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Article

Impact of transmission power on safety message communication under sparse vehicular ad hoc networks

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ABSTRACT

Transmission power is an important determinant of the performance of Vehicular Ad Hoc Networks (VANETs) due to its direct influence on the reliability and efficiency of safety message communication in both vehicle-to-vehicle and vehicle-to-roadside unit encounters. Vehicular mobility-induced dynamic topology makes it difficult to maintain stable connectivity, especially in sparse and intermittently connected network environments. As a result, resorting to fixed transmission power levels leads to network performance and connectivity degradation. This paper presents a novel model for connectivity assessment that aims to study the effect of varying transmission power levels under various VANET scenarios. The model evaluates network performance across multiple transmission power configurations and traffic densities using key efficacy metrics, including connectivity stability, communication overhead, latency, and safety message delivery performance. The results demonstrate that inappropriate transmission power selection negatively affects VANET connectivity by increasing channel contention in dense regions and significantly reducing communication reliability in sparse and void areas.

1. Introduction

Smart Vehicular ad hoc networks (VANETs) became a hot area for researchers to solve their issues because it deals with the lives of citizens directly [1,2]. The main objectives of the VANETs are reducing traffic jams, fuel consumption, waiting time, and the most important feature is saving people lives in the street by applying safety applications in vehicles for sharing and receiving alarm messages from surrounding vehicles. This type of network is part of the intelligent transportation systems (ITS) which gives the driver more comfort on the road and enhances the transportation system's performance [3-6]. In infrastructure-less wireless networks, transmission power influences the signal intensity at the receiver, the transmission range, and the interference generated for other receivers within the network [7]. Consequently, the transmission power is regarded as a crucial element in various performance metrics, including throughput, latency, and energy efficiency. Decreasing the transmission power level can diminish energy usage for communication and enhance the spatial reuse of the wireless channel, hence improving the throughput of the wireless network. Conversely, augmenting the transmit power level can extend the transmission distance of nodes, hence decreasing the average number of hops required for each route within the network. As a result, the overall transmission time for each route diminishes [8,9]. In DSRC-based safety communications, transmission power must be carefully controlled to ensure reliable message delivery to neighboring vehicles while avoiding excessive interference, channel congestion, and packet collisions. Therefore, an inherent trade-off exists between communication range and interference, where adaptive power control and congestion-aware mechanisms are often employed to balance coverage requirements with spectrum efficiency and network reliability [8]. VANETs utilize two forms of communication: vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). In vehicle-to-vehicle (V2V) communication, cars can exchange messages with other vehicles within their communication range. For instance, when traffic congestion arises (congestion in vehicular networks occurs when the wireless communication channel becomes overloaded due to simultaneous transmissions from multiple vehicles, leading to packet loss, increased delay, and reduced reliability of time-critical safety messages), the car can utilize vehicle-to-vehicle (V2V) communication to transmit road information with other cars, enabling them to select alternative routes [10,11]. In VANET, vehicle density fluctuates frequently and rapidly due to fast node mobility, resulting in alterations to vehicle distribution and the connectivity graph. In conditions of significant traffic overcrowding, vehicles may be positioned within a few meters of each other. Conversely, on a sparsely populated road, the distance may extend to hundreds of meters. Consequently, VANETs encounter the significant challenge of sustaining connectivity due to rapid changes in topology. When vehicles are densely distributed within each other's transmission range, a greater number of nodes must share the medium, resulting in increased contention, collisions, and delays that diminish network capacity.

Abbreviations

VANET	Vehicular Ad Hoc Networks
V2V	Vehicle-to-Vehicle
RSU	Road Side Unit
ITS	Intellegnt Transportation System
V2I	Vehicle –to-Roadside
DSRC	Dedicated Short Range Communication
BSM	Basic Safety Message
CAM	Cooperative Awareness Message
NC	One-Hop Network Connectivity
MD	Droped Message
CBR	Constant Bit Rate

When vehicles are distributed sparsely and utilize fixed transmission power, some vehicles may be unable to communicate with their neighbors beyond the established transmission range. This can cause some vehicles to be disconnected from each other, preventing the exchange of safety messages or the exchange of additional information. As a result, vehicles using fixed transmission power maintain a constant transmission range, which can lead to network disconnection and, consequently, various efficiency problems and increased message overheads [12-14]. The primary aim of this study is to thoroughly review the impact of different transmission power levels on the spread of safety messages in sparse vehicular ad hoc networks (VANETs). More precisely, the study will perform a comparison and analysis of the main VANET performance metrics that are most influenced by transmission power, such as communication range, packet delivery ratio, end-to-end delay, network connectivity, and interference levels. By examining these metrics, the paper highlights how transmission power affects the reliability, efficiency, and overall robustness of safety message communication in low-density vehicular environments.

In multi-hop communication applications, numerous elements influence communication. Nevertheless, in a standard one-hop safety messaging situation, such as a collision accident safety application, the transmission power of the node is crucial for ensuring comprehensive reach to its immediate neighbors. The one-hop distance is contingent upon the transmission power utilized by the node to convey the safety message; consequently, the ideal choice of the transmission power [15]. The main contribution of this paper is constructing a sparse, Manhattan Grid-based VANET model and conducting an evaluation on the impact of varying transmission power on different aspects of VANET, such as different network densities, safety message intervals, vehicle speeds, and modulation schemes. The remainder of this paper is structured as follows. Section 2 presents the relevant work of other authors. Section 3 presents the operational idea of vehicular safety communication. Section 4 presents the safety messaging principles. Section 5 presents the network modelling. Section 6 presents the evaluation metrics. Section 7 presents the findings and discussion. Finally, Section 8 concludes.

