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Analysis of collaborative wireless vehicular technologies under realistic conditions

Muhammad Naeem Tahir[1] | **Marcos Katz**[2] | **Urooj Rashid**[3]

[1] Faculty of Information Technology and Electrical Engineering, University of Oulu, Oulu, Finland

[2] Centtre for Wireless Communication (CWC) – Networks & Systems, University of Oulu, Oulu, Finland

[3] Faculty of Technology, University of Oulu, Oulu, Finland

Correspondence
Muhammad Naeem Tahir, Faculty of Information Technology and Electrical Engineering, University of Oulu, Finland.
Email: naeem.tahir@oulu.fi

Funding information
Timo Sukuvaara and Kari Mäenpää from Finnish Meteorological Institute (FMI), Finland

Abstract

Reliable communications are essential to provide intelligent services to connected cars. For operational services, connected vehicles in VANET (Vehicle Ad hoc Networks) regularly transfer large amounts of data related to vehicular safety. Similarly, V2X (Vehicle-to-Everything) communications include vehicles exchanging information with each other and with infrastructure that is, Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V). This paper has analyzed the performance of IEEE 802.11p and 5G test network in a collaborative manner under realistic conditions. For performance analysis the exchange of safety-critical road weather and traffic information has been performed to enhance the traffic safety and traffic efficiency in the domain of intelligent transportation system (ITS). The vehicular connectivity is provided in V2V and V2I scenarios by utilizing short-range IEEE 802.11 standard or cellular approaches, such as the 5G network. Here, we consider combining these technologies in a cooperative manner to exploit jointly their advantages. In this cooperative heterogeneous network, the IEEE 802.11p supports safety-related pilot use cases while the provision of non-safety-related pilot use cases are supported by the 5G test network. The performance analysis revealed that the IEEE 802.11p performs quite reasonably well with restricted mobility in contrast of 5G test network in a collaborative manner to avoid road accidents.

1 | INTRODUCTION

In the last two decades, Vehicular Ad hoc Networks (VANETs) have rapidly evolved, becoming more developed and offering sophisticated services. Advanced VANET systems promise to considerably reduce the road accidents by allowing safe mobility and supporting Intelligent Transport Systems (ITS) services. Basically, ITS is aimed to enhance the road safety and road traffic efficiency. One of the main ITS service in VANET is the provision of timely run-time warning alerts for vehicle drivers at whenever hazards on the road occur. This early warning delivery about road traffic would help to improve safety of vehicles by decreasing traffic jams. These kinds of safety critical service alerts and applications are indeed vital in VANETs [1]. Recently, this safety critical ITS services have been installed on the road-side-infrastructure and in vehicles to manage traffic by assisting drivers. To deliver road weather and traffic information in Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) scenarios, a reliable wireless technology is needed. In recent years, the best available wireless technology for VANET system is based on the IEEE 802.11p standard. However, covering the whole road network by IEEE-802.11p, the Access Points (APs) is not a cost-efficient solution. Because IEEE 802.11p has a maximum range of 1000 meter and that would need many APs to cover the road and highway network. And with the installation of APs to cover the road network would be quite expensive solution for VANET. As a solution, a new wireless standard was developed under the tree of the 3rd Generation Partnership Project (3GPP) for VANET safety critical applications that is primarily emphasized on the standardization of cellular broadband [1]. The development and progress of IEEE 802.11p and cellular standardization for vehicular communication is presented in Figure 1. Ever since, the safety of millions of people on roads will rely on the operational implementation and performance of these vehicular networking technologies. The best way to analyse the performance of these VANET

