelled, power and neighbour count saved during the simulation. First, we calculated for each vehicle the rate at which it observed RVs. This calculation was completed once per second. Simply put, against each integer rate ($1 < rate < 10$) we compare the number of times a vehicle was observed at that rate by a neighbour.

According to the results of these calculation as displayed in **Figures 12-14**, the 10 Hz model unsurprisingly dominated the 10 Hz rate. What's more interesting is (excluding the 10 Hz model) the OSC Power method across all three simulations had a sudden drop in transmit rate. Another interesting measurement is the in 1Hz case for **Figure 14**, This high value is likely because of the high level of congestion forcing the transmit rates to the floor of 1Hz.

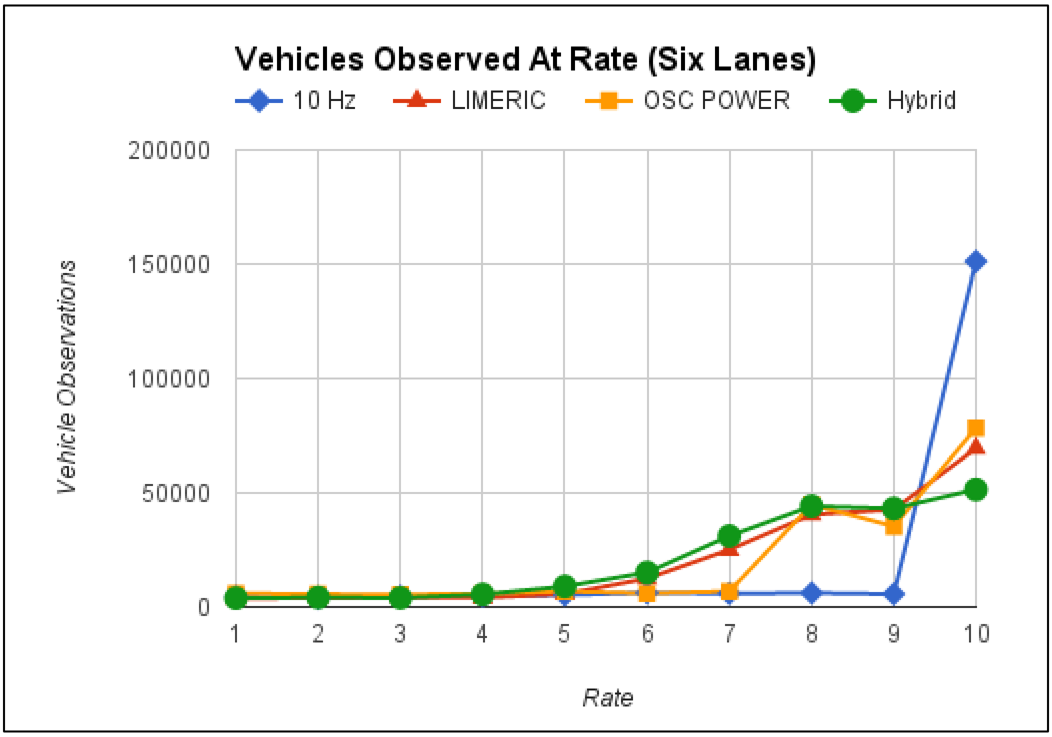

Fig. 12: Vehicles Observed at Rates (Six Lanes)

