PERFORMANCE ANALYSIS OF CSMA-BASED HALF DUPLEX AND FULL DUPLEX MAC PROTOCOLS FOR VEHICULAR NETWORKS

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Performance Analysis of CSMA-based Half Duplex and Full Duplex MAC Protocols for Vehicular Networks
By Ali Serdar Yavuz
September 2021

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

PERFORMANCE ANALYSIS OF CSMA-BASED HALF DUPLEX AND FULL DUPLEX MAC PROTOCOLS FOR VEHICULAR NETWORKS

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Beaconing mechanism used in vehicular networks is an essential mechanism to improve the cooperative awareness between vehicles by periodically broadcasting vehicle kinematic information and other traffic entities. Cooperative awareness between vehicles affects the performance of safety applications in vehicular networks. Therefore, the Quality of Service (QoS) provided by the beaconing mechanism determines whether the strict timeliness and reliability requirements of safety applications are met. The most important state parameter of the beaconing mechanism is the beacon generation rate. Even if increasing it increases the cooperative awareness between vehicles, it also increases the channel congestion. This trade-off poses a challenge in the MAC protocol design of the beaconing mechanism. Moreover, the broadcast nature of beacon packets prevents the usage of acknowledgement mechanism in the beaconing mechanism, further complicating the problem. In this thesis, we examine the performance of two CSMA-based MAC protocols used for the beaconing mechanism. The first one makes use of Half-Duplex radios (HD-MAC), and it does not support collision detection, whereas the second one makes use of Full-Duplex radios (FD-MAC), and it supports collision detection and retransmission. These protocols are analyzed using Markov Chain based queueing models, taking queue state and beacon generation rate into account. FD-MAC model considers missed and false collision detection occuring due to non-ideal behavior of the self-interference cancellation. Using the Markov Chain models, QoS measures such as successful transmission probability, throughput, service delay, packet loss probability and age of information are derived. The accuracy of the Markov Chain based models are validated through simulations. It is shown that the FD-MAC protocol is superior to HD-MAC protocol in terms of throughput, packet loss probability, and age of information.

Keywords: Vehicular networks, beaconing, beacon generation rate, full-duplex MAC protocol, collision detection, errors due to RSI, age of information.

ÖZET

ARAÇLAR ARASI HABERLEŞME İÇİN CSMA TABANLI YARI ÇİFT YÖNLÜ VE TAM ÇİFT YÖNLÜ MAC PROTOKOLLERİNİN PERFORMANS ANALİZİ

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Araçlar arası haberleşmede kullanılan işaretleme mekanizması, araç hareketlilik bilgisinin diğer tüm komşu üniteler ile periyodik şekilde paylaşılması yoluyla araçlar arasındaki kooperatif farkındalığı artıran temel bir mekanizmadır. Araçlar arasındaki kooperatif farkındalık oranı, araçlar arası haberleşmede kullanılan güvenlik uygulamalarının performansını etkilemektedir. Bu nedenle, işaretleme mekanizması ile sağlanan servis kalitesi, güvenlik uygulamalarının katı zamanlılık ve güvenilirlik gereksinimlerinin karşılanıp karşılanmayacağını belirlemektedir. İşaretleme mekanizmasındaki en önemli parametre işaret paketi üretme hızıdır. İşaret paketi üretme hızının artırılması araçlar arasındaki kooperatif farkındalığı artırsa da işaret paketi üretme hızının artması ile kanal sıkışıklığı da artmaktadır. Bu ödünleşim, işaretleme mekanizması MAC protokolü tasarımını zorlaştırmaktadır. Ayrıca, işaret paketleri ile tüm komşu ünitelerin hedeflenmesi, işaretleme mekanizmasında onay mekanizması kullanımını engellemektedir ve bu durum problemi daha da zorlaştırmaktadır. Bu tezde, işaretleme mekanizması için kullanılan iki adet CSMA tabanlı MAC protokolünün performansını inceledik. İlk protokol yarı çift yönlü radyoları kullanmakta ve çakışma tespitini desteklememekteyken (HD-MAC); ikinci protokol tam çift yönlü radyoları kullanmakta ve çakışma tespitini ve tekrar gönderimi desteklemektedir (FD-MAC). Bu protokoller kuyruk durumunun ve işaret üretme hızının dikkate alındığı Markov Zincir modelleri kullanılarak analiz edilmektedir. FD-MAC modeli, öz girişim giderimindeki ideal olmayan davranıştan dolayı oluşan kaçırılan ve hatalı çakışma tespiti durumlarını dikkate almaktadır. Markov Zincir modelleri kullanılarak başarılı gönderim olasılığı, veri hacmi, servis gecikmesi, paket kayıp olasılığı ve bilgi yaşı gibi servis kalitesi ölçütleri elde edilmiştir. Markov Zincir tabanlı

modeller simülasyonlar aracılığıyla doğrulanmıştır. FD-MAC protokolünün HD-MAC protokolünden veri hacmi, paket kayıp olasılığı ve bilgi yaşı performansları açısından daha üstün olduğu gösterilmiştir.

Anahtar sözcükler: Araçlar arası haberleşme, işaretleme, işaret paketi üretme hızı, tam çift yönlü MAC protokolü, çakışma tespiti, RSI kaynaklı hatalar, bilgi yaşı.

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Chapter 1

Introduction

1.1 Overview

Recent advances in wireless technologies and embedded systems extended the use of communication technologies to new fields. Taking advantages of such technological advances, vehicle and equipment manufacturers have recognized the opportunity of enhancing the transportation systems and the vehicle traffic, by using the communication capabilities for vehicular networks to provide an Intelligent Transportation System (ITS) to all elements of the transportation system. The main motivation of this system is to improve the road safety by informing drivers about dangerous situations beforehand, and increasing cooperative awareness between vehicles by exchanging status information such as speed, braking status, position, and direction. Other than the safety applications, applications ranging from transportation efficiency to infotainment applications are also considered for vehicular networks to provide road information and entertainment to travelers. To support such variety of services, vehicular networks provide communication among vehicles, and between vehicles and the roadway infrastructure, travelers, and pedestrians [2].

The safety applications in vehicular networks mainly include periodic real-time information sharing between vehicles using the beacon packets, and strict timeliness and reliability requirements are considered for these kinds of applications. For this reason, the Medium Access Layer (MAC) protocol to be used for vehicular networks plays a crucial role to satisfy the requirements of safety applications. However, periodic broadcasting of beacon packets with higher number of nodes sharing the channel different from the traditional Mobile Ad-hoc Network (MANET) scenarios rise difficulties in the design of MAC protocol due to the problem of high channel congestion encountered in vehicular networks depending on the beacon packet generation rate and the total number of vehicles contending for the channel, and the problem of low cooperative awareness ratio between vehicles depending on the beacon packet generation rate and the mobility of vehicles. Therefore, the trade-off between decreasing the channel congestion and increasing cooperative awareness ratio between vehicles should be considered in the MAC protocol design for vehicular networks.

In this thesis, the performance of two CSMA-based MAC protocols for vehicular networks is analyzed. These protocols are differentiated in terms of the collision detection capability. For the first protocol used with Half-Duplex (HD) radios, collision detection is not applicable due to the broadcast nature of beacon packets. This protocol is called as HD-MAC protocol in this thesis, and it is defined in the well-known V2X standard IEEE 802.11p. The second protocol makes use of Full-Duplex (FD) radios for collision detection, and employs retransmissions in case of collision detection to increase the performance of the safety applications. This protocol is called as FD-MAC protocol in this thesis, and it is proposed to improve the timeliness and reliability performance of the beaconing mechanism used in vehicular networks.

1.2 Thesis Contributions

The main contribution of this thesis is the detailed analytical solution proposed for HD-MAC and FD-MAC protocols. For both protocols, Markov Chain queueing models are proposed considering unsaturated operation of the beaconing mechanism. To model the unsaturated operation in the Markov Chain model, packet arrival probabilities for transmission and non-transmission states are modeled assuming Poisson packet arrivals, and the queue state after the completion of the service of the current packet is considered in the Markov Chain model.

A queue service discipline which minimizes the Age-of-Information (AoI) is considered in this thesis. According to this model, the most recently arrived packet is sent out first, and when the queue is full, the oldest packet is dropped first. Also, by keeping only one packet in the queue, only the most recently arrived packet is sent out, and the channel is not occupied with packets that have larger AoI values than the packets that are previously sent. This queue service model is proposed in several studies in the literature [3–5]. However, any of these studies provides an analytical solution for mean AoI and packet loss probability of the beaconing mechanism.

Another contribution of this thesis is using the FD radios in vehicular networks for collision detection, reduced delay and improved reliability. We provide a detailed analytical solution considering the collision detection errors encountered in FD radios. Although, the idea of using FD radios for collision detection is known for a while [6–8], there is no study in the literature that examines the unsaturated performance of a CSMA-based MAC protocol using FD radios.

1.3 Thesis Outline

Chapter 2 introduces the V2X communication by giving details about the current V2X standards, V2X use cases, and service level requirements of V2X. Moreover, the beaconing mechanism used to provide cooperative awareness between vehicles is detailed, and the motivation behind using beacon rate adaptation techniques in the beaconing mechanism is given in Chapter 2. Finally, the details of the queue service model, and the MAC layer protocols used for the beaconing mechanism are explained.

Chapter 3 introduces the Markov Chain queueing models used for HD-MAC and FD-MAC protocols of the beaconing mechanism. For both protocols, the Markov Chain models are solved to obtain an analytical solution for throughput, successful transmission probability, service delay, packet loss probability, and mean AoI.

Chapter 4 presents the numerical results for the analytical solution obtained in Chapter 3, and for the simulations conducted for HD-MAC and FD-MAC protocols. Moreover, the performance of HD-MAC and FD-MAC protocols are compared using the numerical results.

Chapter 5 presents the conclusions.

Chapter 2

Vehicle-to-Everything (V2X) Communication

Vehicle-to-everything (V2X) is a vehicular communication system that aims to provide high bandwidth, low latency and highly reliable communication between a vehicle and any other entity which may affect the vehicle.

Types of V2X communication (Figure 2.1) including the communication between a vehicle and any other entity can be summarized as below :

- V2V (Vehicle-to-vehicle)
- V2P (Vehicle-to-pedestrian)
- V2I (Vehicle-to-infrastructure)
- V2N (Vehicle-to-network)

Vehicle-to-everything (V2X) communication grabs significant attention since it promises to,

- improve road traffic safety by decreasing the number of traffic accidents

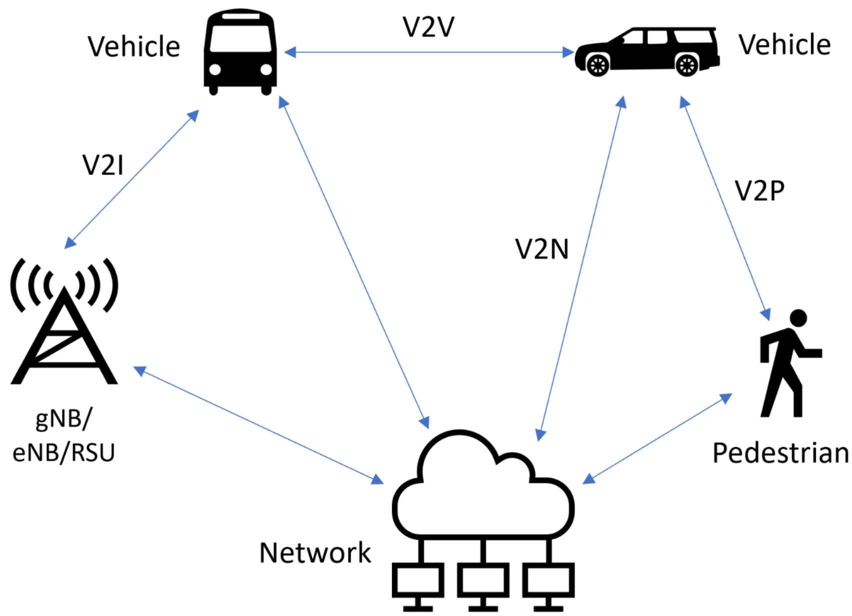


Figure 2.1: V2X scenarios

- increase road traffic efficiency by decreasing the congestion
- enable high level of vehicle automation
- increase energy savings

In this chapter, firstly, the information about current V2X standards and possible V2X use cases will be provided. Then, the beaconing mechanism used in V2X communication to provide awareness between vehicles will be explained. Finally, the details of CSMA-based half duplex and full duplex MAC protocols used for the beaconing mechanism will be discussed.

2.1 V2X Standards

There are currently two main technologies to support first generation V2X communication: WLAN-based V2X and cellular-based V2X.

The first V2X technology is IEEE802.11p, and it is the first WLAN-based

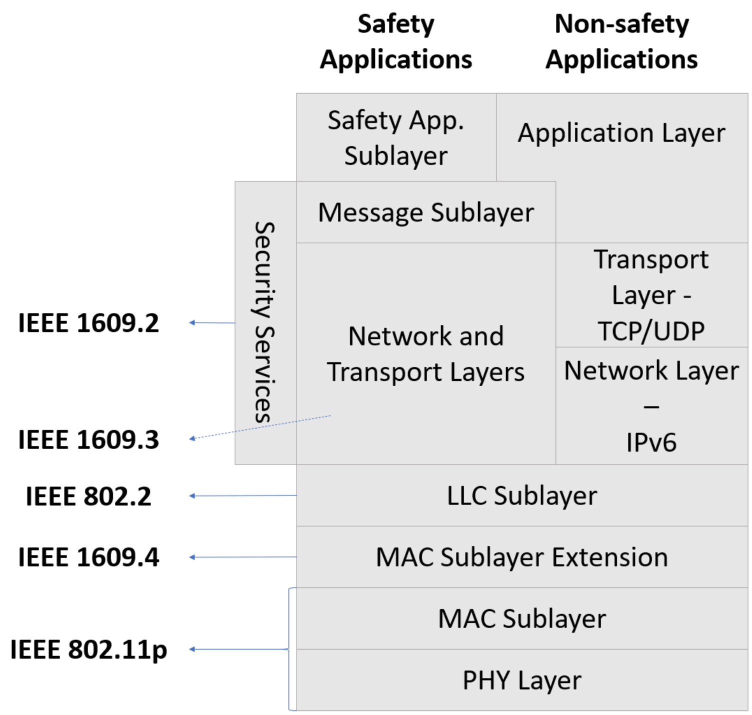


Figure 2.2: DSRC architecture

V2X technology which is first published in 2010 [9]. IEEE802.11p is the basis for DSRC (Dedicated Short-range Communications) and ITS-G5 (Intelligent Transport Systems) standards. DSRC is the general name for the WLAN-based V2X architecture, and it includes other WLAN-based standards to meet the requirements of different layers in the OSI model communication stack as shown in Figure 2.2. IEEE.802.11p defines the physical and MAC (Medium Access Control) layers of the DSRC architecture. ITS aims to determine use cases and services to be supported by V2X technologies. ITS also takes IEEE802.11p standard as a basis since it is the first standard that defines the underlying radio communication of the V2X technology.

IEEE 802.11p uses an OFDM (Orthogonal Frequency Division Multiplexing)-based physical layer with a channel bandwidth of 10 MHz. The IEEE 802.11p uses the Distributed Coordination Function (DCF) method of IEEE 802.11 as multiple access method. This method is known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [10].

The second V2X technology is the cellular-based V2X technology studied by 3GPP working groups and other industry organizations such as 5GAA (5G Automotive Association). Specification about cellular V2X (C-V2X) is first published in 2017. The first generation C-V2X is also called LTE-V2X since it was based on LTE as the underlying radio communication technology. Different from WLAN-based V2X technology, C-V2X supports V2N type of V2X communication by using existing cellular network infrastructure.

LTE-V2X uses a DFT spread OFDM-based physical (PHY) layer with multiple channel bandwidth options such as 1.4 MHz, 5 MHz, 10 MHz and 20 MHz. LTE-V2X uses the Semi-persistent Scheduling (SPS) method as multiple access method. This method is used to make periodic reservations for resources to decrease scheduling overhead [11].

IEEE 802.11p and LTE-V2X are the state of the art technologies for V2X communication, and they are primarily designed to increase vehicular safety and to obtain better traffic management. However, since not all use cases and applications of V2X are very well known at first, loose requirements were considered for the first generation V2X technologies. Therefore, in order to support the new use cases and requirements, IEEE and 3GPPP groups work on next generation V2X technologies which are named as IEEE 802.11bd and NR-V2X, respectively. Although the standardization processes continue for the next generation V2X technologies, it is expected that the next generation V2X technologies will support higher bandwidth, reliable operation, robustness to high relative speeds, longer communication range and configuration flexibility [10].

In this thesis, IEEE 802.11p-based V2X technology is considered, and the performance of IEEE 802.11p MAC layer is investigated for some specific V2X scenarios.

2.2 V2X Use Cases and Service Level Requirements

V2X use cases and requirements were firstly based on road safety and traffic efficiency, and the first generation V2X standards aim to support these use cases. Then, advanced use cases of V2X such as platooning and advanced driving are defined, and these use cases and the corresponding requirements are also included and supported in the next generation V2X standards.

V2X use cases are studied by different organizations such as 3GPP [12, 13], ETSI ITS [14, 15], 5GAA [1] and 5GCAR [16]. Although these organizations have published different technical reports, the use cases defined in these reports are substantially similar to each other.

In this section, V2X use cases and requirements will be summarized based on the technical report published by 5GAA group. According to [1], the use cases of V2X can be divided into several groups as given below:

- **Safety**: Emergency braking, intersection management, assisted collision warning, lane change, etc.
- **Vehicle Operations Management**: Sensor monitoring, remote support, etc.
- **Convenience**: Infotainment, cooperative navigation, autonomous smart parking, etc.
- **Autonomous Driving**: Automated intersection crossing, cooperative lane merge, cooperative maneuvers of autonomous vehicles for emergency situations, etc.
- **Platooning**: Platoon management, e.g., establish a platoon, manage distance within platoon, control of platoon in steady state, etc.

- **Traffic Efficiency and Environmental Friendliness**: Traffic jam information, smart routing, continuous traffic flow via green lights coordination, etc.

- **Society and Community**: Emergency vehicle approaching, traffic light priority, patient monitoring, etc.

The key service level parameters of V2X can be listed as below:

- Communication Range
- Payload Size
- Service Level Latency
- Service Level Reliability
- The Maximum Relative Speed
- Vehicle Density
- Positioning Accuracy
- Interoperability

The value of each of the service level requirements regarding these parameters may change depending on the V2X use case. Therefore, there is an ongoing study about V2X use cases and the corresponding requirements of the V2X use cases, which is conducted by different organizations involved in the V2X studies.

As an example, two use cases that use the cooperative awareness messages to accomplish the corresponding requirements are described below according to [1]:

- **Use Case 1**: Exchange of cooperative awareness messages between automated vehicles. Automation levels of these vehicles are low compared to those used in the second use case. The risk for collision is calculated according to the collected data.

Table 2.1: The requirements for sample cooperative awareness use cases according to [1]

Use Case	Use Case 1 Lower Automation Level	Use Case 2 Higher Automation Level
Payload Size (B)	300	1000
Service Level Latency (ms)	<100	<10
Service Level Reliability	>90%	>99.9%

- **Use Case 2**: Exchange of cooperative awareness messages between automated vehicles that have higher automation levels. More accurate predictions are made regarding possible collisions.

As seen in Table 2.1, as the automation levels of the vehicles increase, the requirements for the V2X use cases become more stringent. Since the final purpose of automated driving studies is to make driverless vehicles possible, studies about V2X communication continue to improve the V2X performance considering automated driving scenarios. For more information about the automation levels, the technical report prepared by SAE (Society of Automotive Engineers) can be examined [17].

In this thesis, only the use cases that need cooperative awareness between vehicles are considered and studied since the cooperative awareness between vehicles is the essential part of the V2X communication, and it determines the performance of safety related applications and automated driving applications.

2.3 Cooperative Awareness between Vehicles Using the Beaconing Mechanism

In order to support the use cases and the requirements of V2X, several message types for V2X communication are defined by the V2X community. CAM (Co-operative Awareness Message) and DENM (Decentralized Environment Notification Message) messages are defined by ETSI ITS group, and they are used by both IEEE 802.11p and C-V2X. CAM and DENM messages are the most known and referred message types for V2X communication in the literature. Therefore, in this section, CAM and DENM messages will be further explained.

CAM and DENM messages are broadcasted by each vehicle to its neighbors. However, while CAM packets are only transmitted to single-hop neighbors, DENM packets may be forwarded to the vehicles that are not single-hop neighbors of the source vehicle (multi-hop). Moreover, CAMs are periodically transmitted messages used to provide status information such as position, speed, direction, etc. On the contrary, DENMs are event-triggered messages broadcasted to alert other vehicles about a hazardous event [18, 19].

CAM packets are also called beacon packets. Beaconing mechanism term is used in this thesis to refer the usage of CAM or beacon packets in V2X communication. In this thesis, only the usage of beacon packets is considered, and the scenario where each vehicle periodically transmit beacon packets to its neighbors is studied.

Beacon packets are periodically generated because the status information of each vehicle may change in time, and the neighbors of each vehicle may change in time. The most important parameter of the beaconing mechanism is the beacon rate parameter. Beacon rate parameter determines how frequently the beacon packets are generated. For the usage of the beacon rate parameter in the beaconing mechanism, two approaches can be considered: Constant beacon rate and adaptive beacon rate. While beacon rate value in the constant beacon rate approach is not changed in time, beacon rate value in the adaptive beacon rate approach may change in time considering the requirements of safety applications and channel congestion. Most of the early studies about IEEE 802.11p beaconing mechanism considers the constant beacon rate approach to evaluate the performance of the beaconing mechanism [20–23]. However, for a vehicle, change in vehicle status does not always occur at a constant rate. For example, when a vehicle travels at a high speed, vehicle position changes more rapidly. In such a case, beacon rate should be increased to inform other vehicles about changing states more quickly. On the other hand, when a vehicle travels at a slow speed, change in vehicle state will be slow, and beacon rate can be reduced to decrease channel congestion. Therefore, adapting beacon rate parameter considering the rate of change in vehicle status will improve the overall beaconing mechanism performance in terms of decrease in age of information and channel congestion. In the next section, more detailed analysis will be provided about why adaptive beacon rate for the beaconing mechanism should be used.