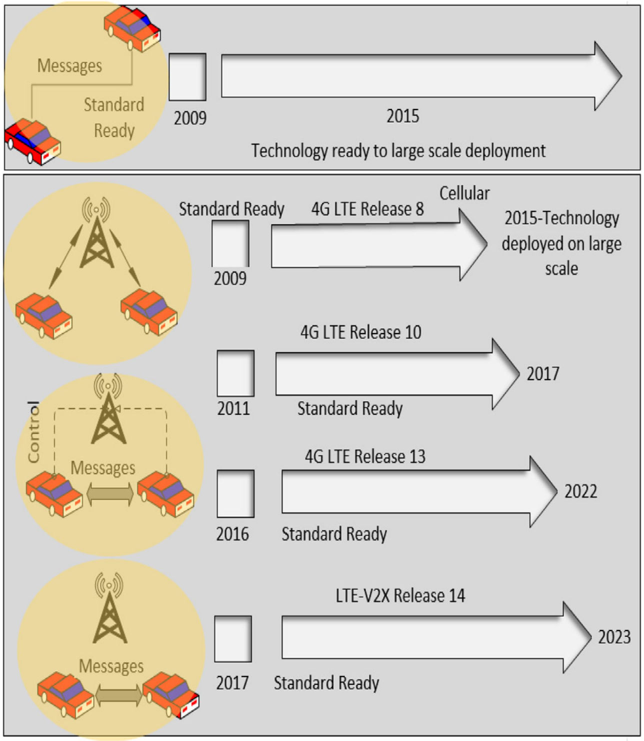

FIGURE 1 Evolution of vehicular networking technologies

technologies is to implement them in real-time realistic environments by delivering road weather and traffic information. In this way, we can understand the behaviour and assess the performance of each VANET technology [2, 3]. Our approach to enhance the VANET systems performance in an optimal way is to utilize these wireless technologies in a hybrid (IEEE-802.11p + 4G/5G) manner. In this paper, we study the cooperation of a long-range 5G Test Network (5GTN) and s short-range IEEE 802.11p-based network [4]. These technologies have been investigated while delivering real-time road weather and traffic data in V2V and V2I scenarios. The field measurements have been conducted on a Finnish Meteorological Institute (FMI) owned test-track in Sodankylä, Finland. The implementation of these wireless technologies in a cooperative way results in a heterogeneous system for VANET leveraging the best of both technologies. In this cooperative heterogeneous network, the IEEE 802.11p supports safety-related pilot use cases while the provision of non-safety-related pilot use cases are supported by the 5G test network.

2 | AIM SCOPE AND STRUCTURE

The aim of this paper is to analyse the performance of wireless technologies IEEE-802.11p and 5GTN in a realistic vehicular environment. The performance assessment is performed by connecting the vehicles in V2I and V2V scenarios by exchanging real-time road traffic and weather data [5]. The used communication technologies IEEE-802.11p and cellular 5GTN supports the field measurements to exchange the desired safety critical information on a test track hosted by FMI. These two wireless technologies are deployed to evaluate the vehicular communication performance, that would support the conventional Vehicular Ad hoc Networking (VANET). To perform pilot filed measurements and further ITS research, an advanced road-side infrastructure is designed and established by Finnish Meteorological Institute (FMI). The FMI is continuously performing research to design, develop and analyse the Intelligent Transport System (ITS) applications using road traffic and weather data. FMI is mainly working on vehicular communication and analysing the network performance by transmitting road weather and traffic information using short- range IEEE 802.11p and cellular based 4G/5G. The Arctic Research Centre FMI, Sodankylä, Finland has developed a testbed for VANET that is capable to perform tests associated to road weather and traffic data as well as potential weather facilities for connected and automated transport. In the developed testbed the Road Weather Stations (RWSs) are integrated together with the Road-side Unit (RSUs) to exchange real-time weather and road traffic related information with nearby vehicles. To study and validate the ITS applications and services related to vehicular networking, "Intelligent Road Weather Testbeds" are implemented and installed with advanced wireless technologies. Similarly, this paper discusses the importance of road traffic and weather services by exploiting advanced short-range and cellular wireless technologies to provide real-time information to the vehicles. The research in this paper is an extension of our earlier study on vehicular networking by offering a new perception and better findings using two different wireless technologies in VANET. This research work extends our previous research paper [6] published in Radio Wireless Week (RWW) 2021.We have performed the pilot measurements once again by also considering the network throughput. latency and packet loss. This paper concentrates entirely on road weather and traffic information that are key factors for the development of ITS functions by using wireless technologies. Moreover, it would be advantageous to build the advanced vehicular communication platform exploiting an ultralow-latency hybrid network (IEEE-802.11p and 5GTN technologies). This paper is structured as follows: Section 3 presents the ITS road weather and traffic services, while Section 4 illustrates the VANET wireless technologies (IEEE-802.11p and 5GTN). Section 5 presents the test locations followed by the Section 6 briefly discussed the pilot measurement setup in the considered V2V and V2I scenarios. The Section 7 presents and discusses the results and finally, the Section 8 concludes the paper.

