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ADDRESSING OUTDOOR THROUGHPUT SENSITIVITY FOR MOBILE VEHICLES BY ENHANCING THE VMESH MAC PROTOCOL

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BY

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Table of Contents

List of Figures

List of Acronyms

AIFS = Arbitrary Inter-frame Space

AP = Access Point

BEB = Binary Exponential Back-off

CCH = Control Channel

CSMA/CA = Carrier Sense Multiple Access with Collision Avoidance

CTS = Clear to Send

DCF = Distributed Coordination Function

DIFS = Distributed Inter-frame Space

DRP = Distributed Reservation Protocol

DSRC = Dedicated Short Range Communications Spectrum

EDCA = Enhanced Distributed Channel Access

GPS = Global Position System

IE = Information Enhancement

ITS = Intelligent Transportation System

LMAO = Linear Modulus Autonomous Ordering

MAC = Medium Access Control

NAV = Network Allocation Vector

R-ALOHA = Reservation ALOHA

RTS = Request to Send

SCH = Service Channel

SIFS = Short Inter-frame Space

TDMA = Time Divided Multiple Access

UTC = Coordinated Universal Time

VANET = Vehicular Ad-Hoc Network

VMESH = Vehicular MESH

WAVE = Wireless Access in Vehicular Environments

WSA = WAVE Service Announcement

Abstract

To provide safe and efficient transportation, Vehicular Ad-Hoc Networks (VANETs) allow for the communication between a vehicle to another vehicle and for the communication between vehicles and stations near the road. As autonomous vehicles become closer to commercializing, the ability for moving vehicles to quickly and successfully send and receive packets becomes increasingly important. In this thesis, the 802.11p WAVE MAC protocol which was created specifically to address Vehicular Ad-Hoc Networks (VANETs), was analyzed. After reviewing existing models used to enhance throughput, the VMESH protocol was found to be better than the legacy WAVE MAC protocol. However, the VMESH protocol's channel allocation contention resolving scheme leads to a decreased throughput. This thesis proposes a new channel allocation scheme, Linear Modulus Autonomous Ordering (LMAO), that allows maximum channel utilization and therefore, an increased throughput. Given the number of cars in a system, the number of channels in a system, and the range of neighbors a car can see, the LMAO channel allocation methodology is found to perform significantly better than the VMESH and an upper bound approximated WAVE MAC channel allocation method.

Chapter 1

Introduction

Vehicular Ad-Hoc Networks (VANETs) allow for the communication between vehicles and between vehicles with stations near the road to provide safe and efficient transportation. VANETS help a group of vehicles set up and maintain an Ad-Hoc Network, or in other words, a communication network without a central base station with global access [30]. The IEEE 802.11p is an approved amendment to the IEEE 802.11 standard to add wireless access in vehicular environments (WAVE), to provide a vehicular communication system standard [15].

The IEEE 802.11 Distributed Coordination Function (DCF) uses a contention-based Medium Access Control (MAC) protocol called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) in order to mitigate packet loss in the media access control layer [13]. As a Random Access Protocol, CSMA/CA attempts to give equal priority to all nodes [22]. The Random Access Protocol simply allows a node to transmit a package on a shared channel until the package successfully transmits and if a collision were to take place, the nodes would wait for random delays and then re-transmit the package. CSMA/CA is a channel access method whose algorithm uses slotted binary exponential back-off (BEB) intervals to space out repeated re-transmissions of the same block of data to avoid network congestion. To overcome collision inefficiencies, which would occur on a shared channel if all stations with a packet to transmit sends the information as soon as they have information to transmit, a slotted protocol is used, where time is divided into slots equal to increments of time required to transmit one frame. In this slotted scheme, a station can only transmit at the beginning of each slot time, therefore playing a significant role in the performance of the 802.11 protocol [41].

The IEEE 802.11p amendment introduces the notion of Control Channel (CCH) intervals and Service Channel (SCH) intervals to prioritize the processing of high-priority safety related messages. A new proposed model called the Vehicular MESH (VMESH) MAC protocol has been shown to outperform the standard WAVE MAC protocol during high saturation [39]. However, the are limitations and disadvantages the VMESH MAC protocol regarding channel allocation and usage as discussed in Section 2.4. In this thesis, the issue with the VMESH MAC protocol channel allocation scheme is solved. The efficient allocation of cars onto channels at different during the same time slot is the metric used to determine the utilization of channels available. The *objective* of this thesis is to propose a new channel allocation scheme, Linear Modulus Autonomous Ordering (LMAO), that allows maximum channel utilization and therefore, an increased throughput. Given the number of cars in a system, the number of channels in a system, and the range of neighbors a car can see, the objective can be realized. LMAO is an allocation method that determines which cars should use which channels during a single time slot to fully maximize channel utilization by reducing contention for the same channels.

1.1 Contributions of this Thesis

Rather than assigning channel slots based on priority using a back-off exponential binary algorithm to allocate channel space, the proposed model uses modulus arithmetic to sequentially order and evenly space the number of vehicles on the network with the number of channels available. The contribution of this thesis is the proposal of the significance of ordering vehicles to assign channel slots and a method for each vehicle to update their ordered position without a global unit to keep track of such ordering to allow every vehicle to use a channel during one time slot.

1.2 Thesis Outline

The outline of this thesis is as follows: The background information about the IEEE 802.11 WAVE MAC protocol standard is discussed in Chapter 2. In Chapter 3, the limitations of the WAVE MAC protocol is further analyzed and the motivation for developing a new protocol is discussed. Chapter 4 includes the description of the proposed LMAO protocol. Simulated results of the effectiveness of channel allocation based on the proposed LMAO protocol compared to previous WAVE MAC and VMESH schemes are given and discussed in Chapter 5. Chapter 6 concludes this thesis and gives some outlooks on future works.

Chapter 2

Literature Review

In this chapter, a review of the contents, the contributions that led up to, and the current proposed models to improve the IEEE 802.11p MAC protocol is discussed.

2.1 OSI Model

Introduced in 1978, the Open Systems Interconnection (OSI) model is a conceptual model made by the International Organization for Standardization to define and standardize abstract the communication system into seven abstracted layers [9]. The Data Link Layer (DLL), or Layer 2, is responsible for transmitting data across a physical network link [40]. In the DDL there is a sub-layer called the media access control (MAC) layer whose primary purpose is to prevent loss of frames sent by different nodes onto a shared link or channel [27].

2.2 IEEE 1609.4/IEEE 802.11P MAC Protocol

2.2.1 802.11p Distributed Coordination Function

The 802.11 Distributed Coordination Function (DCF) protocol is one of the most widely used protocols for wireless networking. Although, a major downfall of the model is that it does not solve the hidden terminal problem, which

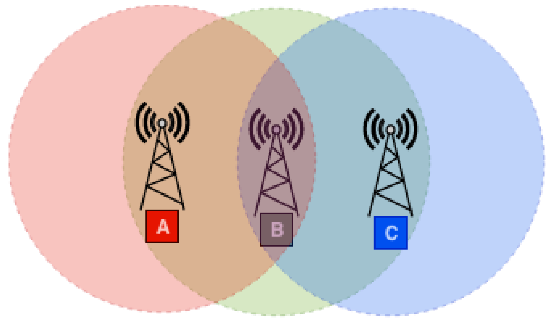

Figure 2.1: Illustration of the hidden terminal problem with three stations.

occurs when a node must communicate with a wireless access point (AP) node to communicate with other nodes because direct node communication without the AP is not possible [33]. Figure 2.1 shows an example of the hidden terminal problem. In this scenario, Station A can communicate with Station B and Station C can communicate with Station B. Stations A and C cannot communicate with each other as they are out of range of each other; but, as an access point, Station B can be used for stations A and C to communicate with each other. As a result, a packet collision may occur when a node is receiving more than one packet at a time, therefore resulting in neither packet being correctly received. To mitigate these collisions, DCF employs wave carrier sensing and has two different handshaking mechanisms to transmit a package. In both of the handshaking mechanisms, two devices send several messages back and forth to collaborate and agree on a communication protocol. In addition to DCF, the protocol also uses inter-frame spaces to ensure that a channel is truly free.

Before transmitting a packet, a station observes whether or not the channel is being used. If the channel has been idle for a time equal to the Distributed Inter-frame Space (DIFS), the station attempts to transmit the package. However, if the channel is being used by another station, the packet transmission is delayed and the station will continue to monitor the channel until an idle period of

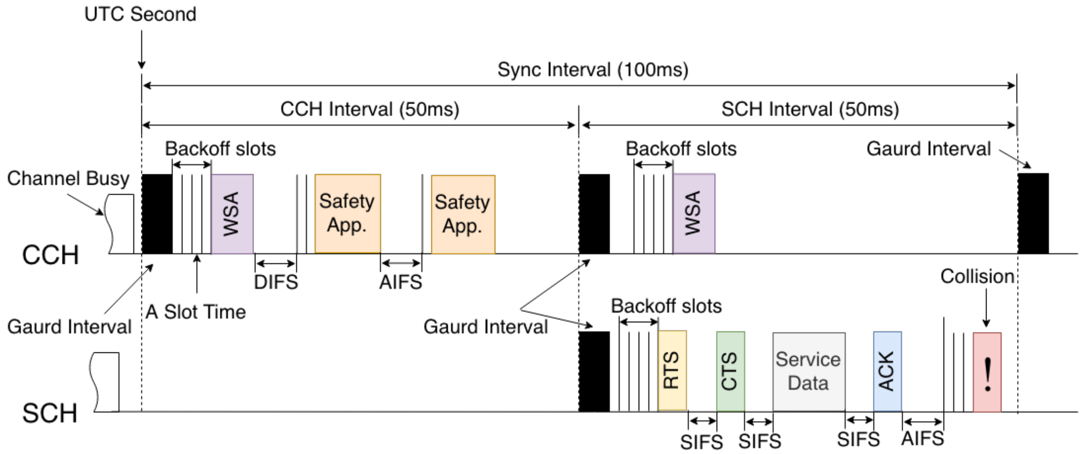

Figure 2.2: The channel structure of the WAVE standard [18].

DIFS occurs. In addition, in order to prevent one station from monopolizing the channel, a station must wait for the duration of a random back-off time after transmitting a packet, even if the channel is sensed idle in the DIFs time [41]. The following Chapter 3 will go into more detail about the DCF back-off protocol.

The IEEE 802.11p protocol is an amendment of the IEEE 802.11 specification, developed to address VANET [15]. The MAC layer of the IEEE 802.11p protocol uses several elements from the 802.11e amendment where Enhanced Distributed Channel Access (EDCA). 802.11e uses Access categories (ACs) which differentiate packet priority levels. Prioritizing based on shorter arbitration inter-frame spaces (AIFSs) for higher priority packets, 802.11e creates a Tiered Contention Multiple Access (TCMA) protocol. AIFSs are small time intervals between subsequent beacon transmissions. When a node wants to send a message, the channel has to be idle for the duration of their AIFS. When the channel is sensed busy, the packets uses the Binary Exponential Back-off (BEB) algorithm to assign a new back-off time.

The following Sections 2.2.2, 2.2.3, and 2.2.4 discuss the components of Figure 2.2, starting with how the BEB chooses a random time interval for a packet to send. Then the handshaking protocols is discussed, which these protocols use Request-To-Send (RTS), Clear-To-Send (CTS), and Acknowledgement (ACK) messages to confirm that the channel is unoccupied and that the receiving station is able to consume messages. Next, the Dedicated Short Range Communications (DSRC) Spectrum and how the seven channels allow VANETs multi-channel access is discussed. Afterwards, the division of synchronized intervals are mentioned. Finally, periodically transmitted beacons, which contain information that helps synchronize members in the network, such as the WAVE service announcement (WSA) message are discussed.

2.2.2 Binary Exponential Back-off (BEB)

In computer networks, binary exponential back-off (BEB) is an algorithm used to avoid network congestion by spacing out data that must be re-transmitted due to previously failed transmission attempts [12]. In attempt to fairly distribute channels for transmitting packets, Algorithm 1 modifies the back-off counter based on the state of the channel. The initial value of the back-off counter is a value uniformly chosen between $[0, W-1]$, where W is the contention window. When the station has a packet to send, the channel is checked to be idle or busy. If the channel is idle and the back-off counter has a value of zero, then the station proceeds to transmit its packet. Idle is defined as a period of time where no activity occurs on the channel for the time frame equal to or greater than the DIFS. If the back-off counter is not zero, the back-off counter is subtracted and the channel sensing step occurs until the packet is transmitted.

Upon the first attempt to transmit the packet, W is set to W_{MIN} as the minimum contention window. When a station is unable to successfully transmit a packet, the station doubles the value of W after each failed transmission, up to the maximum back-off contention window, W_{MAX}. The relationship between W and the W_{MAX} and W_{MIN} bounds are summarized in Equations (3.6) and (3.7).

```
back-off counter = value between [0, W − 1];
while station has a packet to send do
    if channel == busy then
        back-off counter pauses;
    else
        if channel == idle then
            if back-off counter == 0 then
                station transmits packet;
            else
                back-off counter = back-off counter -1;
            end
        else
    end
end
```

Algorithm 1: Station sends packet based on the state of the channel and the back-off counter.

When a data frame is successfully received, either the two-way handshaking mechanism or the four-way handshaking mechanism is used to confirm the packet transfer. The two-way handshaking mechanism, called the basic access mechanism, occurs where the receiving station sends an acknowledging (ACK) frame after a Short Inter-frame Space (SIFS) period. The second mechanism introduced in the 802.11 DCF protocol to detect collision is four-way handshaking mechanism known as RTS/CTS. The RTS/CTS protocol is introduced in attempts to combat the hidden terminal problem. The RTS/CTS protocol, which is a part of the DCF's Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol, is referenced in Figure 2.1 [7].

In RTS/CTS, the RTS and CTS frames include information about the length of the packet to be transmitted. The listening stations, including the AP, can update the network allocation vector (NAV) which is a carrier sensing mechanism that ensures adequate medium reservation for frame traffic control [29]. As the intermediary node, the response of the AP node will be seen by the nodes trying to communicate. As a result, the peripheral nodes can synchronize their transmissions to not interfere.

In the RTS/CTS algorithm, as described in Algorithm 2, a station sends packet based on back-off counter, which occurs after a SIFS period. This sending action occurs after the sending station correctly receiving a CTS from the receiving station. If the station does not correctly receive a CTS, after a RTS request, the back-off counter is reassigned the value of two times the original uniformly chosen W value.