In this thesis, performance of the beaconing mechanism will be examined for different beacon rates. Performance metrics that will be used to evaluate the performance of the beaconing mechanism are given below:

- **Successful Transmission Probability**: The probability that the transmission attempt will be successful.
- **Packet Loss Probability**: The probability that the generated packet in the application layer will be lost due to finite retry count or finite queue length.
- **Throughput**: The percentage of time that is used to successfully transmit the useful payload data.
- **Service Delay**: The time between a packet becomes head-of-line and it is successfully transmitted.
- **Age of Information (AoI)**: Freshness of the information at the receiver, depends on packet inter-arrival time, service delay and queue delay. Sample variation of AoI $\Delta_i(t)$, for source i as a function of time, is shown in Figure 2.3. Average AoI is defined as follows for the observation interval T,

$$\overline{\Delta_i} = \frac{1}{T}\int_0^T \Delta_i(t)dt \qquad (2.1)$$

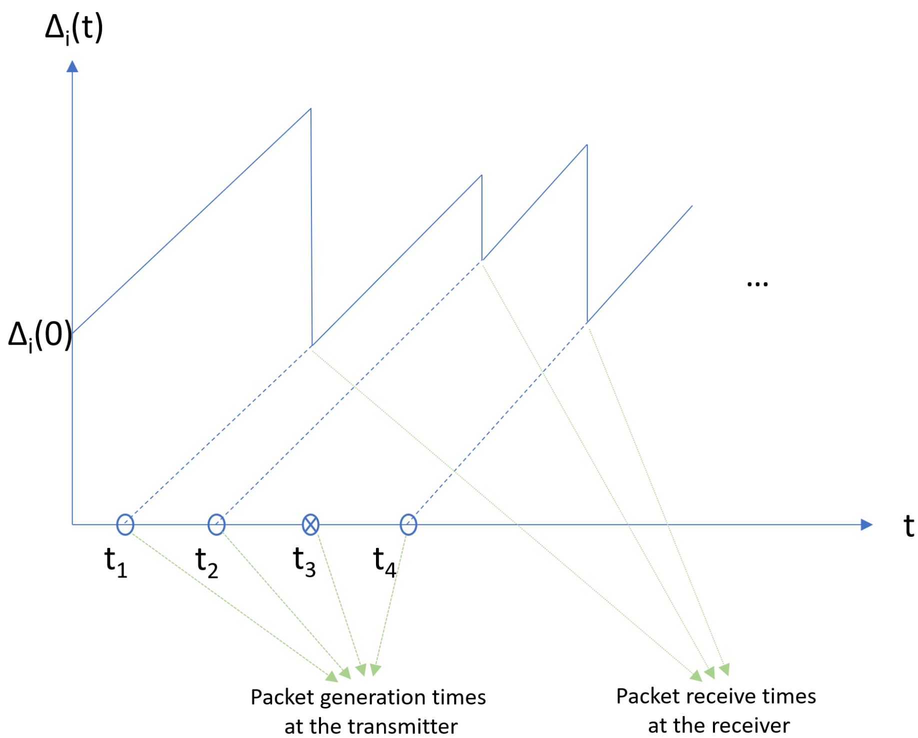


Figure 2.3: Sample variation AoI as a function of time

2.4 Why Using Adaptive Beacon Rates for the Beaconing Mechanism is Necessary?

In this section, vehicle traffic flow description and time series description of vehicle traffic will be used to show that using constant beacon rate approach for the eaconing mechanism limits and worsens the performance of the beaconing mechanism.

2.4.1 Vehicle Traffic Flow Description

Different descriptions exist in the literature to describe the traffic flow in V2X networks. The most preferred descriptions in the literature are microscopic and macroscopic traffic descriptions. While microscopic traffic description uses the traffic variables of individual vehicles on the road, macroscopic traffic description uses the traffic variables aggregated over several vehicles or a road segment [24].

In this thesis, only the macroscopic traffic flow description is considered. In macroscopic description, instead of individual vehicles, the aggregated traffic variables are considered for each road section. Aggregated traffic variables used in macroscopic description are speed, density, and flow. The average speed of the vehicles on a road section is denoted by u. Density variable k describes the average number of vehicles inside a road section. Finally, the flow (or volume) q describes the number of vehicles passing a reference point per unit time [25].

The relationship between traffic variables for macroscopic traffic flow description is called as the fundamental relationship in traffic flow theory [25]. For macroscopic traffic model, the fundamental relationship between average speed, density, and flow values is given as,

$$u = \frac{q}{k} \tag{2.2}$$

Fundamental diagrams of the macroscopic traffic flow model can be obtained by using (2.2) as shown in Figure 2.4. The flow (or volume) value q is upper bounded by the critical flow value q_{crit}. Speed and density values corresponding to q_{crit} are called critical speed u_{crit} and critical density k_{crit}, respectively. Using these critical values, state points of macroscopic traffic flow model can be described as follows:

- **Free flowing traffic:** Density k is lower than the critical density k_{crit}. At this state point, vehicles can travel at speeds close to the maximum allowable speed considering the speed limit of the road.
- **Capacity traffic:** Flow q is equal to the critical flow q_{crit}. At this state point, vehicle traffic is fully utilized since the number of vehicles passing through a reference point is maximized.
- **Saturated traffic:** Density k is larger than the critical density k_{crit}. This state occurs in case of a traffic jam. Density values will be close to the

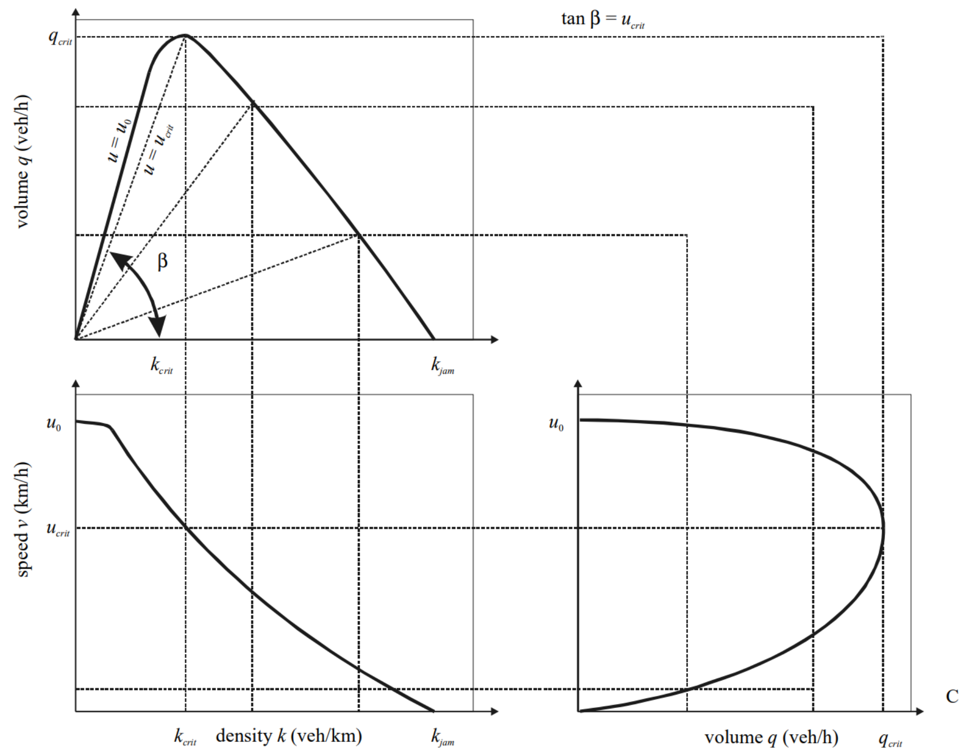


Figure 2.4: Fundamental diagrams of the macroscopic traffic flow model

maximum possible vehicle density on the road. As a result, at this state, flow rate and speed values will be close to zero.

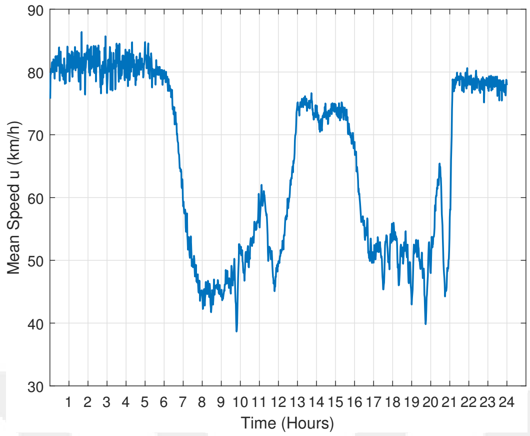
Fundamental diagram shows the different congestion states on the road. While the range of density values on the fundamental diagram can change considering different road networks, different lane counts, and different road capacities, the range of speed values on the fundamental diagram can change considering the maximum speed limit values on the road, and different vehicle types on the road. Therefore, for different traffic scenarios, the range of values for speed, density, and flow variables on the fundamental diagram will be different. However, independent of the considered traffic scenario, flow value will be upper bounded with the critical flow value, and speed and density values will be inversely proportional according to the macroscopic traffic flow theory.

2.4.2 Time Series Description of the Macroscopic Traffic Variables

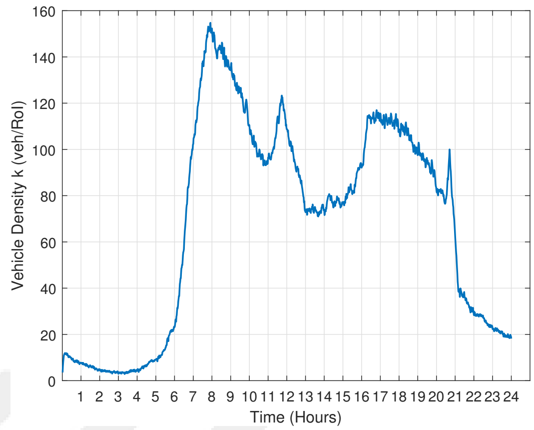
In the previous section, it is shown that by using macroscopic traffic flow model, it is possible to model different state points of the vehicle traffic such as free-flowing traffic, capacity traffic, and saturated traffic, and to characterize cooperative behavior of vehicles. However, since the variables of the macroscopic traffic flow model may be used to model beacon traffic in vehicular networks, it is necessary to obtain how these variables change in time.

The macroscopic traffic flow variables usually show repeated pattern in a daily or a weekly manner, even if they vary within the time of day. For example, for a weekday, the vehicle density values start from a very low level at midnight and increases gradually up to the first peak during morning rush hour, often between 7:00 and 9:00 AM, and to the second peak between 5:00 and 7:00 PM. Except from occasional occurrence of accidents or other unexpected cases, a routine traffic flow on the road in the macroscopic level often shows inherent repeatability [26]. It can be shown that, the traffic flow patterns in the same weekday of two consecutive weeks are very close. Likewise, the similarity on a monthly basis or even a yearly basis can also be shown. Moreover, when different traffic flow datasets used in the literature [27, 28] are examined, the similarity and the repeatability of the traffic flow variables for weekdays and weekends can be observed.

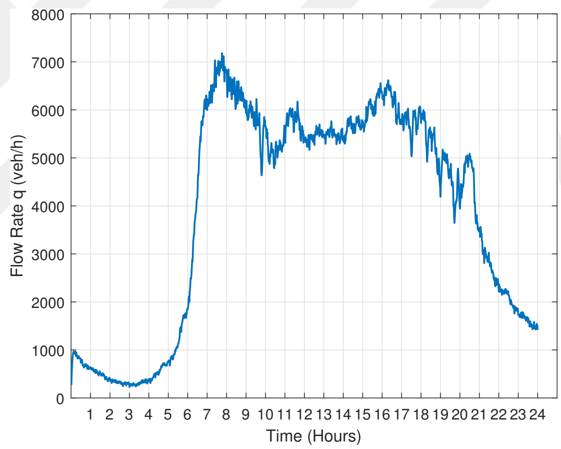
In this section, "Simulation of Urban MObility" (SUMO) library [29] is used to simulate the vehicle traffic for highway traffic scenario for a weekday. This scenario is considered to obtain time series description of macroscopic traffic variables for 24 hours. For this purpose, SUMO model given in [30] is used. This dataset provides traffic demands for sample urban and highway scenarios that can be simulated using SUMO. Using the provided traffic demands, simulation is run for 24 hours in a day with 0.5 seconds time intervals. Macroscopic traffic variables vehicle density and average vehicle speed values are recorded at every 1 minute. To collect the statistics about these variables, only small part of the road segment called region-of-interest is considered. Region-of-interest is chosen as the



(a) Average vehicle speed



(b) Average vehicle density



(c) Average flow rate

Figure 2.5: Time series description of macroscopic traffic flow variables in a weekday for highway traffic scenario

circle with 300m radius at the center of the road network. This value is chosen considering the typical communication range of IEEE802.11p beacon messages.

In Figure 2.5, average vehicle speed, average vehicle density, and average flow rate values in a weekday for highway scenario at different time instants are depicted. From these figures, the inverse relationship between average speed values and average vehicle density values can be observed. Moreover, average flow rate values that show the average number of vehicles passing through a specific region are given to show the traffic utilization at different time instants.

Figure 2.5a shows that the average speed values of vehicles change in time.

When the average speeds of surrounding vehicles increase, vehicle parameters such as speed, acceleration, and position change more frequently. In case of frequent change of these parameters, to ensure the requirements of safety related applications, information age of the safety related parameters should be kept small. Therefore, when the average speed values change decently, beacon rates should be adapted to ensure that information age of safety related parameters is kept at a desired level.

When Figure 2.5b is examined, it is observed that average vehicle density values change in time. If the beacon rate value is increased considering the information age of safety related parameters in case of high vehicle density, i.e., the number of surrounding vehicles, then the corresponding channel load can cause channel congestion, and packet loss ratio can increase. Therefore, while adapting beacon rate values considering average vehicle speed and density, both information age of safety related parameters and channel congestion should be considered.

As a result, it can be asserted that constant beacon rate approach is not the optimal solution for using the channel efficiently and meeting the requirements of safety related applications.

2.5 Queue Service Model Used in the Beaconing Mechanism

In the beaconing mechanism, beacon packets are periodically generated by each vehicle, and they are transmitted to neighbor vehicles. Depending on the service delay caused by the MAC layer protocol, some beacon packets may be generated when another beacon packet is in service, or a beacon packet may be generated when there is no packet in service. For the latter case, the beacon packet is directly taken into service without taken into queue. However, for the former case, queue model options should be considered for the arriving beacon packets while another packet is in service since preemption is not considered in this model. Four different queue service model options can be considered for this case as also indicated in [4]:

- **First-in first-out newest packet drop:** Packets are sent out in the order in which they arrived, and when the queue is full, newest packet is dropped.
- **First-in first-out oldest packet drop:** Packets are sent out in the order in which they arrived, and when the queue is full, oldest packet is dropped.
- **Last-in first-out newest packet drop:** Most recently arrived packet is sent out, and when the queue is full, newest packet is dropped.
- **Last-in first-out oldest packet drop:** Most recently arrived packet is sent out, and when the queue is full, oldest packet is dropped.

In this thesis, among four queue service model options, last-in first-out oldest packet drop option is considered for the beaconing mechanism since it prioritizes the recently arrived packets with smaller AoI values. Moreover, queue size of 1 is chosen since there is no point to transmit packets with larger AoI when the recently arrived packet is already transmitted for the beaconing mechanism. As a result, if more than one beacon packet has arrived while there is a packet in service, only the most recently arrived packet is kept in the queue.

2.6 CSMA-based MAC Layer Protocols for the Beaconing Mechanism

IEEE 802.11 DCF (Distributed Coordination Function) mechanism is a well-known MAC layer protocol for wireless ad hoc networks, which employs CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) with binary exponential back-off scheme. This mechanism is used to reduce the number of collisions due to multiple nodes transmitting simultaneously on a shared channel. Similar to IEEE 802.11 DCF protocol, in IEEE 802.11p standard, EDCA (Enhanced Distributed Channel Access) mechanism is adopted, which supports applications with different priorities to ensure the QoS (Quality-of-Service) requirements of these applications. In this model, 4 priority levels are defined by using different values for IFS (Inter Frame Spacing) time and back-off counter limits to support applications with different QoS requirements.

In IEEE 802.11p, multi-channel operation is supported by the use of seven 10 MHZ channels defined in the DSRC spectrum (5.9 GHz). One of these channels is used as the CCH (Control Channel) for safety related applications and the remaining six channel is used as SCH (Service Channel) for other non-safety applications.

In this thesis, only the CCH channel is considered to be used for the beaconing mechanism. Therefore, only single channel operation of IEEE 802.11p is considered. Moreover, only one priority level is considered for beacon packets. As a result, DCF mechanism is adopted to model the beaconing mechanism rather than EDCA mechanism.

Next, DCF mechanisms to be used by half-duplex and full-duplex radios for the beaconing mechanism will be presented.

2.6.1 Half Duplex MAC (HD-MAC) Protocol

In the beaconing mechanism, as mentioned previously, beacon packets are broadcast packets. That is, beacon packets are transmitted to all neighbors of a vehicle. By using this broadcast mechanism and using half-duplex radios for communication, it is not reasonable to expect that all neighbors of each vehicle send an acknowledgement (ACK) for each beacon packet because this will create significant overhead on the channel. Therefore, collision avoidance mechanism is not applicable for the beaconing mechanism with half duplex radios.

According to IEEE 802.11 DCF mechanism, back-off stage value i starts from zero, and it is increased by 1 every time when retransmission attempt is unsuccessful. The value of back-off stage is reset to 0 after a successful transmission. The back-off counter value k is chosen uniformly between [0, W_i-1] if the node is in ith retransmission attempt, where $W_i = 2^i CW_{min}$, and CW_{min} is the minimum contention window size. The value of the back-off counter is decremented when the slot is idle or channel is sensed idle for a period of DIFS (Distributed Inter-Frame Space) time after a busy period. Transmission is attempted when the back-off counter value is equal to 0.

In the beaconing mechanism, since the collisions cannot be detected by the vehicles using half duplex radios, binary exponential back-off algorithm cannot be used as described above. The back-off counter value is chosen uniformly for the back-off stage 0, and transmission is attempted when back-off counter value is equal to 0 as previous. However, the back-off stage value is never increased. This mechanism is referred as HD-MAC protocol in this thesis.

In the beaconing mechanism, as stated previously in Section 2.5, it is possible to find the queue empty or with a beacon packet when the transmission attempt is finished. Therefore, depending on the beacon rate value, the number of vehicles contending for the channel and the MAC layer protocol, it may not be possible to make the saturated operation assumption as in [31], and unsaturated operation should also be considered for the HD-MAC protocol.

For the HD-MAC protocol, a post back-off stage is defined for unsaturated operation. If the queue is found empty after a transmission (successful or not), the vehicle starts the post back-off stage, and chooses a back-off counter value uniformly between [0, W_i-1] for the post back-off stage. Then, if a beacon packet is arrived before the back-off counter value is reached to 0, arriving beacon packet is transmitted when back-off counter value is reached to 0. On the other hand, if no beacon packet is arrived before the back-off counter value is reached to 0, the vehicle goes into the idle state and waits for a beacon packet arrival. When a beacon packet is arrived, while the beacon packet is directly transmitted if the channel is sensed idle, the beacon packet is transmitted after back-off stage 0 if the channel is sensed busy.

2.6.1.1 Related Works

The Markov Chain model for IEEE 802.11 DCF mechanism is first proposed in [31], and many studies use this model as a basis to analyze other IEEE 802.11-based standards. The model proposed in [31] operates in saturation condition assuming that all nodes have a packet waiting for service when another packet is in service. Therefore, this model characterizes the performance of IEEE 802.11 DCF assuming saturation traffic conditions and infinite buffer size. An unsaturated model for IEEE 802.11 DCF mechanism is proposed in [32]. This model uses post back-off states when the queue is found empty after successful transmission to model unsaturated traffic conditions. However, this model operates in bufferless mode. That is, packets generated while another packet is in service are not queued, and only the packets generated while the current packet is successfully transmitted are queued, and are taken into service. Therefore, this model underestimates the total load on the channel by assuming bufferless operation. Another unsaturated model for IEEE 802.11 DCF mechanism is proposed in [33]. This model uses 3D Markov Chain model to include the effect of current buffer size in the Markov Chain model. Different from the previous model, packets generated while another packet is in service are queued, and buffer size states are also kept in this model. Therefore, this model characterizes the unsaturated traffic load condition with finite buffer size more accurately for IEEE 802.11 MAC protocol.

Markov Chain models are also used to characterize the performance of IEEE 802.11p broadcast beaconing mechanism. In [34], saturation performance of the beaconing mechanism is studied. In [35], a Markov Chain model and D/M/1 queue model are combined to analyze the performance of the beaconing mechanism in unsaturated traffic conditions. To model unsaturated condition, an idle state is used in the Markov Chain model. In this model, infinite buffer size is assumed since D/M/1 queue model is used, and no packet blocking due to finite buffer size is considered. In [36], a 2D Markov Chain model for the beaconing mechanism is proposed by assuming unsaturated traffic conditions and finite buffer size. This model uses the post back-off states to model unsaturated behavior, and characterizes the beaconing performance for finite buffer size and no collision detection ability.

2.6.2 Full Duplex MAC (FD-MAC) Protocol

Full-duplex (FD) radio communication enables radios to transmit and receive simultaneously on the same channel [37]. Therefore, the usage of FD radios can ideally double the system capacity compared to the usage of HD radios.

In the beaconing mechanism, FD operation can be used to detect the collision on the channel eliminating the need for ACK messages. When a vehicle starts to transmit a beacon packet using the first antenna, the second antenna is used to sense the channel to detect possible collisions for a period packet header duration.

Different from the HD-MAC protocol described in Section 2.6.1, collision detection mechanism is applicable for the FD-MAC protocol. Therefore, the binary exponential back-off algorithm can be used, and back-off stage value can be increased in case of collision detection for FD-MAC protocol similar to the IEEE 802.11 DCF protocol.

For the FD-MAC protocol, the back-off stage value is increased by 1 for each collision detection until the maximum back-off stage value r is reached. The maximum back-off stage value is used to limit the number of retransmission attempts. If the last retransmission attempt is also failed, the beacon packet is discarded. Moreover, different from IEEE 802.11 DCF protocol, the contention window size at back-off stage i is defined as $W_i = 2^{min(i,m)} CW_{min}$ where m parameter is used to prevent FD-MAC protocol to increase contention window size after m retransmission attempts.

In FD-MAC protocol, after a beacon packet is successfully transmitted or it is discarded due to maximum retransmission attempts, the vehicle may find the queue empty as in the HD-MAC protocol. Therefore, the post back-off procedure described for HD-MAC protocol in Section 2.6.1 is also used for the FD-MAC protocol. For the post back-off stage, the minimum contention window size is used as in HD-MAC.