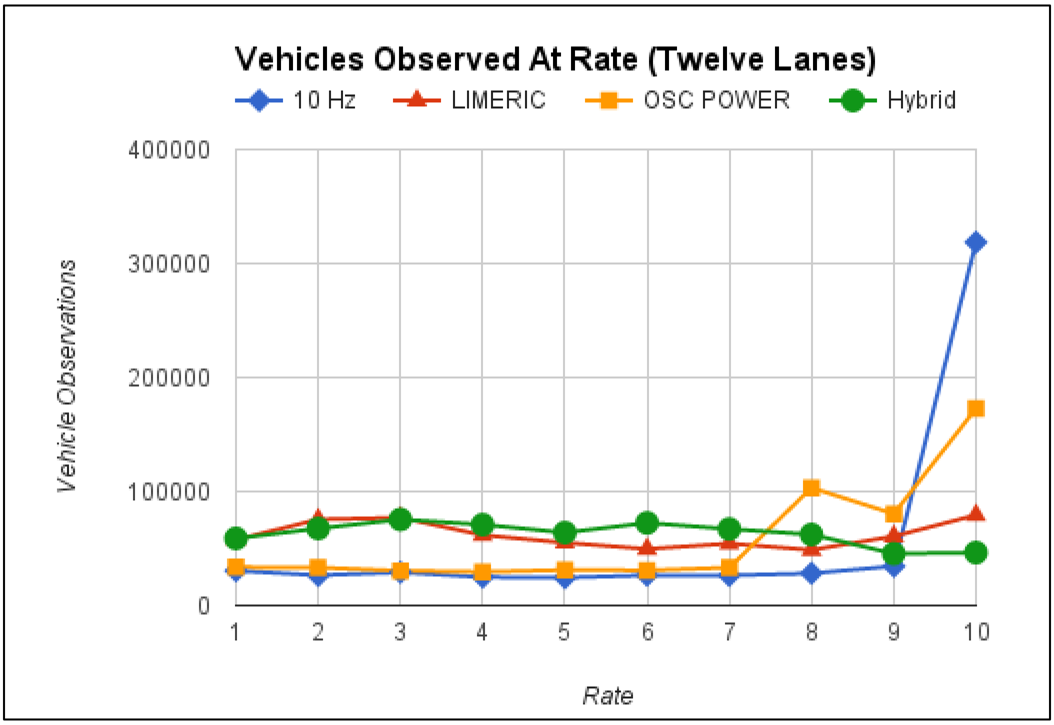

Fig. 13: Vehicles Observed at Rates (Twelve Lanes)

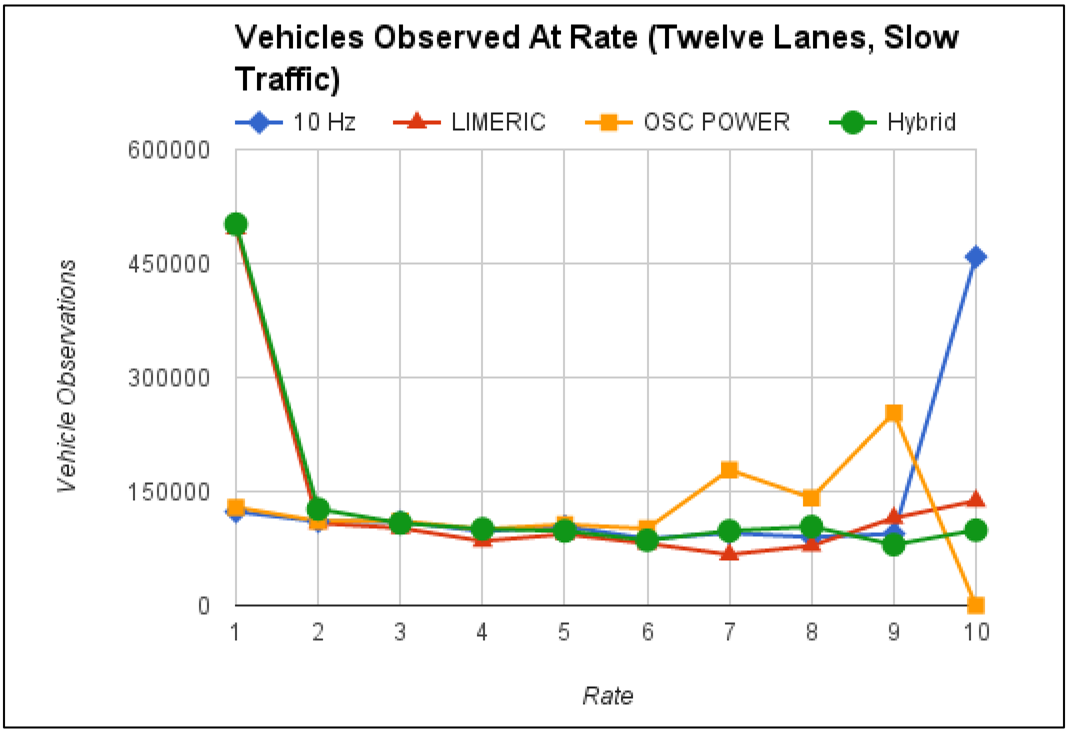

Fig. 14: Vehicles Observed at Rates (Twelve Lanes, Slow)

4.5 Awareness

The final statistic investigated was the inter-packet delay (IPD). This was calculated by first finding the average IPD each second that an EV had with every RV, and the average transmission distance during that second. Next, the distances were grouped into 20m intervals and the average IPDs were averaged across all vehicles who had measurements within the interval.