2. Related work

Transmission power directly determines the effective communication range over which a message can be reliably received by neighboring vehicles. Consequently, numerous studies have investigated the impact of transmission power on the overall performance of vehicular ad hoc networks (VANETs). The tremendous amount of data generated in the Internet of Vehicles (IoV) can lead to channel congestion, packet loss, and delay of time-sensitive messages. This can have a serious impact on the performance of applications and services provided by a vehicular network, particularly safety applications that are time-critical. As such, network congestion control is a topic in vehicular networks, and various methods of controlling the message transmission rate and power have been explored to date. Caitlin Facchina and Arunita Jaekel [16] introduced a distributed, adaptive congestion control algorithm for VANETs, where vehicles adjust their transmission power based on their speed. The idea here is that the faster a car is travelling, the less dense the network is (as vehicles need to leave more space at higher speeds).

With more space between vehicles, higher transmission powers can be used, while a low-speed traffic network may suffer from heavy congestion at the same power. Thus, the lower-speed vehicles reduce their transmission power. The results indicated that the proposed approach enhanced the quantity of received messages by decreasing the number of lost packets. The 5G New Radio Vehicle-to-Everything (5G-NR-V2X) side-link communication enables direct device-to-device interaction among vehicles via the PC5 interface without relying on cellular infrastructure. Specifically, it offers ultra-low latency and high reliability, and it can thus be used for high-end safety and cooperative driving applications. Compared with DSRC and LTE-V2X, 5G, NR-V2X provides better scalability, higher data rates, and more flexible resource allocations. Thus, it is considered to be the main driver of the next-generation intelligent transportation systems. Delivering the best possible network performance, which means high reliability, low latency, high throughput and overall communication efficiency, and solving the problems brought by congestion are vital regarding the current networks.

Tian, Jiawei, et al. [17] demonstrated a hybrid power and rate control management strategy for distributed congestion control (HPR-DCC), which they tested with 5G, NR-V2X side-link communications. The underlying principle of the method is that an efficient control becomes possible when the transmission parameters are adjusted dynamically based on the network conditions, thus improving the network performance and at the same time avoiding congestion. Their results show that during heavy congestion, the proposed approach is able to keep the maximum CBR value at 64% which, in turn, results in a 6% performance improvement over the conventional DCC approach. Furthermore, this approach enhanced the signal reception range by 20 m while maintaining the 90% packet reception ratio (PRR). The limited channel capacity and high message rates needed to ensure an adequate level of awareness (awareness denotes a vehicle's capability to maintain an up-to-date understanding of nearby vehicles and road conditions through the reliable reception of exchanged messages) make the reliable delivery of BSMs a challenging problem for VANETs. Xiaofeng Liu et al. [18] introduced a decentralized congestion control algorithm that employs varying transmission power levels to diminish the channel busy ratio while preserving a high degree of awareness for nearby cars. The simulation results showed that the proposed method can effectively reach a compromise between awareness and bandwidth consumption in an optimal manner. The rapidly changing network topology in vehicular networks (VANETs) heavily influences the data transmission and reception processes. Moreover, the continuous arrival of new vehicles on the road will inevitably increase receiver blocking. Therefore, it is still a highly challenging issue to decrease blocking and improve the reliability of data transmission. B. Liao et al. [19] proposed a distributed power control and multiple antennas (DPC-MA) scheme, which achieves higher throughput by blocking less. Furthermore, the authors constructed an optimization model to decide the best transmission power and the number of vehicle antennas based on their neighborhood relationship. The result analysis revealed that the newly developed method performed well in terms of achieving high throughput, particularly in vehicle concentration scenarios.

As the number of vehicles increases in VANETs, the limited bandwidth of the wireless channel, which is used for vehicle-to-vehicle (V2V) communication, may become congested, resulting in packet drops or delays. VANET congestion control techniques attempt to address this by adjusting different transmission parameters, including the data rate, message rate, and transmission power. B. St. Amour and A. Jaekel [20] proposed a decentralized congestion control algorithm where each factor adjusts the data rate used to transmit its wireless packet congestion based on the current load on the channel. The channel load is estimated independently by each vehicle using the measured channel busy ratio (CBR). The simulation results demonstrate that the proposed approach outperforms existing data rate-based algorithms in terms of both packet reception and overall channel load.

Previous studies [16–20] have mainly concentrated on vehicular network congestion control leveraging various adaptive transmission power, rate control, or hybrid strategies; most of these works focus on dense vehicular scenarios, 5G-enabled environments, or joint power-rate optimization aimed at mitigating channel congestion. As an example, previous studies have researched power changes, setting vehicle density or speed as the base, using a combination of power and rate control systems, and developing decentralized schemes aimed at a balance between awareness and bandwidth usage or a throughput enhancement under the condition of high traffic density. However, the current study specifically focuses on sparse VANET situations where there are still problems with network connectivity and reliable dissemination of safety messages resulting from low vehicle density rather than channel overload. While the earlier methods have focused on congestion avoidance or throughput optimization, this study fractionally isolates and investigates the effect of different transmission power levels on safety message dissemination.

Furthermore, this study also looks at a wider range of performance metrics, including communication range, packet delivery ratio, end-to-end delay, network connectivity, and interference levels, to thoroughly evaluate the impact of transmission power on the reliability, efficiency, and robustness of safety communications in low-density vehicular networks. This focused analysis complements existing congestion-oriented studies by addressing a less-explored yet critical VANET operating condition. The studies reviewed in this section highlight the significant role of transmission parameters and congestion-related mechanisms in shaping vehicular network performance, particularly for safety-critical communications. Motivated by these findings, Section 3 introduces the operational concept of vehicular safety communication, outlining the underlying assumptions and mechanisms that form the foundation for analyzing the impact of transmission power on safety message dissemination.