When the collision detection mechanism is provided by FD radios, collision is detected in a smaller time interval compared to the collision detection time provided by acknowledgement mechanism.

The drawback of using FD radios for radio communication is the residual self-interference (RSI) problem. RSI causes sensing errors. That is, in case of only one vehicle transmits a beacon packet, collision may be falsely detected by the second antenna due to the RSI effect (False Alarm). When more than one vehicle transmits a beacon packet creating a collision, the collision may be missed by one vehicle or more than one vehicle due to the RSI effect (Miss Detection). As a result, when FD radios are used for collision detection in the beaconing mechanism, sensing errors should be considered for the performance analysis of the FD-MAC protocol.

2.6.2.1 Related Works

In [6], a Markov Chain model for FD MAC protocol that uses FD radios for collision detection is proposed. This model operates in saturation conditions, and the saturation throughput is characterized in this model for the proposed FD MAC protocol. Moreover, the sensing errors due to RSI effect are considered, and they are analytically studied using the proposed Markov Chain model.

To the best of our knowledge, there are no studies in the literature that uses a Markov Chain model that characterize the performance of FD MAC protocol operating in unsaturated conditions.

In [7], to improve the beaconing performance, the usage of FD radios in vehicular networks is proposed. It is stated that the FD radios can be used to detect collisions in the beaconing mechanism. In this study, performance analysis of the proposed FD MAC protocol is made via simulations. In [8], a more comprehensive analysis of FD MAC protocol for the beaconing mechanism is provided. In this study, collisions due to hidden nodes are also considered, and direct collision and hidden collision probabilities are analytically solved to characterize the performance of the FD MAC protocol. The usage of FD radios in vehicular networks are also considered in [38, 39]. However, none of these studies considers the unsaturated operation and the finite buffer size conditions in their analytical solution.

Chapter 3

Markov Chain Queueing Model for Beaconing Mechanism

In this chapter, Markov Chain based queueing models are presented for HD-MAC and FD-MAC protocols. It is assumed that the Markov Chain models given in this chapter can be considered independantly for each vehicle by following the assumptions made in [31]. The Markov Chain models presented in this chapter also consider the unsaturated load case and the packet arrival probabilities in each state, which is different from the Markov Chain model presented in [31].

3.1 Markov Chain Model for HD-MAC Protocol

To investigate the performance of HD-MAC protocol described in Section 2.6.1, a Markov Chain model is proposed for HD-MAC protocol as given in Figure 3.1. This Markov Chain model uses 2-tuple (h, k) to describe the states of the HD-MAC protocol. While k denotes the back-off counter, $0 \leq k \leq W_0 - 1$, h corresponds to the queue state, and it can take 3 different values as described below:

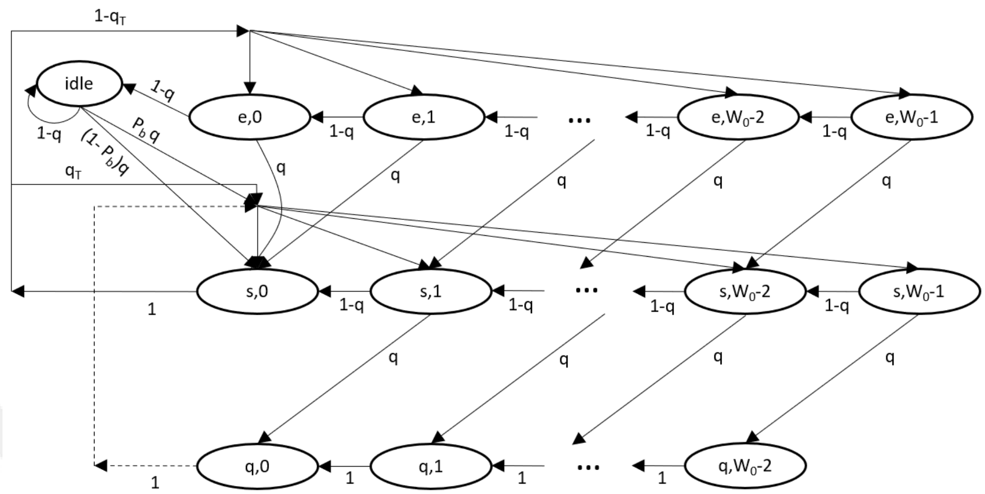


Figure 3.1: Markov Chain model for HD-MAC protocol

- e**:** Used to model the post back-off states where queue is empty after the transmission.
- s**:** Used to model the states where there is a packet in service and queue is empty.
- q**:** Used to model the states where there is a packet in service, and queue is not empty and keeps the recently arrived packet.

To describe the packet arrival probabilities in each state of the Markov Chain model, q and q_T parameters are used. While q is the probability that a packet arrives in a non-transmission state, q_T is the probability that a packet arrives in a transmission state. This distinction is made since average state durations for non-transmission states and transmission states are different. Lastly, P_b parameter is used in the HD-MAC Markov Chain model to describe the channel busy probability.

In this section, the HD-MAC Markov Chain model is solved to obtain a mathematical expression for the transmission probability. Then, this solution is used to obtain other performance metrics of the HD-MAC protocol such as successful transmission probability, throughput, service delay, packet loss probability, and age-of-information.

3.1.1 Transition Probabilities

According to the HD-MAC protocol described in Section 2.6.1, when a packet arrives in the idle state, if the channel is sensed free, the vehicle directly enters the transmission state. Otherwise, if the channel is sensed busy, the vehicle enters the back-off stage. If no packet arrives in the idle state, the vehicle stays in the idle state. To model this behavior, P_b parameter is used as given below,

$$P[(s,0)|(idle)] = (1-P_b)q \tag{3.1}$$

$$P[(s,k)|(idle)] = \frac{P_b q}{W_0}, 0 \le k \le W_0 - 1 \tag{3.2}$$

$$P[(idle)|(idle)] = 1-q \tag{3.3}$$

If the vehicle is in one of the (e,k) or (s,k) back-off states, where there is no packet in the queue, the next state depends on whether at least one packet arrives in that state or not, and it is modeled using q parameter as given below for $1 \le k \le W_0 - 1$,

$$P[(e,k-1)|(e,k)] = 1-q \tag{3.4}$$

$$P[(s,k-1)|(e,k)] = q \tag{3.5}$$

$$P[(s,k-1)|(s,k)] = 1-q \tag{3.6}$$

$$P[(q,k-1)|(s,k)] = q \tag{3.7}$$

If a packet arrives in $(e,0)$ state, the vehicle directly enters the transmission state $(s,0)$. Otherwise, if no packet arrives in $(e,0)$ state, the vehicle enters the idle state as given below,

$$P[(s,0)|(e,0)] = q \tag{3.8}$$

$$P[(idle)|(e,0)] = 1-q \tag{3.9}$$

If one of the (q,k) back-off states is reached, where there is a packet in the queue, the next state does not depend on the packet arrival in that state since only the most recently arrived packet is kept in the queue. For $1 \le k \le W_0 - 1$,

$$P[(q,k-1)|(q,k)] = 1 \tag{3.10}$$

When a transmission occurs in $(s, 0)$ state, where the queue is empty, the next state depends on whether a packet arrives or not in that state. While one of the (e, k) back-off states will be the next state in case of no packet arrival, one of the (s, k) back-off states will be the next state in case of a packet arrival during transmission, where $0 \leq k \leq W_0 - 1$. Moreover, when a transmission occurs in $(q, 0)$ state, where the queue is full, independent of a packet arrival in that state, the next state will be one of the (s, k) back-off states, where $0 \leq k \leq W_0 - 1$.

$$P[(e, k)|(s, 0)] = \frac{1 - q_T}{W_0} \tag{3.11}$$

$$P[(s, k)|(s, 0)] = \frac{q_T}{W_0} \tag{3.12}$$

$$P[(s, k)|(q, 0)] = \frac{1}{W_0} \tag{3.13}$$

The set of transition probabilities given in this section describes the behavior of HD-MAC protocol by using a 2-D Markov Chain model.

3.1.2 Transmission Probability Analysis

The Markov Chain model described in the previous section will be used to compute the transmission probability in a slot. For this purpose, the stationary probabilities of all states will be found in terms of the stationary probability of $(e, 0)$ state. Then, the normalization equation will be used to find the corresponding transmission probability.

In this section, $b(h, k)$ notation will be used to describe stationary probability of being in (h, k) state. Moreover, X_k^{hd} denotes the value of the function X at k.

$b(e, k)$ probabilities are firstly found in terms of $b(e, 0)$ for $0 \leq k \leq W_0 - 1$,

$$b(e, k) = \sum_{t=0}^{W_0-1-k} (1 - q)^t b(e, W_0 - 1) \tag{3.14}$$

$$b(e, k) = b(e, 0) D_k^{hd} \tag{3.15}$$

$$D_k^{hd} = \frac{1 - (1 - q)^{W_0 - k}}{1 - (1 - q)^{W_0}} \tag{3.16}$$

By using (3.15), $b(s,0)$ can be found in terms of $b(e,0)$,

$$b(s,0) = b(e,0)A^{hd} \tag{3.17}$$

$$A^{hd} = \frac{qW_0}{(1-(1-q)^{W_0})(1-q_T)} \tag{3.18}$$

The stationary probability of idle state can be expressed in terms of $b(e,0)$ as follows,

$$b(idle) = b(e,0)\frac{1-q}{q} \tag{3.19}$$

Stationary probability of $(q,0)$ state is found by using $b(s,W_0-1)$, $b(s,0)$ which is given in (3.17), and $b(idle)$ which is given in (3.19), and by solving $b(q,0)$ in terms of $b(s,W_0-1)$.

$$b(s,W_0-1) = \frac{b(q,0)+b(s,0)q_T+b(idle)qP_b}{W_0} \tag{3.20}$$

$$b(q,0) = b(e,0)B^{hd} \tag{3.21}$$

$$B^{hd} = \frac{q}{1-(1-q)^{W_0}}\Bigg[A^{hd}W_0 - (A^{hd}q_T+(1-q)P_b)\frac{1-(1-q)^{W_0}}{q} - A^{hd}(1-q_T)H_0^{hd} - W_0(1+qP_b-P_b)\Bigg] \tag{3.22}$$

$$H_k^{hd} = \frac{1-(1-q)^{W_0-k-1}}{q} - (W_0-k-1)(1-q)^{W_0-k-1} \tag{3.23}$$

Since $b(s,0)$, $b(q,0)$ and $b(idle)$ probabilities are found in terms of $b(e,0)$, $b(s,k)$ can also be expressed by $b(e,0)$ using A^{hd} given in (3.18), B^{hd} given in (3.22) and H_k^{hd} given in (3.23) for $1 \le k \le W_0-1$,

$$b(s,k) = b(e,0)C_k^{hd} \tag{3.24}$$

$$C_k^{hd} = \frac{B^{hd}+A^{hd}q_T+(1-q)P_b}{W_0}\frac{1-(1-q)^{W_0-k}}{q} + \frac{A^{hd}(1-q_T)}{W_0}H_k^{hd} \tag{3.25}$$

Finally, $b(q,k)$ can be found by using the expression found for $b(s,k)$ given in (3.24) for $1 \le k \le W_0-2$,

$$b(q,k) = b(e,0)E_k^{hd} \tag{3.26}$$

$$E_k^{hd} = q \sum_{t=k+1}^{W_0-1} C_t^{hd} \tag{3.27}$$

Transmission probability τ can be expressed as $b(e,0)(A^{hd} + B^{hd})$, and $b(e,0)$ can be found by using the normalization equation as follows,

$$1/b(e,0) = \frac{1-q}{q} + \sum_{t=0}^{W_0-1} D_t^{hd} + A^{hd} + \sum_{t=1}^{W_0-1} C_t^{hd} + B^{hd} + \sum_{t=1}^{W_0-2} E_t^{hd} \tag{3.28}$$

$$\tau = \frac{A^{hd} + B^{hd}}{\frac{1-q}{q} + \sum_{t=0}^{W_0-1} D_t^{hd} + A^{hd} + \sum_{t=1}^{W_0-1} C_t^{hd} + B^{hd} + \sum_{t=1}^{W_0-2} E_t^{hd}} \tag{3.29}$$

(3.29) should be solved to find τ since both sides of the equation depends on τ. To solve for τ in (3.29), the binary iterative search method is used, and the τ value that minimizes the error ($< 10^{-6}$) between both sides of the equation is chosen as the solution.

3.1.3 Modeling Offered Load in Markov Chain Model

To model offered load in HD-MAC Markov Chain model, q and q_T parameters are used. As a packet arrival process, Poisson process is considered. The probability of at least one packet arrival in a state duration is found considering Poisson arrival process. Packet arrival probability is differentiated as q and q_T considering whether the vehicle is transmitting in a given state or not. If the vehicle is in a transmission state, the probability of at least one packet arrival is defined as q_T. Otherwise, if the vehicle is in a non-transmission state, the probability of at least one packet arrival is defined as q.

If it is known that a vehicle is not transmitting in a given state, idle case probability $P_e^{'}$, successful case probability $P_s^{'}$ and collision case probability $P_c^{'}$ can be defined as follows,

$$P_e^{'} = (1-\tau)^{n-1} \tag{3.30}$$

$$P_s^{'} = (n-1)\tau(1-\tau)^{n-2} \tag{3.31}$$

$$P_c^{'} = 1 - P_e^{'} - P_s^{'} \tag{3.32}$$

If it is known that a vehicle is transmitting in a given state, successful case probability $P_s^{''}$ and collision case probability $P_c^{''}$ can be defined as follows,

$$P_s^{''} = (1-\tau)^{n-1} \tag{3.33}$$

$$P_c^{''} = 1 - P_s^{''} \tag{3.34}$$

Finally, q and q_T probabilities can be defined considering the probabilities defined for transmission and non-transmission states, state durations for idle case σ, successful case T_s, and collision case T_c, and using the beacon rate λ. In HD-MAC protocol, T_s and T_c durations are same since no collision detection mechanism is used. However, both is used in q and q_T definitons to make them more comprehensible.

$$q = P_e^{'}(1-e^{-\lambda\sigma}) + P_s^{'}(1-e^{-\lambda T_s}) + P_c^{'}(1-e^{-\lambda T_c}) \tag{3.35}$$

$$q_T = P_s^{''}(1-e^{-\lambda T_s}) + P_c^{''}(1-e^{-\lambda T_c}) \tag{3.36}$$

3.1.4 Successful Transmission Probability Analysis

Successful transmission probability $P_s^{''}$ can be found for HD-MAC protocol by using the transmission probability τ derived in the previous section. $P_s^{''}$ is the probability that no other vehicle will attempt transmission when a vehicle starts transmission, which is also defined in (3.33).

$$P_s^{''} = (1-\tau)^{n-1} \tag{3.37}$$

3.1.5 Normalized Throughput Analysis

To analyze the normalized system throughput, average state duration of the Markov Chain should be found. For HD-MAC Markov Chain model, there are 3 different cases to be considered,

- **Idle Case:** No vehicle transmits. Idle case probability is denoted as P_e and state duration for idle case is σ.

- **Successful Case:** Only one vehicle transmits. Successful case probability is denoted as P_s and state duration for successful case is T_s.
- **Collision Case:** Two or more vehicles transmits simultaneously. Collision case probability is denoted as P_c and state duration for collision case is T_c.

Average state duration E_s can be found by using P_e, P_s and P_c probabilities as follows,

$$E_s = P_e\sigma + P_sT_s + P_cT_c \tag{3.38}$$

$$P_e = (1-\tau)^n \tag{3.39}$$

$$P_s = n\tau(1-\tau)^{n-1} \tag{3.40}$$

$$P_c = 1 - P_e - P_s \tag{3.41}$$

Throughput is defined as the percentage of time that is used to successfully transmit the useful payload data. Therefore, only the time spent for transmitting payload data T_p is considered for throughput analysis excluding the time spent for header transmission.

$$Throughput = \frac{T_pP_s}{E_s} \tag{3.42}$$

3.1.6 Service Delay Analysis

Service time is defined as the time between a packet becomes head-of-line and it is successfully transmitted. For the service delay analysis, two cases should be considered. Firstly, if the queue is found with a packet after the transmission, this packet is directly taken into service, and $W_0/2$ back-off states on the average are used for service for this packet. On the other hand, if the queue is found empty after the transmission, the vehicle goes into the post back-off stage. In the post back-off stage, how many back-off states will be used for service for the generated packet depends on the packet arrival time. If a new packet arrives in one of the post back-off states, the packet is transmitted when the post back-off counter is equal to 0. Otherwise, if a new packet arrives in *idle* state, the channel is sensed to decide whether the packet will be transmitted directly, or it will be transmitted after back-off stage 0.

When a packet is found in the queue after the transmission, the time spent for service can be approximated considering the average state durations for transmission state and non-transmission states as follows,

$$T_{qne} = T_s + \left(\frac{W_0}{2} - 1\right)E_s^{'} \tag{3.43}$$

When the queue is found empty after the transmission, the time spent for service can be approximated considering the chosen post back-off counter value k, and the arrival of a packet after j states as follows,

$$\begin{aligned} T_{qe} = \sum_{k=0}^{W_0-1} \frac{1}{W_0} \Bigg[& \sum_{j=0}^{k-1} q(1-q)^j \big[(k-j)E_s^{'} + T_s\big] + \\ & \sum_{j=k}^{\infty} q(1-q)^j \big[(1-P_b)T_s + P_b T_{qne}\big] \Bigg] \end{aligned} \tag{3.44}$$

Depending on the queue state after the transmission i.e. empty or with a packet, average service delay is defined. Queue state after the transmission depends on the packet arrival probability during the service time. That is, if at least one packet arrives during T_{qe} or T_{qne}, the service time for the next packet will be equal to T_{qne}. Otherwise, if no packet arrives during T_{qe} or T_{qne}, the service time for the next packet will be equal to T_{qe}. This behavior can be modeled using a Markov Chain model shown in Figure 3.2.

P_{qne} and P_{qe} probabilities can be found by using the Markov Chain model as follows,

$$P_{qne} = \frac{1 - e^{-\lambda T_{qe}}}{1 - e^{-\lambda T_{qe}} + e^{-\lambda T_{qne}}} \tag{3.45}$$

$$P_{qe} = 1 - P_{qne} \tag{3.46}$$

In (3.44), the probability that the channel is found busy P_b is used. P_b is approximated as collision probability p for the stationary probability analysis of

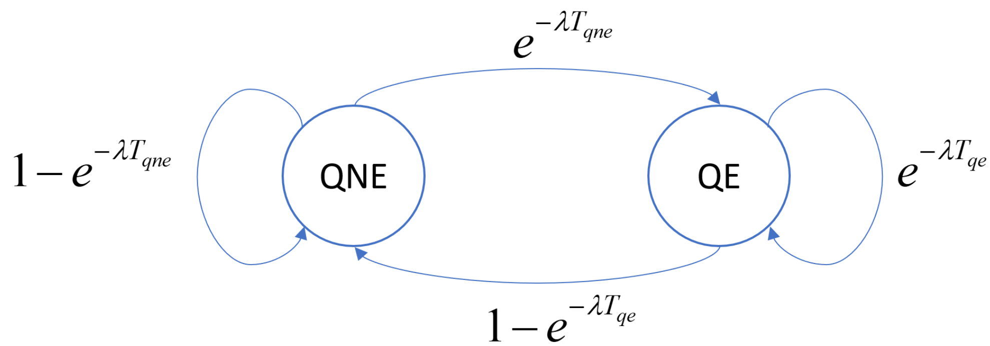


Figure 3.2: Markov Chain model for the queue state after the transmission

the Markov Chain model. However, for the calculation of the service delay, P_b is converted to time probability considering idle and busy slot lengths as follows [32],

$$P_b = 1 - \left[(1-p) \frac{T_e}{E_s'} \right] \tag{3.47}$$

Finally, average service delay experienced by a packet for HD-MAC protocol can be approximated as follows,

$$T_{sd} = P_{qne} T_{qne} + P_{qe} T_{qe} \tag{3.48}$$

3.1.7 Packet Loss Probability Analysis

While successful transmission probability is used to analyze HD-MAC protocol per transmission, packet loss probability is used to analyze HD-MAC protocol per packet. A beacon packet generated by a vehicle may be lost due to 2 reasons in HD-MAC protocol,

- **Maximum Queue Size:** If the queue has already one packet in it, when a new packet arrives, older beacon packet is dropped from the queue and new beacon packet is queued.
- **Maximum Retry Count:** Since no collision detection mechanism exists in HD-MAC protocol, maximum retry count for HD-MAC is 1. That is, if

the transmission of a beacon packet in service is failed due to collision, this packet cannot be retransmited and it is lost.