3 | ITS ROAD WEATHER AND TRAFFIC SERVICES

Currently, the research community is working to design and develop ITS operational services, applications, and techniques to obtain real-time location-based information. The road weather services perform a key role in ITS in order to get the necessary road traffic related data, as illustrated in Figure 2. The RWSs-RSUs and vehicles exchange real-time road weather

FIGURE 2 Aerial view of a test track for pilot road weather and traffic services

and traffic data by allowing accurate real-time service creation precisely to different road transport actors. To deliver this road weather and traffic service data, the combination of short and long-range communication technologies (VANET & cellular network) can be exploited [6, 7]. The combination of these wireless technologies assists the "Next Generation Application" that forecasts, measures, and deliver the weather effects on different road traffic actors. The next generation applications are aimed to build greater accuracy associated to weather forecasts and its effect on the roads. These applications call for several approaches to alleviate the effect of road weather and traffic. By designing such applications, real-time data is efficiently used to improve the situational awareness for road safety. Moreover, applications can also improve the efficiency of resource usage, as well as to generate real-time road weather and traffic alerts. These applications also improve the capability to react instantly to reduce the road accidents [8]. Winter is typically very harsh in Northern Europe and it is one of main reason of road accidents. Basically, the ITS research unit in FMI has a long history of developing and deploying road weather and traffic services in real environments to deal with the road traffic challenges. The developed ITS services and applications help to reduce the road fatalities and offer business development opportunities in ITS by providing provision of road safety. These ITS services include precise, accurate and reliable road-weather data, weather forecasts and road warning alerts. The real-time updates for ITS services include measurements of air quality and humidity, road condition updates, fog alerts, vehicle safety alerts, driver visibility improvement and perception of driver's behaviour. To deliver these service data and alerts between vehicles and road-side-infrastructure, IEEE-802.11p was launched in 2012 to communicate in V2I and V2V scenarios [9]. Nevertheless, IEEE-802-11p has a limited communication range (max. 1000 m) and safety information cannot tolerate long network delays connected to central safety systems. To minimize the network delays in absence of short-range networks, the cellular communication (4G/5G) is beneficial to add the missing element in vehicular networking. The cellular networking is also aiming to provide vehicular communication with high bandwidth and ultra-low network latency. IEEE802.11p and 4G/5G technologies together make a heterogeneous hybrid network to support road and traffic service applications for road safety [10, 11].

4 | VANET WIRELESS TECHNOLOGIES

4.1 | IEEE 802.11p

IEEE launched a standard for vehicular networking called Wireless-Access-in-the-Vehicular-Environment (WAVE). Wave is comprised of two types of standards: (12) 802.11p (PHY and MAC) and (2) IEEE 1609 (network security and management) also covering other aspects of VANETs. Based on IEEE-802.11p, two key standards for vehicular networking have been evolved in recent years using the specifically allocated 75 MHz in the unlicensed band of 5.9 GHz. The first one, developed in 1999 by United States (US), is called Dedicated-Short-Range-Communications (DSRC) protocol [12,13], and the second one was defined in 2004 by the European Telecommunications Standards Institute (ETSI), and called ITS-G5 [14] These two standards, DSRC in US and ITS-G5 in Europe, are exclusively in use for vehicle-to-vehicle and vehicle-to-infrastructure communications. Both VANET standards have proven to fulfil all the requirements in vehicular networking, as extensive pilot use-case scenarios and field trials have been executed in US and several countries of Europe. In recent years, road safety is demanding more advanced services and equipment exploiting real-time environmental and traffic data. Countries set out to use roadside-infrastructures including different IoT-sensors and cameras to collect road weather and traffic data [15]. For this, IEEE-802.11p provides a platform with best available characteristics for the vehicular networks. Because this standard is aimed to meet different V2X application needs with the most advanced specifications. With all these features, IEEE-802.11p can help reducing the road accidents [5]. Nevertheless, IEEE-802.11p considerably raises the load of the communication network. This is mainly due to the requirement of high message frequency for safety applications in a shared wireless spectrum. The IEEE-802.11p also has feature to deal with congestion by using different techniques for congestion control that is, adaptations in contention window, message frequency and transmit power to all the medium access control (MAC) layers. This protocol also allows distributed access to the wireless network with no need of resource allocation process [10]. The Physical Layer (PHY) of IEEE802.11p can be utilized with eight possible modes of Modulation and Coding Schemes (MCSs). Depending on the used MCS mode, the data-rate can vary between 3–54 Mbps [16].