Figures 15-17 demonstrate that the Hybrid and Oscillating Power methods were able to maintain lower IPDs throughout the closer distance intervals (< 150m) due to the effects of the power modulation. The 10 Hz method did have the lowest IPD throughout, but this includes the vehicles at a greater range, which we consider to be a waste of resources. Finally both the OSC Power and Hybrid methods showed an increase in IPD in the greater distances, with the Hybrid method showing a more drastic increase. This is to be expected due to the combination of rate and power adaptation having an additive effect on packet delay.

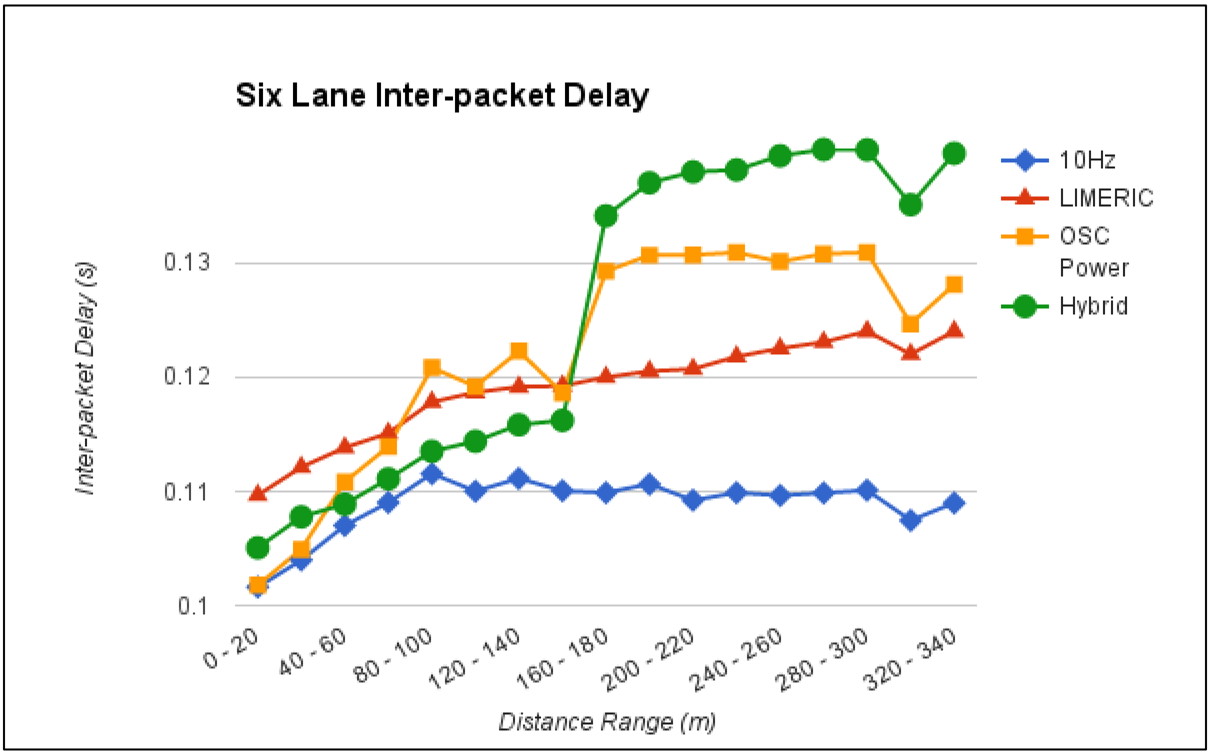

Fig. 15: Six Lane Scenario Average IPD

Figures 16 and 17 show that Hybrid and LIMERIC both had an increased IPD when compared to the remaining methods. This is to be expected as the main difference between these two groups is the rate control element. This is showing as a result of increased channel load in the last two simulations