Although the CSMA/CA protocol does introduce latency, with the need to keep track of each node signaling their intent to transmit before actually doing so, the overhead can often be greater than the cost, particularly for short data packets and for the sake of improving packet transmission success. The RTS/CTS mechanism is rather effective for large packet transmission traffic as less bandwidth would be wasted. When a station notices a RTS or CTS frame on the channel, the station can accordingly further delay transmission, and as a result, avoid collision.

```
original back-off counter = new value between [0, W − 1];
back-off counter = original back-off counter;
while station has a packet to send do
    if channel == busy then
        back-off counter pauses;
    else
        if channel == idle then
            if back-off counter == 0 then
                station transmits RTS;
                if station receives CTS then
                    station transmits packet;
                else
                    back-off counter = original back-off counter *2;
                end
            else
                back-off counter = back-off counter -1;
            end
        else
    end
end
```

Algorithm 2: Station sends packet based on back-off counter, RTS/CTS, and channel state.

2.2.3 Dedicated Short Range Communications (DSRC) Spectrum

The Wireless Access in Vehicular Environments (WAVE) system is intended to service users, such as the Intelligent Transportation System (ITS), the ability to exchange and make use of information in a transportation system [20], [21]. By providing vehicle systems and drivers a greater situational awareness of events around them, including potential collisions and hazards, the WAVE system enables the development and support of transportation safety, efficiency, and sustainability [35]. Thus, devices operating in the WAVE system can enhance user comfort and convenience.

Through the U.S. Federal Communication Commission standardization, 75 MHz of the DSRC spectrum band at 5.9GHz was allocated exclusively for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [10]. This spectrum is divided into seven channels which allow VANETs multi-channel access [3]. As shown in Figure 2.3, the Control Channel (CCH) occupies CH 178, only one of the seven channels of the 5.9 GHz WAVE system. The messages on the CCH are considered high priority and can only be used for safety applications, system control, and management. As high priority messages, it is of great importance that The messages are sent reliably and with low delay [36]. The remaining six channels are Service Channels (SCH). SCH are used for non-safety applications. EDCA MAC protocols are recommended for CCH and SCH but no specific designs are mentioned in the standard [25].

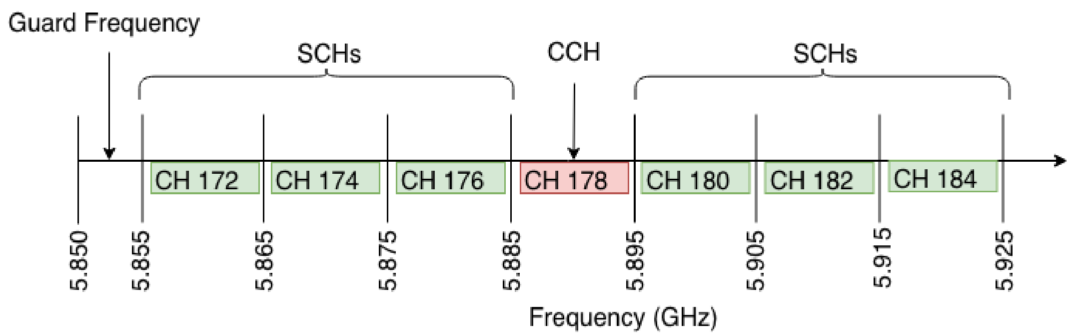

Figure 2.3: Frequency channel layout of 5.9 GHz WAVE system.

2.2.4 Multi-Channel Operation in WAVE

The WAVE standard consists of sync intervals that each last for 100 ms[1]. Each sync interval are repeating time intervals split by a 50 ms interval of the CCH and a 50 ms interval of SCH, as shown in Figure 2.4. During the CCH intervals, all devices must listen on the CCH. Alternatively, during the SCH intervals, the devices on a SCH can optionally switch to the CCH. On the CCH, each vehicle relays a periodic beacon and an emergency (event-driven) message. Beacon frames, which contain information such as the vehicle's location, speed, and acceleration, assist with building a cooperative awareness in all VANET nodes [28]. With the APs frequently broadcasting beacon information to all nodes in range, the nodes in the system are able to update their databases to reflect the changing environment [31]. Note that as based on IEEE P1609.4, when two or more stations want to exchange data on the same channel, the alternating radio channel access for WAVE is synchronized based on the Coordinated Universal Time (UTC) whose synchronization can be achieved through the use of Global Position Systems (GPSs) [5].

[1]IEEE Std 1609.4 specifies that a guard interval of 4 ms starts before each alternating CCH and SCH interval of 50 ms. The guard interval indicates to a transmitting device that packets should not be sent to the channel. During a guard interval, the device is assumed to be switching channels and thus, unable to receive packets [16].

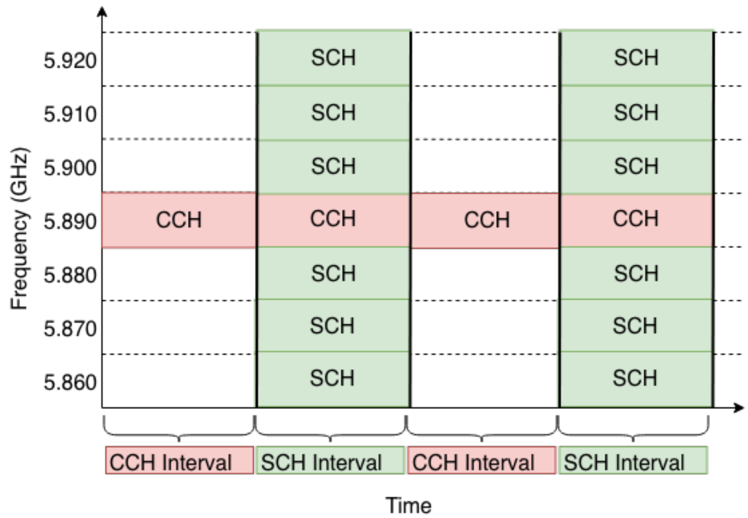

Figure 2.4: Multi-channel Cooperation in WAVE.

2.3 Review on MAC Protocol Improvements

In this section, a brief overview of research, used to improve the legacy multi-channel MAC scheme, is reviewed. To address congestion control for SCH applications, Wang et. al. [34] propose adjusting the length of the ratio between the CCH and SCHs. In [40], the authors propose further dividing the CCH and SCH intervals and applying a distributed beaconing scheme to designate channel reservations. Similar to RFID slot allocation, when the number of nodes is greater than the number of allocation slots available, the rate of collisions increase substantially [26]. To address this issue, Akbarifar et. al. [2] and Yoo et. al. [37] introduced a scheme to dynamically adjust SCH and CCH ratios. Amadeo et. al. [4] proposes allocation based on vehicle position-based parameters and a polling scheme to reserve slots for reachable nodes. The CRaSH scheme uses a gossip-based reservation mechanism to select the least congested SCH [8]. Jain et. al. [17] makes use of the receiver-side channel state information to select the channel that reduces the most collisions. To allocate channel resources, the schemes proposed by the various researchers had varying throughput results based on the saturation conditions. However, the method proposed by Zhang et. al. [40] proposed a method to avoid contention during the MAC layer slot allocation, making the scheme ideal for research. The IEEE 1609.4 compliant multi-channel operation scheme introduced was found to outperform typical WAVE MAC system throughput [19]. However, in low saturation situation, the VMESH protocol under performed. In the following Section 2.4, the VMESH protocol is described.

2.4 VMESH Protocol

The novel MAC protocol using VMESH from [38] outperforms the legacy WAVE protocol. The VMESH introduces four new attributes and is shown to be more performant compared to the legacy MAC protocol.

The VMESH MAC Protocol uses distributed beaconing to dynamically reserve channels on SCHs. Zang et. al. [39] have shown that under high throughput, VMESH outperforms the WAVE protocol in terms of throughput which the description of the assumptions and methodology is reproduced below. The following assumptions were made in their study:

1. The underlying channel is ideal and has no transmission error. Packet error occurs only when two packets collide.

2. No hidden station exists in the scenarios, i.e. all stations are within communication range of each other.

3. The impact from the mobility of devices on the packet transmission is ignorable, because the duration is short enough, i.e. SCH interval (50ms).

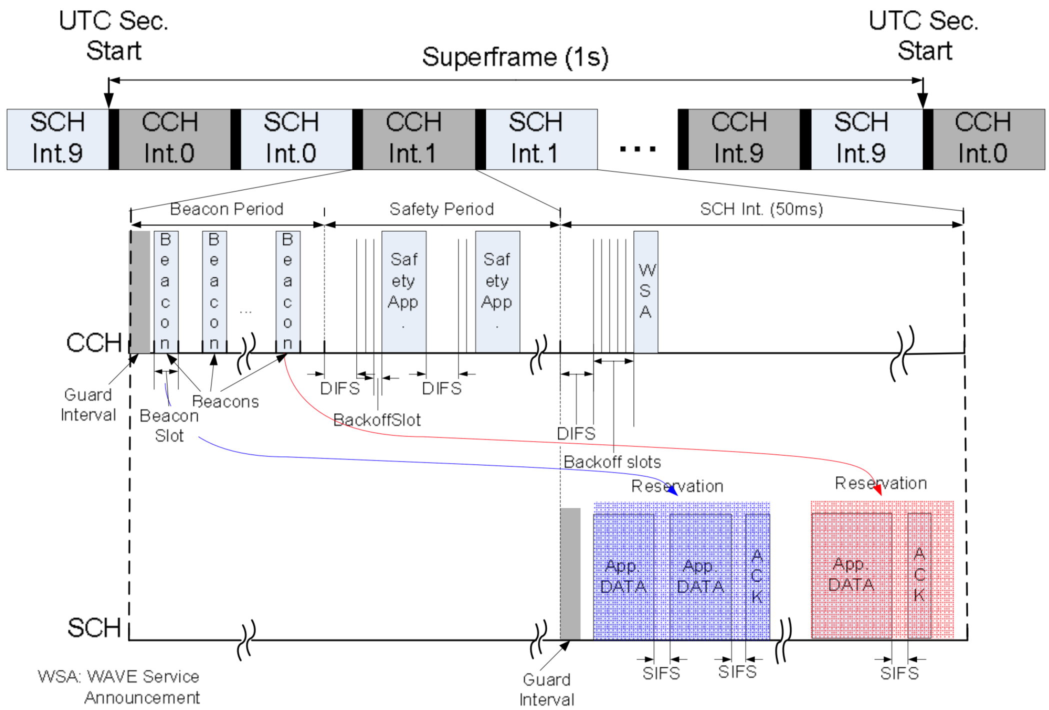

Figure 2.5: Channel access process of VMESH MAC. [39]

4. The system is in a saturated stable state, i.e. every device always has a packet to transmit.

In order to improve throughput in high density networks, four new attributes are introduced in the VMESH MAC Protocol to modify the CCH and multiple SCHs architecture of the WAVE system.

1. A VMESH superframe starts at the beginning of each UTC second and consists of 10 consecutive synchronization intervals as specified in the IEEE 1609.4 protocol.

2. The CCH interval from IEEE 1609.4 is further divided into the Beacon Period (BP) and the Safety Period (SP). The BP consists of several beacon slots. During the SP, devices must following the legacy EDCA back-off protocols for transmitting specifically safety application messages.

3. Each device transmits their beacon during their uniquely assigned beacon slot, based on the Reservation-ALOHA (R-ALOHA) protocol.

   The R-ALOHA scheme can be viewed as a combination of slotted ALOHA and time division multiplexing (TDM) protocols [24]. In the R-ALOHA system, the contention is limited to the short reservation subslots, while the transmission in the message slots is contention-free. R-ALOHA is discussed in more detail in the following Section 2.5.

4. Rather than using contention based access, VMESH uses Time Divided Multiple Access(TDMA). The major advantage of the table-based safety message broadcast scheme is that reservations allow nodes to only need to listen an broadcast for their own assigned time slot [1]. To reserve channel time in the SCHs for the TDMA, the following Distributed Reservation Protocol (DRP) is used:

   - A device initiates a reservation request after getting a beacon from the service provider based on the network state information gained from receiving beacons.
   - The reservation request is broadcast within the next beacon from the initiator.
   - If the service provider notices the reservation will cause a collision, a different channel is proposed or a rejection message is sent to the initiator within its next beacon to indicate that the initiator must negotiate in the next DRP round.
   - If there was no conflict to be seen, then a DRP Information Element (IE) informs all neighbors about the upcoming transmission.

- During the booked reservation time, both service user and the service provider switch to the reserved SCH to exchange data.
- The DRP IE of the reservation is included in the beacons of the service user and the service provider to indicate channel usage and to prevent the hidden terminal problem.
- The channel resource is freed by removing the DRP IE from the beacons of both the service user and service provider, which occurs when the two are out of range of each other due to the mobility feature.

The throughput of VMESH MAC on SCH is shown in Equation (2.1).

$$S_{\text{VMESH}} = \frac{\text{Information Delivered in One Reservation}}{\text{Reservation Length}} \quad (2.1)$$

Equation (2.1) can also be rewritten as Equation (2.2), where N_p is the maximum number of packets that can be transmitted given the length of the reservation T_res.

$$S_{\text{VMESH}} = \frac{N_p E[\text{Packet Size}]}{T_{res}} \quad (2.2)$$

In their study, Zang et. al. [39] find that the throughput of the VMESH MAC stays constant with the use of the "outband" signaling for coordinating channel access. When a control signal uses a separate channel from the channel used to transmit data, they are considered "out-of-band" signals [32]. In comparison, the WAVE MAC is found to have an overall 18% less throughput in part because RTC/CTS overhead in addition to more idle back-off slots.

The next Section 2.5 goes into detail about the R-ALOHA protocol used in the VMESH scheme.

2.5 R-ALOHA Overview

R-ALOHA has two alternating modes: the unreserved mode and the reserved mode. In the R-ALOHA scheme, each node can hear reservation messages and therefore update their knowledge base on who is in the queue and how long the queue is. When the queue length is equal to zero, the system switches to unreserved mode.

During the unreserved mode, which contains equal-length reservation subslots, an initiator may send a reservation request to reserve one or more slots. The number of reservation subslots R, relative to the number of message slots, depends on the design of the system which has trade off issues. The number of reservation subslots should be small enough to keep system overhead low, but large enough so that the expected reservation requests can be addressed [24]. In the R-ALOHA system, contention is limited to the reservation subslots, allowing transmission during the message slots to be contention-free. A positive ACK message is sent to the initiator if there is no other reservation for that slot. The system then switches to the reserved mode.

During the reserved mode, the frames are split into $M + 1$ equal length slots, where the first M slots are used for the message data and the last slot is further divided into R reservation subslots which are used for reservations, as mentioned above. An initiator that has received an ACK message is then able to successively send packets during message slots, skipping reservation subslots when they are encountered. When a station successfully uses a slot, the station is considered to temporarily "own" the slot. When there are no more reserved slots, the system returns back to the unreserved mode.