3. Dedicated short range communication (DSRC) Overview

At the end of the 19th century, in the United States, the Federal Communications Commission specified 75 MHz of the DSRC spectrum at 5.9GHz to be used only for vehicular purposes. DSRC is a wireless radio technology that is based on Wi-Fi to assist in exchanging data in a short and highly dynamic network. DSRC is designed to be incorporated in the automotive industry. DSRC is a group of protocols and criteria that contain all parts of the layers, its physical layer (PHY), and medium access control (MAC) layer defined in the IEEE802.11p, which belongs to the 802.11family[21]. The DSRC properties are represented in low connection delay and high data transfer [21]. DSRC contains 7 channels (CH172 - CH 184) channels. For each channel, 10 MHz and the remaining 5 MHz is reserved for guard band. (CCH_178) This is the control channel. The DSRC's channels are divided into two categories: the control channel (CCH) and the remaining service channels (SCHs). DSRC works with a different kind of data rate transfer, such as (3, 4, 5, 6, 9, 12, 18, 24, and 27 Mbps) for the 10 MHz channel. 6 Mbps is the most optimal data rate transfer [21]. The vehicular network working on DSRC bands can be considered as a key enabler technology for the new marketing for the intelligent transport system (ITS).

4. Operation concept of vehicular-safety communication

4.1 Link-layer behavior and control-channel

Many factors define the link-layer behavior of the control channel for safety messages in DSRC-based vehicular communications. These factors can be summarized as follows:

- Single-hop communication: Most safety applications rely on rapid, low-latency communication among vehicles within the same transmission range; therefore, multi-hop networking capabilities are not required in the DSRC communication design [22].
- Message characteristics: Safety messages are self-configured, typically short in length (approximately 100–300 bytes), and are transmitted within a single MAC frame [22].
- Uncoordinated access: Channel access is fully distributed and does not require a centralized coordinator, which simplifies medium access control for safety communications [22].
- Broadcast transmission: Safety messages are broadcast with sufficient transmission power to reach all potentially affected neighboring vehicles [23].
- Neighbor awareness: All DSRC-equipped vehicles within the transmission range are capable of communicating with one another, and scalability is a key consideration in the design of safety communication systems.
- Dedicated control channel: The control channel is primarily reserved for safety-related message exchanges, while non-safety communications are restricted to specific applications operating over service channels (SCHs) [23].

5. Safety messaging fundamentals

Vehicular Ad Hoc Networks (VANETs) are a subclass of mobile ad hoc networks that enable vehicles to communicate with one another and with roadside infrastructure to support road safety, traffic management, and other cooperative applications. In VANETs, safety messages basically convey a vehicle's location, speed, and hazard information to vehicles in the vicinity, which is essential for prompt hazard recognition and accident prevention [23]. Usually, traffic accidents result from a combination of factors, which may include abrupt physical changes, e.g., sudden vehicle deceleration due to emergency braking, or vehicles inadvertently staying in dangerous paths. These scenarios highlight the urgent necessity for the fastest possible broadcasting of safety messages to improve traffic safety and decrease accidents. A vehicular ad hoc network (VANET) provides two kinds of safety messages that can be used [24].

- Routine safety messages like the Basic Safety Message (BSM) and the Cooperative Awareness Message (CAM) include data about the vehicle's location, speed, direction, and other basic. They are transmitted at regular intervals of (100-300) milliseconds, thus enabling the vehicles around to keep updating their understanding of the traffic situation. After receiving and analyzing these messages, the users will be able to accurately know the position and movement of the nearby vehicles, which is essential for implementing the safety measures before the accident happens, such as collision avoidance and cooperative driving [25].
- Event-driven safety messages, e.g., the Decentralized Environmental Notification Message (DENM), are only transmitted if a hazardous event or an unusually dangerous traffic condition takes place. Routine safety messages, on the other hand, are continuously transmitted to create awareness of the situation. For example, a DENM message is only sent when a vehicle suddenly slows down (hard braking) or when it detects that there is a risk of collision.

Such messages help the vehicles that are near the source of the message to understand the situation and take timely action; thus, they work well with the routine broadcasts to create a safer driving environment for all.

6. Research methodology

This study employed a systematic and simulation-based method to test the impact of different transmission power levels on VANET nodes' connectivity and the efficient dissemination of safety messages. Since vehicles are continuously moving, making the network topology always changing, it is dealing with sparse and low-density scenarios that are hard to keep reliable connectivity in. Therefore, the method aims at a realistic vehicle-to-vehicle (V2V) communication scenario under different network conditions. It combines a newly developed connectivity estimation model to investigate the performance of VANET under different transmission power levels and traffic densities. Network communication is designed based on well-known vehicular networking concepts that enable measuring the key performance indicators of a network, e.g., node connectivity, bandwidth utilization, latency, and packet loss. By varying transmission power levels in a controlled manner, the method yields data on how fixed or less-than-optimal power settings impact network performance, either by resulting in more channel contention in a geographic location with high node density or by causing a shorter communication range in a less populated area. In order to maintain high standards of analysis, performance measurements are based on well-controlled simulation scenarios that reflect different mobility patterns and densities of nodes. A thorough set of tools is provided to qualitatively and quantitatively evaluate the power transmission adaptability, thus laying a solid foundation for improving VANET connectivity and giving directions for the design of adaptive power control methods that are the most effective for real-world vehicular networks.

6.1 Network modelling

It is crucial to have a detailed network modeling framework when one intends to assess how transmission power affects safety message communication. Here, we discuss how Vehicular Ad Hoc Networks (VANETs) are modeled in such a way that the movement of vehicles and characteristics of the wireless communication environment are both taken into account. The model incorporates realistic vehicular movement patterns and traffic scenarios to simulate vehicle-to-vehicle (V2V). The study has ensured that a strict conduct of the establishment of a strong and flexible network framework performance evaluation, including connectivity analysis, message delivery, and delay measurements, is done in a wireless vehicular network environment with a sparse and mixed density layout. A network model that is capable of handling the changes in operating conditions is required.