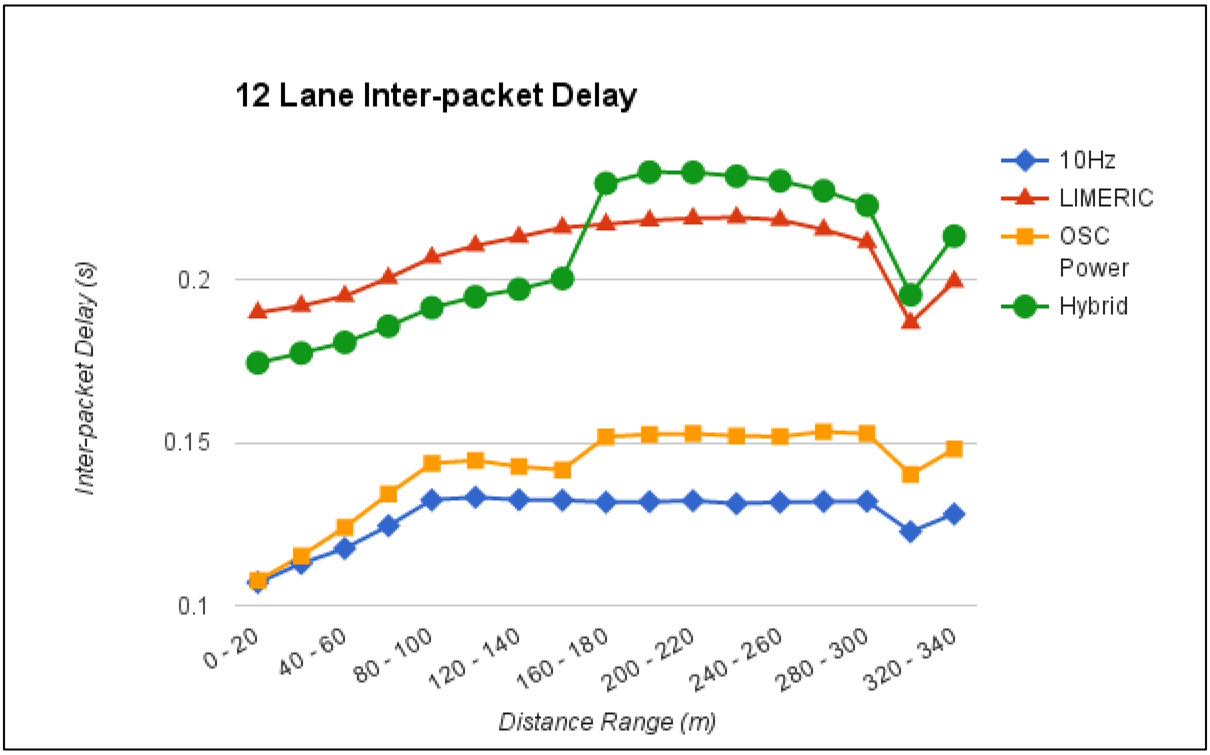

Fig. 16: Twelve Lane Scenario Average IPD

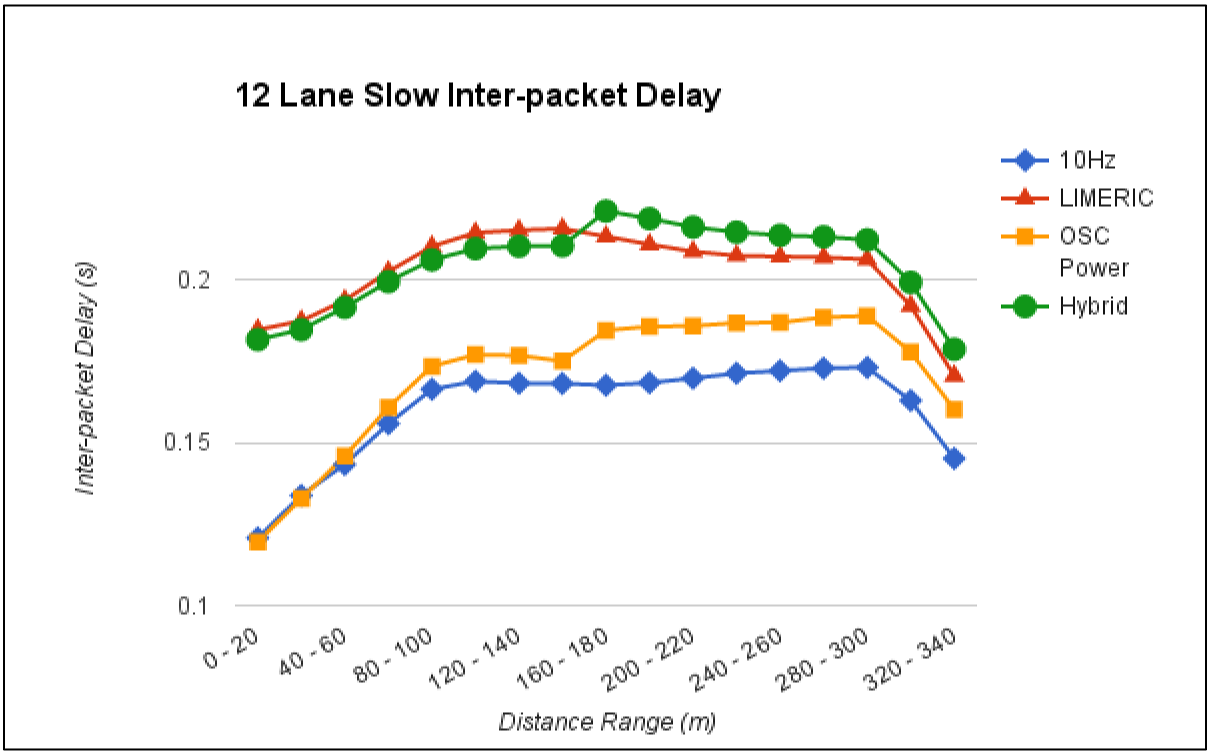

Fig. 17: Slow Twelve Lane Scenario Average IPD

Chapter 5 - Conclusion

5.1 Summary of Findings

The goal of the proposed algorithm was to exploit the power level to range relationship of packet transmissions in order to increase the awareness of near vehicles while sacrificing some awareness for distant vehicles. The Oscillating Power method was shown to have this effect on its own as compared to the standard as it is implemented now, this supports our initial hypothesis. Further we found that improvements were more significant when the rate adaptation from LIMERIC was incorporated with the Power Control Algorithm.

When observing the sent to received packet ratio in **Figure 9**, we learned that the Hybrid method reached almost exactly the same number of vehicles as the 10 Hz standard. LIMERIC was able to reach more vehicles per sent packet, however this was at a cost of a reduced rate (and in turn increased IPD). This is in contrast to the lower IPD maintained at closer distances by the Hybrid method, supporting our goal of sacrificing the awareness of vehicles at a distance.

We were able to confirm, according to **Figure 6**, that the packets from the modified transmission power were sent the appropriate distance. These results show that we were able to target near and far vehicles separately in order to reduce the number of packets sent to distant vehicles, while still reaching nearby vehicles at a high rate.

While the channel utilization of the Hybrid method only was slightly reduced relative to LIMERIC, the channel utilization of the Oscillating Power method alone showed a decrease in congestion compared to the 10 Hz implementation. This decrease in channel utilization can be attributed to the reduction of BRR between vehicles at a greater distance as was our intended behavior from the power adaptation.

5.2 Future Work