The probability that the generated packet will be dropped due to maximum queue size P_{mq} is defined considering the cases in which the queue is empty or not after the transmission as in the service delay analysis described in Section 3.1.6. When the queue has a packet after the transmission, while this packet is in service, the probability that more than one packet will be generated should be considered. On the other hand, when the queue is empty after the transmission, a packet arrives during a non-transmission state. If more than one packet is generated during this state, this packet is dropped due to maximum queue size limit. Moreover, while the generated packet is in service, only the recently arrived packet is kept in the queue and the rest is dropped due to maximum queue size limit. Therefore, by using the probabilities P_{qne} and P_{qe}, and the service times T_{qne} and T_{qe}, P_{mq} can be approximated as follows,

$$P_{mq} = \frac{P_{qne}\left[\frac{\lambda T_{qne}}{1-e^{-\lambda T_{qne}}} - 1\right] + P_{qe}\left[\left(\frac{\lambda T_{qe}}{1-e^{-\lambda T_{qe}}} - 1\right) + \left(\frac{\lambda E_s{}'}{1-e^{-\lambda E_s'}} - 1\right)\right]}{P_{qne}\left[\frac{\lambda T_{qne}}{1-e^{-\lambda T_{qne}}}\right] + P_{qe}\left[\frac{\lambda T_{qe}}{1-e^{-\lambda T_{qe}}} + \frac{\lambda E_s'}{1-e^{-\lambda E_s'}}\right]} \quad (3.49)$$

If the generated packet is not dropped due to maximum queue size limit, it may be dropped due to maximum retry limit. In HD-MAC protocol, there is no collision detection mechanism as described previously. Therefore, if the transmission attempt for the generated packet is failed due to collision on the channel, this packet is dropped in the first attempt. The probability that the generated packet will be dropped due to maximum retry limit P_{mr} is defined as follows,

$$P_{mr} = p(1 - P_{mq}) \quad (3.50)$$

Finally, packet loss probability P_{loss} is found as the sum of the packet drop probabilities due to maximum queue size limit and maximum retry limit as follows,

$$P_{loss} = P_{mq} + P_{mr} \quad (3.51)$$

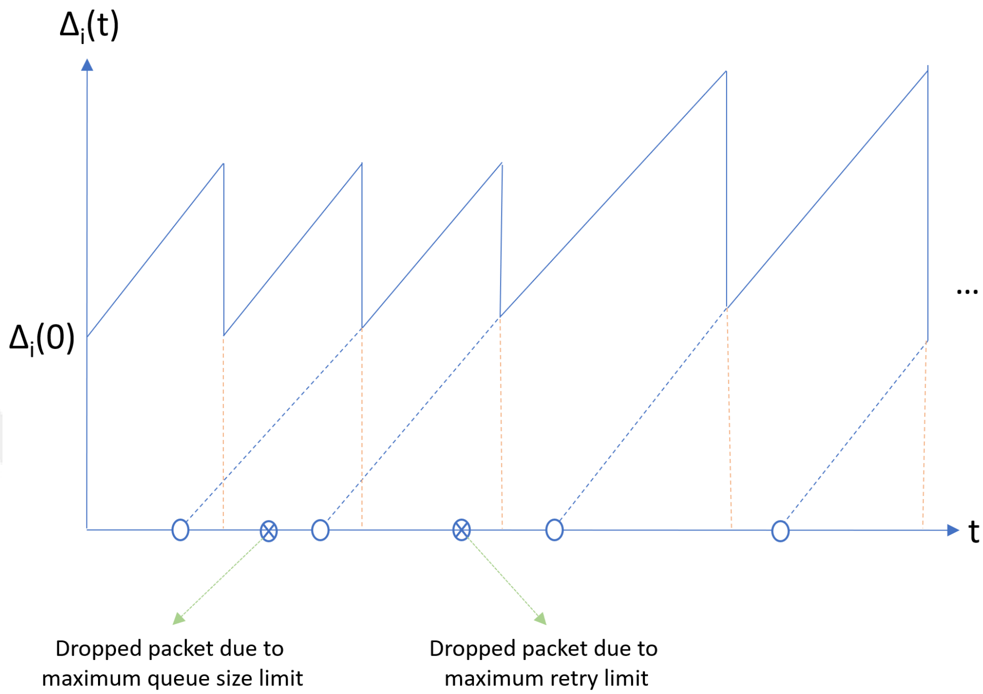


Figure 3.3: Sample variation of AoI for HD-MAC protocol

3.1.8 Age-of-Information Analysis

To measure the freshness of data, AoI, a new metric for communication systems, was introduced in [40]. In this section, this metric will be used to quantify the performance of the beaconing mechanism when HD-MAC protocol is used. In Figure 3.3, sample variation of AoI for HD-MAC protocol is shown. If more than one packet arrives when another packet is in service, only the recently received packet is kept in the queue as shown. Moreover, if the transmission attempt for a packet is failed, this packet will be dropped due to maximum retry limit of HD-MAC protocol, and this will increase the interval between successive packet receive times as shown.

To find average AoI in HD-MAC protocol, average value of the time interval between successive packet receive times and the AoI value at packet receive times are considered. Then, average AoI is approximated as follows, where t_0 and t_1 are two successive packet receive times, and $\Delta(0)$ is the AoI value at t_0 as shown

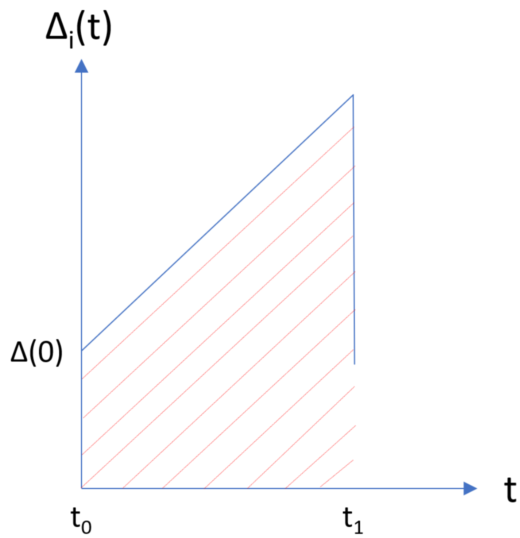


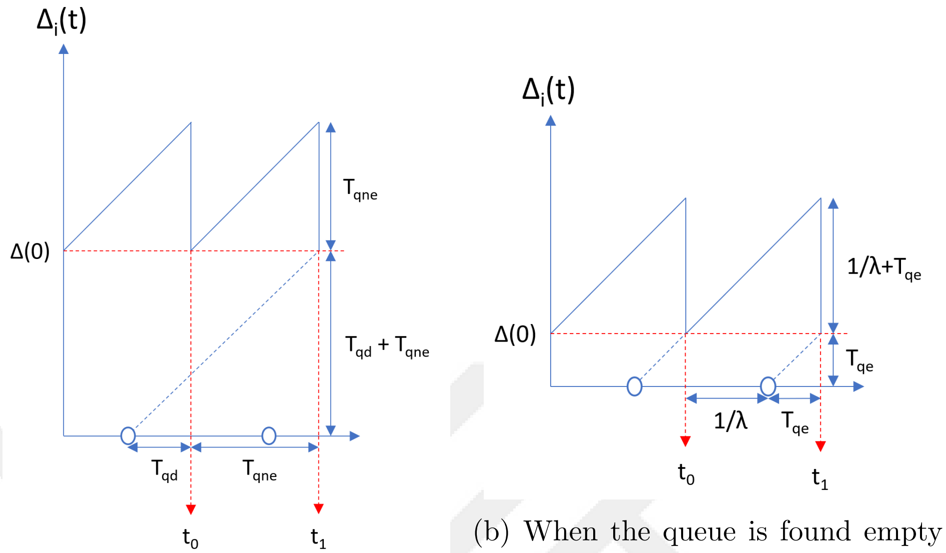
Figure 3.4: Average AoI approximation using average values of the packet inter-arrival times at the receiver and the AoI values at packet receive times

in Figure 3.4.

$$\overline{\Delta} = \frac{\frac{(t_1-t_0)^2}{2} + (t_1 - t_0)\Delta(0)}{(t_1 - t_0)} \tag{3.52}$$

$$\overline{\Delta} = \frac{(t_1 - t_0)}{2} + \Delta(0) \tag{3.53}$$

Firstly, assuming no packet loss, average $\Delta(0)_s$ and $(t_1 - t_0)_s$ values for HD-MAC protocol are found considering the queue state after the transmission. If the queue is found with a packet after the transmission, $(t_1 - t_0)_s$ is equal to average service delay T_{qne} since the packet in the queue is directly taken into service, and $\Delta(0)_s$ is equal to sum of the average queuing delay T_{qd} and service delay T_{qne} as shown in Figure 3.5a. On the other hand, if the queue is found empty after transmission, $(t_1 - t_0)_s$ is equal to sum of the average packet generation interval $1/\lambda$ considering the beacon generation rate λ and the memoryless property of Poisson process, and the average service delay when the queue is found empty T_{qe} assuming no packet loss. Here, queuing delay of the generated packet is neglected since it is small compared to $1/\lambda$ and T_{sd}. Moreover, $\Delta(0)_s$ is estimated as the average service delay T_{qe} as shown in Figure 3.5b. As a result, average $\Delta_s(0)$ and



(a) When the queue is found with a packet after transmission

(b) When the queue is found empty after transmission

Figure 3.5: Average AoI variation depending on whether the queue is found empty or not after transmission assuming that two successive packets are successfully transmitted

$(t_1 - t_0)_s$ values are defined for no packet loss case as follows,

$$\Delta_s(0) = P_{qne}(T_{qd} + T_{qne}) + P_{qe}T_{qe} \tag{3.54}$$

$$(t_1 - t_0)_s = P_{qne}(T_{qne}) + P_{qe}\left(\frac{1}{\lambda} + T_{qe}\right) \tag{3.55}$$

In case of packet losses due to maximum retry limit, average AoI will increase due to the increase in $(t_1 - t_0)$. $\Delta(0)$ value does not change since the recently received packet is used. Average $\Delta(0)$ and $(t_1 - t_0)$ values are found considering packet loss probability p and j successive packet losses as follows,

$$\Delta(0) = \Delta_s(0) \tag{3.56}$$

$$(t_1 - t_0) = \sum_{j=0}^{\infty} p^j(1-p)(j+1)(t_1 - t_0)_s = \frac{(t_1 - t_0)_s}{1-p} \tag{3.57}$$

The average queuing delay T_{qd} in non-empty queue case is found considering the residual time after the last packet arrival in T_{qne} duration. T_{qd} will be equal to

$T_{qne}/(n+1)$ if n arrivals occur in T_{qne}. Therefore, T_{qd} will be found conditioning on the number of arrivals when at least one arrival occurs in T_{qne}. Since packet arrivals are modeled as a Poisson arrival process, following approach can be used to estimate T_{qd} in non-empty queue case

$$T_{qd} = \sum_{n=0}^{\infty} \frac{T_{qne}}{n+1} \frac{\frac{(\lambda T_{qne})^n}{n!} e^{-\lambda T_{qne}}}{1 - e^{\lambda T_{qne}}} \tag{3.58}$$

$$T_{qd} = \frac{1 - e^{-\lambda T_{qne}} - \lambda T_{qne} e^{-\lambda T_{qne}}}{\lambda(1 - e^{-\lambda T_{qne}})} \tag{3.59}$$

Finally, average AoI $\overline{\Delta}$ for HD-MAC protocol is found as follows,

$$\overline{\Delta} = \frac{P_{qne}(T_{qne}) + P_{qe}\left(\frac{1}{\lambda} + T_{qe}\right)}{2 * (1-p)} + P_{qne}(T_{qd} + T_{qne}) + P_{qe}T_{qe} \tag{3.60}$$

3.2 Markov Chain Model for FD-MAC Protocol

To investigate the performance of FD-MAC protocol described in Section 2.6.2, a Markov Chain model is proposed for FD-MAC protocol as given in Figure 3.6. This Markov Chain model uses 3-tuple (h, i, k) model to describe all different states of the FD-MAC protocol. While k models the back-off counter, $0 \leq k \leq W_i - 1$, i models the back-off stage value, $0 \leq i \leq r$, and h models the queue state which can take 3 different values as described below:

- e**:** Used to model the post back-off states where queue is empty after the transmission.
- s**:** Used to model the states where there is a packet in service and queue is empty.
- q**:** Used to model the states where there is a packet in service, and queue is not empty and keeps the recently arrived packet.

To describe the packet arrival probabilities in each state of the FD-MAC Markov Chain model, q and q_T parameters are used. P_b parameter is used in

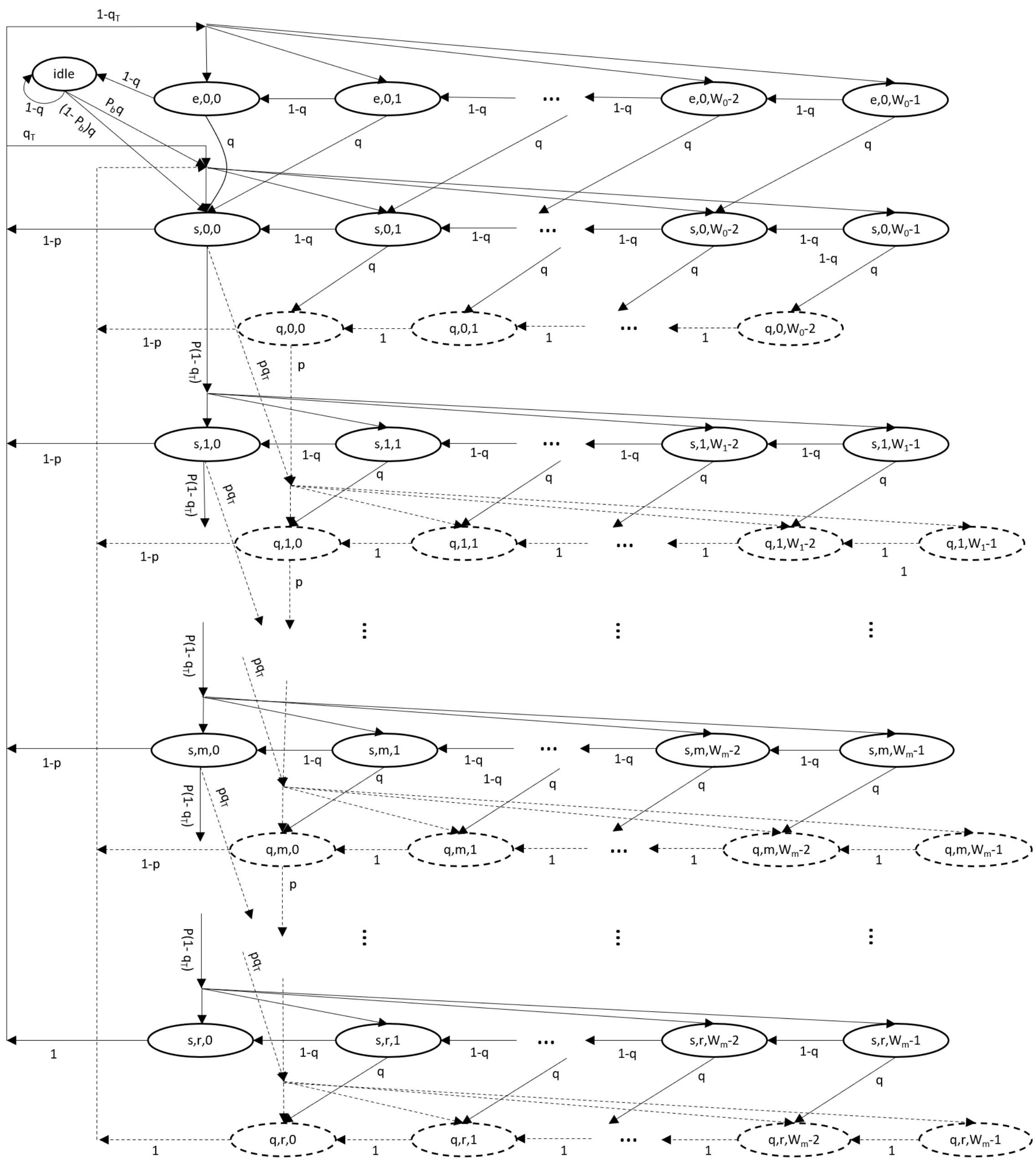


Figure 3.6: Markov Chain model for FD-MAC protocol

the FD-MAC Markov Chain model to describe the channel busy probability as in HD-MAC Markov Chain model.

In this section, the FD-MAC Markov Chain model is solved to obtain a mathematical expression for the transmission probability. Then, this solution is used to obtain other performance metrics of the FD-MAC protocol such as successful transmission probability, throughput, packet loss probability, service delay, and age-of-information.

3.2.1 Transition Probabilities

According to the FD-MAC protocol described in Section 2.6.2, when a packet arrives in the idle state, if the channel is sensed free, the vehicle directly enters the transmission state. Otherwise, if the channel is sensed busy, the vehicle enters the back-off stage. If no packet arrives in idle state, the vehicle stays in the idle state. To model this behavior, P_b parameter is used as given below,

$$P[(s,0,0)|(idle)] = (1-P_b)q \tag{3.61}$$

$$P[(s,0,k)|(idle)] = \frac{P_b q}{W_0}, 0 \leq k \leq W_0 - 1 \tag{3.62}$$

$$P[(idle)|(idle)] = 1-q \tag{3.63}$$

If the vehicle is in one of the (e,i,k) or (s,i,k) back-off states where there is no packet in the queue, the next state depends on whether at least one packet arrives in that state or not, and it is modeled using q parameter as given below for $1 \leq k \leq W_0 - 1$ and $0 \leq i \leq r$

$$P[(e,0,k-1)|(e,0,k)] = 1-q \tag{3.64}$$

$$P[(s,0,k-1)|(e,0,k)] = q \tag{3.65}$$

$$P[(s,i,k-1)|(s,i,k)] = 1-q \tag{3.66}$$

$$P[(q,i,k-1)|(s,i,k)] = q \tag{3.67}$$

In $(e,0,0)$ state, if a packet arrives the vehicle directly enters the transmission state $(s, 0, 0)$. Otherwise, if no packet arrives in $(e, 0, 0)$ state, the vehicle enters the *idle* state as given below,

$$P[(s, 0, 0)|(e, 0, 0)] = q \quad (3.68)$$

$$P[(idle)|(e, 0, 0)] = 1 - q \quad (3.69)$$

If one of the (q, i, k) back-off states is reached, where there is a packet in the qeueue, the next state does not depend on the packet arrival in that state since only the most recently arrived packet is kept in the queue. For $1 \leq k \leq W_0 - 1$ and $0 \leq i \leq r$

$$P[(q, i, k - 1)|(q, i, k)] = 1 \quad (3.70)$$

When the vehicle is in one of the transmission states, the next state depends on whether at least one more vehicle start transmission in the same slot and whether false alarm or miss detection cases occur due to RSI effect on full duplex radios. Collision, miss detection and false alarm probabilities are modeled using p parameter for FD-MAC Markov Chain model. Therefore, p is not simply used to define the collision probability for FD-MAC Markov Chain model. A more detailed definition of p will be provided in Section 3.2.3. Here, p describes the probability that the back-off stage will be increased after the transmission, and 1-p describes the probability of returning to the first back-off stage after transmission.

When a transmission occurs in one of $(s, i, 0)$ states, where the queue is empty, the next state is determined by the p probability and at least one packet arrival probability during the transmission q_T as described below,

- For $0 \leq i < r$, and $0 \leq k \leq W_0 - 1$,

$$P[(e, 0, k)|(s, i, 0)] = \frac{(1 - p)(1 - q_T)}{W_0} \quad (3.71)$$

$$P[(s, 0, k)|(s, i, 0)] = \frac{(1 - p)q_T}{W_0} \quad (3.72)$$

- For $0 \leq i < r$, and $0 \leq k \leq W_{min(i+1,m)} - 1$,

$$P[(s, i+1, k)|(s, i, 0)] = \frac{p(1-q_T)}{W_{min(i+1,m)}} \quad (3.73)$$

$$P[(q, i+1, k)|(s, i, 0)] = \frac{pq_T}{W_{min(i+1,m)}} \quad (3.74)$$

- For $i = r$, and $0 \leq k \leq W_0 - 1$,

$$P[(e, 0, k)|(s, r, 0)] = \frac{1-q_T}{W_0} \quad (3.75)$$

$$P[(s, 0, k)|(s, r, 0)] = \frac{q_T}{W_0} \quad (3.76)$$

When a transmission occurs in one of $(q, i, 0)$ states, where the queue is full, the next state does not depend on whether a packet arrives or not during the transmission. This behavior is modeled as follows,

- For $0 \leq i < r$, and $0 \leq k \leq W_0 - 1$,

$$P[(s, 0, k)|(q, i, 0)] = \frac{1-p}{W_0} \quad (3.77)$$

- For $0 \leq i < r$, and $0 \leq k \leq W_{min(i+1,m)} - 1$,

$$P[(q, i+1, k)|(q, i, 0)] = \frac{p}{W_{min(i+1,m)}} \quad (3.78)$$

- For $i = r$, and $0 \leq k \leq W_0 - 1$,

$$P[(s, 0, k)|(q, r, 0)] = \frac{1}{W_0} \quad (3.79)$$

The set of transition probabilities given in this section describes the behavior of FD-MAC protocol by using a 3-D Markov Chain model.

3.2.2 Transmission Probability Analysis

The Markov Chain model described in the previous section will be used find transmission probability in a slot. For this purpose, the stationary probabilities of all states will be found in terms of the stationary probability of $(e, 0, 0)$ state. Then, the normalization equation will be used to find the corresponding transmission probability.

In this section, $b(h, i, k)$ notation will be used to describe stationary probability of being in (h, i, k) state. Moreover, X_k notation will be used to describe the value of the function X at k.