6.2 The Manhattan grid topology modeling

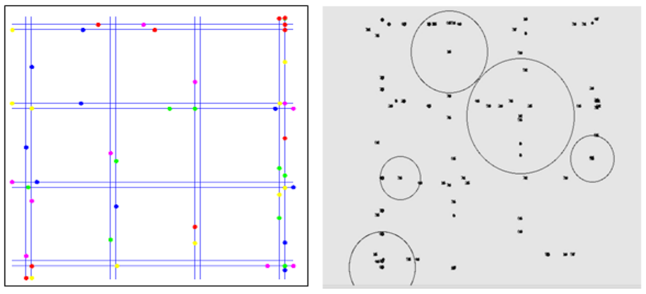
The "grid road topology" is employed in the Manhattan mobility model, which is used for vehicle movement, and it is called the "Manhattan model. This is because it takes into consideration the urban vehicular settings with avenues running parallel and perpendicular to each other, and thus a combination of points with four ways, where vehicle accidents and safety events occur most of the time. For this reason, it is suitable to use it for the evaluation of the dissemination, latency, and reliability of safety messages in VANETs under dynamic topology and dense traffic conditions. Therefore, this mobility model provides a realistic and controlled framework for testing network performance in urban vehicular environments. The Manhattan model operates effectively in regions with structured road networks. In an urban map, mobile nodes within this mobility model travel either vertically or horizontally. The Manhattan model selects node motions using a probabilistic method. A car decides to continue traveling in the same direction at every crossing. Going straight has a 0.5 chance, whereas choosing left or right has a 0.25 chance. Highway networks are not a good fit for the Manhattan model. This approach restricts node movement geographically even as it gives the nodes the freedom to change direction [26]. Table 1 shows the parameter settings used in MobiSim for mobility trace generation. The visualization of the Manhattan road scenario under Mobisim and a Sample NAM output of simulated Manhattan grid topology is shown in Figure 1.

6.3 801.11p MAC and physical layer parameters setting

The IEEE 802.11p MAC and physical layer parameters are explicitly specified to ensure a realistic and reproducible evaluation of vehicular communication performance. MAC-layer settings directly affect channel access behavior, contention, collision probability, and the latency of safety message dissemination, while physical-layer parameters determine communication range, signal reliability, and interference characteristics. Since VANET performance is highly sensitive to these parameters, it is thus necessary that they be properly defined to accurately represent the real-world operating conditions and, at the same time, to maintain compliance with the DSRC communication standards. Table 2 shows the parameter setting that was used to model the 801. 11p MAC layer under ns2, while Table 3 shows the parameters that were used to model the 801. 11p physical layer under ns2.

Table 1. Mobisim parameters setting

Attribute	Value
Models	Manhattan
Range algorithms	Null Power Algorithm
dir12lanespace	20
Height	1000
Width	1000
h-lines	50,350,650,950,
V-lines	50,350,650,950,
Max acceleration	2
Positive acceleration ratio	2.0
Max stop time	10
Simulation Duration	300
Maximum speed	20
Minimum speed	5
Safe distance ratio	2.0



(A) (B)

Figure 1. (A) Visualization of the Manhattan road scenario, (B) Sample NAM output of the simulated Manhattan grid topology

Table 2. Dsrc/802.11p MAC layer parameter settings

Parameters	Value
CWMin_	15
CWMax_	1023
Slot Time_	0.000013
SIFS_	0.000032
ShortRetryLimit_	7
LongRetryLimit_	4
HeaderDuration_	0.000040
SymbolDuration_	0.000008
BasicModulationScheme_	0,1,2,3
use_802_11a_flag_	true
RTSThreshold_	2346
MAC_DBG	0
Logbackoff	1

Table 3. DSRC/802.11p physical layer parameter settings

Parameters	Value
PhyCSThresh_	3.162e-12 (-85 dBm)
Phyfreq_	5.9e+9
PhyBasicModulationScheme_	0,1,2,3
PhyPreambleCaptureSwitch_	1
PhyDataCaptureSwitch_	0
PhySINR_PreambleCapture_	2.5118(4 dB)
PhySINR_DataCapture_	100.0 (10 dB)
Phytrace_dist_	HY trace until this distance)

6.4 Ns2 Simulation Setup

Besides the MAC and physical layer setups, some other key parameters need to be determined in the model that is being proposed if one wants to accurately and reliably evaluate performance. These parameters have an impact on network behavior, mobile dynamics, and safety message distribution, and their correct configuration is necessary for realistically simulating vehicular communication scenarios and thus, allowing for a valid comparison with existing works. Table 4 shows the parameters that must be set in our model.

7. Evaluation metrics

The chosen metrics for assessing the influence of varying transmission power on safety message communication under sparse vehicular ad hoc networks are [27]:

- One-Hop Network Connectivity (%): The ratio is calculated by comparing the "All Safety Messages Successfully Received" to the "All Safety Messages Generated" at its one-hop neighbors, as shown in Eq. (1).

$$NC(\%)=\frac{SRi(t)}{SGi(t)} \times 100\% \qquad (1)$$

Where NC is one-hop network connectivity, $SRi(t)$ is the total number of successfully received safety messages by vehicle (i) at unit time (t), and $SGi(t)$ is the total number of generated safety messages by vehicle (i) at unit time (t).

- Network Bandwidth Consumption (Kbps): The ratio is determined by the "Size of All Safety Messages received" in relation to the time of the communication, as shown in Eq. (2).

$$Bandwidth\ Consumption(Kbps)=\left(\frac{\sum_{i=1}^{N} Si}{T}\right) * 10\text{-}3 \qquad (2)$$

Where Si is the i-th received safety message in bytes, N is the total number of received safety messages, T is the total communication time in seconds.