4.2 | 5G Wireless network (mmWave)

Vehicular communication needs to have a seamless connectivity for road safety. Furthermore, in a VANET, the vehicles also demand sufficient reaction time to the possible dangers in case of hazardous situations. For this purpose, cellular 5G wireless network can play a crucial role in VANET having ultra-low latency. 5G technology can therefore play a key role for the development of smart cities and intelligent roadside-infrastructure having ultra-low latency network to exchange real-time information between vehicles and roadside-

TABLE 1 Wireless technology comparison for vehicular networking

Vehicular technology	5G (mmWave)	IEEE-802-11p
Type of communications	V2X	V2X
Speed	High speed capacity	High speed capacity (doppler spread sensitive)
Capacity	20 Gbps (Max)	3–54 Mbps
Bandwidth	Sub-6 GHz and mmWave	75 MHz
Communication technology	OFDM with CSMA	5G NR air interface alongside OFDM
Security		Public key infrastructures with cryptography
Quality of service (Qos)	SAE Bearer; PER, GBR, MBR	EDCA parameters (802.11 e)
Deployment and scalability	Upgraded the existing cellular infrastructure	Deployment of access points and gateways

infrastructure [15, 16]. The 5th generation technology is already launched to tackle these cellular issues for vehicular communication. The implementation of 5G technology permits vehicular communication to manage traffic systems efficiently and adjust the traffic routes according to the situation by providing the best available routes towards destination [17]. The 5G cellular technology exploiting mmWave technology is fundamental to provide ultra-low latency services. mmWave technology uses the spectrum between 30 GHz to 300 GHz, having the channelization of 2.16 GHz with the carrier frequencies spreading around 60 GHz. The mmWave technology in 5G uses beamforming techniques with attain high-array gains by deploying large antenna arrays that would help to attain higher data-rates normally goes up-to several Gbps [18]. Similarly, the initial mmWave standard by IEEE is 802.11ay to completely define PHY and MAC layers to allow fixed radio access in an unlicensed spectrum of 60 GHz. It would be able to provide a data-rate up-to 7 Gbps with an end-to-end network latency of less than 10 ms. Moreover, under ideal transmission conditions, undoubtedly mmWave technology outperforms LTE/LTE-A and IEEE802.11p/DSRC standards for V2X communication [19, 20]. Table 1 presents a comparison between 5G (mmWave) technology and IEEE802.11p.

5 | TEST LOCATIONS

In the pilot filed measurements, we have used two testing locations called Sod5G and Petäjämaa. These two locations are developed by the FMI for real-time field measurements. These locations are equipped with two road-weather-stations, one 5G test network base station, IoT sensors for road weather and traffic data collections. Figure 3 illustrates the testing equipment's on the test track with red spots showing the IoT sensors for road weather and traffic data collection. These testing sites are used for different research purposes, as defined below. The Petäjämaa test site is used for the following field measurements.

1. Road weather and traffic data collection that is, road temperature measurement, wind direction and speed, air speed and temperature, weather cameras, visibility, snow and frost depth measurements, friction measurements (both RWS and vehicle).
2. Special field measurements data analysis supporting VANET protocols.