2.6 Summary

In the OSI model, the 2nd layer contains a sub-layer called the media access control (MAC) layer whose primary purpose is to prevent loss of frames sent by different nodes onto a shared link or channel. The IEEE 802.11 was amended with the IEEE 802.11p protocol to address VANETs. However, a major downfall of the model is that it does not solve the hidden terminal problem. The 802.11p allocates seven channels that are split into SCH and CCH intervals. When transmission contention occurs on a channel, the BEB algorithm is used to designate a time to re-transmit the previously unsuccessful message. The VMESH Protocol proposes to use TDMA to reserve channel time in the SCHs rather than using the original contention based access method. The R-ALOHA is finally discussed in detail. In the R-ALOHA system, contention is limited to the reservation subslots, allowing transmission during the message slots to be contention-free. However, the design choice of the number of message slots and reservation slots really depend on the fluctuation of message saturation. To understand how the VMESH Protocol throughput exceeds the previous WAVE MAC Protocol, the following Chapter 3 goes into further detail analyzing the WAVE MAC Protocol. Noting that the contention issues occur during the reservation of subslots, Chapter 3 reveals inspiration for solving the contention issues that occur in the R-ALOHA of VMESH.

Chapter 3

Analytical Model of WAVE MAC

The WAVE MAC protocol has a low throughput, especially in densely populated scenarios [38]. In order to understand this reasoning, a detailed modeling analysis, through mathematical derivation expansion of the MAC protocol, was preformed to get a better understanding of the reason for the low throughput.

3.1 Detailed Analytical Model

3.1.1 Markov Model of 802.11 MAC layer

Initial schemes are modeled as a Markov Chain with a back-off window scheme with n discrete contending stations. The analytical model developed by [6] for IEEE 802.11 DCF is famous and commonly used to model the throughput of 802.11 DCF. The Markov Chain model shows the discrete-time transitions that occur during the DCF slot times given the Binary Exponential Back-off (BEB) scheme, as shown in Figure 3.1. p is the probability that a transmitted packet faces a collision on the channel, which is referred to as the conditional collision probability. Let MAX represent the maximum back-off stage. p is dependent on the stochastic process state $s(t)$ representing the back-off stage $(0, ..., MAX)$ of the station. Let $b(t)$ be the stochastic process representing the back-off window size of a given station at slot time t, resulting in the bi-dimensional process

$\{s(t), b(t)\}$. From analysis of the Markov model, the throughput τ can be calculated to the following Equation (3.1).

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^{MAX})} \tag{3.1}$$

In a system managed by the basic access mechanism, as shown in figure (3.2), the average time the channel is sensed busy because of a successful transmission and the average time the channel has wasted time due to a collision, can be found in Equations (3.2) and (3.3) respectively, where T_{data} includes the time intervals in the transmission of the data, along with the PHY and MAC headers. δ corresponds to propagation time, and T_{ack} represents time to transmit the bits in an acknowledgement packet.

$$T_s^{bas} = DIFS + T_{data} + \delta + SIFS + T_{ack} + \delta \tag{3.2}$$

$$T_c^{bas} = DIFS + T_{data} + \delta \tag{3.3}$$

In a system managed by the RTS/CTS mechanism, T_s and T_c is represented by the Equations (3.4) and (3.5). In these Equations, T_{rts} and T_{cts} represent the time to transmit the RTS and CTS bits, respectively (including the PHY and MAC headers).

$$T_s^{rts} = DIFS + T_{rts} + \delta + SIFS + T_{cts} + \delta + SIFS + T_{data} + \delta + SIFS + T_{ack} + \delta \tag{3.4}$$

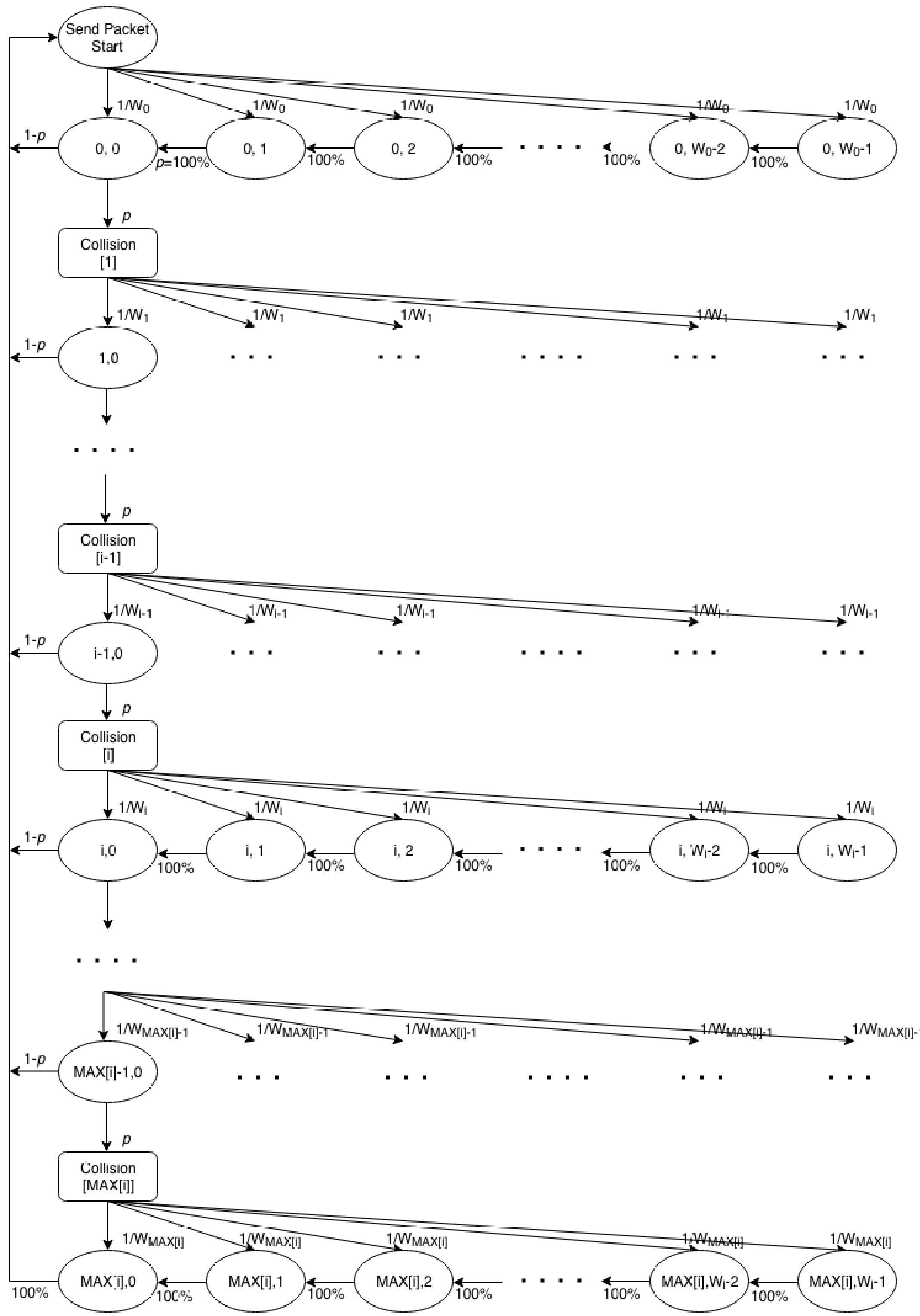

Figure 3.1: Markov Chain model for the back-off window scheme [6].

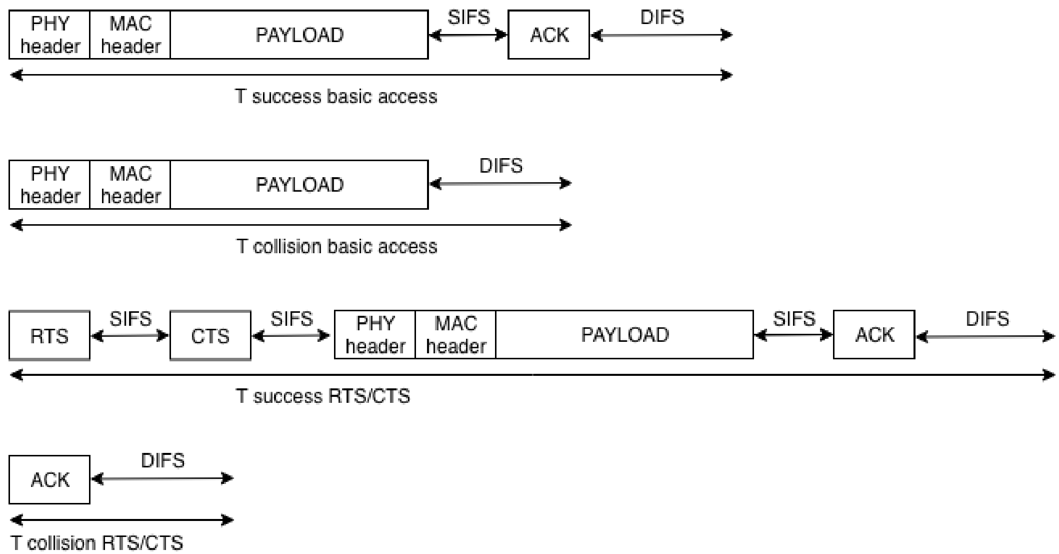

Figure 3.2: DCF basic access models with RTS/CTS mechanisms for T_s, the average time the channel is sensed busy because of a successful transmission, and T_c, the average time the channel is sensed busy because of a collision [23].

$$T_c^{rts} = DIFS + T_{rts} + \delta \tag{3.5}$$

The derivation and analysis of the mathematical throughput modeling is further expanded in the following Section 3.1.2.

3.1.2 Analytical Model to Compute Throughput of 802.11

Using the parameters assigned to the Direct Spread Spectrum (DSSS) PHY in 802.11, W_{MIN} and W_{MAX} are equal to 31 and 1023 respectively. The range of W was chosen to help limit excessive delay with the small window sizes when there is a low probability for collision. When there are several nodes in the system, the higher probability of collision is mitigated with the the larger W sizes.

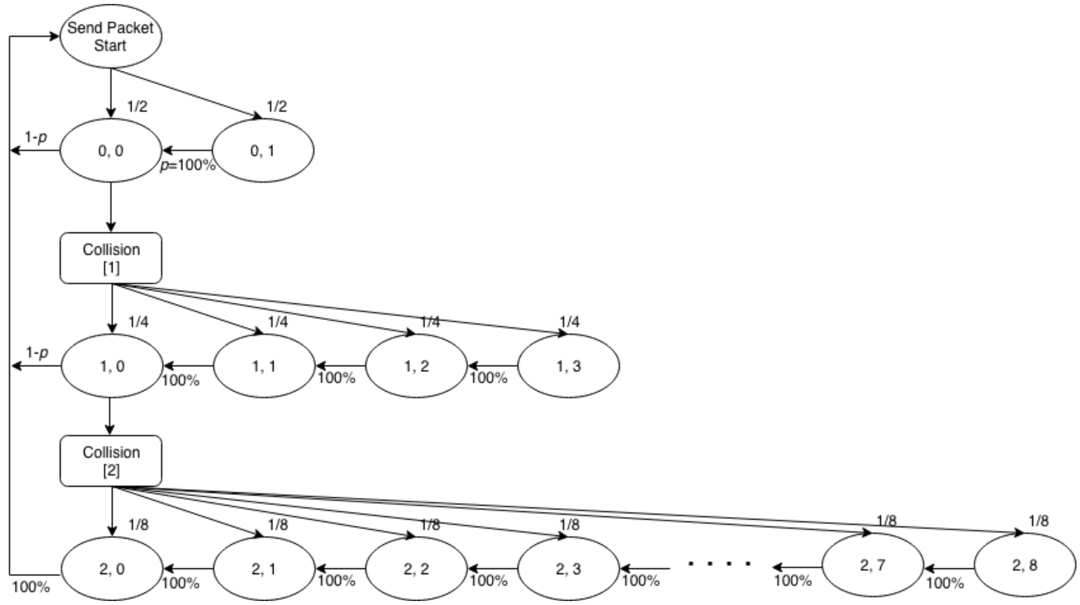

Figure 3.3: Example of Markov Chain model with back-offs where $W = 2$, $W_{MIN} = 0$, and $W_{MAX} = 3$.

$$W_i = 2^i W \qquad i \leq MAX' \tag{3.6}$$

$$W_i = 2^{MAX'} W \qquad i > MAX' \tag{3.7}$$

With $W = W_{MIN} + 1$, and $2^{MAX'}W = (W_{MAX} + 1)$, and substituting DSSS parameters into Equations (1) and (2), we get:

$$W = (31 + 1) = 32$$

$$2^{MAX'}W = (1023 + 1) = 1024$$

$$2^{MAX'}(32)/32 = 1024/32$$

$$2^{MAX'} = 32$$

$$MAX' = 5$$

When $i = MAX$, the probability of a successful and unsuccessful transmission is $(1+p-p)/W_0$; At this maximum back-off stage, the contention window, W, resets. Observing the non-null one-step transition probabilities:

$$P\{i, k \,|\, i, k+1\} = 1 \qquad k \in [0, W_i - 2] \qquad i \in [0, MAX] \tag{3.8}$$

In Equation (3.8), at the beginning of slot time t, the back-off counter does not reach zero, indicating successful transmission did not occur. At time t, the channel was idle for a segment of the slot until $t+1$. At the beginning of $t+1$ the back-off counter is decremented by 1.

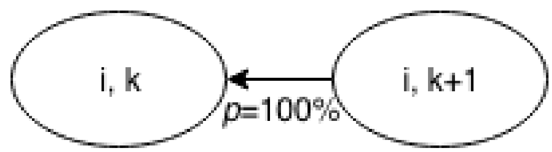

Figure 3.4: Decremented back-off timer modeling Equation (3.8).

$$P\{\text{Send Packet Start} \,|\, i, 0\} = 1 - p \qquad i \in [0, MAX] \tag{3.9}$$

$$P\{0, k \,|\, \text{Send Packet Start}\} = \frac{1}{W_0} \qquad k \in [0, W_0 - 1] \tag{3.10}$$

$$P\{0, k \,|\, i, 0\} = \frac{1-p}{W_0} \quad \text{for} \quad \mathrm{k} \in [0, \mathrm{W}_0 - 1]\,, \mathrm{i} \in [0, \mathrm{MAX}] \tag{3.11}$$

Multiplying the state probabilities in Equations (3.9) and (3.10), we can get Equation (3.11), which shows that a new back-off starts with back-off stage 0, following a successful packet transmission.

$$P\{\text{Collision } [i+1] \,|\, i, 0\} = p \qquad i \in [1, MAX] \tag{3.12}$$

$$P\{i,k\,|\,\text{Collision }[i]\} = \frac{1}{W_i} \quad \text{for} \quad \mathrm{k} \in [0, \mathrm{W_i} - 1]\,, \mathrm{i} \in [1, \mathrm{MAX}] \tag{3.13}$$

$$P\{i,k\,|\,i-1,0\} = \frac{p}{W_i} \quad \text{for} \quad \mathrm{k} \in [0, \mathrm{W_i} - 1]\,, \mathrm{i} \in [1, \mathrm{MAX}] \tag{3.14}$$

Multiplying the probabilities of Equations (3.12) and (3.13), we get Equation (3.14), which represents the probability that an unsuccessful transmission occurring at back-off stage $i-1$, which causes the back-off stage to increase and therefore resulting in the new back-off value to be uniformly chosen in the range $(0, W_i - 1)$ with probability p/W_i.