- Average Message Delay (ms): The average duration required for all messages to arrive at their immediate neighboring destination. It is measured in milliseconds.
- Total Drop Message: Total message drop represents the difference between transmitted and successfully received safety messages over the communication duration, capturing the overall impact of channel impairments, including interference, collisions, and buffer limitations, as shown in Eq. (3).

$$MD_{total} = SG(t) - SR(t) \qquad (3)$$

Where MD_{total} is the total number of dropped messages at unit time (t), SG represents the total number of messages generated per unit time (t), SR denotes the total number of successfully received messages per unit time (t).

Table 4. Parameter settings of the ns2 simulation

Attribute	Value
The Periodic Safety Message Application Simulation Agent	PBC
Modulation Schemes	0 -BPSK and 1/2 coding rate: 3 Mbps, 1 - QPSK and 1/2 coding rate: 6 Mbps, 2-QAM16 and 1/2 coding rate: 12 Mbps, 3-QAM 64 and 2/3 coding rate: 24 Mbps.
Broadcast Variance	0.05
Safety Message Size	100
Safety Message Broadcast Interval	0.05 0.1 0.15 0.2 0.25 0.3
Tx Ranges	100 m, 200 m, 300 m, 400 m, 500 m
Number of Vehicles to simulate a sparse VANET	20, 40, 60, 80, 100
Vehicle Speed	15 m/s, 30 m/s
Interface Queue	DropTail/PriQueue
Queue Length	20
Antenna	OmniAntenna
Topographical Area	1000 m × 1000 m
Routing Agent	DumbAgent (No Routing)
SimulatedTraffic Duration	30 seconds

The performance metrics selected are particularly those that give an accurate picture of the primary needs of DSRC, based on safety communications in VANETs. Safety applications predominantly depend on single-hop broadcast communication; thus, the reliability of one-hop connectivity is of utmost importance because it guarantees that safety messages are delivered to the neighbors of the vehicle in the safety zone within the time required. Network bandwidth consumption is one of the criteria evaluated in the consideration of channel efficiency when the message generation rate is high, such as in safety applications, because a significantly high amount of overhead may cause congestion and thus lead to communication performance degradation. The average message delay is an essential parameter for systems whose functioning is highly dependent on safety, because the messages must be disseminated in a timely manner to meet the restrictive latency requirements that are associated with collision avoidance and hazard warning applications. Moreover, interference-induced total message drop is taken into account to directly measure the extent of channel contention and wireless interference, which are the main issues in dense traffic scenarios. Other performance metrics, such as end-to-end throughput, packet delivery ratio, jitter, or multi-hop routing efficiency, are not emphasized in this study because they are less relevant to single-hop, time-critical safety message dissemination and would not provide additional insight into the primary objectives of the proposed model.

8. Result and discussion

8.1 Network connectivity analysis

Figure 2 illustrates the relationship between one-hop network connectivity and transmission range. In this analysis, a total of 60 vehicles were maintained, and the modulation scheme employed was QAM16 with a ½ coding rate. Six plots are presented, each representing distinct intervals for safety messages. As the transmission range expands, the network connectivity increases at each interval. Moreover, Figure 2 shows that the network connectivity is not significantly affected by the change in safety message interval.

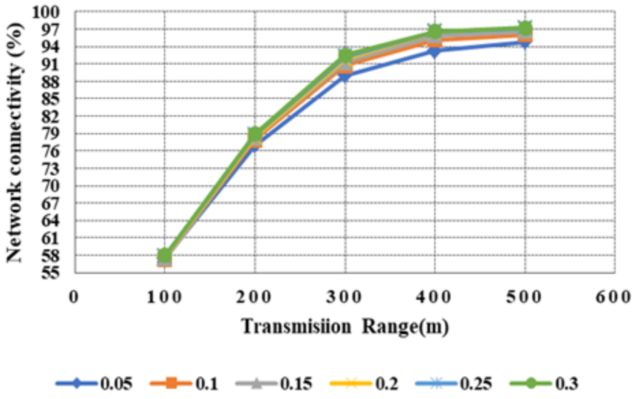


Figure 2. Network connectivity vs. transmission range at different message intervals

Figure 3 shows the one-hop network connectivity versus the transmission range at different modulation schemes. During this analysis, the number of vehicles was kept to 60, and a 0.2-second safety message interval was used. There are four plots, each corresponding to a different modulation scheme. For each scheme, the network connectivity starts to increase with an increase in transmission range. On the other hand, Figure 3 demonstrates that the network connectivity for high data rate (54 Mbps) is less than the connectivity for low data rate (6 Mbps). This is because the number of messages at the high rate is pumped faster than at the low rate, which leads to filling the queue of the data link layer faster. As a result, when the buffer of the MAC layer reaches its capacity, it leads to the discarding of all overflow packets, which in turn impacts network connectivity.

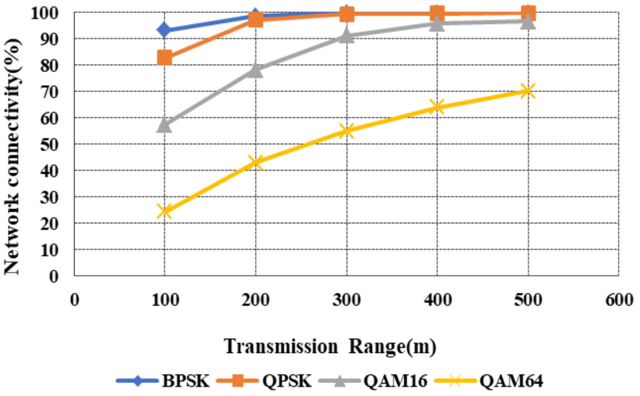


Figure 3. Network connectivity vs. transmission range at different modulation schemes

Figure 4 illustrates the relationship between one-hop network connectivity and transmission range across varying vehicle densities. In this analysis, the QAM16 modulation scheme with a ½ coding rate is employed, and a safety message interval is established at 0.2 seconds. Five plots are presented, each representing distinct density levels. As the transmission range increases, there is a corresponding rise in network connectivity for each density level. Figure 4 demonstrates that the network connectivity for low vehicle densities is less than the connectivity for high vehicle densities.