The second test site is Sod5G; http://sod5g.fmi.fi. This test site is featured with state-of-the-art 5G-test network base station working at 2.3 GHz band. This 5GTN works standalone separately from the public wireless network. This test track also supports Wi-Fi and ITS-G5 protocols with two road-weather-stations (2 RWS). The length of this test site is the 1.7 km (gravel/concrete), as presented in Figure 3. The devices used for pilot field measurements includes Sunit vehicle PCs, Cohda MK5 transceivers, Teconers, Lufft MarwisUMB, conventional laptops, Android tablets and 5G test network supported phones.

6 | PILOT FIELD MEASUREMENTS SET-UP

In this section, we discuss the deployment and execution of pilot measurements in the V2V and V2I scenarios. These field measurements are aimed to evaluate and validate the performance of heterogeneous network (IEEE-802.11p and 5GTN) in realistic environments. Table 2 shows the technical parameters settings for the field measurements. As mentioned earlier, the test sites are featured with different sensors and RWSs, cameras etc., as presented in Figure 3. For our pilot measurements on test track, we have used Cohda MK5 (Wireless Transceivers), laptops or android tablets. In vehicles we have used On-board Units (OBUs) and SUNIT F-series vehicle PC as a User-Interface (UI). The OBUs delivers the relevant messages between vehicles and road-side infrastructure. Figure 4 illustrates the connection setup and operational process in the V2V and V2I communication scenarios using road weather and traffic data. For our pilot measurements, we have developed a Python program in a vehicle PC (Sunit). When the field measurements are conducted, all the programs start processing simultaneously in vehicles and RWSs. The vehicle radios continuously search the nearby IEEE 802.11p/5GTN networks to make a connection by transmitting bacon (Hello) messages.

After the establishing a connection with IEEE-802.11p /5GTN the vehicles start exchanging the data, first in the V2I mode and then in the V2V mode. The information is collected and broadcasted with the help of the transfer layer that safeguards the networking between local server of FMI, RWSs and OBUs. The OBUs collects the real-time road weather and traffic data using cellular and IEEE 802–11p networks. The integration of these IEEE 802–11p and 5GTN networks on

FIGURE 3 Test track (Sod5G and Petäjämaa) equipped with testing infrastructure

TABLE 2 Parameter settings of IEEE-802.11p and 5GTN

Parameter	IEEE-802.11p setting	5GTN setting
Transmit power range (dBm)	−10 to +23	41.8
Channel bandwidth (MHz)	5, 10, 20	40
Data rate (Mbps)	27/54	10 (each user)
Operating frequency (GHz)	5.9	2.3
Data traffic (us)	Bi-directional	66.66
Symbol duration (us)	16, 8, 4	Bi-directional
Temperature (°C)	−40 °C to +85	−40 to +85
Supply voltage (volts)	12	230
Max transmission range	1000 m	1000–2000 m
Modulation schemes	BPSK, QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM
Antenna gain (dBi)	3	16

a single platform ensures the seamless networking between OBUs and RWSs.

7 | RESULTS AND ANALYSIS: CELLULAR VS IEEE-802.11P (DSRC)

This section discusses the results our pilot field measurements utilizing road weather and traffic data in the V2V and V2I scenarios. One method to carry out a performance comparison of IEEE-802.11p and 5G can be performed by considering real-time performance tests in outdoor conditions in the same environment. Field measurement results provides the opportunity to make a fair comparison between IEEE 802.11p and 5GTN. In this performance analysis and comparison, the 5GTN is marginally extra sensitive to the locations where the signals are received by the user form more than one transmitter with different level of powers that is, the near-far problem,