To simplify the formulation, A and B equations are defined to describe the probability of returning to the first back-off stage after the transmission from $b(s, i, 0)$ and $b(q, i, 0)$ states for $0 < i < W_0 - 1$, respectively.

$$A = (1 - p) \sum_{t=0}^{r-1} b(s, t, 0) + b(s, r, 0) \tag{3.80}$$

$$B = (1 - p) \sum_{t=0}^{r-1} b(q, t, 0) + b(q, r, 0) \tag{3.81}$$

The stationary probability of idle state is described using $b(e, 0, 0)$ as follows,

$$b(idle) = b(e, 0, 0)\frac{1 - q}{q} \tag{3.82}$$

$b(e, 0, k)$ probabilities are found in terms of $b(e, 0, 0)$ for $0 \leq k \leq W_0 - 1$ as follows,

$$b(e, 0, W_0 - 1) = \frac{A(1 - q_T)}{W_0} \tag{3.83}$$

$$b(e, 0, k) = \sum_{t=0}^{W_0-1-k} (1 - q)^t b(e, 0, W_0 - 1) \tag{3.84}$$

$$b(e, 0, k) = b(e, 0, 0)M_k \tag{3.85}$$

$$M_k = \frac{1 - (1 - q)^{W_0-k}}{1 - (1 - q)^{W_0}} \tag{3.86}$$

By using the (3.83), A can be found in terms of $b(e, 0, 0)$ as follows,

$$A = b(e, 0, 0)F \tag{3.87}$$

$$F = \frac{qW_0}{(1 - q_T)(1 - (1 - q)^{W_0})} \tag{3.88}$$

$b(s,0,k)$ can be described using $b(s,0,W_0-1)$ and $b(e,0,W_0-1)$ given in (3.90). $b(s,0,k)$ will be defined in terms of $b(e,0,0)$ when B is defined in terms of $b(e,0,0)$. For $1 \leq k \leq W_0 - 1$,

$$b(s,0,W_0-1) = \frac{AqT + B + b(idle)qP_b}{W_0} \tag{3.89}$$

$$b(s,0,k) = b(s,0,W_0-1)\frac{1-(1-q)^{W_0-k}}{q} + b(e,0,W_0-1)H_k \tag{3.90}$$

$$H_k = \frac{1-(1-q)^{W_0-k-1}}{q} - (W_0-k-1)(1-q)^{W_0-k-1} \tag{3.91}$$

For $k = 0$, $b(s,0,k)$ is defined differently since the transmission state can be directly reached from $b(idle)$ and $b(e,0,0)$ states without selecting a back-off counter value. Therefore, the effect of these transition probabilities is included in $b(s,0,k)$ for $k=0$ as follows,

$$b(s,0,0) = b(s,0,W_0-1)\frac{1-(1-q)^{W_0}}{q} + b(e,0,W_0-1)H_0 + b(e,0,0)(1+P_bq-P_b) \tag{3.92}$$

For $1 \leq i \leq m$ and $0 \leq k \leq W_i - 1$, $b(s,i,k)$ can be found in terms of $b(s,0,0)$ as follows,

$$b(s,i,k) = b(s,0,0)\left(\frac{p(1-q_T)}{q}\right)^i \frac{1-(1-q)^{W_i-k}}{W_i} \prod_{t=1}^{i-1} \frac{1-(1-q)^{W_t}}{W_t} \tag{3.93}$$

Maximum value of the back-off counter is not increased when the back-off stage value is larger than m. Therefore, $b(s,i,k)$ is defined for $1 \leq i \leq m$ and $m < i \leq r$ differently. $b(s,m,0)$ probability obtained using (3.93) is used to find the stationary probabilities of the states with back-off stage value larger than m.

$$b(s,m,0) = b(s,0,0)C \tag{3.94}$$

$$C = \left(\frac{p(1-q_T)}{q}\right)^m \prod_{t=1}^{m} \frac{1-(1-q)^{W_t}}{W_t} \tag{3.95}$$

As a result, for $m < i \leq r$ and $0 \leq k \leq W_m - 1$, $b(s,i,k)$ is defined as follows,

$$b(s,i,k) = b(s,0,0)C\frac{1-(1-q)^{W_m-k}}{q}\left(\frac{1-(1-q)^{W_m}}{q}\right)^{i-m-1}\left(\frac{p(1-q_T)}{W_m}\right)^{i-m} \tag{3.96}$$

Until now, all $b(s,i,k)$ states are defined in terms of $b(s,0,0)$. Now, $b(s,0,0)$ can be found in terms of $b(e,0,0)$ using the definition of A given in (3.80) and F given in (3.87) as follows,

$$\sum_{t=0}^{r-1} b(s,t,0) = b(s,0,0)D \tag{3.97}$$

$$D = 1 + \sum_{y=1}^{m}\left(\frac{p(1-q_T)}{q}\right)^{y}\prod_{t=1}^{y}\frac{1-(1-q)^{W_t}}{W_t} + C\sum_{y=m+1}^{r-1}\left(\frac{1-(1-q)^{W_m}}{q}\right)\left(\frac{p(1-q_T)}{W_m}\right)^{y-m} \tag{3.98}$$

$$b(s,r,0) = b(s,0,0)E \tag{3.99}$$

$$E = C\left(\frac{1-(1-q)^{W_m}}{q}\frac{p(1-q_T)}{W_m}\right)^{r-m} \tag{3.100}$$

$$A = b(s,0,0)[(1-p)D + E] \tag{3.101}$$

$$b(s,0,0) = b(e,0,0)G \tag{3.102}$$

$$G = \frac{F}{(1-p)D + E} \tag{3.103}$$

Then, (3.92) is used to find B in terms of $b(e,0,0)$ as follows,

$$B = b(e,0,0)I \tag{3.104}$$

$$I = \frac{qW_0 - [Fq_T + (1-q)P_b]\left(\frac{1-(1-q)^{W_0}}{q}\right) - F(1-q_T)H_0 - W_0(1 + P_b q - P_b)}{\frac{1-(1-q)^{W_0}}{q}} \tag{3.105}$$

When B is found in terms of $b(e,0,0)$, $b(s,0,k)$ given in (3.90) can be expressed in terms of $b(e,0,0)$ for $0 \leq k \leq W_0 - 1$ as follows,

$$b(s,0,k) = \begin{cases} b(e,0,0)K_k, & \text{if } 1 \leq k \leq W_0 - 1 \\ b(e,0,0)[K_0 + (1 + P_b q - P_b)], & \text{if } k = 0 \end{cases} \tag{3.106}$$

$$K_k = \frac{[Fq_T + I + (1-q)P_b]\frac{1-(1-q)^{W_0-k}}{q} + (F(1-q_T)H_K)}{W_0} \tag{3.107}$$

Since $b(s,0,0)$ is expressed in terms of $b(e,0,0)$ in (3.102), $b(s,i,k)$ probabilities for back-off stage values larger than 0 can also be expressed in terms of $b(e,0,0)$ for $0 \leq k \leq W_{min(i,m)} - 1$ and $1 \leq i \leq r$ as follows,

$$b(s,i,k) = b(e,0,0)N_{i,k} \tag{3.108}$$

$$N_{i,k} = \begin{cases} G\frac{1-(1-q)^{W_i-k}}{W_i}\left(\frac{p(1-q_T)}{q}\right)^i \prod_{t=1}^{i-1}\frac{1-(1-q)^{W_t}}{W_t}, & \text{if } 1 \leq i \leq m \\ GC\frac{1-(1-q)^{W_m-k}}{q}\left(\frac{1-(1-q)^{W_m}}{q}\right)^{i-m-1}\left(\frac{p(1-q_T)}{W_m}\right)^{i-m}, & \text{if } m < i \leq r \end{cases} \tag{3.109}$$

Until now, $b(s,i,k)$ stationary probabilities for $0 \leq k \leq W_0 - 1$ and $0 \leq i \leq r$ are defined in terms of $b(e,0,0)$, Now, $b(q,i,k)$ stationary probabilities will also be defined in terms of $b(e,0,0)$ to complete analysis of the Markov Chain model. To find $b(q,i,k)$ stationary probabilities, firstly, $b(q,1,0)$ is found in terms of $b(e,0,0)$, and then, $b(q,i,0)$ probabilities are defined in terms of $b(e,0,0)$ using the $b(q,1,0)$ definition as follows,

- For $i = 1$,

$$b(q,1,0) = b(e,0,0)R \tag{3.110}$$

$$R = q_T pG + pq\sum_{t=1}^{W_0-1} K_t + q\sum_{y=1}^{W_1-1} N_{1,y} \tag{3.111}$$

- For $2 \leq i \leq r$,

$$b(q,i,0) = b(e,0,0)T_i \tag{3.112}$$

$$T_i = q_T\sum_{t=1}^{i-1} p^{i-t}N_{t,0} + p^{i-1}R + q\sum_{t=2}^{i} p^{i-t}\sum_{y=1}^{W_{min(t,m)}-1} N_{t,y} \tag{3.113}$$

$b(q,0,k)$ for $0 \leq k \leq W_0 - 1$ can be defined using (3.106) since $(q,0,k)$ states can only be accessible from $(s,0,k)$ states.

$$b(q,0,k) = b(e,0,0)Z_k \tag{3.114}$$

$$Z_k = q \sum_{t=k+1}^{W_0-1} K_t \tag{3.115}$$

$b(q,1,k)$ can be defined in terms of $b(e,0,0)$ using (3.110) for $0 \leq k \leq W_1 - 1$ as follows,

$$b(q,1,k) = b(e,0,0)U_k \tag{3.116}$$

$$U_k = \frac{W_1 - k}{W_1}\left[q_T pG + pq \sum_{t=1}^{W_0-1} K_t\right] + q \sum_{t=k+1}^{W_1-1} N_{1,t} \tag{3.117}$$

Finally, $b(q,i,k)$ is expressed in terms of $b(e,0,0)$ using (3.110) and (3.112) for $0 \leq k \leq W_{min(i,m)} - 1$ and $2 \leq i \leq r$,

$$b(q,i,k) = b(e,0,0)Y_{i,k} \tag{3.118}$$

$$Y_{i,k} = \begin{cases} \frac{W_{min(i,m)}-k}{W_{min(i,m)}}(q_T pN_{i-1,0} + pR) + q\sum_{t=k+1}^{W_{min(i,m)}-1} N_{i,t}, & \text{if } i = 2 \\ \frac{W_{min(i,m)}-k}{W_{min(i,m)}}(q_T pN_{i-1,0} + pT_{i-1}) + q\sum_{t=k+1}^{W_{min(i,m)}-1} N_{i,t}, & \text{if } 3 \leq i \leq r \end{cases} \tag{3.119}$$

After finding the definitions of all stationary probabilities in terms of $b(e,0,0)$, normalization equation given in (3.120) can be used to find the stationary probability of $b(e,0,0)$. Then, stationary probabilities of all transmission states are summed to find the transmission probability in terms of $b(e,0,0)$ as follows,

$$\begin{aligned} 1/b(e,0,0) = \frac{1-q}{q} + \sum_{t=0}^{W_0-1} M_t + \sum_{t=0}^{W_0-1} K_t + \sum_{t=1}^{r}\sum_{y=0}^{W_t-1} N_{t,y} + \\ \sum_{t=0}^{W_0-1} Z_t + \sum_{t=0}^{W_1-1} U_t + \sum_{t=2}^{r}\sum_{y=0}^{W_t-1} Y_{t,y} \end{aligned} \tag{3.120}$$

$$\tau = b(e,0,0)\left[K_0 + \sum_{t=1}^{r} N_{t,0} + Z_0 + U_0 + \sum_{t=2}^{r} Y_{t,0}\right] \tag{3.121}$$

(3.121) is solved to find τ since both sides of the equation depends on τ. To solve for τ in (3.121), the binary iterative search method is used, and the τ value that minimizes the error ($< 10^{-6}$) between both sides of the equation is chosen as the solution.

3.2.3 Modeling RSI Effect in Markov Chain Model

For FD-MAC Markov Chain model, RSI effect on full duplex radios should also be considered as described previously. When there is no RSI effect, the vehicle increases the back-off stage value in case of collision and the vehicle returns to the first back-off stage in case of successful transmission. This behavior is modeled using the collision probability p. When the RSI effect is considered, the vehicle increases the back-off stage value in case of collision or false alarm, and the vehicle returns to the first back-off stage in case of successful transmission or miss detection. Here, miss detection is only considered when only two vehicles transmit on the same slot. That is, it is assumed that if more than two vehicles are transmitting at the same slot, collision detection is perfect. This assumption is applicable since the signal level received by the second antenna will increase when the number of vehicles transmitting on the same slot increase, and the correct detection probability will increase. As a result, p is modeled for No RSI case and RSI case using miss detection probability P_m, and false alarm probability P_f as follows,

$$1 - p = \begin{cases} (1-\tau)^{n-1}, & \text{No RSI case} \\ (1-\tau)^{n-1}(1-P_f) + (n-1)\tau(1-\tau)^{n-2}P_m, & \text{RSI case} \end{cases} \tag{3.122}$$

In FD-MAC protocol, it is assumed that the collision is detected in a header duration which is used to transmit the header data. Since beacon packet is composed of header data and payload data and header data is sent before payload data, the collision can be detected before transmitting whole packet using FD radios. Therefore, FD-MAC protocol decreases the collision detection time significantly compared to the collision detection time of MAC protocols using the acknowledgement mechanism. RTS/CTS mechanism can be used to avoid some collisions. However, while in RTS/CTS mechanism, the time for successfully transmitting the whole packet is increased due to RTS and CTS messages, in FD-MAC protocol, the successful transmission duration is not increased, and it is equal to the packet duration which is only used to transmit the whole packet.

State durations for successful case T_s, for correct detection case T_{cd}, for miss detection case T_{md}, for false alarm case T_{fa}, and for idle case T_e can be defined in terms of header duration T_h and payload duration T_p as follows,

$$T_s = T_h + T_p + DIFS \tag{3.123}$$

$$T_{cd} = T_h + DIFS \tag{3.124}$$

$$T_{md} = T_h + T_p + DIFS \tag{3.125}$$

$$T_{fa} = T_h + DIFS \tag{3.126}$$

$$T_e = \sigma \tag{3.127}$$

3.2.4 Modeling Offered Load in Markov Chain Model

To model offered load in FD-MAC Markov Chain model, q and q_T parameters are used as in HD-MAC model. As a packet arrival process, Poisson process is considered. The probability of at least one packet arrival in a state duration is found considering Poisson arrival process. Packet arrival probability is differentiated as q and q_T considering whether the vehicle is transmitting in a given state or not. If the vehicle is in a transmission state, the probability of at least one packet arrival is defined as q_T. Otherwise, if the vehicle is in a non-transmission state, the probability of at least one packet arrival is defined as q.

If it is known that a vehicle is not transmitting in a given state, idle case probability $P_e^{'}$, successful case probability $P_s^{'}$, correct detection case probability $P_{cd}^{'}$, miss detection case probability $P_{md}^{'}$, and false alarm case probability $P_{fa}^{'}$ can be defined as follows,

$$P_e^{'} = (1-\tau)^{n-1} \tag{3.128}$$

$$P_s^{'} = (n-1)\tau(1-\tau)^{n-1}(1-P_f) \tag{3.129}$$

$$P_{fa}^{'} = (n-1)\tau(1-\tau)^{n-1}P_f \tag{3.130}$$

$$P_{md}^{'} = \binom{n-1}{2}\tau^2(1-\tau)^{n-3}(1-(1-P_m)^2) \tag{3.131}$$

$$P_{cd}^{'} = 1 - P_e^{'} - P_s^{'} - P_{fa}^{'} - P_{md}^{'} \tag{3.132}$$

If it is known that a vehicle is transmitting in a given state, successful case probability $P_s^{''}$, correct detection case probability $P_{cd}^{''}$, miss detection case probability $P_{md}^{''}$, and false alarm case probability $P_{fa}^{''}$ can be defined as follows,

$$P_s^{''} = (1-\tau)^{n-1}(1-P_f) \tag{3.133}$$

$$P_{fa}^{''} = (1-\tau)^{n-1}P_f \tag{3.134}$$

$$P_{md}^{''} = (n-1)\tau(1-\tau)^{n-2}(1-(1-P_m)^2) \tag{3.135}$$

$$P_{cd}^{''} = 1 - P_s^{''} - P_{fa}^{''} - P_{md}^{''} \tag{3.136}$$

Finally, q and qT probabilities can be defined considering the probabilities defined for transmission and non-transmission states, the state durations for different cases defined above, and using the beacon rate λ.

$$\begin{aligned} q = {} & P_e{'}(1-e^{-\lambda\sigma}) + P_s{'}(1-e^{-\lambda T_s}) + P_{fa}{'}(1-e^{-\lambda T_{fa}}) + \\ & P_{md}{'}(1-e^{-\lambda T_{md}}) + P_{cd}{'}(1-e^{-\lambda T_{cd}}) \end{aligned} \tag{3.137}$$

$$\begin{aligned} q_T = {} & P_s{''}(1-e^{-\lambda T_s}) + P_{fa}{''}(1-e^{-\lambda T_{fa}}) + P_{md}{''}(1-e^{-\lambda T_{md}}) + \\ & P_{cd}{''}(1-e^{-\lambda T_{cd}}) \end{aligned} \tag{3.138}$$

3.2.5 Successful Transmission Probability Analysis

Successful transmission probability $P_s^{''}$ for FD-MAC protocol can be found by using the transmission probability τ derived in Section 3.2.2. $P_s^{''}$ is the probability that no other vehicle will attempt transmission, and no collision is falsely detected due to RSI effect when the vehicle starts transmission, which is also defined in (3.133).

$$P_s^{''} = (1-\tau)^{n-1}(1-P_f) \tag{3.139}$$

3.2.6 Normalized Throughput Analysis

To analyze the normalized system throughput, average state duration of the Markov Chain should be found. For FD-MAC Markov Chain model, there are 5 different cases to be considered,

- **Idle Case:** No vehicle transmits. Idle case probability is denoted as P_e.
- **Successful Case:** Only one vehicle transmits, and no collision is falsely detected. Successful case probability is denoted as P_s.
- **False Alarm Case:** Only one vehicle transmits, and collision is falsely detected. False alarm case probability is denoted as P_{fa}.
- **Miss Detection Case:** Only two vehicles transmit simultaneously, and at least one of them could not detect the collision. Miss detection case probability is denoted as P_{md}.
- **Correct Detection Case:** Only two vehicles transmit simultaneously, and both of them detects the collision correctly or more than two vehicles transmits simultaneously. Correct detection case probability is denoted as P_{cd}.

Average state duration E_s can be found by using P_e, P_s, P_{fa}, P_{md} and P_{cd} probabilities as follows,

$$E_s = P_e\sigma + P_sT_s + P_{fa}T_{fa} + P_{md}T_{md} + P_{cd}T_{cd} \tag{3.140}$$

$$P_e = (1-\tau)^n \tag{3.141}$$

$$P_s = n\tau(1-\tau)^{n-1}(1-P_f) \tag{3.142}$$

$$P_{fa} = n\tau(1-\tau)^{n-1}P_f \tag{3.143}$$

$$P_{md} = \binom{n}{2}\tau^2(1-\tau)^{n-2}(1-(1-P_m)^2) \tag{3.144}$$

$$P_{cd} = 1 - P_e - P_s - P_{fa} - P_{md} \tag{3.145}$$

Throughput is defined as the percentage of time that is used to successfully transmit the useful payload data. Therefore, only the time spent for transmitting payload data T_p is considered for throughput analysis excluding the time spent for header transmission.

$$Throughput = \frac{T_p P_s}{E_s} \tag{3.146}$$

3.2.7 Service Delay Analysis

Service time is defined as the time between a packet becomes head-of-line and it is successfully transmitted. For the service delay analysis, two cases should be considered as in the HD-MAC case. Firstly, if the queue is found with a packet after the transmission, this packet is directly taken into service. On the other hand, if the queue is found empty after the transmission, the vehicle goes into the post back-off stage. In the post back-off stage, how many back-off states will be used for service for the generated packet depends on the packet arrival time. If a new packet arrives in one of the post back-off states, the packet is transmitted when the post back-off counter is equal to 0. Otherwise, if a new packet arrives in idle state, the channel is sensed to decide whether the packet will be transmitted directly, or it will be transmitted after back-off stage 0. The back-stage value in FD-MAC protocol can be increased using collision detection mechanism in case of collision or false alarm. Therefore, the number back-off states passed before returning to the first back-off stage increases with the number of successive collisions and false alarms.

When a packet is found in the queue after the transmission, the packet is directly taken into service starting from back-off stage 0. Then, depending on the number of retransmission events, and considering the average state durations for transmission and non-transmission states, average service delay for non-empty queue case can be found as follows,

$$T_{qne} = X_0 \tag{3.147}$$

$$X_0 = \sum_{j=0}^{r} \frac{p^j(1-p)}{1-p^{r+1}} \left[jT_c + T_s + \sum_{k=0}^{j} \left(\frac{W_{min(k,m)}}{2} - 1 \right) E_s^{'} \right] \tag{3.148}$$

When the queue is found empty after the transmission, the time spent for service can be approximated considering the chosen post back-off counter value k, the arrival of a packet after j states, and the average time to be used for transmission starting from back-off stage 0 (X_0) and back-off stage 1 (X_1) as follows,

$$\begin{aligned} T_{qe} = \sum_{k=0}^{W_0-1} \frac{1}{W_0} \Bigg[& \sum_{j=0}^{k-1} q(1-q)^j \big[(k-j)E_s^{'} + (1-p)T_s + p(T_c + X_1) \big] + \\ & \sum_{j=k}^{\infty} q(1-q)^j \big[(1-P_b)\big((1-p)T_s + p(T_c + X_1)\big) + P_b X_0 \big] \Bigg] \end{aligned} \tag{3.149}$$

$$X_1 = \sum_{j=0}^{r-1} \frac{p^j(1-p)}{1-p^{r}} \left[jT_c + T_s + \sum_{k=0}^{j} \left(\frac{W_{min(k,m)}}{2} - 1 \right) E_s^{'} \right] \tag{3.150}$$

The probability that the queue is found with a packet after the transmission is called as P_{qne}, and the probability that the queue is found empty after the transmission is called as P_{qe}. P_{qne} and P_{qe} probabilities are estimated using the Markov Chain given in Figure 3.2 as in HD-MAC case.

$$P_{qne} = \frac{1 - e^{-\lambda T_{qe}}}{1 - e^{-\lambda T_{qe}} + e^{-\lambda T_{qne}}} \tag{3.151}$$

$$P_{qe} = 1 - P_{qne} \tag{3.152}$$

As in the service delay analysis for HD-MAC protocol, P_b probability is converted to time probability as given in (3.47) considering idle and average busy slot lengths.

Finally, average service delay experienced by a packet for FD-MAC protocol can be approximated as follows,

$$T_{sd} = P_{qne} T_{qne} + P_{qe} T_{qe} \tag{3.153}$$

3.2.8 Packet Loss Probability Analysis

While successful transmission probability is used to analyze FD-MAC protocol per transmission, packet loss probability is used to analyze FD-MAC protocol per packet. A beacon packet generated by a vehicle may be lost due to 3 reasons in FD-MAC protocol,

- **Maximum Queue Size:** If the queue has already one packet in it, when a new packet arrives, older beacon packet is dropped from the queue and new beacon packet is queued.
- **Maximum Retry Count:** Maximum retry count for FD-MAC protocol is r since collision detection is applicable in FD-MAC protocol. That is, if the transmission of a beacon packet in service is failed r times successively due to collision or false alarm, this packet cannot be retransmited and it is lost.
- **Miss Detection due to RSI Effect:** When two vehicles transmit simultaneously, a packet may be lost if any of these vehicles miss the collision due to RSI effect.

The probability that the generated packet will be dropped due to maximum queue size P_{mq} is defined considering the cases in which the queue is empty or not after the transmission as in the packet loss probability analysis for HD-MAC protocol in Section 3.1.7. When the queue has a packet after the transmission, while this packet is in service, the probability that more than one packet will be generated should be considered. On the other hand, when the queue is empty after the transmission, a packet arrives during a post back-off state. If more than one packet is generated during this state, this packet is dropped due to maximum queue size limit. Moreover, while the generated packet is in service, only the recently arrived packet is kept in the queue and the rest is dropped due to maximum queue size limit. Therefore, by using the probabilities P_{qne} and P_{qe}, and the service times T_{qne} and T_{qe}, P_{mq} can be approximated as follows,

$$P_{mq} = \frac{P_{qne}\left[\frac{\lambda T_{qne}}{1-e^{-\lambda T_{qne}}} - 1\right] + P_{qe}\left[\left(\frac{\lambda T_{qe}}{1-e^{-\lambda T_{qe}}} - 1\right) + \left(\frac{\lambda {E_s}'}{1-e^{-\lambda E_s'}} - 1\right)\right]}{P_{qne}\left[\frac{\lambda T_{qne}}{1-e^{-\lambda T_{qne}}}\right] + P_{qe}\left[\frac{\lambda T_{qe}}{1-e^{-\lambda T_{qe}}} + \frac{\lambda E_s'}{1-e^{-\lambda E_s'}}\right]} \tag{3.154}$$

If the generated packet is not dropped due to maximum queue size limit, it may be dropped due to maximum retry limit. In FD-MAC protocol, there is a collision detection mechanism as described previously. Therefore, if the transmission attempt for the generated packet is failed more than r times due to collision on the channel or false alarm due to RSI effect, this packet is dropped. The probability that the generated packet will be dropped due to maximum retry limit P_{mr} is defined as follows,

$$P_{mr} = p^{r+1}(1 - P_{mq}) \tag{3.155}$$

If the generated packet is not dropped due to maximum queue size limit or maximum retry limit, it may be dropped due to miss collision detection. The probability that the generated packet will be dropped due to miss detection P_{md} is defined as follows,

$$P_{md} = \frac{(n-1)\tau(1-\tau)^{n-2}P_m}{1-p}(1 - P_{mq})(1 - P_{mr}) \tag{3.156}$$

Finally, packet loss probability P_{loss} is found as the sum of the packet drop probabilities due to maximum queue size limit, maximum retry limit and miss detection as follows,

$$P_{loss} = P_{mq} + P_{mr} + P_{md} \tag{3.157}$$

3.2.9 Age-of-Information Analysis

As in HD-MAC protocol, AoI metric is used to quantify the performance of the beaconing mechanism when FD-MAC protocol is used. Definition of AoI and sample variation of AoI depending on time are provided in Section 3.1.8. Different from HD-MAC protocol, a packet in FD-MAC protocol may be lost due to miss detection errors in FD radios apart from the packet losses due to maximum queue size and maximum retry limit.