Let $b_{i,k}$ be the stationary distribution of the Markov chain. To transition from one back-off stage to the next, we multiply the back-off stage with probability of a packet collision during transmission, as shown in Equation (3.15). Equation (3.16) which is equivalent to Equation (3.15), fulfills the definition of a regular chain, where some power of chain has only positive elements given that a) for any pair of states b, b' that have nonzero probability, there exists some path from b to b' with nonzero probability and b) for all b with nonzero probability, the *self loop* probability $b \to b$ is nonzero.

$$pb_{i-1,0} = b_{i,0} \qquad 0 < i \leq MAX \tag{3.15}$$

$$b_{i,0} = p^i b_{0,0} \qquad 0 \leq i \leq MAX \tag{3.16}$$

Given that the chain is regular, for each $k \in (0, W_i - 1)$, we have (3.17), where the state $b_{i,k}$ is equal to the product of an incremented back-off time over all possible back-off stages multiplied by the probability of successful packet transmission times the summation of back-off stages.

$$b_{i,k} = \frac{W_i - k}{W_i} * (1-p) \left(\sum_{j=0}^{MAX-1} b_{j,0} + b_{MAX,0} \right) \qquad i = 0 \tag{3.17}$$

$$b_{i,k} = \frac{W_i - k}{W_i} * p \left(b_{i-1,0} \right) \qquad 0 < i \leq MAX \tag{3.18}$$

Note that when m goes to infinity, $\sum_{i=0}^{MAX} b_{i,0}$ is equivalent to $\frac{b_{0,0}}{1-p}$. Combining Equations (3.17) and (3.18), we get (3.19).

$$\begin{aligned}
b_{i,k} &= \frac{W_i - k}{W_i} * (1-p) \left(\sum_{j=0}^{MAX-1} b_{j,0} + b_{MAX,0} \right) \qquad\qquad 0 \leq i \leq MAX \\
&= \frac{W_i - k}{W_i} * (1-p) \left(\sum_{j=0}^{MAX} b_{j,0} \right) \\
&= \frac{W_i - k}{W_i} * (1-p) \left(\sum_{i=0}^{MAX} b_{i,0} \right) \\
&= \frac{W_i - k}{W_i} * (1-p) \frac{p^i b_{0,0}}{1-p} \\
&= \frac{W_i - k}{W_i} * p^i b_{0,0} \\
&= \frac{W_i - k}{W_i} * b_{i,0}
\end{aligned}$$

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \qquad i \in (0, MAX) \qquad k \in (0, W_i - 1) \tag{3.19}$$

Using the normalization condition, where all stationary probabilities, $\sum_{\forall = i} P_i = 1$, for stationary distribution:

$$1 = \sum_{i=0}^{MAX} \sum_{k=0}^{W_{i-1}} b_{i,k} \tag{3.20}$$

Let $f(k) = \frac{W_i - k}{W_i}$, which $\sum_{i=0}^{MAX} \sum_{k=0}^{W_{i-1}} f(k) b_{i,0}$ would result in $[f(k_1)b_{i,0} + f(k_2)b_{i,0} + ...]$ which is equivalent to $b_{i,0}[f(k_1) + f(k_2) + ...]$ allowing us to simplify Equation (3.20) further:

$$\begin{aligned}
1 &= \sum_{i=0}^{MAX} \sum_{k=0}^{W_{i-1}} b_{i,k} \\
&= \sum_{i=0}^{MAX} \left(\sum_{k=0}^{W_{i-1}} \frac{W_i - k}{W_i} b_{i,0} \right) \\
&= \sum_{i=0}^{MAX} \left(b_{i,0} \sum_{k=0}^{W_{i-1}} \frac{W_i - k}{W_i} \right) \\
&= \sum_{i=0}^{MAX} \left(b_{i,0} \left[\frac{1}{W_i} \sum_{k=0}^{W_{i-1}} W_i - k \right] \right) \\
&= \sum_{i=0}^{MAX} \left(b_{i,0} \left[\frac{1}{W_i} \sum_{k=0}^{W_{i-1}} W_i - \frac{1}{W_i} \sum_{k=0}^{W_{i-1}} k \right] \right) \\
&= \sum_{i=0}^{MAX} \left(b_{i,0} \left[\frac{1}{W_i} * W_i^2 - \frac{1}{W_i} * \frac{W_i(W_i - 1)}{2} \right] \right) \\
&= \sum_{i=0}^{MAX} \left(b_{i,0} \left[W_i - \frac{W_i - 1}{2} \right] \right) \\
&= \sum_{i=0}^{MAX} \left(b_{i,0} \left[\frac{2W_i - (W_i - 1)}{2} \right] \right) \\
&= \sum_{i=0}^{MAX} \left(b_{i,0} \left[\frac{W_i - 1}{2} \right] \right)
\end{aligned}$$

$$1 = \sum_{i=0}^{MAX} b_{i,0} \frac{W_i - 1}{2} \tag{3.21}$$

Using Equations (3.6)(3.7)(3.19)(3.21), and noting the properties of a geometric series, we can get Equation (3.22) as follows; substituting in the W_{MIN} constraints:

$$
\begin{aligned}
1 &= \sum_{i=0}^{MAX} b_{i,0}\frac{W_i+1}{2} = \left(\sum_{i=0}^{MAX-1} b_{i,0}\frac{W_i+1}{2}\right) + b_{MAX,0}\frac{W_{MAX}+1}{2} \\
&= \left(\sum_{i=0}^{MAX-1} p^i b_{0,0}\frac{W_i+1}{2}\right) + \frac{p^{MAX}b_{0,0}}{1-p}\left(\frac{W_{MAX}+1}{2}\right) \\
&= \frac{b_{0,0}}{2}\left[\left(\sum_{i=0}^{MAX-1} p^i(W_i+1)\right) + \frac{p^{MAX}(W_{MAX}+1)}{1-p}\right] \\
&= \frac{b_{0,0}}{2}\left[\left(\sum_{i=0}^{MAX-1} p^i(2^iW+1)\right) + \frac{p^{MAX}(2^{MAX}W+1)}{1-p}\right] \\
&= \frac{b_{0,0}}{2}\left[\left(\sum_{i=0}^{MAX-1} 2^ip^iW\right) + \left(\sum_{i=0}^{MAX-1} p^i\right) + \frac{2^{MAX}p^{MAX}W+p^{MAX}}{1-p}\right] \\
&= \frac{b_{0,0}}{2}\left[\left(W\left[\frac{1-2^{MAX}p^{MAX}}{1-2p}\right]\right) + \left(\frac{1-p^{MAX}}{1-p}\right) + \frac{2^{MAX}p^{MAX}W+p^{MAX}}{1-p}\right] \\
&= \frac{b_{0,0}}{2}\Bigg[\left(\frac{W-2^{MAX}p^{MAX}W}{1-2p}\right)\frac{1-p}{1-p} + \left(\frac{1-p^{MAX}}{1-p}\right)\frac{1-2p}{1-2p} \\
&\qquad + \left(\frac{2^{MAX}p^{MAX}W+p^{MAX}}{1-p}\right)\frac{1-2p}{1-2p}\Bigg] \\
&= \frac{b_{0,0}}{2}\Bigg[\left(\frac{W-2^{MAX}p^{MAX}W-pW+2^{MAX}p^{MAX+1}W}{(1-2p)(1-p)}\right) \\
&\qquad + \left(\frac{1-p^{MAX}-2p+2p^{MAX+1}}{(1-p)(1-2p)}\right) \\
&\qquad + \left(\frac{2^{MAX}p^{MAX}W_{MAX}+p^{MAX}-2^{MAX+1}p^{MAX+1}W-2p^{MAX+1}}{(1-p)(1-2p)}\right)\Bigg] \\
&= \frac{b_{0,0}}{2}\left[\frac{W-pW+2^{MAX}p^{MAX+1}W+1-2p-2^{MAX+1}p^{MAX+1}W}{(1-2p)(1-p)}\right] \\
&= \frac{b_{0,0}}{2}\left[\frac{W-pW+1(2^{MAX}p^{MAX+1}W)+1-2p-2(2^{MAX}p^{MAX+1}W)}{(1-2p)(1-p)}\right] \\
&= \frac{b_{0,0}}{2}\left[\frac{W-pW+1-2p-(2^{MAX}p^{MAX+1}W)}{(1-2p)(1-p)}\right] \\
&= \frac{b_{0,0}}{2}\left[\frac{W-pW+1-2p+(pW-pW)-(2^{MAX}p^{MAX+1}W)}{(1-2p)(1-p)}\right] \\
&= \frac{b_{0,0}}{2}\left[\frac{W-2pW+1-2p+pW-(2^{MAX}p^{MAX+1}W)}{(1-2p)(1-p)}\right] \\
&= \frac{b_{0,0}}{2}\left[\frac{(1-2p)(W+1)+pW(1-(2p)^{MAX})}{(1-2p)(1-p)}\right]
\end{aligned}
$$

$$b_{0,0} = \frac{2(1-2p)(1-p)}{(1-2p)(W+1) + pW(1-(2p)^{MAX})} \tag{3.22}$$

Noting that when the back-off time counter is equal to zero, regardless of the back-off state, we can find τ, the probability that a station transmits in the bounds of a randomly chosen slot time.

$$\tau = \sum_{i=0}^{MAX} b_{i,0} = \frac{b_{0,0}}{1-p} = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^{MAX})} \tag{3.23}$$

Under the assumption that each packet transmission occurs independent of time, or in other words, in steady state, we can find the value for p, the probability that a collision can occur when more than one station transmits during the same time slot.

$$p = 1 - (1-\tau)^{n-1} \tag{3.24}$$

Note that while a station is sending a frame, a collision can occur when one of the $n-1$ other stations decide to transmit. As shown in the following Equation, the number of contenting stations, n, and their respective transmission probabilities, τ, impacts P_{tr}, the probability that there is at least one transmission occurring in the slot time.

$$P_{tr} = 1 - (1-\tau)^{n} \tag{3.25}$$

In the channel, the probability of a successful transmission where no packet collisions occur during the span of a randomly chosen slot time can be calculated as P_s.

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} \tag{3.26}$$

P_σ represents the probability that the slot time is empty,

$$P_\sigma = 1 - P_{tr} \tag{3.27}$$

The throughput, S, of the normalized system can be expressed as the ratio,

$$S = \frac{E[\text{Payload Information Transmitted in a slot time}]}{E[\text{Length of a slot time}]} \tag{3.28}$$

Let $E[P]$ be the average packet payload size. With $P_{tr}P_s$ as the probability of a successful transmission during the slot time, the average payload information successfully transmitted is equivalent to $P_{tr}P_sE[P]$. Assigning σ as the duration of an empty slot time, T_s as the average time the channel is sensed busy because of a successful transmission, and T_c as the average time the channel is sensed busy because of a collision, throughput can be rewritten as:

$$S = \frac{P_sP_{tr}E[P]}{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c} \tag{3.29}$$

3.2 Motivation for Developing a New Protocol

The existing scheme randomly assigns a BEB which, by definition, is a limitation that decreases the probability of immediately sending packets. Rather than continuously going through the entire back-off process, ideally, the node is able to recognize their channel assignment. The best case is if the packets are able to forgo the collisions and random back-off assignments and simply send their

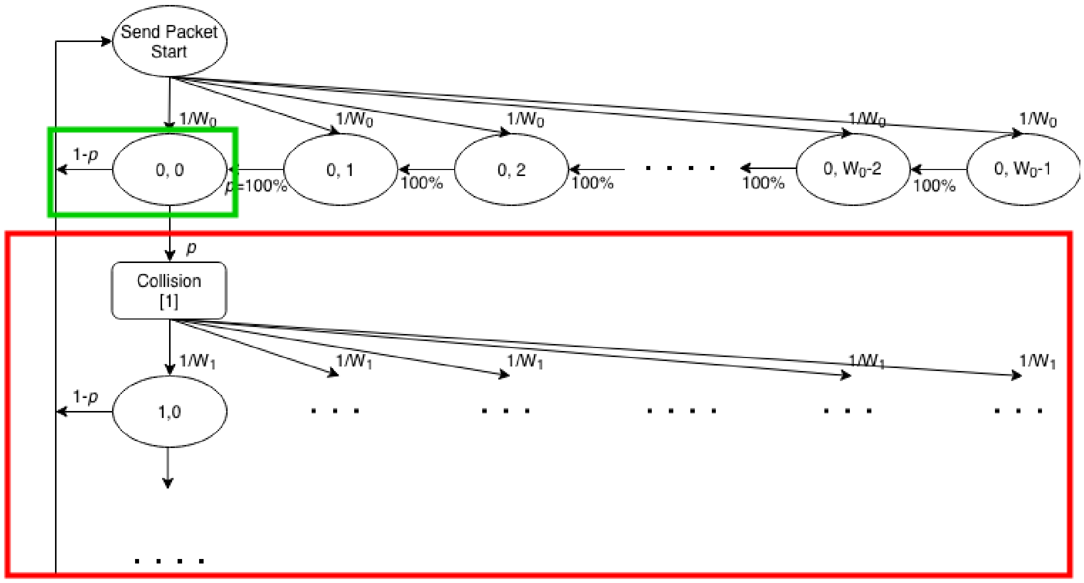

Figure 3.5: The boxes indicated in red show the random back-off period that a station must wait after a collision before re-transmitting. Looking at the box in green, the ideal case can be seen when the probability to transmit is 100%.

messages given a preassigned order. In order to achieve this, the nodes must know in advance which channels are allocated to them as shown in Figure 3.5.

3.3 Summary

Based on the observation that channel allocation assigned in advance can significantly improve throughput, a new model is proposed in Chapter 4.