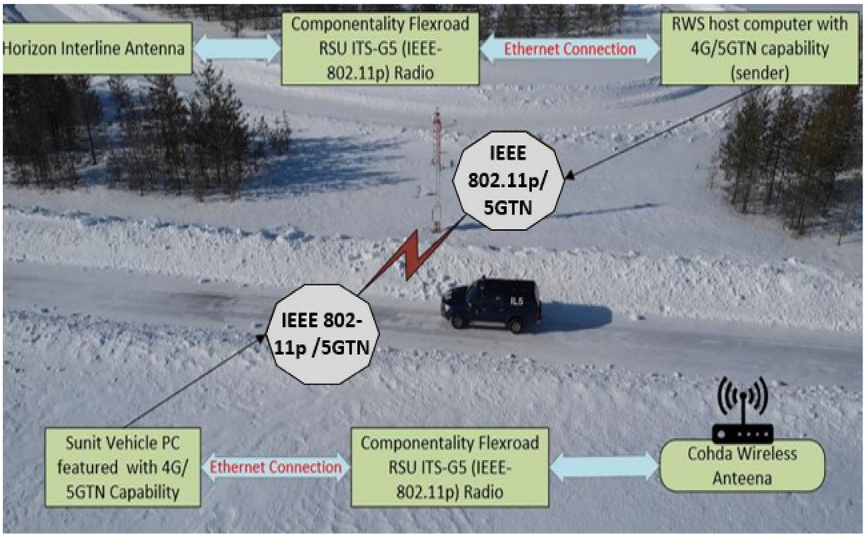

FIGURE 4 Connection setup and operational process using wireless technologies

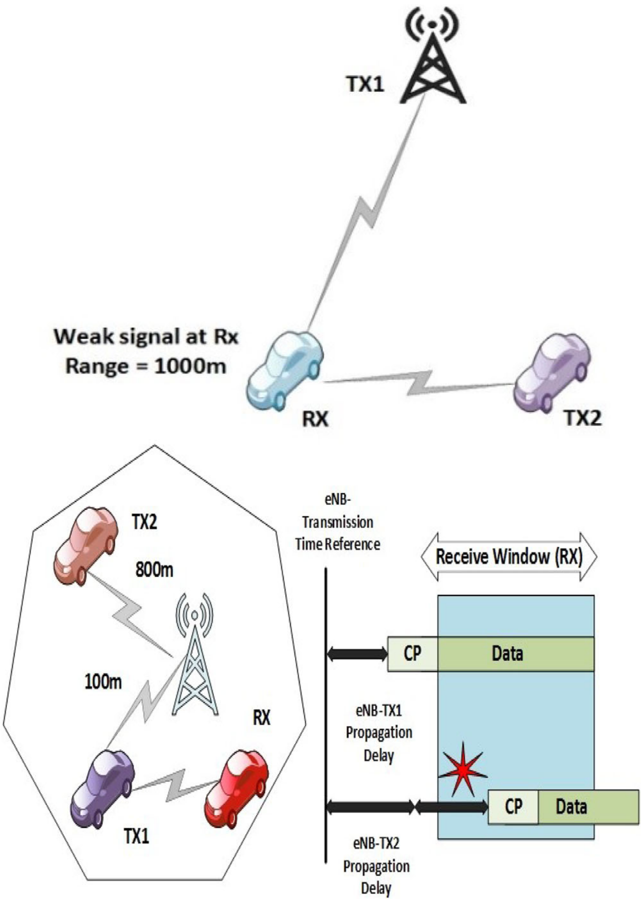

FIGURE 5 ITS protocols effect of cyclic prefix in distance [14]

as presented in Figure 5. Variation in the power levels might arise even for two adjacent wireless transmitters, even though one of the transmitters (Tx) is blocked/obstructed. Meanwhile, IEEE 802.11p allows each user to transfer in a separate OFDM symbol, and according to the situation the receiver can change its parameter settings for example, time offset estimation, automatic gain controller (AGC) and autonomous estimation of frequency offset in an ideal situation for each user. Conversely, the 5GTN offers similar kinds of resources for users within same OFDM symbol but the receiver (Rx) adapts its AGC gain depending on the specific combined signal. Therefore, in the 5GTN, the capacity of the receiver (Rx) to identify the weak messages in the presence of strong messages is limited [21].