Figure 5 shows the one-hop network connectivity versus the transmission range at different vehicle speeds. During this analysis, the number of vehicles is kept to 60; these vehicles are distributed within a (1000 m × 1000 m) simulation area. There are two plots, each corresponding to a different vehicle speed. For each speed, the network connectivity starts to increase with an increase in transmission range. This is because increasing transmission range reduces the spatial reuse of the wireless medium, which leads to increased network connectivity. Moreover, the graph shows a slight effect due to different vehicle speeds since the network uses broadcasting to send safety messages rather than unicast.

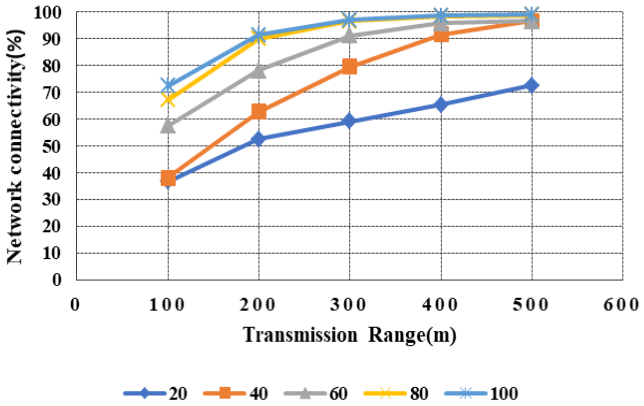


Figure 4. Network connectivity vs. transmission range at different vehicle densities

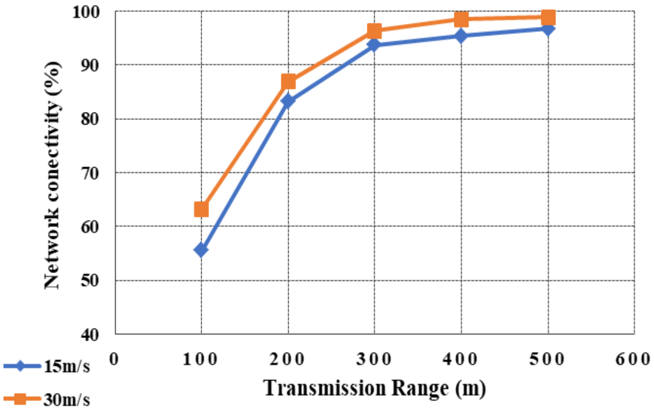


Figure 5. Network connectivity vs. transmission range at different vehicle speeds

8.2 Dropped packets/messages analysis

The total number of dropped messages at various safety message intervals is plotted against the transmission range in Figure 6. The modulation method QAM16 with ½ coding rate is employed during this analysis, and the number of cars is maintained at 60. Each of the six plots represents a distinct gap between safety messages. As the transmission range increases for each interval, the quantity of dropped messages begins to rise. Figure 6 further demonstrates how the safety message interval has a significant impact on the quantity of messages dropped as a result of physical layer interference. This is because the MAC layer is forced to discard all overflow messages in its buffer when the message interval is minimal. Additionally, as the message interval decreases, more messages are waiting to be sent in the MAC layer buffer. The MAC layer discards any communications that go beyond its waiting time limit.

Figure 7 demonstrates a comparison of lost messages relative to transmission range across various modulation schemes. Here, the vehicle count has been kept at 60, and the safety message interval has been set at 0. 2 seconds. There are four plots, each reflecting a different modulation scheme. For every method, the number of dropped messages starts to increase with the expansion of the transmission range. Figure 7 shows that the number of dropped messages is greatly influenced by the transmission range. For example, a lower data rate leads to more dropped messages than a higher data rate.

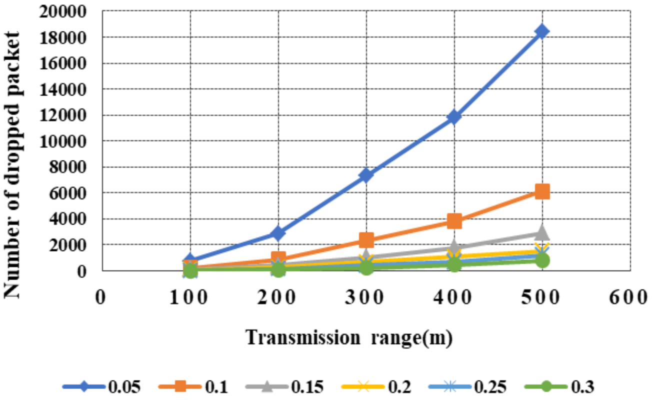


Figure 6. Number of dropped messages vs. transmission range at different message intervals

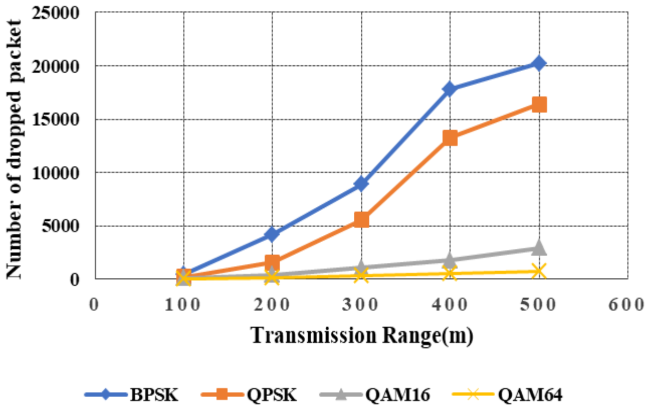


Figure 7. Total number of dropped messages vs. transmission range at different modulation schemes