To find average AoI in FD-MAC protocol, average values of the interval between successive packet receive times and the AoI value at packet receive times are considered as in HD-MAC protocol.

Assuming no packet loss, average $\Delta(0)_s$ and $(t_1 - t_0)_s$ values for FD-MAC protocol are defined using the corresponding values for FD-MAC protocol as in (3.54) and (3.55), respectively.

In case of packet losses due to maximum retry limit and miss detection, average AoI will increase due to the increase in $(t_1 - t_0)$. $\Delta(0)$ value does not change since the recently received packet is used. The probability p is used in HD-MAC protocol as the packet loss probability when the packet is taken into service. For FD-MAC protocol, the packet loss probability when the packet is taken into service P_{ls} is defined differently from HD-MAC protocol as follows,

$$P_{ls} = p^{r+1} + (1 - p^{r+1}) \frac{(n-1)\tau(1-\tau)^{n-2} P_m}{1-p} \tag{3.158}$$

Average $\Delta(0)$ and $(t_1 - t_0)$ values are found considering j successive packet losses as follows,

$$\Delta(0) = \Delta(0)_s \tag{3.159}$$

$$(t_1 - t_0) = \frac{(t_1 - t_0)_s}{1 - P_{ls}} \tag{3.160}$$

Finally, average AoI $\overline{\Delta}$ is found for FD-MAC protocol employing a similar approach used in Section 3.1.8 as follows,

$$\overline{\Delta} = \frac{P_{qne}(T_{qne}) + P_{qe}\left(\frac{1}{\lambda} + T_{qe}\right)}{2 * (1 - P_{ls})} + P_{qne}(T_{qd} + T_{qne}) + P_{qe} T_{qe} \tag{3.161}$$

In the next chapter, numerical results for the queueing models given in this chapter will be presented.

Chapter 4

Numerical Results

In this chapter, the performance of HD-MAC and FD-MAC protocols used in beaconing mechanism is examined using the analytical solution proposed in Chapter 3, and the system level simulations conducted for these protocols will be presented for comparison. The simulations are used to validate the proposed Markov Chain models and the analytical solution. Quality-of-Service (QoS) metrics such as successful transmission probability, throughput, packet loss probability, service delay and AoI are used to evaluate the performance of the MAC protocols.

The assumptions made for the system level simulations and the Markov Chain models can be summarized as below,

- No hidden nodes are considered. That is, all vehicles contending for the channel can perfectly sense the transmissions from all other vehicles.
- No physical layer imperfections are considered except for the RSI effect in FD radios.
- The channel is used only for beacon messages, and all beacon messages are broadcasted to all other vehicles contending for the same channel.
- For a given beacon rate, it is assumed that all nodes use the same beacon

Table 4.1: The parameters used for the system level simulations

Parameter	**Value**
T_e, Slot Time (μs)	13
T_h, Header Duration (μs)	40
T_p, Payload Duration (μs)	440
$DIFS$, Distributed Iner-frame Space (μs)	58
CW_{min}, Minimum Contention Window Size	32

rate value to generate beacon packets, i.e. the heterogeneous case is not considered.

In Table 4.1, the parameters used for the system level simulations are given. The parameter values are chosen in accordance with IEEE 802.11p system parameters [8].

Other than the parameters given in Table 4.1, m parameter is used to describe the maximum contention window size (i.e., $CW_{max} = CW_{min}2^m$), and r is used to describe the maximum retry count for FD-MAC protocol. Moreover, P_f is used to describe false alarm probability, and P_m is used to describe miss detection probability, which are used to model the RSI effect on FD radios.

The numerical results are found for beacon rates up to 100 packet/seconds. This value is chosen by considering the latency requirements of the V2X applications since some autonomous driving use cases defined for vehicular networks require 10 ms maximum latency [1]. Moreover, beacon rates up to 100 Hz are also considered in some other studies in the literature to analyze the performance of the beaconing mechanism in vehicular networks [41, 42].

In this section, firstly, the results for HD-MAC protocol will be examined. Then, the results for FD-MAC protocol will be presented for without RSI effect and with RSI effect cases, and for different maximum retry counts. Finally, the performance of HD-MAC and FD-MAC protocols will be compared for without RSI effect case using the numerical results.

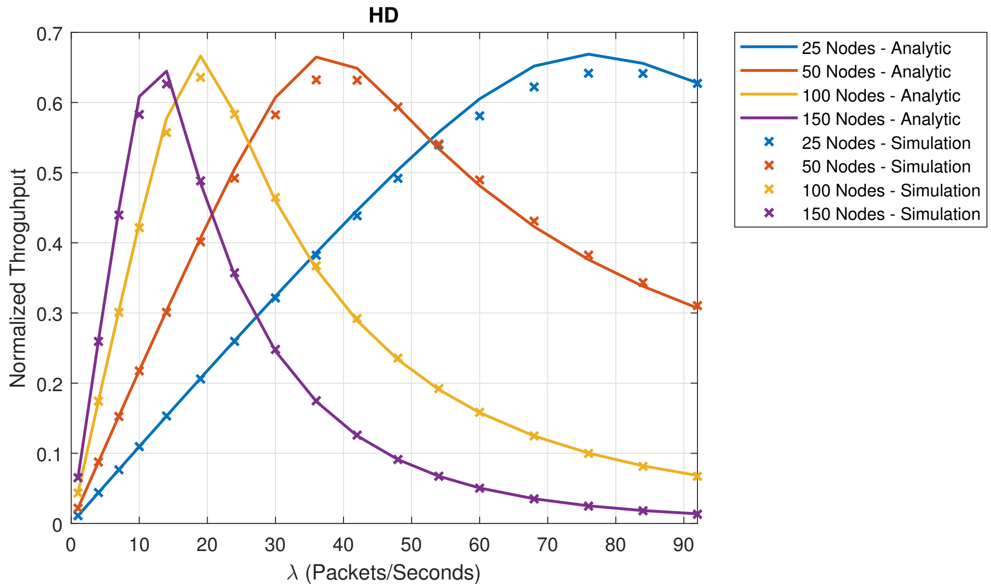


Figure 4.1: Normalized throughput vs beacon rate for HD-MAC protocol

4.1 Simulation and Analytic Results for HD-MAC Protocol

In this section, the performance of HD-MAC protocol is analyzed using simulations and the analytic model presented in Section 3.1.

The result for the normalized throughput is given in Figure 4.1. This result shows that the maximum throughput for the beaconing mechanism can be achieved at different beacon rates depending on the number of nodes contending for the channel. This is reasonable since the number of transmission attempts in a slot increases when the number of nodes that uses the same beacon rate value increases. An increase in node count increases the collision probability as shown in Figure 4.2, and it causes spending more time for collided packets, and thus decreasing the throughput. Otherwise, when the beacon rate is relatively small, the number of idle slots increases, and the throughput decreases as shown in Figure 4.1. Therefore, to maximize the throughput, the beacon rate value should be chosen large enough to decrease the number of idle slots, and it should be chosen small enough to decrease the number of collisions.

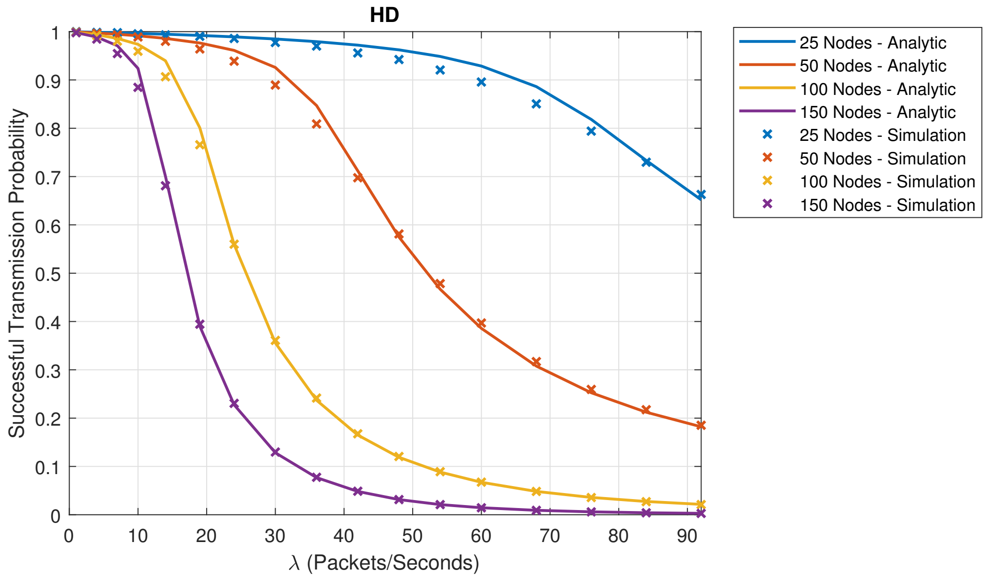


Figure 4.2: Successful transmission probability vs beacon rate for HD-MAC protocol

In Figure 4.2, successful transmission probability is plotted. As expected, it decreases when the beacon rate and the number of nodes is increased. Since there is no collision detection mechanism in HD-MAC protocol, in case of collision, the back-off stage is not increased, and this results in a rapid decrease in successful transmission probability when the beacon rate is increased.

In Figure 4.3, mean MAC service delay is given for the HD-MAC protocol. Even if the mean number of back-off states waited for transmission are equal for each different node counts and beacon rates. The mean time spent for a back-off state changes with them since the idle slot time is relatively small compared to the busy slot time, and the probability that the channel is busy during the back-off state increases with beacon rate and node count. As a result, mean service delay increases with beacon rate and node count as shown.

Packet loss proability for HD-MAC protocol is plotted in Figure 4.4. As described in Section 3.1.7, a beacon packet may be lost in HD-MAC protocol due to maximum queue size or maximum retry count limits. A packet loss due to maximum queue size limit occurs when more than one packet arrives during the service of another beacon packet. This probability is relatively small in HD-MAC

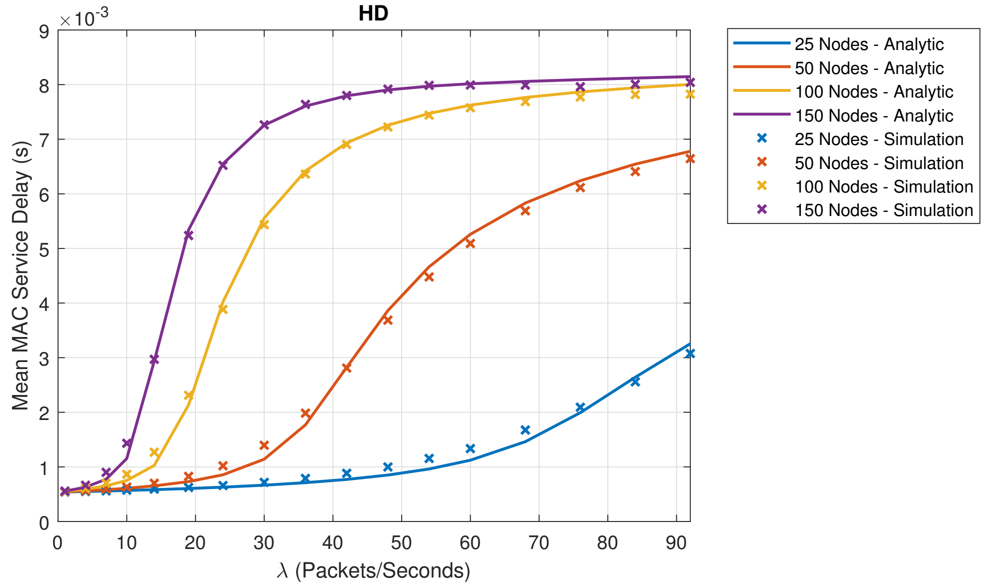


Figure 4.3: Mean service delay vs beacon rate for HD-MAC protocol

protocol since only one back-off stage is considered, and further retransmission attempts are not possible. Moreover, packet loss probability due to maximum retry count can be found directly using successful transmission probability given in Figure 4.2 since the maximum retry count for a beacon packet is 1 for HD-MAC protocol. Therefore, packet loss probability given in Figure 4.4 is dominated by the packet losses due to maximum retry count limit, and it shows similar trend with the collision probability per transmission for HD-MAC protocol.

Finally, mean AoI for HD-MAC protocol is given in Figure 4.5. Mean AoI uses the mean time between two successive successful beacon packet receive times, and the AoI values obtained at two successive successful beacon packet receive times considering the beacon packet generation times. Therefore, mean AoI increases with queue delay, service delay, packet loss probability, and the time interval between beacon packet generation times. When the interval between beacon packet generation times decreases by increasing the beacon rate, mean AoI values also decreases for relatively small beacon rates as shown. However, when the beacon rates are kept increasing, mean AoI values start increasing after achieving the minimum AoI value since the packet loss probability and service delay values increase for larger beacon rates as shown in Figure 4.2 and Figure 4.3.

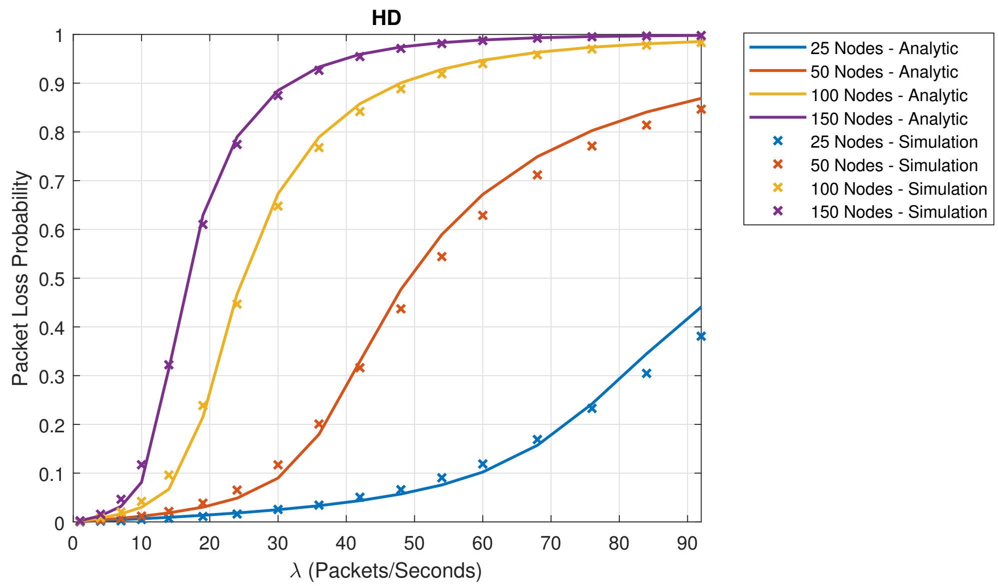


Figure 4.4: Packet loss probability vs beacon rate for HD-MAC protocol

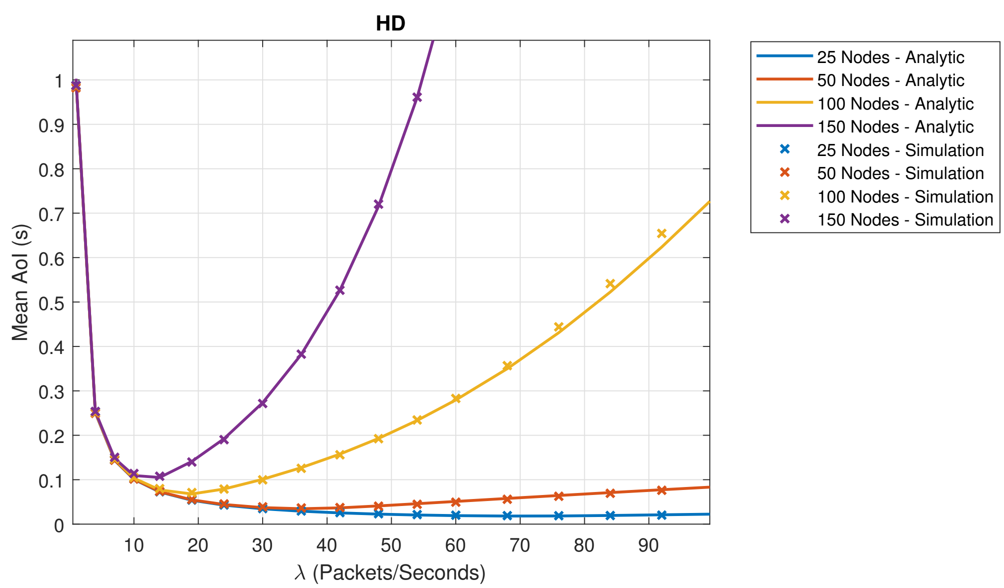


Figure 4.5: Mean age-of-information vs beacon rate for HD-MAC protocol

4.2 Simulation and Analytic Results for FD-MAC Protocol

In this section, the performance of FD-MAC protocol for no RSI case is analyzed using the simulations and the analytic model presented in Section 3.2.

The normalized throughput is depicted in Figure 4.6. Different from HD-MAC protocol, the collisions are detected in FD-MAC protocol, and the collision detection time for FD-MAC protocol is equal to the header duration which is a smaller portion of successful transmission duration. Therefore, for the FD-MAC protocol, even if the number of collisions increases by increasing the beacon rates, the throughput does not decrease dramatically as in the HD-MAC protocol.

In Figure 4.7, successful transmission probability is shown. As in HD-MAC protocol, it decreases when the beacon rate and the number of nodes is increased. Although the back-off stage is increased in the FD-MAC protocol, the number of collisions keeps increasing when the beacon rate is increased. This results in a decrease in successful transmission probability.

In Figure 4.8, mean MAC service delay is given for the FD-MAC protocol. In the FD-MAC protocol, the time spent for a back-off state depends on whether the channel is busy or not as in the HD-MAC protocol. However, different from the HD-MAC protocol, if the channel is busy due to collision, and the collision is detected correctly, the time spent for a back-off state is smaller compared to the successful transmission duration for FD-MAC protocol. Therefore, when the beacon rates are kept increasing, mean service delay starts decreasing since the number of collisions and packet losses due to maximum retry count increase. This behavior can be observed in Figure 4.8 for the scenarios with 100 and 150 nodes.