Chapter 4

LMAO: Proposed Scheme to Improve WAVE MAC Channel Utilization

As vehicles are constrained by roads to traverse on, there is a distinct property where ordering does occur as there are a discrete number of positions the vehicles can be in. By assigning position numbers to each vehicle, the proposed model, Linear Modulus Autonomous Ordering (LMAO) is able to utilize and exploit the hidden terminal problem as a solution to assign vehicles to truly distribute vehicles to channels.

4.1 Inspiration for Framework and Methodology

4.1.1 Problem Statement and Objective

Problem statement: The allocation of cars onto channels at a single time slot determines the utilization of channels available.

Given:

- the number of cars in a system
- the number of channels in a system
- the range of neighbors a car can see

The objective of this thesis is to find an allocation method that determines which cars should use which channels during a single time slot in order to fully maximize channel utilization by reducing contention for the same channels.

4.1.2 Framework Comparison

In order to pre-allocate channels to the nodes to avoid contention, a framework is a established to allow equivalent comparisons to satisfy the stated objective.

4.1.2.1 Simulation Assumptions

The following assumptions are made:

1. The channels are ideal and have no transmission error.
2. The impact from the mobility of devices on the packet transmission can be ignored.
3. Each vehicle has a system that can identify its location, speed, and acceleration and thus, its order.
4. The modulo value, $r = 6$ for the six channels that are available during the SCH interval.
5. $d = 5$, where d is the range of neighbors a vehicle can see; d is $[0, n-1)$.
6. Vehicles at time t are considered alumni vehicles when they are present in the system at the later time, $t + 1$.
7. For simplicity, each system starts with at least two alumni nodes.

4.1.2.2 Simulation Framework Methodology

In the simulation, the calculations for assigning channels during SCH is simulated for each time step. During these calculations, a list of valid values are produced, which are found based on the protocols constraints. From the list of valid values, a random value is selected to assign the node a channel for the next immediate time step.

To simulate the throughput for n nodes random values $[1, n]$, indicating the order that the node claims a channel, were assigned to each node. Starting from the random index location containing the value 1, the channel allocation process occurs sequentially by the index location of the random ordering until all values 1 to n were visited. If the one of the valid values are seen assigned to a neighboring channel in the specified range R, before and after the given index, then the seen values are removed from the valid values list. R, as previously specified, has a value of 5. If all of the valid values in the list are removed, the given node can not utilize a channel due to the collision that would occur.

Note that the list of valid values may be empty, which means that no valid channel can be assign to the given node as any assignment. For each node in the system, first a list of valid values is calculated and then a random channel selection from the list of valid values is assigned. The mean values of 1000 simulations with 2 to 100 nodes is calculated and compared.

4.1.3 Exploiting the Hidden Terminal Problem

By pre-assigning channel slots using TDMA, VANET is able to achieve a consistently high throughput, but one of the underlying throughput constraints lies in the reservations based on the R-ALOHA. In addition, the hidden terminal

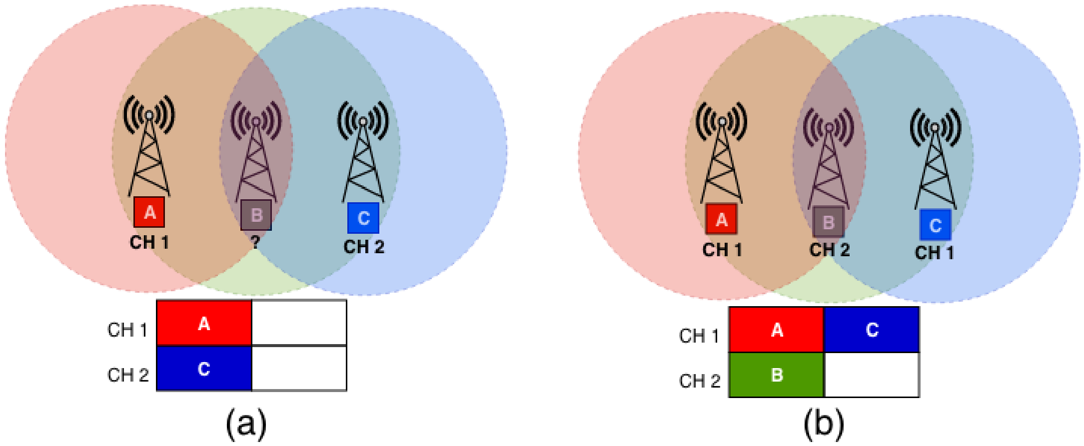

Figure 4.1: Figure (a) shows a non-ideal situation when only stations can use the two channels and Figure (b) shows an ideal situation when all three station can use the two channels given a hidden terminal properties apply.

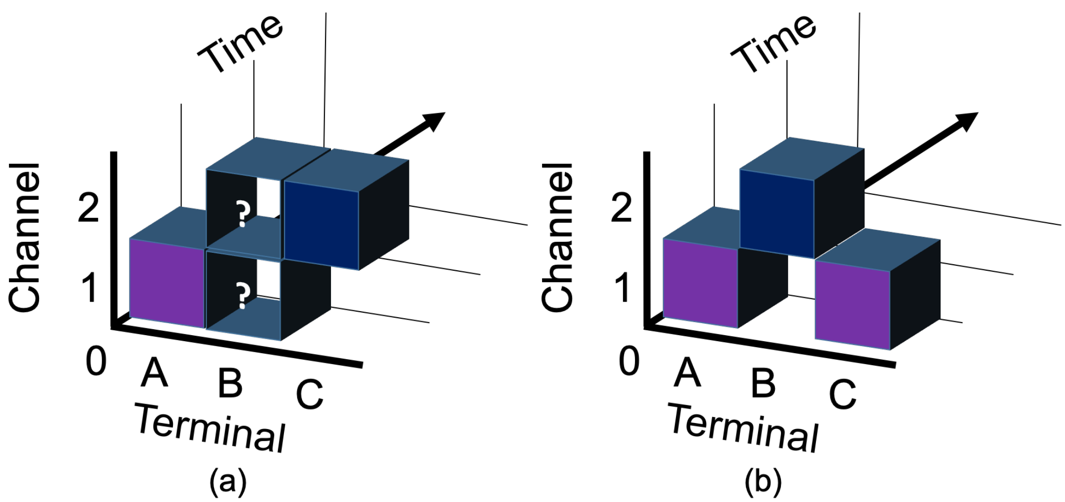

Figure 4.2: During a single time slot and given the hidden terminal properties apply, Figure (a) shows a non-ideal situation when only stations can use the two channels and Figure (b) shows an ideal situation when all three station can use the two channels.

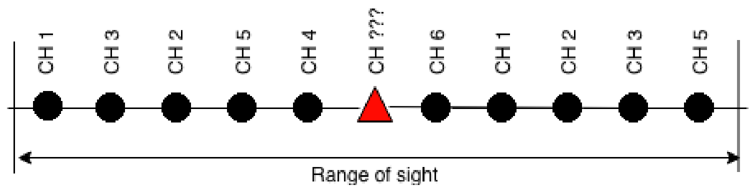

Figure 4.3: Example of random channel assignment.

problem was not explored in the evaluation of the VANET MAC Protocol. However, there are interesting properties of the hidden terminal problem that can lead to improving the throughput of VANET, specifically during the reservation period.

Given the constraint of the channels available, stations attempt to communicate on the same channel that the sending or receiving station is on. With the hidden terminal problem, multiple nodes cause collision as they try to send data to a channel at the same time, not realizing that they are doing so. To prevent this scenario causing packet loss, one solution would be to have all nodes to send their packets on separate channels as their transmissions would not interfere with each other. Yet, there is a limited number of channels available. In addition, having a large fixed number of channels with the variation in the network saturation can leave many channels underutilized.

In the hidden terminal case, the intermediary station, who is able to pass on messages, is able to recognize the channels being used by both of its neighbors. As a result, the intermediary station is also able to calculate which channel is not being used by its immediate neighbors.

Figure 4.1(a) shows an example of a non-ideal case where, of three stations, only two are able to transmit information. Figures 4.1(a) and 4.1(b) show an example of three stations needing channel space when only two channels are available. Figure 4.1(a) shows that Station B does not get a channel as Station

A and Station C are occupying Channels 1 and 2 respectively. Figure 4.1(b) shows that all three stations are able to talk on the channels. Observing that Stations A and Station C are not able to directly communicate with each other, sending messages on the same channel will not interfere with their transmission. As a result, Stations A and C can both be on Channel 1 leaving space for Station B to occupy Channel 2. In contrast, Figure 4.1(b) shows an example of an ideal case where, of three stations, all three stations are able to transmit information as their messages will not collide with each other.

The solution in Figure 4.1(b) is valid because even though Station A and Station C are talking on the same channel, they are at a range far enough from each other that they are unable to hear each others message, therefore avoiding collision. Depending on the channels each node and their neighbors are on, there are situations where the channels are fully utilized and underutilized. The exact scenarios in Figure 4.1 is represented a second form in Figure 4.2 except with the addition of a time slot, introducing the notion that the channel allocation occurs for a single time slot. Similar to Station B in Figure 4.1(a), Figure 4.3(a) shows an example of a node, represented with a red triangle, unable to use a open channel. Figure 4.3 assumes that there only six channels available and that each node has a range of, at most, five neighbors that a node can see.

Yoo et. al. [37] briefly observed that the hidden terminal overlap can lead to an increase in the ratio of successfully broadcast and delivered beacons. However, the observation led to the conclusion that nodes within the same contention domain as well as nodes hidden from them should share the same safety interval. In contrast, in this thesis, the exploitation of the hidden terminal property is thoroughly explored and is a key aspect to allow every node a valid channel to use during a single time slot.

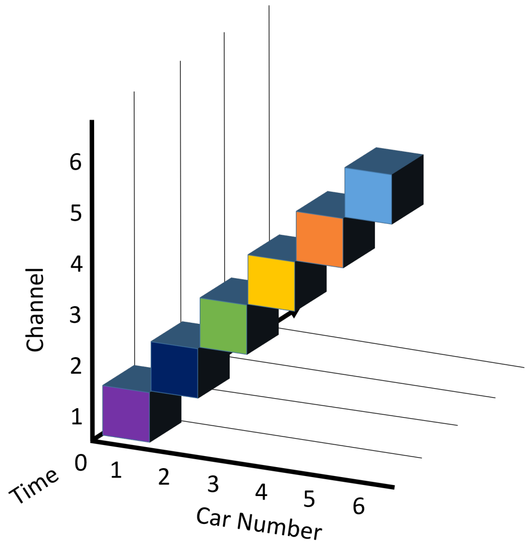

Figure 4.4: A simple best case example occurs when the all of the channels can be evenly distributed among the cars trying to send a message over a single time step.

The following Section 4.2.1 discusses the importance in channel allocation ordering.

4.2 Proposed Model

4.2.1 Ordering in a Line to Combat Random Ordering

In the 802.11p WAVE MAC protocol, slot allocation occurs through random assignment of slot times based on priority levels and random BEB assignment. The major advantage for VMESH's higher throughput is possible through the TDMA pre-assignment of channel slot reservation.

As shown in Figure 4.5, randomly assigning cars to a discrete number of channel slots gives about a 25% throughput utilization loss. However, if the packets were in order, predetermined intentional channel slot allocation can allow the throughput to reach the maximum capacity, therefore resulting in a

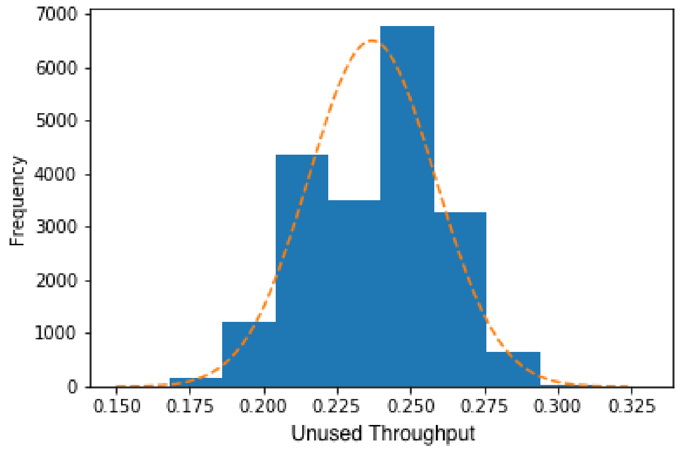

Figure 4.5: Random assigning of 100 cars into 6 channels slots 20,000 times gives a throughput a mean of .763.

better throughput, such as the channel allocation shown in Figure 4.4. Using the two-sample T test we can demonstrate this result is statistically significant at a 0.01 confidence level.

Keeping track of an order, such as sequential numbering, can significantly increase throughput. But the issue arises when a RSU needs to constantly update its table of global information to figure out where each vehicle unit is and in what order as soon as the vehicles enter and leave the range of the RSU. To alleviate the load on the RSUs that are repeatedly collecting information from incoming beacons, the LMAO model proposes that each vehicle is in charge of knowing their own position. This can be achieved by storing and updating a moving average value for each individual vehicle, truly making the system autonomous. For example, say we have vehicles A and B with weights 1.0 and 2.0 respectively. Now say a new vehicle, C, enters the traffic in between A and B. Vehicle C can calculate its own weight by adding weights of neighbors A and B and dividing that value by 2 to get 1.5. Vehicle B knows that the value 1.5 is less than its own weight of 2.0 so the vehicle that just joined must be in

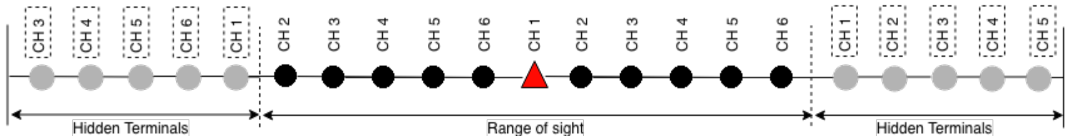

Figure 4.6: Case 1 where the immediate neighbors, in front and behind, are present and visible.

front of vehicle B. Vehicle A knows that the value 1.5 is greater than its own weight of 1.0 so the vehicle that just joined must be behind of vehicle A. Each vehicle only needs to pay attention to their immediate neighbors to calculate their weight when both of their immediate neighbors are visible to them, as shown in Figure 4.6. In Case 1, the weight of a channel can be obtained from the immediate neighbors as they are both in the range of sight. Even if there are hidden terminals, they are no concern to the node.

However the more complicated issue arises when the vehicle is Case 2 in the front of the sequence, where only the weight of the neighbor behind is visible or Case 3 in the end of the sequence, where only the weight of the neighbor in front is visible. In Case 2, there are no neighbors in front, aka the specified car looks like the first car in the list, as it is too far to join another channel, as shown in Figure 4.7. In Case 3, there are no neighbors behind, aka the specified car looks like the last car in the list, as it is too far to join another channel. Note that Figures 4.6, 4.7, and 4.8 assume that there only six channels available and that each node has a range of sight equal to at most five nodes.