Our results reveal that, the messages with weak signal strength might have higher significance in contrast to strong signals. For example, if we consider TCP connection, a safety critical message with low power can be obtained from a vehicle OBU with a lag, and a previously received message with good power quality can be ignored. This kind of low significance to good power quality of safety critical messages might make communication risky. Table 3 presents a performance analysis and comparison between IEEE 802.11p and 5GTN. These two technologies provide a deep insight of their performance analysis. The 5GTN shows advantage over IEEE-802.11p in terms of communication range on a test track. Table 3 and Figure 6 reveal that the performance of 5GTN is better in the transmission of UDP data packets. The light green and dark green colour show the data packet capture by using 5GTN and the orange colour shows the data packet capture by IEEE 802.11p. The IEEE 802.11p needs the deployment of more APs and gateways that increases the cost as well as deployment time [14, 22, 23].

The above-mentioned comparative Table 3 shows that the field measurements provide a 5GTN communication range between 1000–1700 m and the IEEE 802.11p 500–1000 m. Unfortunately, the 5G-V2X complete pilot measurements were not conducted and presented yet for comparison because 5GV2X is not standardized yet. In the meantime, the IEEE 802.11p synchronization concept restricts the network range for communication in vehicular networks. It is due to the new role assigned to the cyclic prefix (CP), as shown in Figure 5 and Table 3. Figure 7 illustrates the network latency of 5GTN and IEEE 802.11p. Figure 7 and Table 3 show that the network latency and jitter measurements in the 5GTN network are

TABLE 3 Wireless transmission protocols comparison

Parameter	IEEE-802.11p (DSRC)	5GTN
Range (m)	500–1000	1000–1700
Jitter (ms)	2.46	3.89
Throughput (Mbps)	1.79	2.45
Packet loss (%)	10	18.3
Network latency (ms)	39.23	62.67
Cyclic-prefix (CP)	1.70 μs	4.51 μs
Purpose of cyclic-prefix (CP)	Delay spread	Timing errors, propagation time and delay spread

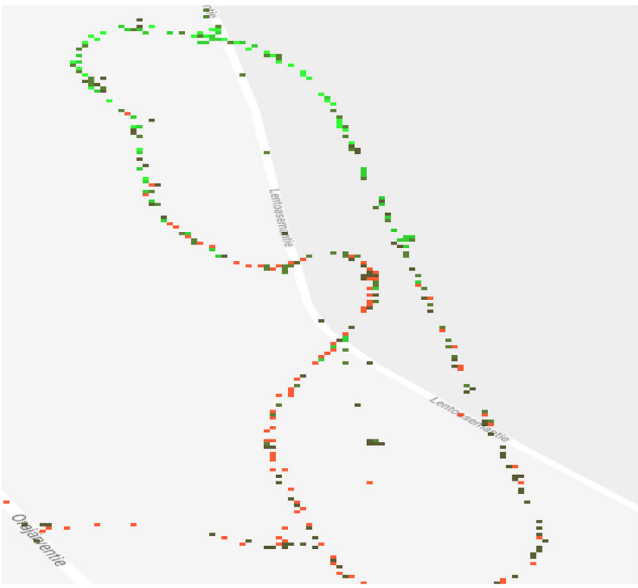

FIGURE 6 Data packet capture using 5GTN and IEEE 802.11p

slightly higher as compared to the IEEE 802.11p case. The large latency and jitter in 5GTN are based on the test track interferences (multifrequency signals of other networks). This latency is also due to the network coverage holes on test track. The network latency in 5GTN is also affected by the OFDM symbol duration, that is restricted by the CP length. Even the latency is slightly high in 5GTN, but the Figure 8 shows that it has a better throughput in contrast to IEEE 802.11p. This is because of improved robustness for packet loss in access-layer, better transmission bandwidth and dual carrier modulation. But still 5GTN needs time to roll-out entirely for V2X applications, as compared to IEEE-802.11p.