Packet loss probability for the FD-MAC protocol is plotted in Figure 4.9. As described in Section 3.2.8, a beacon packet may be lost in the FD-MAC protocol due to maximum queue size limit, maximum retry count limit or miss detection on FD radios. Since without RSI case is considered in Figure 4.9, packet loss

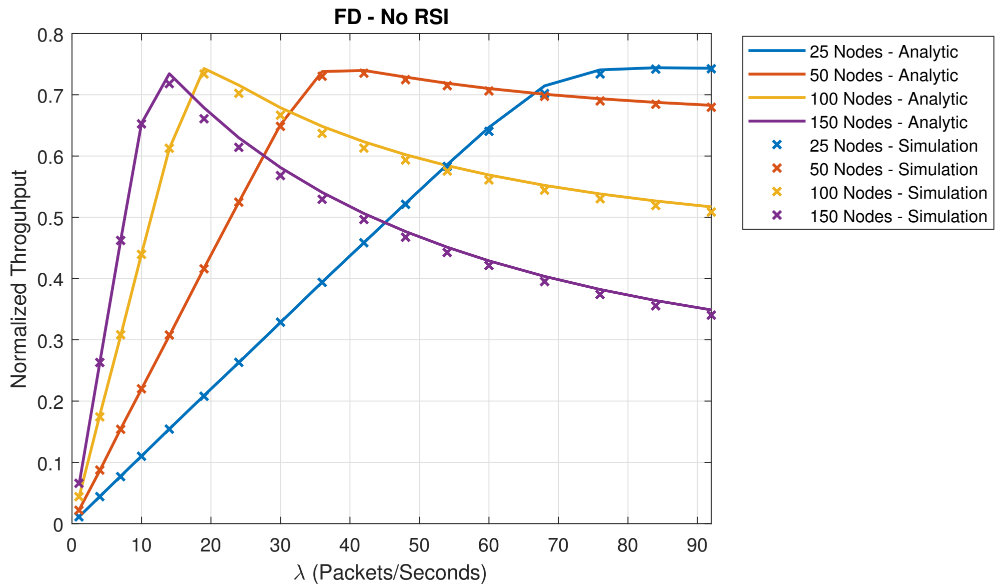


Figure 4.6: Normalized throughput vs beacon rate for FD-MAC protocol when m=2, and r=2

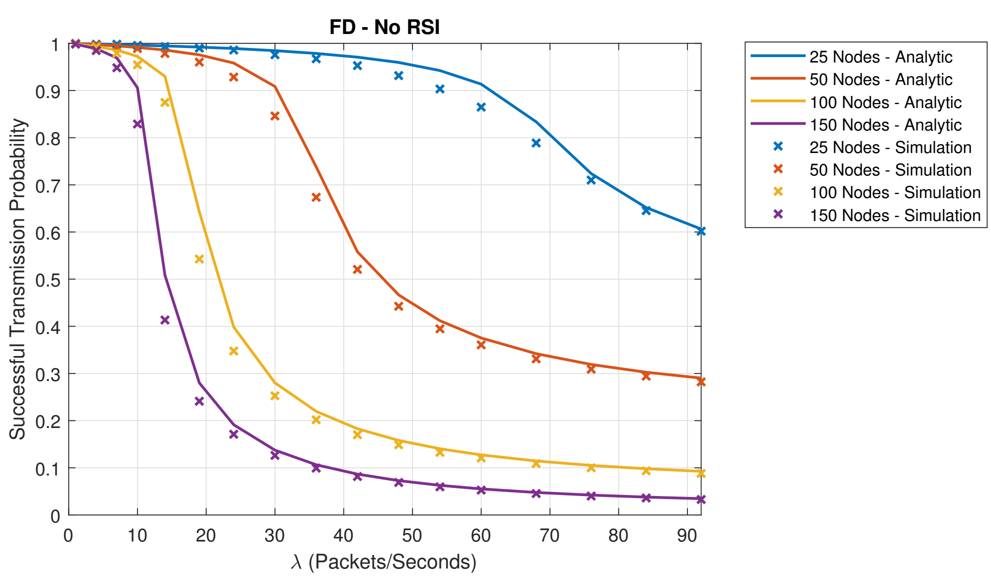


Figure 4.7: Successful transmission probability vs beacon rate for FD-MAC protocol when m=2, and r=2

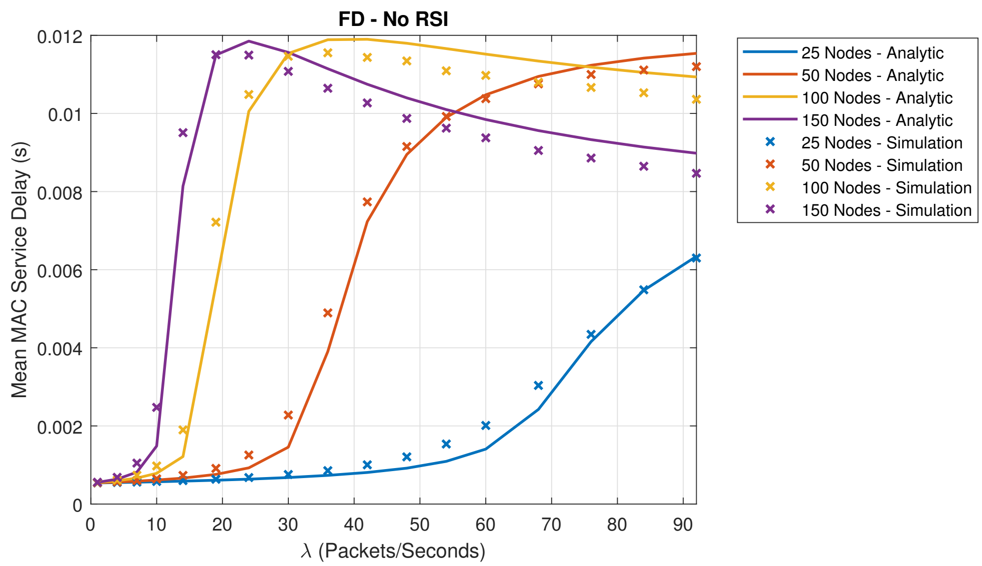


Figure 4.8: Mean service delay vs beacon rate for FD-MAC protocol when m=2, and r=2

due to miss detection is zero. On the other hand, the probability of packet loss due to maximum queue size is larger in the FD-MAC protocol since the service delay increases when the number of back-off stages increases. However, different from HD-MAC protocol, a packet is not dropped after the first collision, and it can be retransmitted r times, which decreases the packet loss probability of the FD-MAC protocol.

Finally, mean AoI for the FD-MAC protocol is given in Figure 4.10. As in HD-MAC protocol, mean AoI decreases when the beacon rate increases for small beacon rates, and when the beacon rates are kept increasing, mean AoI values start increasing after achieving the minimum AoI value. The increase in mean AoI for large beacon rates is relatively small for the FD-MAC protocol compared to the HD-MAC protocol, since the packet loss probability is smaller in the FD-MAC protocol through the collision detection mechanism.

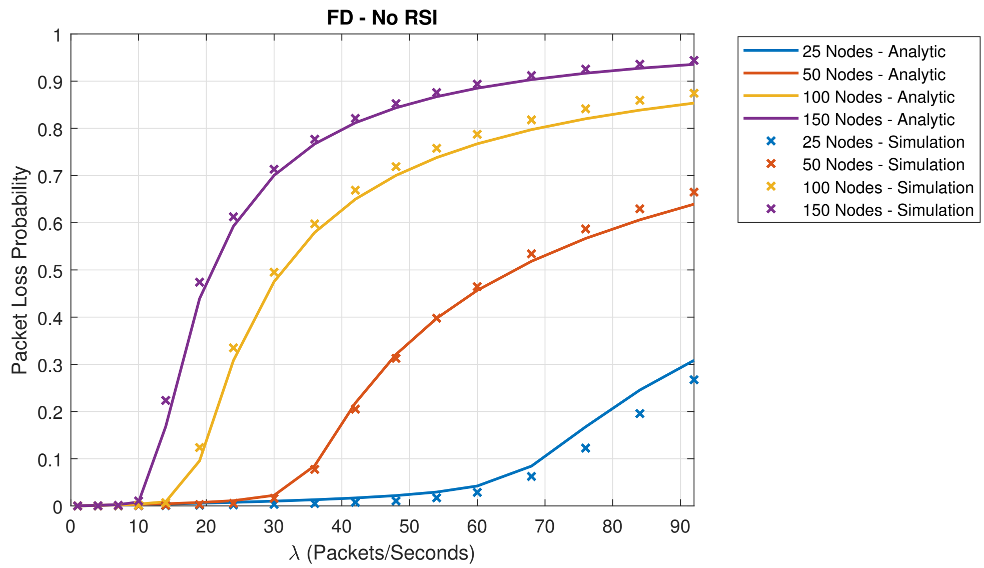


Figure 4.9: Packet loss probability vs beacon rate for FD-MAC protocol when m=2, and r=2

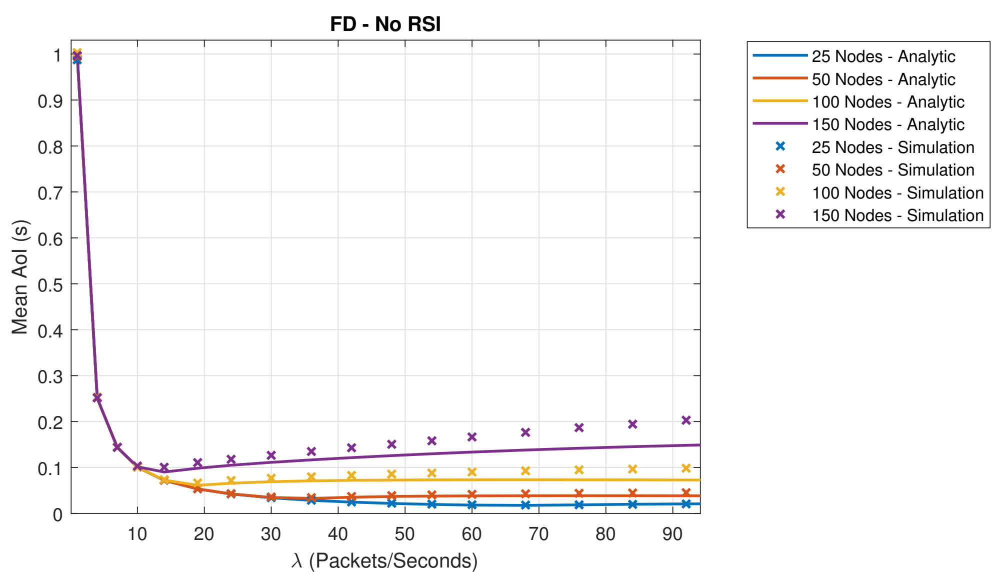


Figure 4.10: Mean age-of-information vs beacon rate for FD-MAC protocol when m=2, and r=2

4.2.1 Results with Sensing Errors for FD Radios

In the previous section, the results of the FD-MAC protocol for no RSI case was presented. In this section, the results with RSI will be given for imperfect collision detection with false alarm and miss detection cases.

In Figure 4.11, the normalized throughput is shown for only the false alarm case. As shown, when the false alarm probability increases, the throughput decreases since the number of retransmissions are increased by stopping the transmissions falsely due to sensing errors. This causes spending more time for unsuccessful transmissions, dropping packets due maximum retry limit, and thus decreasing throughput. The decrease in throughput for larger false alarm probabilities is only observed for large beacon rates, since the channel is mostly idle, and packet loss probability due to maximum retry limit is relatively small for small beacon rates.

Successful transmission probability is plotted in Figure 4.12 for different false alarm probabilities. Since the false alarm can only occur when only one node attempts transmission in a slot, it decreases the successful transmission probability as shown.

In Figure 4.13, mean MAC service delay for different false alarm probabilities is presented. When the false alarm probability is increased, mean service delay decreases for large beacon rates since the channel is only used for header duration in case of false alarm, and the number of successful transmissions decrease due to channel congestion and false alarms.

Packet loss probability and mean AoI are not presented for different false alarm probabilities, since the effect of false alarm probability on these results is very small. False alarm probability does not affect the packet loss significantly, since several retransmission attempts are possible in the FD-MAC protocol, and the probability of dropping a packet due to only false alarms is very small for small false alarm probabilities and large maximum retry counts.

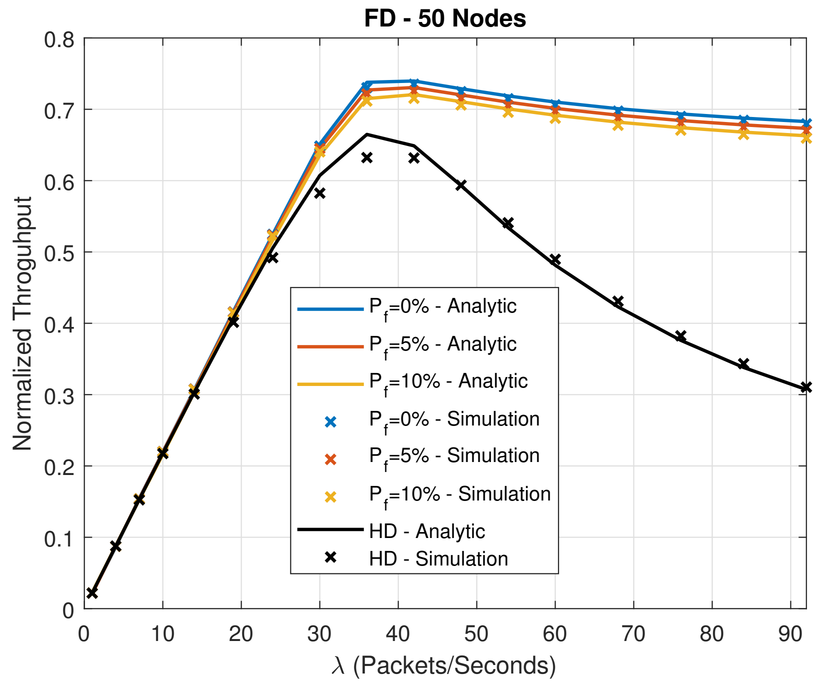


Figure 4.11: Normalized throughput vs beacon rate for FD-MAC protocol for only false alarm case when m=2, r=2, and P_m=0

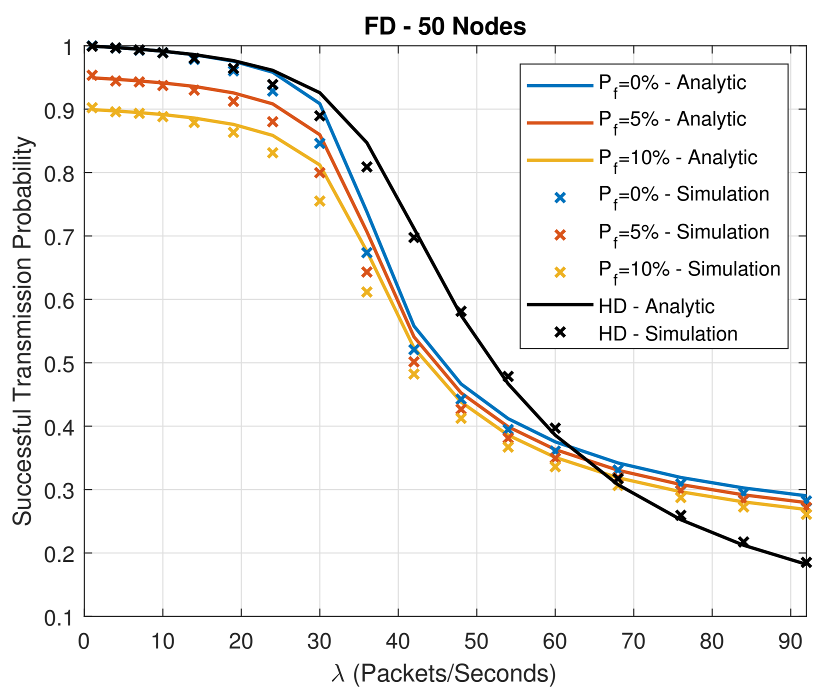


Figure 4.12: Successful transmission probability vs beacon rate for FD-MAC protocol for only false alarm case when m=2, r=2, and P_m=0

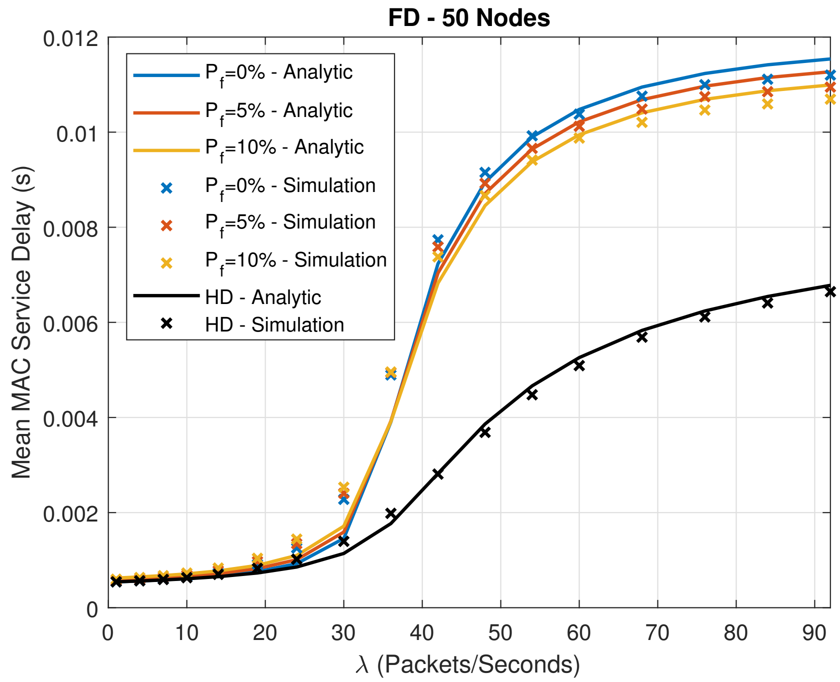


Figure 4.13: Mean service delay vs beacon rate for FD-MAC protocol for only false alarm case when m=2, r=2, and P_m=0

In Figure 4.14, the normalized throughput for different miss detection probabilities is given. It is shown that when the miss detection probability is increased, the throughput decreases since the back-off state duration for miss detection case is equal to the successful transmission duration, which is larger compared to the back-off state duration for the correct detection case. This behavior can only be observed for large beacon rates since miss detection can only occur when more than one node attempt transmission at the same slot.

Mean MAC service delay for different miss detection probabilities is plotted in Figure 4.15. It is shown that the service delay increases when the miss detection probability is increased, since the probability that a node detects the collision correctly, and the other node miss the collision is higher than the probability that both nodes miss the collision. In this case, while one vehicle increases the back-off stage value, other vehicle returns to the first back-off stage. This will increase service delay by increasing the collision duration due to miss detection.

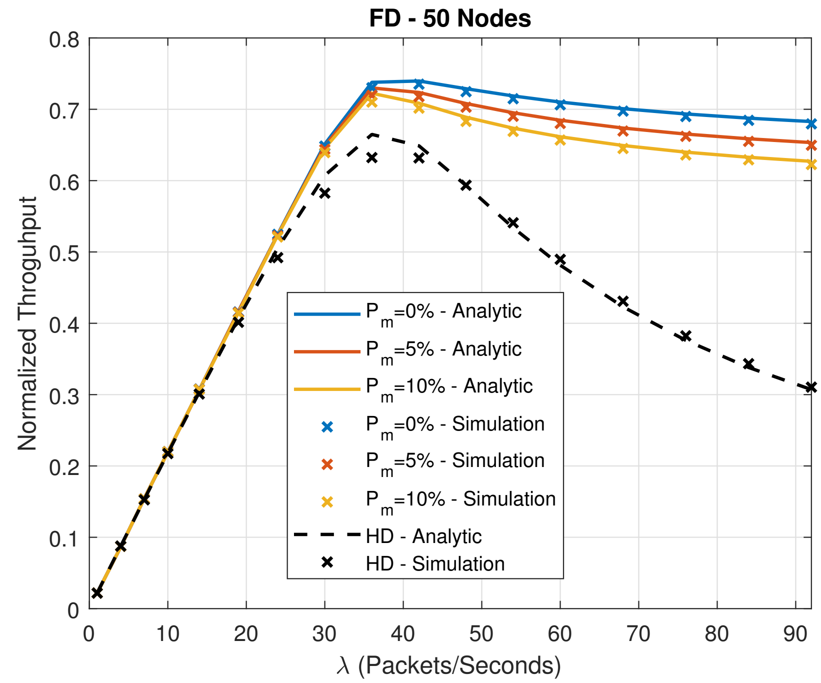


Figure 4.14: Normalized throughput vs beacon rate for FD-MAC protocol for only miss detection case when m=2, r=2, and P_f=0

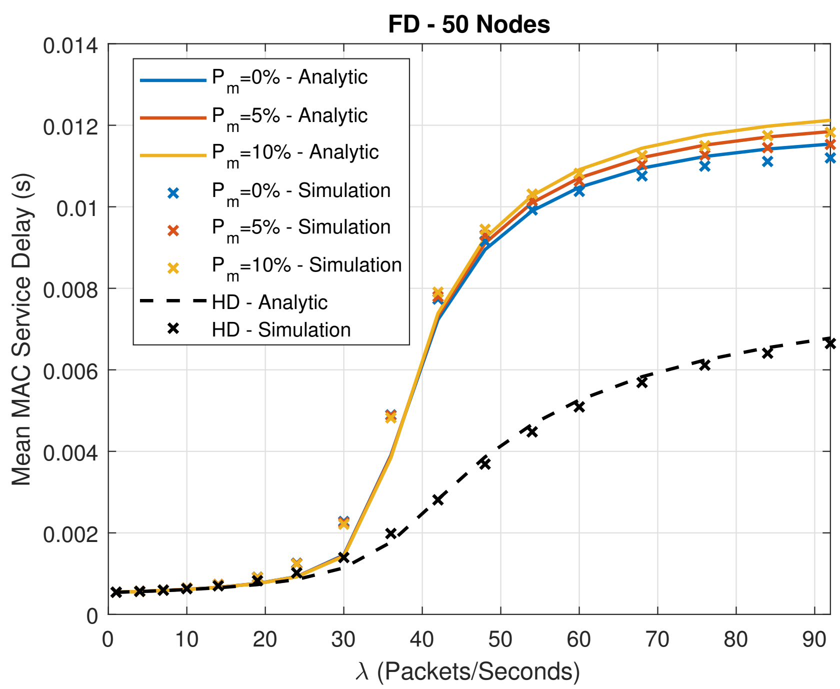


Figure 4.15: Mean service delay vs beacon rate for FD-MAC protocol for only miss detection case when m=2, r=2, and P_f=0

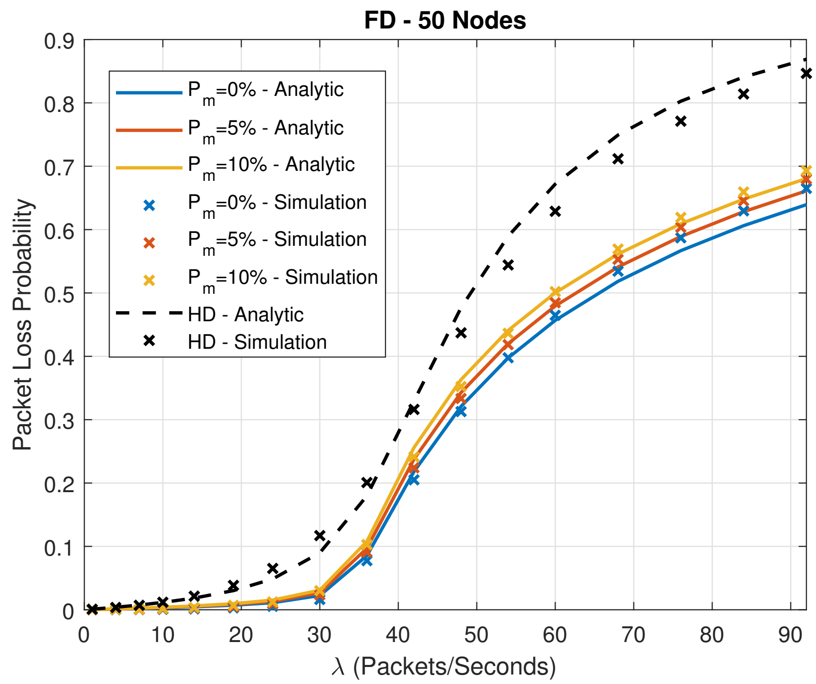


Figure 4.16: Packet loss probability vs beacon rate for FD-MAC protocol for only miss detection case when m=2, r=2, and P_f=0

As described in Section 3.2.8, a packet may be lost due to miss detection in the FD-MAC protocol. Therefore, an increase in the miss detection probability increases the packet loss probability as shown in Figure 4.16.

Finally, mean AoI is shown for different miss detection probabilities in Figure 4.17. The effect of the miss detection probability on mean AoI is relatively small for small miss detection probabilities. However, it is observed that mean AoI tends to increase with the increase in the miss detection probability for large beacon rates since an increase in the packet loss probability due to miss detection increases the time between successive packet receive times.

Successful transmission probability is not presented for different miss detection probabilities, since the effect of miss detection probability on successful transmission probability is relatively small for miss detection values smaller than 10%.