Given the issue with dynamically modifying the weight of a node when inserted at the beginning or the end of the vehicle traffic order, the following section discusses how linear autonomous ordering can be achieved using modulus arithmetic.

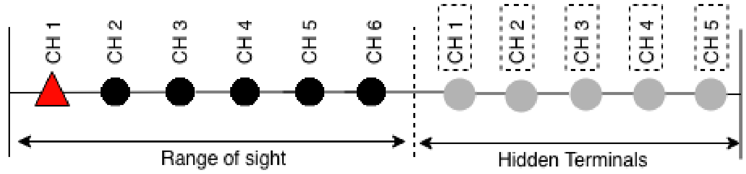

Figure 4.7: Case 2 were there are no visible neighbors in front but at least one visible neighbor behind the given node.

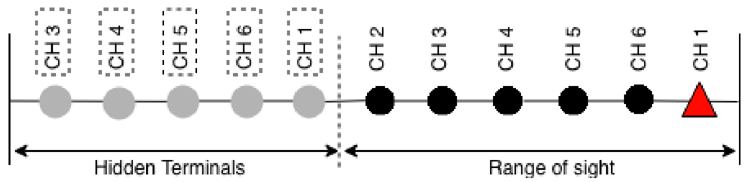

Figure 4.8: Case 3 when there are no visible neighbors behind, but there is a visible neighbor in front of the given node.

4.2.2 Review of Modular Arithmetic

Modular arithmetic is highly used in the field of cryptography [11]. As a result, many modular arithmetic applications are centered around encryption and the security of accessing and transporting packets. Although an interesting application applies when the properties of a modulus is applied on the distribution of packets on a channel, which positively affects the throughput of a system.

'Mod' represents the modulo operation to enable repetition of the integer indices within the bounds defined by variable r. For a positive number i, two numbers, a and b are said to be congruent mod r, if the difference of $a - b$ is an integer multiple of r, as denoted in the following equation.

$$a \equiv b(\text{mod} \quad i) \qquad a \in [0, r) \tag{4.1}$$

For example, 8 mod 6 = 2 shows that 8 is an equivalence class for 2. -2 mod 2 = 2 shows that -2 is an equivalence class for 2 as well. Therefore we can write 8 ≡ -2 (mod 6).

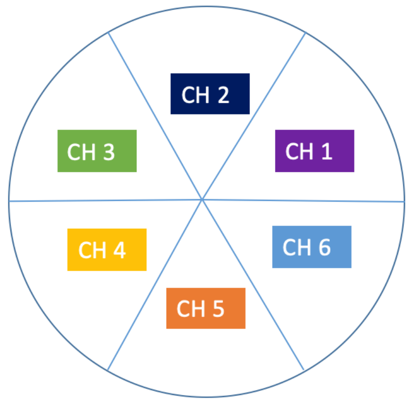

Figure 4.9: Vehicles can use modulus arithmetic to claim and utilize channels.

4.2.3 Linear Modulus Autonomous Ordering (LMAO)

As specified in the WAVE system, during the CCH, each vehicle is able to update their knowledge of the position of their neighbors as beacons are transmitted. The proposed LMAO method can be described by the following steps:

1. During the CCH interval, the vehicles calculate their weight by averaging the weight of the immediate neighbor in front of them with the immediate neighbor behind them to get their current position value.
    - If a neighbor in front is not present, the furthest node behind the given node that is within the range vision of the node is used to calculate the average weight.
    - If a neighbor behind is not present, the furthest node in front of the given node that is within the range vision of the node is used to calculate the average weight.
2. The value found in Step 1 is then modulated with the number of channels that the given node has access to so that the resulting channel is a valid channel index.

3. Steps 1 and 2 can be updated multiple times to spread out and stabilize their spaced-out weight values.

4. Each node then calculates which and how many full channels it may occupy by taking its own weight value and subtracting the value by the front neighbor's weight value and rounding down. The resulting value is the number of channels the node can occupy. The channel values that can be occupied by the given node is the range calculated by subtracting the given node's weight with the calculated result of the number of channels the node can occupy. Note that in all of these calculations, the modulus properties apply.

The LMAO method allows synchronization of selecting channels between the given node and the nodes hidden to it. This allows available channels to be properly allocated and fully utilized.

Using modular arithmetic, the allocation of channels to vehicles can be preformed and given time to stabilize and equally spread out between the number of channels and the number of nodes trying send a message on a channel, the channel utilization can increase. By using the number of channels available as r and by iteratively distributing neighbors using the weighted averages of the neighbors, as mentioned in the previous section, the channel to assign the node to (i.e. the equivalence class) can be found.

Figure 4.10 demonstrates how iterative calculations of each node's weight, based on the bounds from the node's neighbors, push each node towards a slot value to utilize all channel space/the available resources. Here three vehicles enter the ad-hoc network. In this case, we are using modulo 6 as there are 6 channels available from the SCH intervals. As seen in Figure 4.10(a), at

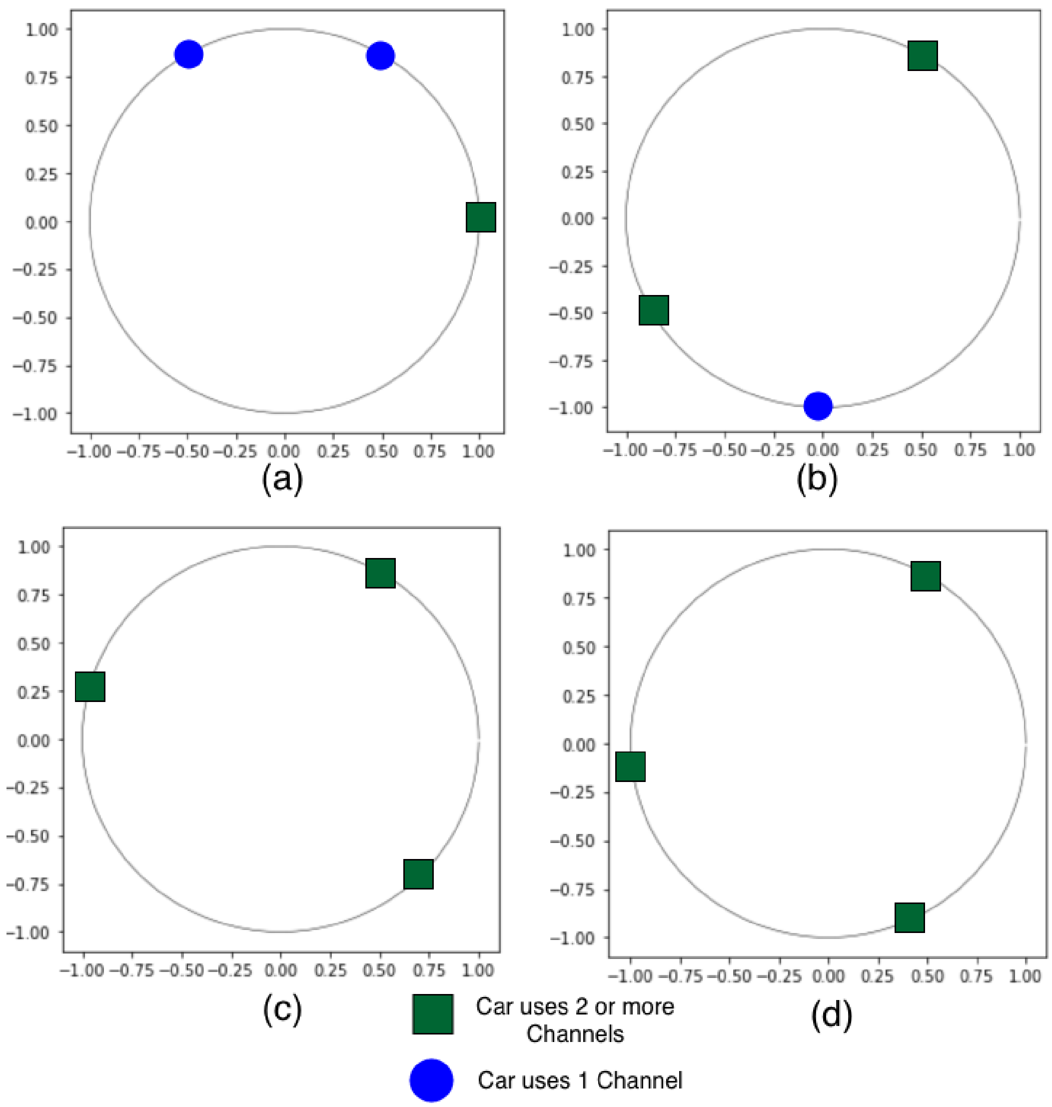

Figure 4.10: Stabilizing the weight values of three nodes over 3 stabilizing algorithm steps with Figure (a) as the plot of initial weight values.

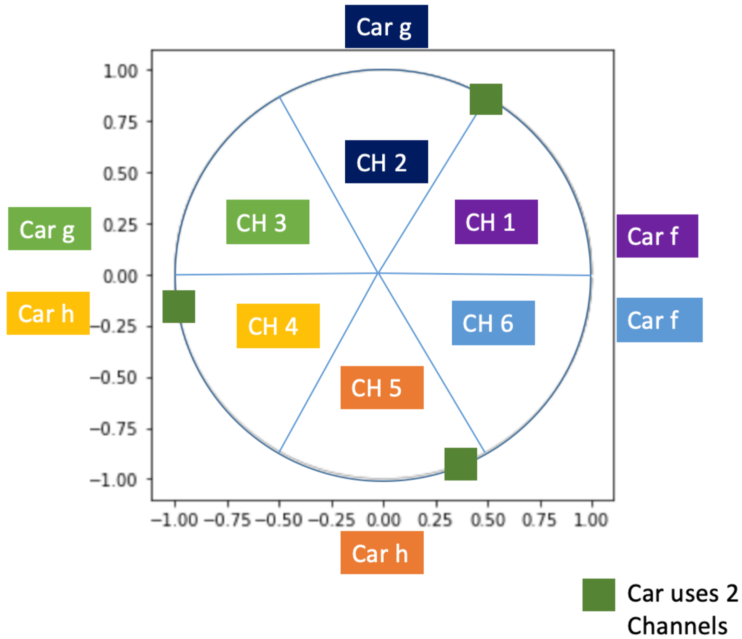

Figure 4.11: Channel allocation for each car for Figure 4.10(d).

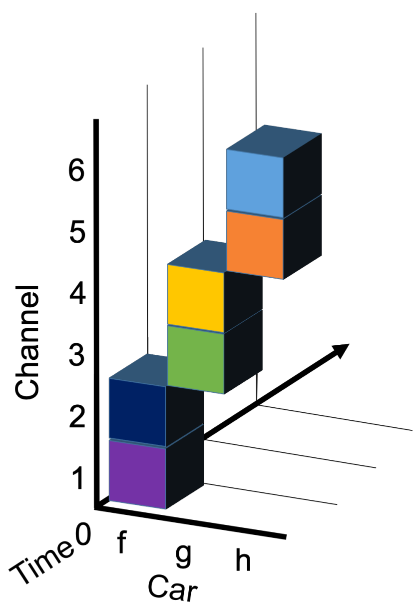

Figure 4.12: Channel allocation based on Figure 4.11 where each car is able to utilize more than one channel.

algorithm stabilization step 1, the three cars are able to each claim a channel. Notice that while two cars use one channel each, the last car is able to use the remaining 4 channels. At algorithm stabilization step 2, as shown in 4.10(b), the distance between the first and the third node allows for a large noticeable push that spreads the nodes away from their previous location. Here, now two vehicles are able to use more than one channel. In 4.10(c), the values are leveling out and in 4.10(d) they are nearly stabilized.Note that Cartesian coordinates (1,0) represents a 0.0 weight, (0,1) represents a 1.5 weight, (-1,0) represents a 3.0 weight, and (0,-1) represents a 4.5 weight. Figure A shows three nodes, f, g, and h with weights 0.0, 1.0, and 2.0 respectively. The image shows node f using more than two channels and nodes g and h using one channel each. In the next algorithm stabilization step, Figure B shows the weight of f updates to 4.5 as the neighbor weights $((2.0 + 6) + 1.0)/2 = 4.5$. The weight of g stays as 1.0 with $(0.0 + 2.0)/2$. The weight of h is $(0.0 + (1.0 + 6))/2 = 4.5$. Note that first, in the first algorithm stabilization step, both f and h had the number of channels, 6, added to the calculations before getting the average. The modulus value, i.e. the number of channels, is added so that the weighted values can properly "circle around the ring" properly. Second, because there is no neighbor in front of car f, as there is no number smaller than 0.0, the weight of f is used for the weight of a front neighbor. Similarly, because there is no neighbor behind h, as there is no number larger than 2.0, the weight of h is used for the weight of a behind neighbor. In the next stabilization step shown in Figure C, the weights of f, g, and h update to $5.25 = (1.0 + (6 + 3.5))/2$, $1.0 = [(3.5 + (6 + 4.5))/2] \bmod 6$, and $2.75 = (4.5 + 1.0)/2$. Note the mod of the number of channels, 6, was used to calculate g in this algorithm stabilization step. And in Figure 4.10(d), the nodes look nearly evenly spaced away from each other, considering the nodes are stable at that point, the channel allocation is determined. To calculate which channel the node occupies, range from the weight of the node up to the weight of the immediate neighbor that is larger (indicating that the neighbor is behind the said node) is found. The the value between the range found is then rounded to the nearest integer to determine the channel(s) the said node should occupy. If the value found ends in .5, the number is rounded to the nearest whole even number as per IEEE 754 [14]. The channel allocation of Figure 4.10(d) is shown in Figure 4.11, noting that the channel allocation occurs in one time step, as shown in Figure 4.12.

4.2.4 LMAO Limitations

The LMAO algorithm does not currently account for how to calculate the node's weight, and thus, position, when a node can see a range greater than the number channels. The effect that algorithm steps have on the even distribution based on the number of nodes present in the system is also uncertain. In addition, as the LMAO model is for linear cases, the model is unable to handle nodes that are not sequential (i.e. if two cars are side by side on a road and therefore have the same weight). In our simulations, the number of algorithm stabilization steps but is assumed to be fast enough with at max 100 steps for 100 nodes each. Future research can explore these limitations.