Figure 8 illustrates the overall count of dropped messages in relation to the transmission range across varying vehicle densities. This analysis employs the QAM16 modulation scheme with a ½ coding rate, and a safety message interval of 0.2 seconds is established. There are five charts, each representing distinct densities. For each density, the overall quantity of dropped messages escalates with an increase in transmission range. Furthermore, Figure 8 illustrates that the aggregate quantity of dropped communications at low vehicle density is inferior to that at high vehicle density. The rise in the number of cars compels the MAC layer to eliminate all overflow messages in its buffer.

Figure 9 shows the total number of dropped messages versus the transmission range at different vehicle speeds. During this analysis, the number of vehicles is kept to 60; these vehicles are distributed within a (1000 m × 1000 m) simulation area. There are two plots, each corresponding to a different vehicle speed. For each vehicle speed, the number of dropped messages increases with an increase in transmission range. This is because increasing the transmission range of the node decreases the spectral reuse of the channel, which leads to the message exceeding the waiting time in the MAC layer buffer. When the message waiting time has expired, the MAC layer discards the message. Figure 9 also shows that the number of dropped messages due to higher vehicle speed is larger than the number of dropped messages due to lower vehicle speed.

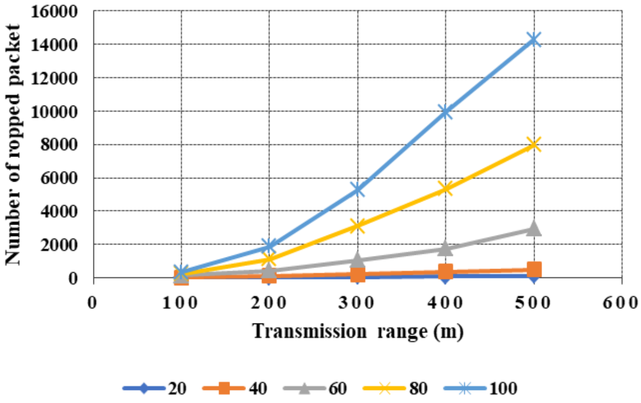


Figure 8. Total number of dropped messages vs. the transmission range at different vehicle densities

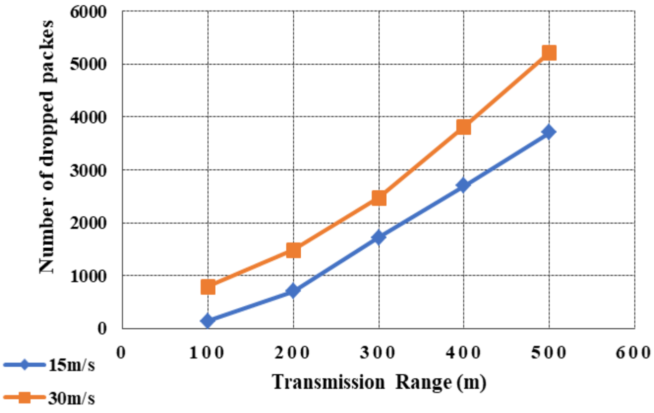


Figure 9. Number of dropped messages vs. transmission range at different vehicle speeds

8.3 Network bandwidth consumption analysis

Figure 10 illustrates the network bandwidth utilization (in Kbps) in relation to the transmission range across various safety message intervals. In this analysis, the vehicle count is maintained at 60, utilizing the QAM16 modulation technique with a ½ coding rate. There are six plots, each corresponding to different safety message intervals. For each interval, the bandwidth consumption starts to increase with an increase in transmission range. As seen in Figure 10, more data is pushed into the network when safety message intervals are shortened. The bandwidth use rises as a result of this data push (the smaller the message interval, the higher the bandwidth consumption).

Figure 11 shows the network bandwidth consumption (in Kbps) versus the transmission range at different modulation schemes. During this analysis, the number of vehicles was kept to 60, and a 0.2-second safety message interval was used. There are four plots, each corresponding to a different modulation scheme. For each scheme, the network bandwidth consumption starts to increase with an increase in transmission range. On the other hand, Figure 11 demonstrates that the network bandwidth consumption using BPSK is less than the network bandwidth consumption using other schemes.

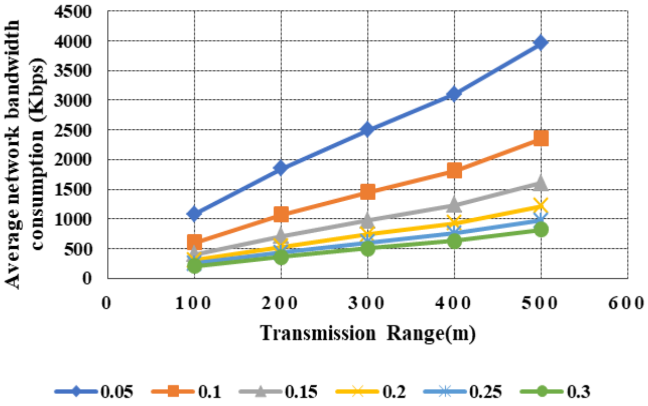


Figure 10. Bandwidth consumption (in kbps) vs. the transmission range at different safety message intervals