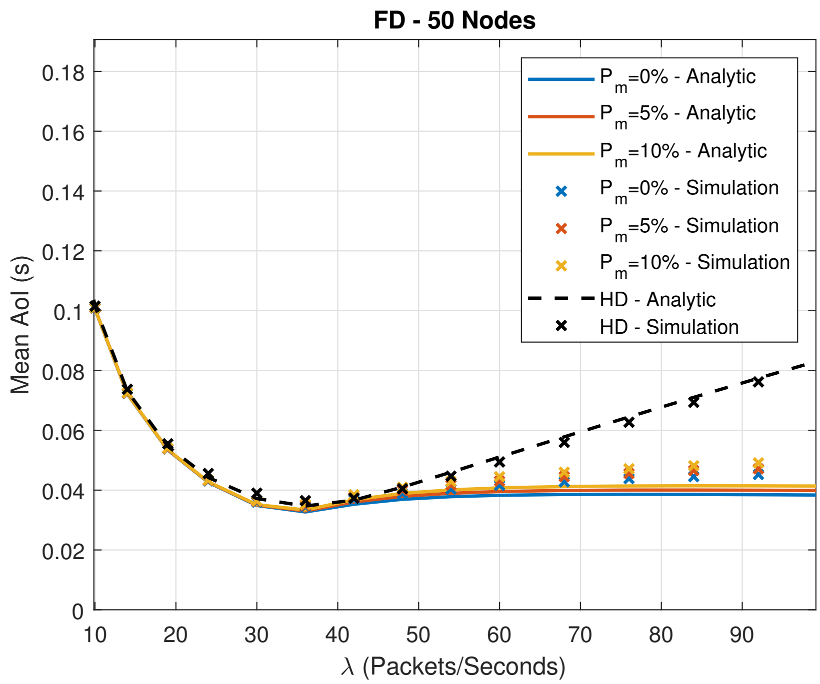


Figure 4.17: Mean age-of-information vs beacon rate for FD-MAC protocol for only miss detection case when m=2, r=2, and P_f=0

4.2.2 Results for Different Maximum Retry Counts

In this section, mean service delay and mean AoI results are examined for different maximum retry counts (r) in the FD-MAC protocol. Firstly, in Figure 4.18, it is shown that mean service delay increases with an increase in maximum retry count. This is expected since the number of back-off states used before a successful transmission increases when the number of back-stages is increased. Secondly, mean AoI, shown in Figure 4.19 for different maximum retry counts, tends to increase for large beacon rates when the maximum retry count is increased due to the increase in mean service delay for large beacon rates as shown in Figure 4.18.

For large beacon rates, the service delay is larger due to the collisions observed in the channel, which causes an increase in the mean AoI as shown in Figure 4.19. To prevent this, a mechanism that can adaptively change the maximum retry counts depending on the beacon rate values can be considered as a future work. By decreasing the maximum retry count for large beacon rates, a packet waiting

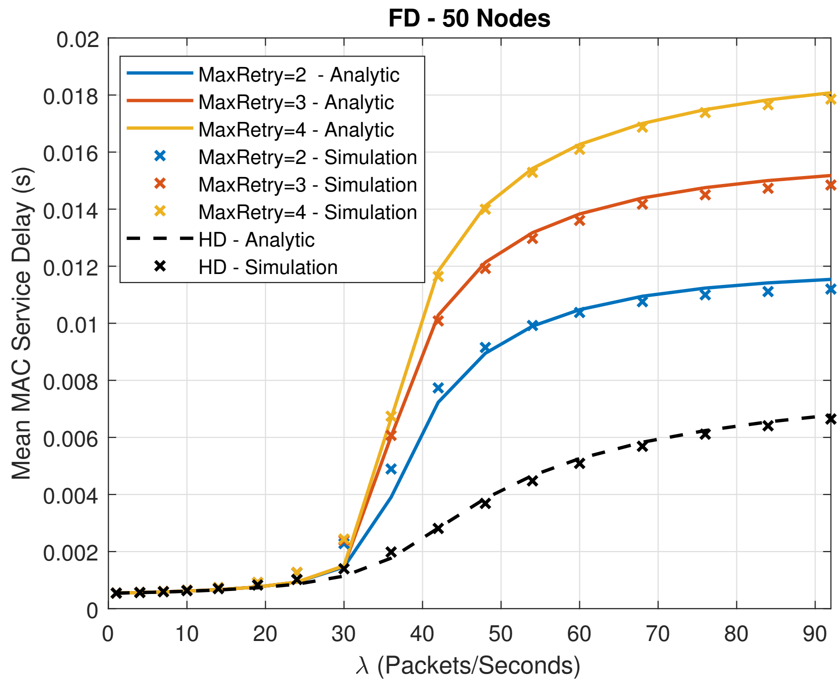


Figure 4.18: Mean service delay vs beacon rate for FD-MAC protocol for different maximum retry counts (r) when m=2, and No RSI

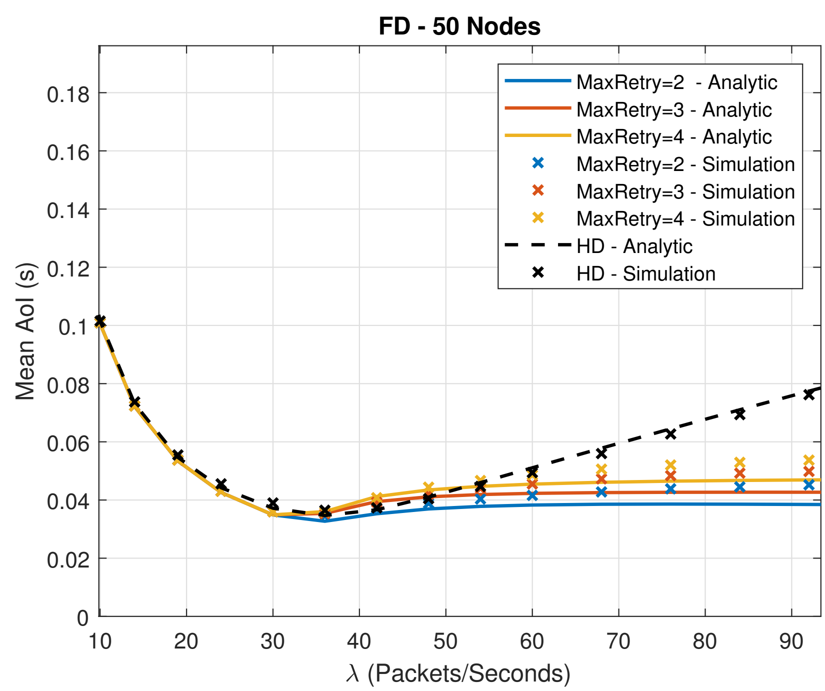


Figure 4.19: Mean age-of-information vs beacon rate for FD-MAC protocol for different maximum retry counts (r) when m=2, and No RSI

in the queue with a smaller AoI value can be transmitted instead of transmitting the packet with larger AoI value, and mean AoI performance can be improved for large beacon rates.

4.3 Comparison of HD-MAC and FD-MAC Protocols

In this section, the performance of HD-MAC and FD-MAC protocols is compared using the results obtained from the analytical models presented in Section 3.1 and Section 3.2

Firstly, the throughput is compared for different beacon rates and node counts in Figure 4.20. It is observed that the throughput for small beacon rates depending on the number of nodes show similar behavior for both protocols. However, when the maximum throughput value is reached, while the throughput of the HD-MAC protocol decreases sharply, the throughput of the FD-MAC protocol decreases moderately. This behavior can be explained with the usage of collision detection mechanism in the FD-MAC protocol since the time spent for collisions is decreased by detecting collisions within the header duration.

Secondly, successful transmission probability for HD-MAC and FD-MAC protocols is shown in Figure 4.21. As shown, while successful transmission probabilities for small beacon rated are better for the HD-MAC protocol, successful transmission probabilities for large beacon rates are better for the FD-MAC protocol depending on the number of node counts. For small beacon rates, the channel is not congested, and the collision detection mechanism increases the channel congestion by allowing nodes to retransmit a collided packet, which increases the collision probability in the FD-MAC protocol for small beacon rates. On the other hand, for large beacon rates, the number of collisions increases for both protocols. However, by increasing the back-off stage values in case of collision and by detecting collisions within the header duration in the FD-MAC

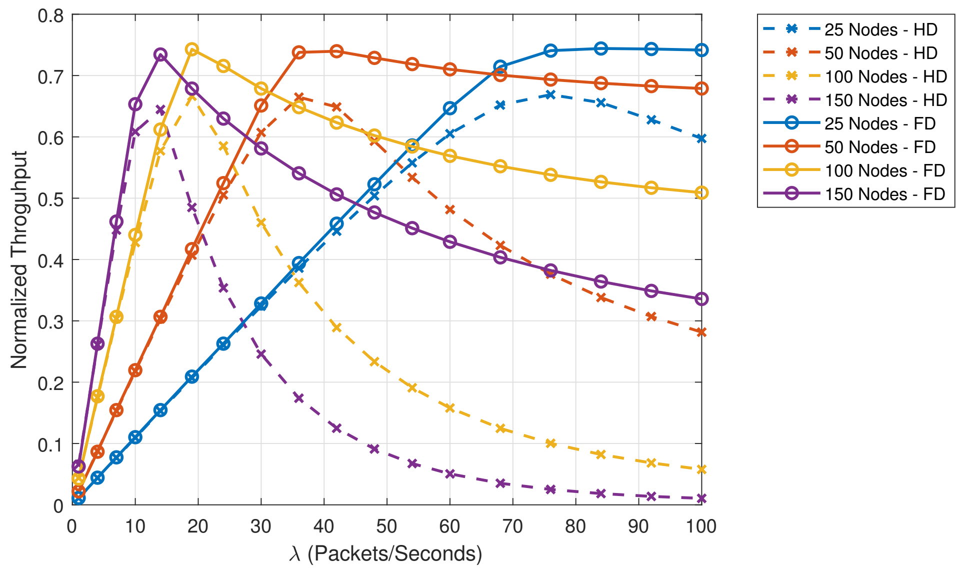


Figure 4.20: Normalized throughput vs beacon rate for HD-MAC and FD-MAC protocols

protocol, successful transmission probability increases for large beacon rates.

Thirdly, mean MAC service delay is compared for HD-MAC and FD-MAC protocols in Figure 4.22. As expected, mean service delay values are larger in the FD-MAC protocol since the number of back-off stages are increased by using the collision detection mechanism. An increase in the number of back-off stages increases the mean number of back-off states used before a successful transmission, which increases the mean service delay. Mean service delay increases when the beacon rate is increased for small beacon rates. However, for large beacon rates, while mean service delay values for the HD-MAC protocol stays constant, mean service delay for the FD-MAC protocol starts decreasing especially for large number of nodes. For the FD-MAC protocol, for large beacon rates, packet losses due to maximum retry count increases, which decreases the duration of back-off states used for retransmission, and thus decreases the mean service delay since the state duration in case of collision is smaller in the FD-MAC protocol.

Fourthly, packet loss probabilities are compared for HD-MAC and FD-MAC protocols in Figure 4.23. Packet loss probabilities decrease by the use of the

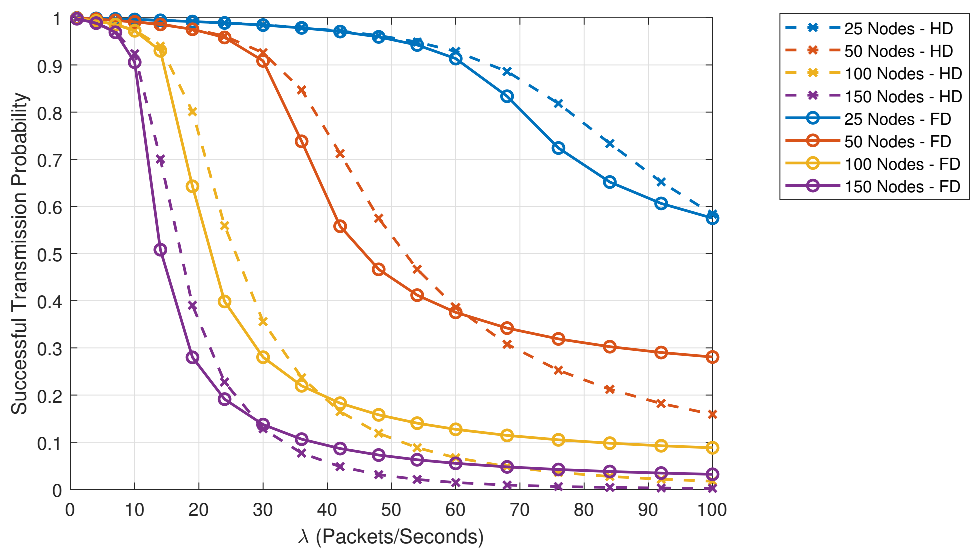


Figure 4.21: Successful transmission probability vs beacon rate for HD-MAC and FD-MAC protocols

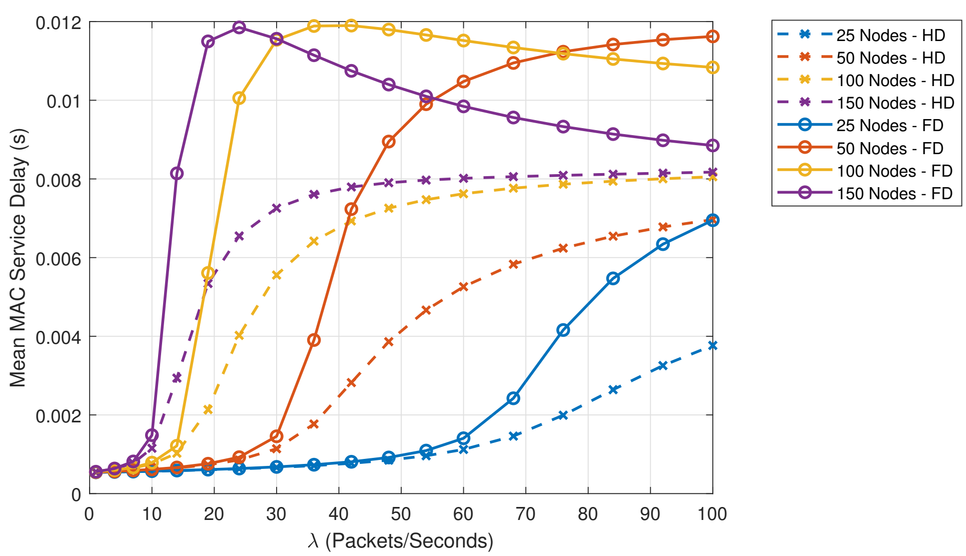


Figure 4.22: Mean service delay vs beacon rate for HD-MAC and FD-MAC protocols

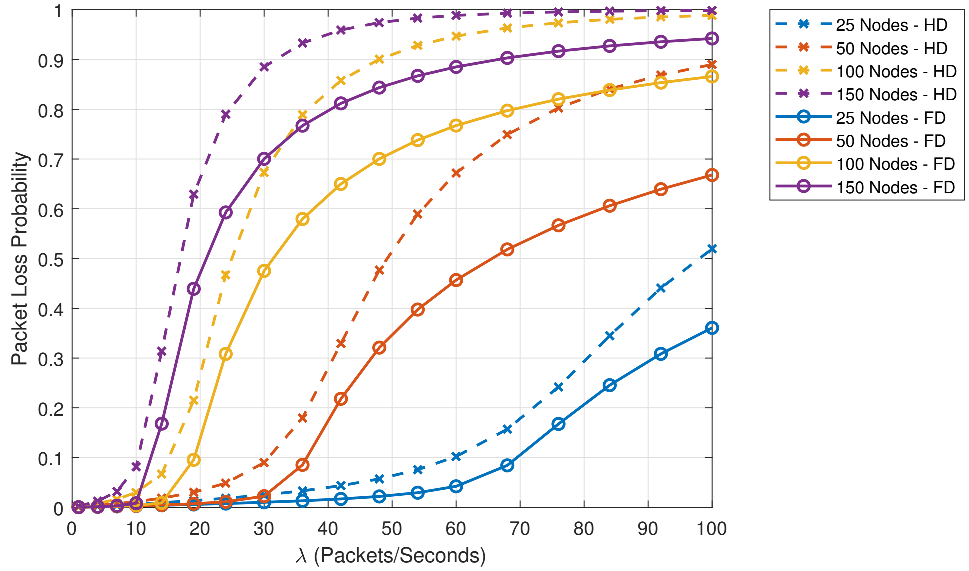


Figure 4.23: Packet loss probability vs beacon rate for HD-MAC and FD-MAC protocols

collision detection mechanism in the FD-MAC protocol for all beacon rates and node counts. Even if the number of packet losses due to maximum queue size limit increases in the FD-MAC protocol since larger service delays are observed, smaller packet loss probabilities are observed in the FD-MAC protocol. This is because the number of packet losses due to maximum retry count dominates the total number of packet losses. Since the number of packet losses due to maximum retry count is decreased by using retransmissions in the FD-MAC protocol, total number of packet losses is decreased.

Finally, mean AoI is compared for HD-MAC and FD-MAC protocols in Figure 4.24. For small beacon rates, increasing the beacon rate decreases mean AoI for both protocols since the time between successive packet generation times is decreased. On the other hand, for large beacon rates, mean AoI starts increasing when the beacon rates are kept increasing due to the increase in the packet loss probability. However, while mean AoI increases sharply for large beacon rates in the HD-MAC protocol, it increases moderately in FD-MAC protocol as shown. This difference stems from the difference between the packet loss probabilities obtained for HD-MAC and FD-MAC protocols.

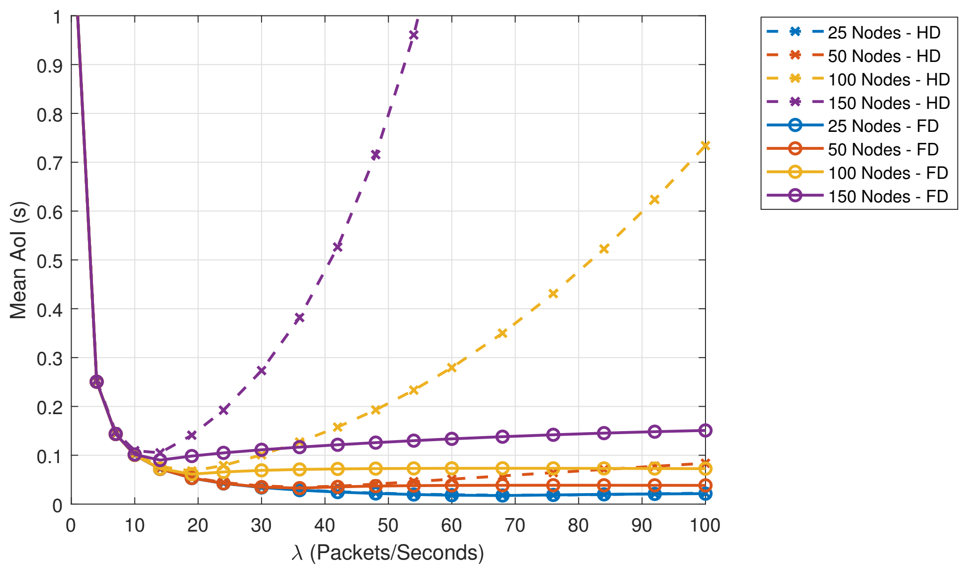


Figure 4.24: Mean age-of-information vs beacon rate for HD-MAC and FD-MAC protocols

Chapter 5

Conclusion

In this thesis, the performance of HD-MAC and FD-MAC protocols for the beaconing mechanism used in vehicular networks is analyzed using Markov Chain based queueing models. The beaconing mechanism in vehicular networks is used to provide cooperative awareness between vehicles and to increase the road safety and vehicle traffic efficiency. Beacon packets used in the beaconing mechanism are broadcast packets, and they include information such as position, speed and direction. Broadcast nature of beacon packets prevents the usage of acknowledgement mechanism in the current V2X standards such as IEEE 802.11p and C-V2X. This limits the performance of beaconing mechanism, and makes it difficult to achieve strict requirements of vehicular networks applications. Therefore, in this thesis, FD radios are used to make collision detection possible in the beaconing mechanism without requiring acknowledgement messages. While the first antenna of FD radios is used to transmit beacon packets, the second antenna of FD radios is used to sense the channel to detect collisions.

In the beaconing mechanism, the beacon packets are generated periodically, and packet generation rate and total node count contending for the channel determine the channel congestion in the network. Therefore, different from most of the existing studies about CSMA-based MAC protocols, saturation assumption is not applicable for the analysis of the beaconing mechanism. Moreover, in the beaconing mechanism by lowering the bacon generation rate, total number of nodes that can be supported can be increased by ensuring the QoS requirements contrary to the existing IEEE 802.11 MAC protocols.

It is shown through the numerical results that the analytical results obtained with the Markov Chain models used for HD-MAC and FD-MAC protocols closely match with the simulation results. The analytical solution is validated for throughput, successful transmission probability, service delay, packet loss probability and AoI. When HD-MAC and FD-MAC protocols are compared using the obtained numerical results, it is observed that the FD-MAC protocol is superior to HD-MAC protocol in terms of throughput, packet loss probability, and mean AoI performances. FD-MAC protocol provides these gains at the cost of increasing mean service delay due to the collision detection mechanism, and using an extra software/hardware component for self-interference cancellation in FD radios. According to the obtained results, the superiority of FD-MAC protocol over HD-MAC protocol is not obvious for small beacon rates since the channel is mostly idle, and the number of collisions is smaller at small beacon rate values. However, for the large beacon rates, superiority of FD-MAC protocol can be observed clearly. Therefore, it can be deduced that if the appropriate beacon rate that maximize the throughput is used for a given node count in the network, a small increase in beacon rate or node count will affect the performance of the FD-MAC protocol less.

Since collisions are detected using FD radios, sensing errors such as false alarm and miss detection can be observed due to the RSI effect. The effect of these sensing errors is considered in this thesis using false alarm and miss detection probabilities in the analytical model. Sensing errors up to 10% is considered, and it is shown that sensing errors reduce the performance of FD-MAC protocol. However, FD-MAC protocol still shows better performance than the HD-MAC protocol under these conditions.

As a future work, beacon rate adaptation methods can be considered. Beacon rate adaptation method aims to find suitable beacon rate values for a given network scenario. This is especially important for vehicular networks, since the vehicles are mostly mobile, and depending on the vehicle traffic congestion, the number of nodes contending for the channel changes frequently. Therefore, beacon rate adaptation can be studied to minimize AoI and to maximize the throughput in the beaconing mechanism.

As a future work, a mechanism that can adaptively change the maximum retry counts depending on the beacon rate values can also be considered. By decreasing the maximum retry count for large beacon rates, a packet waiting in the queue with a smaller AoI value can be transmitted instead of transmitting the packet with larger AoI value, and mean AoI performance can be improved for large beacon rates using this mechanism.

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