4.2.5 Simulation Methodology

4.2.5.1 Simulating Random Throughput

To simulate the random throughput which approximates the upper bound of the WAVE MAC back-off:

For n nodes random values $[1, n]$, indicating the order that the node claims a channel, are assigned to each node (i.e. imitating cars entering the highway at random positions). Sequentially assigning the nodes based on the random values assigned, a random value $[0, r-1]$, is assigned to every node, where r is the number of channels available. The throughput for each node is then calculated by counting the number of nodes within the range of sight that was assigned the same channel as the observed node, and equally dividing the channel with the number of nodes claiming that particular channel to get a throughput utilization percentage. The mean of the throughput percentages for each node is then calculated, approximating the upper bound of the back-off procedure.

4.2.5.2 Simulating VMESH MAC Throughput

To simulate the VMESH MAC throughput: For n nodes random values $[1, n]$, indicating the order that the node claims a channel, were assigned to each node. During the channel allocation, a channel value is randomly selected from a list of valid values. The list of valid values starts as the integer values in the range $[0, 5]$, as $r = 6$ is the number of channels in the system. The valid values are found by removing the channels that were assigned to the neighbors d, because they are within the range of neighbors the given node can see. As those channel values are in the range of sight of the given node, removing those values from the list of valid values is appropriate. The process of assigning unique allocations and reassigning non-unique values with random values occurred repeatedly until all channels were filled. The mean of the throughput percentages for each node is then calculated, to find the average throughput given the n nodes in the system.

4.2.5.3 Simulating LMAO MAC Throughput

To simulate the LMAO MAC throughput: For n nodes values $[1, n]$, indicating the order that the node claims a channel, were sequentially assigned to each node. As stated in the assumptions, each vehicle is aware of their position. Thus, each node has a numerical weight value greater than the weight value of the neighbor behind them and less than the weight value of the neighbor in front of them.

During the channel allocation, each node in the system goes through the stabilization algorithm for a predetermined number of steps before a new node is added (i.e. a car enters the traffic at a random position). The process of adding a new node and stabilizing the weights in the system is repeated for the range of the nodes evaluated. In our simulations, 10, 30, and 100 steps were performed and compared. A channel value is randomly selected from a list of valid values. The list of valid values starts as the integer values in the range $[0, 5]$, as $r = 6$, is the number of channels in the system. The valid values are found by removing the channels that were assigned to the neighbors d of the given node. As those channel values are in the range of sight of the given node, removing those values from the list of valid values is appropriate. The process of assigning unique allocations and reassigning non-unique values with random values occurred repeatedly until all channels were filled. Note that compared to the VANET MAC method, LMAO always has at least one value in the list of valid values as the sequential channel allocation is possible due to the LMAO weighted modulus average scheme. Although a stabilized LMAO assignment would lead to a 100% throughput, and thus a straight line at 1.0 in Figure 5.8, a more interesting comparison of a not-fully-stabilized LMAO allocation using 100 stabilization steps was compared.

4.3 Summary

LMAO helps utilize the allocate available channel resources during the SCH. However, Limitations of the LMAO model include the fact where a node can see weight of cars in a range greater than r (i.e. the number of channels available). In addition, as the LMAO model is for linear cases, the model is unable to handle nodes that are not sequential (i.e. if two cars are side by side on a road and therefore have the same weight). The following Chapter 5 discusses the results found from the experiments described in this chapter.

Chapter 5

Results

This chapter discusses the results of the simulations described in the previous Chapter 4.

5.1 Analysis of LMAO Protocol

The result of applying the LMAO protocol to uniformly distributing channels is shown to evenly distribute each node on separate, collision-free channels given an adequate number of stabilization steps. Figures 5.2 and 5.2 pictorially shows the movement of each node during a stabilization algorithm. In these figures, 10 cars were used. The weights acquired from the alumni cars are set to sequentially have an initial weight in the range (2,3] with 0.1 increments (i.e. Car 1 has weight 2.1, Car 2 has 2.2, etc.) as shown in Figure 5.1(a). In this first figure, based on the algorithm, the first car would claim every channel and the other nine cars are too close in weight to claim a channel. In Figure 5.1(b), taking the average of the end nodes using modulus calculus allows the end nodes, Cars 1 and 10, spread out and each claim more than one channel. Figure 5.1(c) shows that in the stabilization algorithm step 2, four cars are able to claim one channel while the first car is able to claim more than one channel to use. Similarly in Figure 5.1(d), after another stabilization step, even more cars are able to claim one or more channels. An interesting phenomenon occurs in Figure

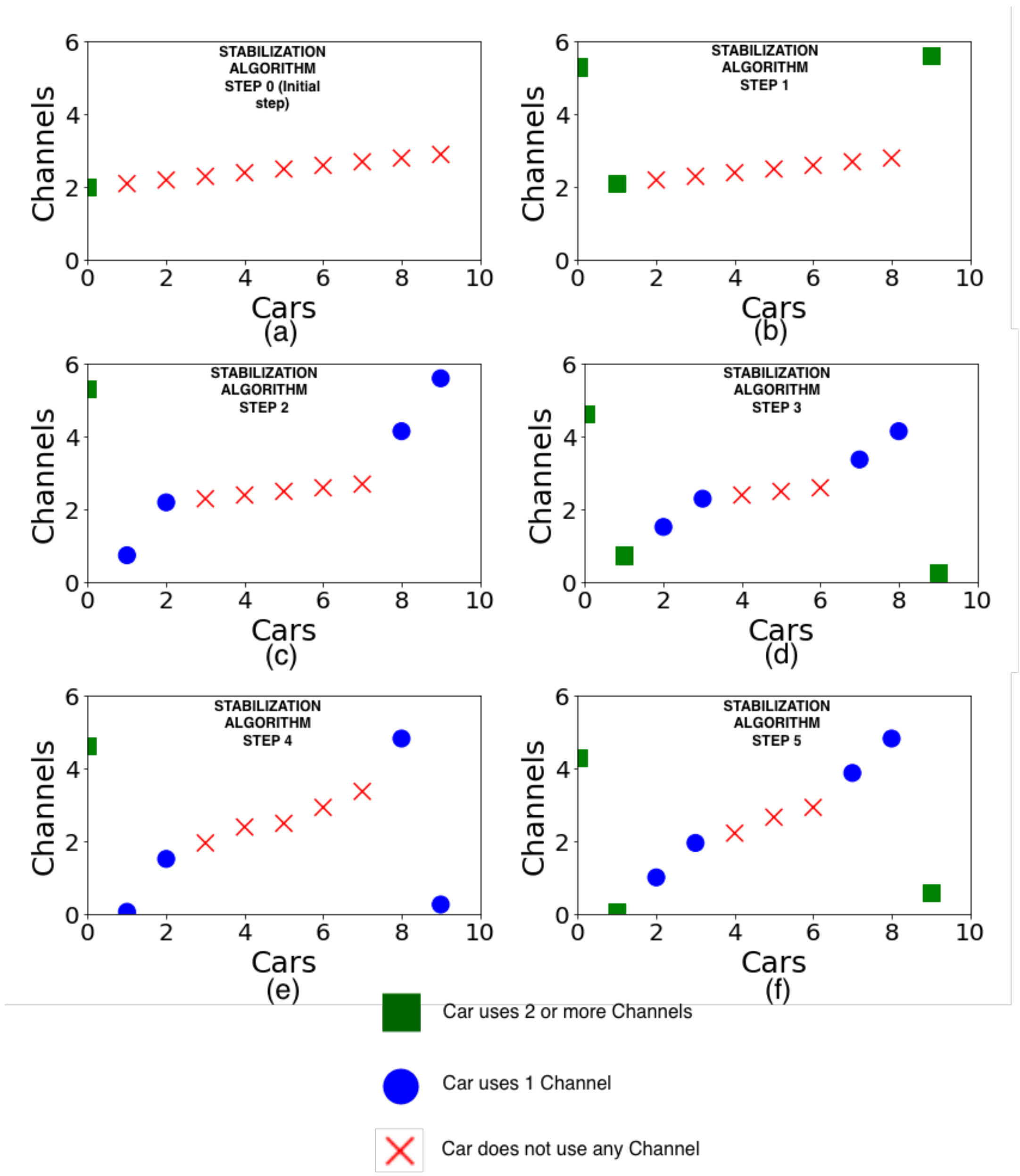

Figure 5.1: The vehicles are able to uniformly distribute onto different channels.

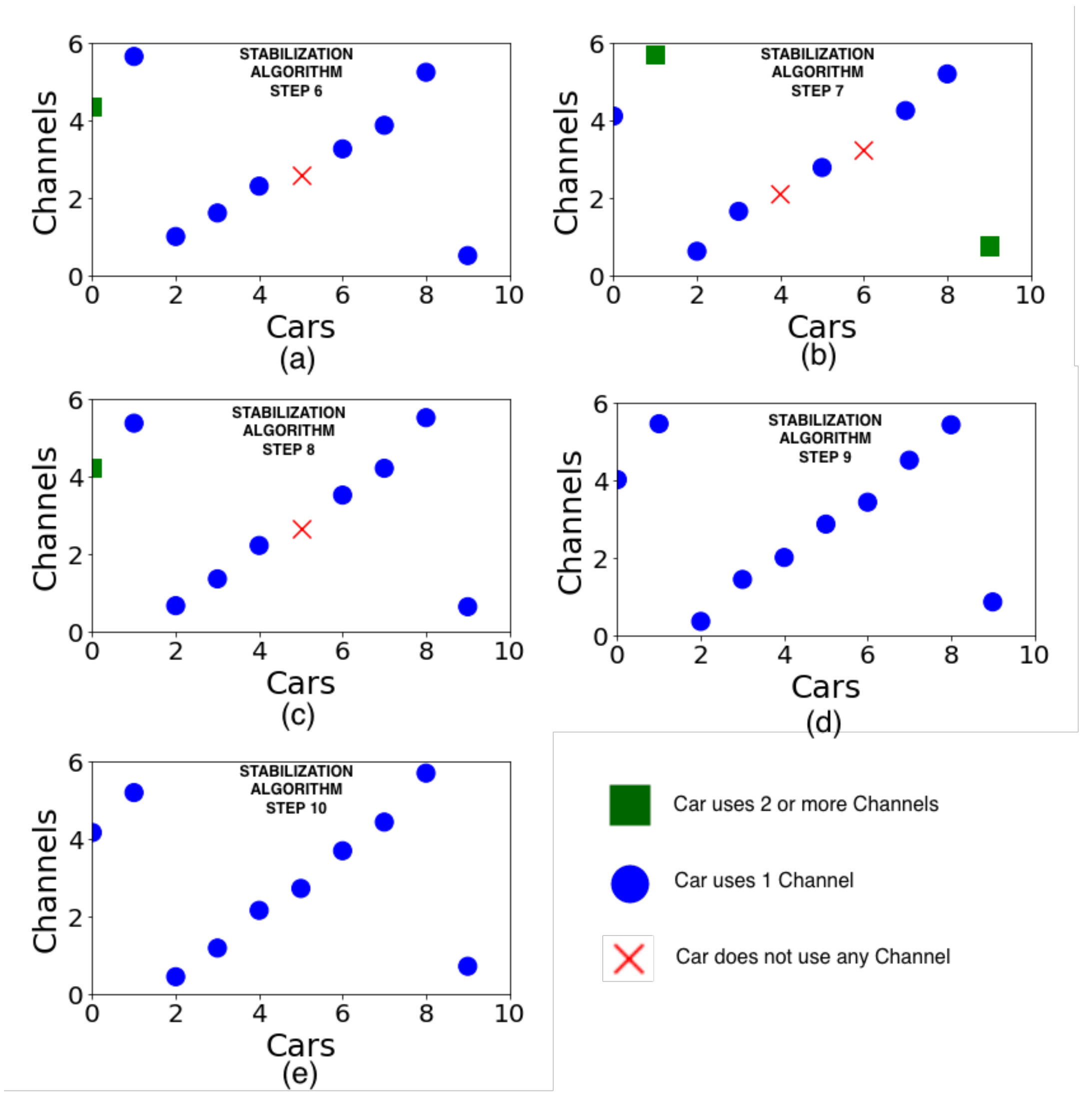

Figure 5.2: The vehicles are able to uniformly distribute onto different channels.

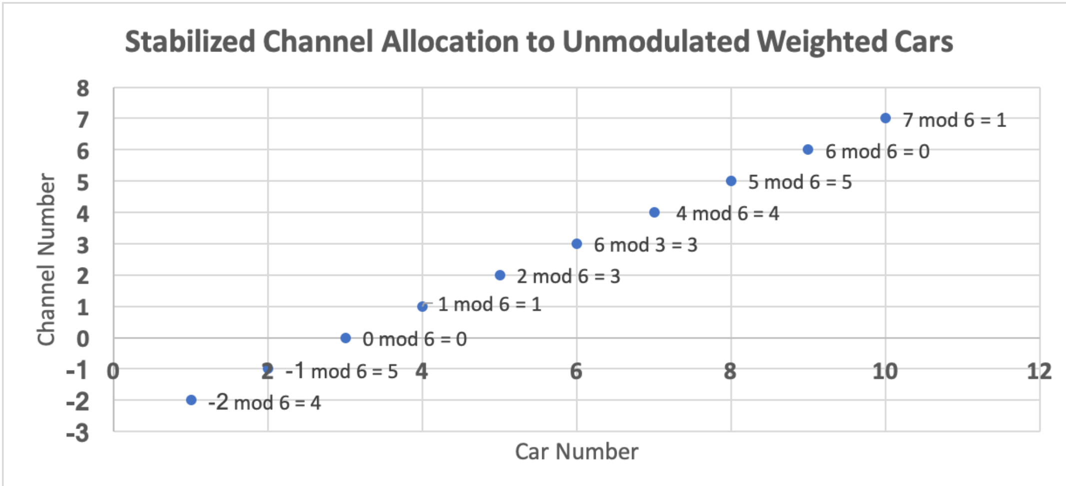

Figure 5.3: Assigning channels to cars from the stabilization algorithm step 10 with unmodulated weights.

5.1(e), where the previous stabilization step resulted in more nodes having at least one channel allocated to them. This makes sense because the outer nodes, i.e. the first and last nodes, spread out very far from the median weight of the nodes very quickly. To accommodate for this drastic weight shift, the nodes over shoot and under shoot their weight values until they obtain their stable state weight. The same phenomenon is seen between Figures 5.2(a) and 5.2(b). Figures 5.2(d) and 5.1(e) demonstrate that the weights of each node begin to stabilize and uniformly occupy the channels available without contention as the nodes on the same channels are out of range of each other. Given enough steps for each node weight value to update and evenly spread out, each node is guaranteed to have at least one channel reserved to transmit a packet on.