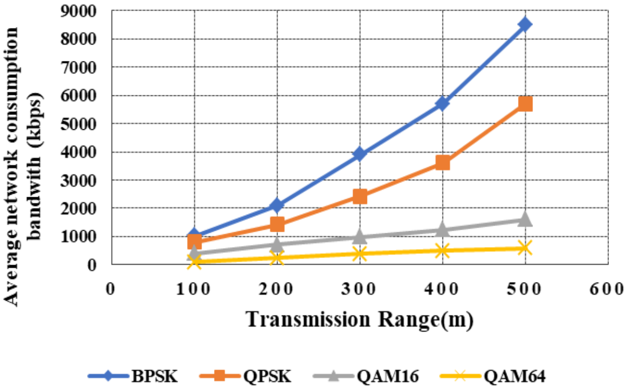


Figure 11. Network bandwidth consumption vs. the transmission range at different modulation schemes

Figure 12 shows the network bandwidth consumption (in Kbps) versus the transmission range at different vehicle densities. During this analysis, the modulation scheme QAM16 with a ½ coding rate is used, and a safety message interval is set to 0.2 seconds. There are five plots, each corresponding to a different density. For each density, the network bandwidth consumption starts to increase with an increase in transmission range. Moreover, Figure 12 demonstrates that the network bandwidth consumption for low vehicle density is less than the network bandwidth consumption for high vehicle density. Apparently, this is because an increase in the number of vehicles means an increase in the number of nodes that can send or receive at the same time. This leads to more message loss due to channel contention and collisions that occur between messages.

Figure 13 shows the network bandwidth consumption (in Kbps) versus the transmission range at different vehicle speeds. During this analysis, the number of vehicles is kept to 60; these vehicles are distributed within a (1000 m × 1000 m) simulation area. The amount of bandwidth that is consumed increases with each speed, and this trend continues as the transmission range increases. This is due to the fact that increasing transmission range results in a decrease in the typical number of hops that are required for each route in the network. Furthermore, a higher transmission range enhances the quality of the signal that is received at the receiver. This, in turn, lowers the bit error probability (BER) of the packets, which ultimately results in an increase in the amount of bandwidth capacity that is utilized.

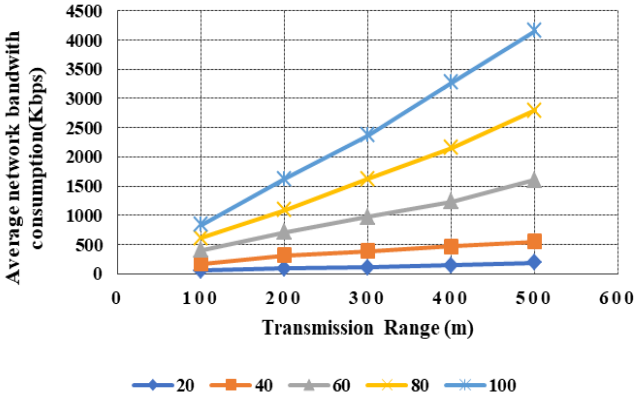


Figure 12. Network bandwidth consumption vs. the transmission range at different vehicle densities

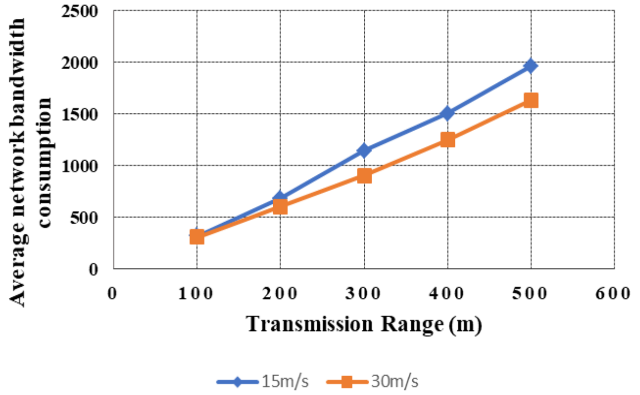


Figure 13. Bandwidth consumption (in kbps) vs. the transmission range

9. Conclusion

Transmission power is an essential factor in wireless communication systems, as it determines the extent to which the wireless medium can be used by impacting the signal strength at the receiver-communication range and the level of interference that the neighboring nodes experience. Generally, in centralized wireless networks, transmission power is set to a predetermined fixed value; however, Vehicular Ad Hoc Networks (VANETs) are decentralized networks in which vehicles as peers communicate and cooperate to exchange safety messages without any central authority. In wireless communication systems, transmission power plays a fundamental role in wireless medium utilization by directly affecting received signal strength, communication range, and the level of interference experienced by neighboring nodes. While transmission power in centralized wireless networks is typically configured at a fixed value, Vehicular Ad Hoc Networks (VANETs) operate in a fully distributed, peer-to-peer manner, where vehicles cooperatively exchange safety messages without centralized coordination. The main problem with the actual implementation of VANETs lies in the dynamic and density-dependent nature of traffic. Due to mobility, the vehicle density may change rapidly, resulting in changes in the network topology and the one-hop connectivity on a regular basis. The study results indicate that connectivity in the network is largely determined by the transmission range, vehicle density, vehicle speed, and modulation scheme used, while changes in the safety message interval have a relatively small effect on connectivity. From a scalability viewpoint, utilizing a fixed transmission power results in a static communication range that might be appropriate under some traffic conditions but will be inefficient under others. Under high traffic conditions, the use of excessive transmission power leads to an increase in interference and the number of packet collisions, which thus reduces the communication reliability. Conversely, in sparse networks or when vehicles move at high speeds, connectivity may be reduced due to the lack of transmission power, and safety message dissemination effectiveness may be limited. These results clearly point to the need for adaptive transmission power control mechanisms that would allow the operation of VANET to be scalable and reliable in different traffic densities and mobility scenarios, thus enhancing the practicality of their deployment in the real world.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically regarding authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with research ethics policies. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the authors.

Conflict of interest

The authors declare no potential conflict of interest.

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