8 | CONCLUSION

In VANETs, communications between vehicles and roadside-infrastructure are expected to offer significant assistance for road safety. The VANET communication platform also supports an advanced road traffic management. To achieve this

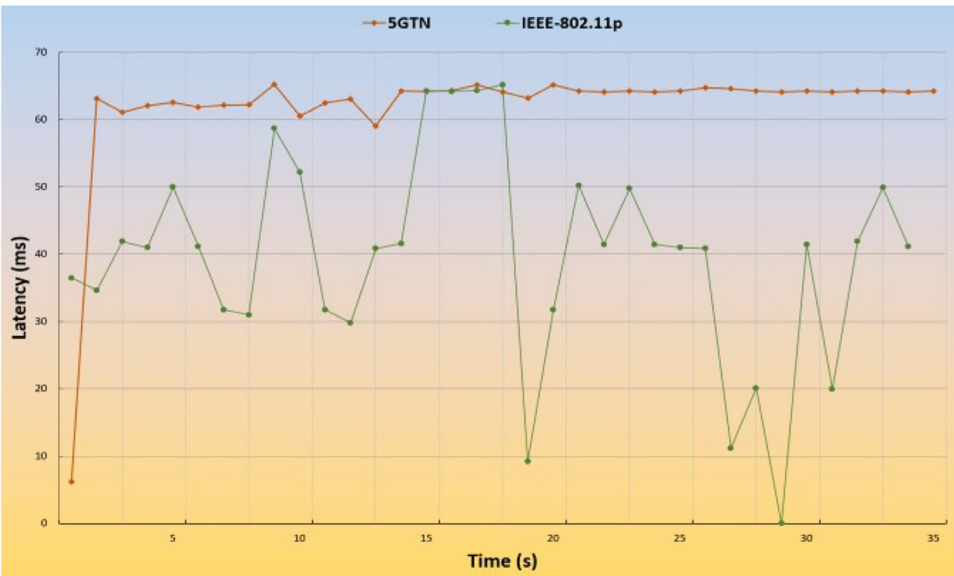

FIGURE 7 Network latency comparison between 5GTN and IEEE 802.11p

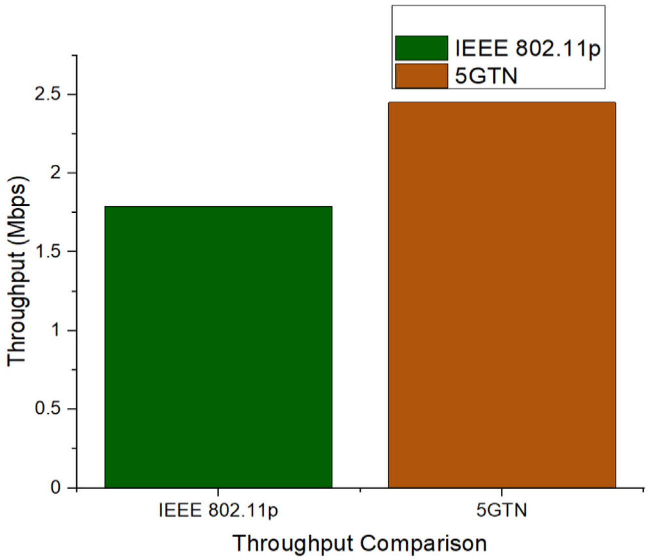

FIGURE 8 Throughput comparison between 5GTN and IEEE 802.11p

road safety, we have designed and developed an ITS-assisted road weather and traffic infrastructure facilitated by IEEE 802.11p and 5GTN at FMI, Sodankylä, Finland. This paper provided performance comparison between IEEE 802.11p and the next generation 5G test network by using road weather and traffic data. This comparative analysis of vehicular communication technologies includes jitter, range, throughput, packet loss, network latency, coverage, and cyclic prefix. The field measurement results show that both networks worked in a cooperative fashion. The IEEE 802.11p offers a reasonable performance with restricted mobility and assistance in contrast to 5G. Moreover, 5G also fulfils many of the VANET application requirements considering jitter, range, throughput, packet loss, network latency, coverage, and cyclic prefix. The important factor in our filed measurements is latency and it is less than the 100 ms for both wireless technologies [24, 25]. Therefore, the expected development of V2X applications in 5G will make more meaning by having more potential for future ITS applications. Meanwhile, many ITS applications established on IEEE-802.11p will further develop in the near future.

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CONFLICT OF INTEREST

The author does not have any conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

N/A

ORCID

Muhammad Naeem Tahir https://orcid.org/0000-0002-6346-2427

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