Since it is often the case that a stretch of highway would be near a cluster of city streets, further investigating the “packet pollution effect” as described in Chapter 3 would be desirable. One could integrate some nearby slow moving traffic to add extra packets to the simulation.

Given the increased performance observed when integrating a rate control algorithm with the Oscillating Power control method, adapting other algorithms that incorporate the relative distances of vehicles should be investigated. An error based approach would be especially interesting as is used in EMBARC for example.

Adapting the simulation to be vehicles distributed around a center point would allow one to control the density of vehicles as it appears from the center. Placing a probe vehicle at this point and other specific distances would allow researchers to more easily understand the effects of the algorithm as this would give a very uniform scenario of congestion.

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Appendices

1 Scalar Results

	Received Beacons	Sent Beacons	Total Lost Packets	Packet Error Rate	Beacon Receive Rate	Average Channel Busy Time
Six Lanes, 10Hz	1762434	18600	285166	0.161802	94.754516	61.6451
Six Lanes, LIMERIC	1722795	17453	171295	0.099429	98.710537	57.8285
Six Lanes, OSC Power	1635727	18600	261329	0.159763	87.942312	57.3018
Six Lanes, Hybrid	1658060	17983	149736	0.090308	92.201524	55.5056
Twelve Lanes, 10Hz	4456875	32400	1699957	0.381424	137.55787	101.9822
Twelve Lanes, LIMERIC	3368248	20858	317232	0.094183	161.484706	64.9989
Twelve Lanes, OSC Power	4159129	32400	1551973	0.373149	128.368179	95.121
Twelve Lanes, Hybrid	3299078	22639	362266	0.109808	145.72543	64.7479
Twelve Slow Lanes, 10Hz	8940538	51628	6706452	0.750117	173.172271	162.8151
Twelve Slow Lanes, LIMERIC	5825569	23964	798996	0.137153	243.096687	78.533
Twelve Slow Lanes, OSC Power	8245963	51628	6272599	0.760687	159.718815	152.9211
Twelve Slow Lanes, Hybrid	5717487	26228	834088	0.145884	217.991726	78.1119

Table. 1: Scalar Results

Vita Auctoris

Jordan Willis was born in 1989 in Windsor, Ontario and attended Belle River District High School. Jordan graduated from the Computer Science with Honors program at the University of Windsor, obtaining his B.Sc. .