Figures 5.3, 5.4, and 5.5 expand on the information that is condensed in Figure 5.2. Using the stabilization algorithm described in Section 4.2.3, these three figures show how every car can be assigned a non-contending channel and channel use overlap is not an issue given the range distance each node has from each other. In Figure 5.3, from y axis, the nodes can be seen to each have a

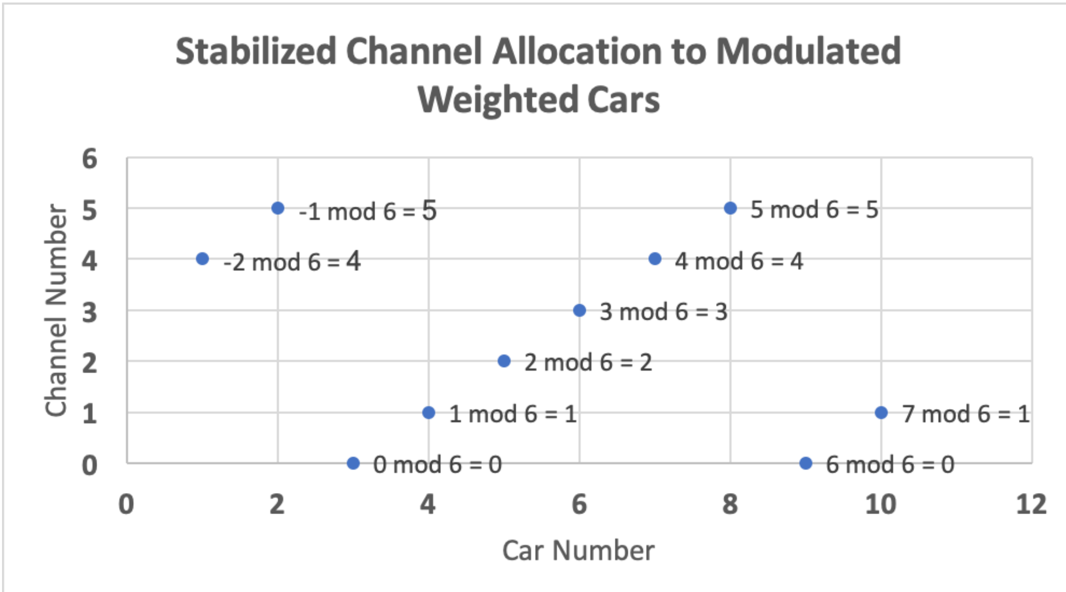

Figure 5.4: Representing Figure 5.3 with modulated values based on the six channels available.

Channels

5	b	-1 mod 6 = 5	bh	bh	bh	bh	bh	5 mod 6 = 5	h	h
4	-2 mod 6 = 4	ag	ag	ag	ag	ag	4 mod 6 = 4	g	g	g
3	i	i	i	i	i	3 mod 6 = 3	i	i	i	i
2	e	e	e	e	2 mod 6 = 2	e	e	e	e	e
1	d	d	d	1 mod 6 = 1	dj	dj	dj	dj	dj	7 mod 6 = 1
0	c	c	0 mod 6 = 0	ci	ci	ci	ci	ci	6 mod 6 = 0	i
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**

Cars

	Legend
	Channel is allocated to Car
	Channel has more than one Car utilizing Channel
	Channel has one Car utilizing Channel

Figure 5.5: Overlap between channel allocation for cars in the system from Figure 5.4.

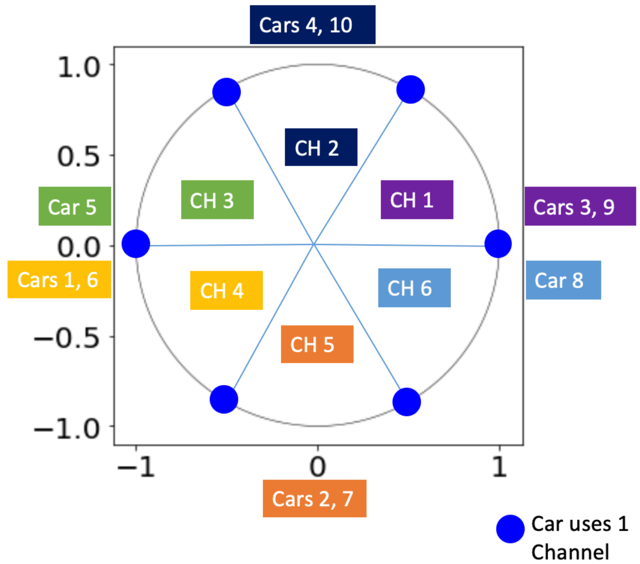

Figure 5.6: Cars are evenly spaced around a circular ring with overlap as the overlap indicates that the nodes are out of range of each other.

separate channel number. Modulating the channel number value of each node with the actual number of channels available, which is 6, each node is assigned the modulated channel value. The nodes are re-plotted in Figure 5.4 given the modulated channel values.

It is valid that some of the nodes are using the same channels as the nodes are out of range from each other, and as a result, no contention would occur. Figure 5.5 shows cars, which are represented with alphabetical values for clarity, and the channels they are using. The cells in green show that the corresponding cars on the x access know that more than one car is talking on the same channel. However, that particular corresponding car does not care as it is not trying to send or receive a message on that channel.

Figures 5.6 and 5.7 show how, once the algorithm is able to stabilize, the resulting weight calculations allow each node to be assigned to at least one channel during a single time slot. Figure 5.6 represents Figure 5.3 with modulated values in a circle graph based on the six channels available. When the LMAO

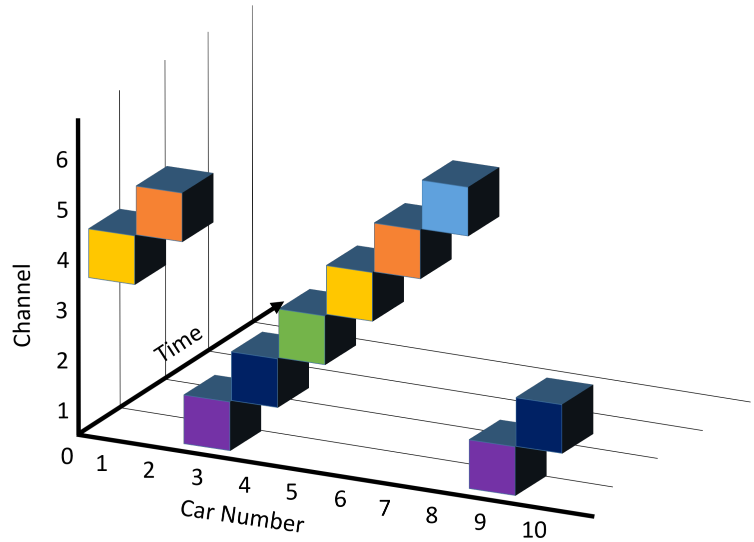

Figure 5.7: Channel allocation of all 10 nodes is possible over a single time slot.

neighbor weight averaging algorithm is used and is able to stabilize, to evenly distribute so that each node is occupying a channel, some cars overlap weights of another node. This is completely valid as the nodes are assumed to only see, a maximum, a distance of cars $n-1$ in front and behind them. This constraint utilizes the hidden terminal property to quickly and evenly derive SCH channel allocation. Figure 5.7, represents Figure 5.3 with modulated values based on the six channels available with a time axis where the calculated channel assignment for every node does occur for one time step, which is the key contribution of the proposed model. Note that the oblique blue lines formed each indicate a separate channel range view, encapsulating how the hidden terminal properties can help notify and inform channels that are available for use.

5.2 WAVE, VMESH, and LMAO Comparisons

The VMESH MAC channel assignment is thoroughly more successful compared to the random channel assignment that approximates the upper bound of the

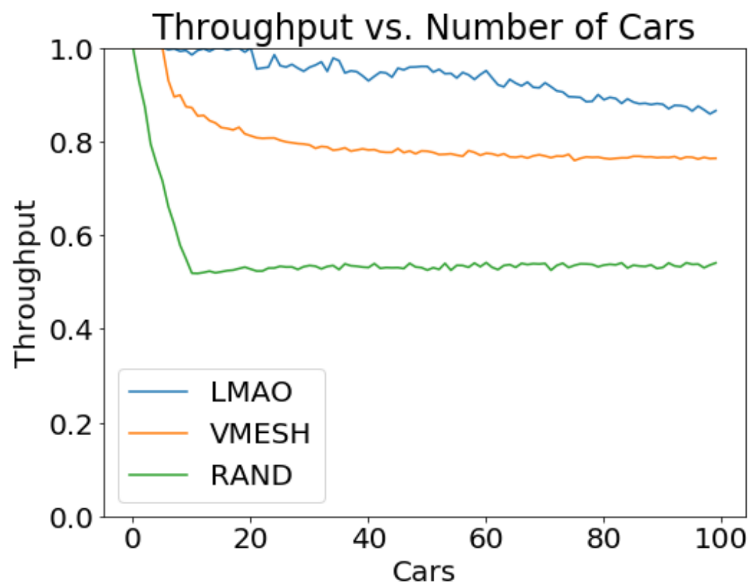

Figure 5.8: Comparing throughput of LMAO, VMESH, and the upper bound of approximated back-off labeled RAND, as a function of the number of cars in the system.

WAVE MAC back-off. As shown in Figure 5.8, as the traffic load increases, VMESH has a distinct advantage over the random channel allocation throughput. Note that, because the WAVE MAC was approximated, when the throughput is low, the VMESH is also shown to have a higher throughput.

Given enough algorithm stabilization steps, which in this case, the number of algorithm stabilization steps was equal to the number of cars in the system, the LMAO MAC channel assignment performs significantly better than the VMESH and random channel allocation methods. This result is consistent throughout the simulation. The LMAO can produce a full throughput value of 1 for each car if the stabilization algorithm is performed enough times so that the car weights are stabilized.

To observe the effect of the number of stabilization algorithm steps has on the throughput, the mean values of LMAO throughput for 100 cars for 10, 30, and 100 steps were calculated, as shown in Figure 5.9. For Cars 1 through

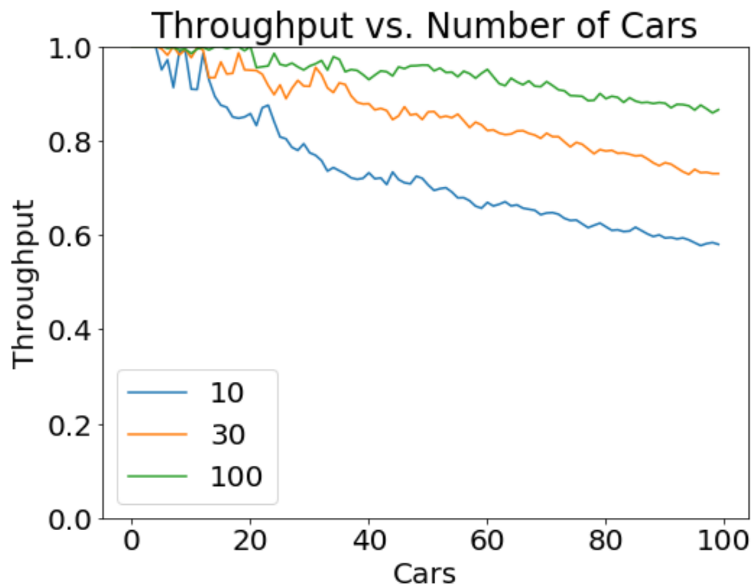

Figure 5.9: LMAO throughput given the number of stabilization algorithm steps taken.

6, the throughput is fully utilized at 1.0. Comparing the differences between the three step values calculated, it is interesting to note that, as the saturation load in the system increases, the number of stabilization algorithm steps used produce diminishing returns. As a result, if not enough stabilization steps are performed, given the number of cars in the system, the the channel assignments would not be fully utilized as the weights are trying to claim the same channels as they are too close to each other. As mentioned in the assumptions, this is not a concern of the paper as the LMAO is assumed to be adequately stabilized before the channel allocation process. However, this may be a good avenue for future research. From the green line using 100 stabilization steps, it can be seen that values from Cars 7 to 20 are at a near ideal throughput. Again, this full throughput utilization can ultimately be achieved with LMAO given enough stabilization algorithm steps as shown in Section 5.1.

5.3 Summary

The LMAO model is able to assign a channel to every node during a single time slot without contention. This results in an ideal throughput where every node needing to send a packet is able to send their packet at the same time. Compared to the VMESH system which outperforms the WAVE MAC protocol, LMAO's ability to assign a channel to each node clearly outperforms the models compared.

Chapter 6

Conclusion

The LMAO scheme allows each node in the system to use at least one channel during a single time slot. Using the weight of each node, the stabilized weight value found by taking the weight of the front and back neighbors can be found. The resulting stabilized weight values of each node can linearly order the nodes giving an order to each node without them knowing their exact position in the list. By having each node realize that their weight value is larger than a node behind them, and smaller than a node in front of them, their weights can help deduce their actual order in the list. Modular arithmetic is then used to exploit properties of the hidden terminal problem. By having a range of neighbors a car can see from 1 to $n-1$, where n is the number of channels available, the ordered weight can be allocated so that nodes that are out of range of each other can use the same channel without contention. This allows each node the ability to reserve and use a channel during the same time slot, as opposed to models such as VMESH and WAVE that require multiple time slots to give every node a chance to use a channel.

In this thesis, the 802.11p WAVE MAC protocol which was created specifically to address Vehicular Ad-Hoc Networks (VANETs) was analyzed. Components of the protocol were reviewed and mathematical analysis of the WAVE MAC throughput led to the motivation for exploring improved collision avoidance schemes. After reviewing existing models used to enhance throughput, the

VMESH protocol was found to be better than the legacy WAVE MAC protocol. A review of the VMESH methodology and limitations led to the LMAO scheme. Given the number of cars in a system, the number of channels in a system, and the range of neighbors a car can see, the LMAO protocol is able to obtain an ideal throughput rate. LMAO's ability to assign a channel to each node outperforms the models compared.

The LMAO, VMESH, and an upper bound approximated WAVE model was simulated and the results were compared. As expected, the hypothesis that the implementation of the LMAO outperforming the throughput of the VMESH and approximated WAVE model was validated. This makes sense because during the channel allocation period, LMAO is able to immediately assign a non-contending channel space to each node for the next channel transmission period.

The effect of the number of stabilization steps, given six channels and a variable number of nodes in the system, were also analyzed. It was found that if not enough stabilization steps are performed, the the channel assignments would not be fully utilized as the weights are trying to claim the same channels as they are too close to each other. Although this is not an issue with this thesis, as this thesis assumes that the steps to stabilize the node weights take a negligible amount of time, it would be interesting to explore how the number of stabilization steps, to get stabilized node weights, correlate with the number of nodes in the system. In addition, future works can explore methods to stabilize (i.e. space out) the node weight values in the modulus ring faster so that fewer stabilization steps are needed.

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