Performance Analysis of an OFDM-based Method for V2X Communication

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***Abstract* — In an effort to enhance traffic safety by employing advanced wireless communication systems, intensive investigations and research are in progress worldwide. V2X communication is one core solution for governing and advancing future traffic safety and mobility. This paper presents a performance analysis of OFDM-based systems for V2X communication, to guarantee frequency non-selectivity and minimum ICI (Inter-Carrier-Interference). Most importantly, this analysis aims to mitigate the Doppler spread due to vehicles moving at high speeds.**

***Index Terms*—V2X, OFDM, Doppler spread, Delay spread, ICI, Slow fading, Frequency selective fading**

I. Introduction

V2X (Vehicle-to-Vehicle/Infrastructure/Nomadic devices) communication systems provide new communication capabilities between vehicles, traffic operators, and service providers based on DSRC (Dedicated Short Range Communication) technology. In this system, each vehicle can collect and share information to be utilized for collision avoidance, emergency vehicle warnings, traffic condition warnings, hazardous location notifications, wrong-way driving warnings, lane change assistance, and slow driving warnings. There are several challenges in the vehicular communication environment due to the randomly time varying nature of the channel. The challenging properties of the vehicular channel have a substantial impact on wireless communication system design. Currently, the IEEE 802.11p standard is utilized for V2X communication. This standard is based on the IEEE 802.11a standard, commonly referred to as the Wi-Fi standard. IEEE 802.11p adopts OFDM to compensate for both time and frequency fading [1] due to the movement of both communicating terminals and objects in the environment. The objective of the proposed scheme is to optimize the following requirements:

(1) Frequency non-selective fading
(2) Slowly fading
(3) Minimum ICI (Inter-Carrier Interference)
(4) Validating the channel estimation: With respect to channel coherence time, channel estimation in the IEEE 802.11a standard occurs at the beginning of a packet, and this estimate is used for the remainder of the packet. (We have to determine the duration of a packet considering the coherence time.)

We must consider the Doppler spread as one of the basic parameters when designing an OFDM system, especially for vehicular communication. Doppler spread primarily depends on vehicle speed, and it has an inverse relationship with coherence time. Coherence time is the short time period when the channel remains time-invariant. Because of short coherence time, fast fading frequently occurs in vehicular communication when those vehicles are traveling at high speeds. Fast fading degrades the performance and robustness of the system. To solve this problem, we present a modified OFDM-based scheme for V2X communication when vehicle speed is high.

The remainder of the paper is organized as follows: section II presents previous V2X communication research. In section III, we present vehicular channel characteristic analysis. The details of the proposed OFDM-based method for V2X are presented in Section IV. The performance analysis scenarios and results are also demonstrated in Section IV. We present our conclusions in Section V.

II. Previous Works

To enhance the capability of the ITS (Intelligent Transport System) to advance road safety improvements and promote favorable driving environments, several research papers have been published [2-12]. Understanding vehicular channel characteristics is one of the significant research issues in V2X communication. To assist communication systems designers, several measurement-based studies have been performed to enhance understanding of V2X channel properties. Vehicular channels are generally characterized by a path loss exponent [8-10], the RMS delay and Doppler spreads [7, 8, 11], the PDP (Power Delay Profile), and the DSD (Doppler power Spectral Density). The smallest value of RMS delay spread is obtained in rural environments [7, 12], and the largest is obtained in urban environments [5, 11-12]. In [13], Doppler spread and coherence time from the vehicle-to-vehicle channel is presented. They observed the dependency of Doppler spread on the effective speed of vehicles, as well as the residual Doppler spread when the vehicles are stationary, which is caused by the motion of other vehicles. It was also observed that coherence time depends on the distance separating the vehicles. Finally, after observing the OFDM parameters for vehicular communication, the authors claimed that further consideration is needed because coherence time is usually significantly shorter than the typical packet duration. Various methods have been proposed to reduce the impact of multiple channel fades over the course of a packet. A pilot-based OFDM scheme for channel estimation was proposed in [14]. This scheme demonstrated potential for Doppler spreads up to 200 Hz; however, Doppler spread in vehicular communication can be as high as 2 KHz [4, 15]. A modification of the coherent OFDM structure of DSRC, referred to as time-domain differential OFDM, has been proposed [16] for providing robustness to short coherence time.

III. Channel Characteristic Analysis for Vehicular Communication

Because the vehicular environment changes rapidly with respect to vehicle speed and location, as well as signal scatters, channel characteristics are not static. V2V and V2I channels not only differ from each other, but also deviate from cellular communications. One of the major impairments of the vehicular channel is high Doppler spread. When vehicles are moving at high speeds, the observed frequency of each signal component will be Doppler shifted, resulting in frequency deviation from the receiver side carrier frequency compared to the transmitted signal. This broadened spectrum results in the time-variant behavior of the V2X channel. The maximum Doppler frequency in V2X communication can be up to four times higher than a cellular channel at the same velocity [17]. This is due to the movement of both Tx and Rx, as well as the relevant scatters in the V2X scenario. In wireless cellular communications, Doppler spread f_D is expressed as [18]

$$f_D = \frac{v_r}{c} f_0 \tag{1}$$

where c is the speed of light, f_0 is the transmission carrier frequency, and v_r is the relative velocity. However, in V2X communication channels, an empirical dependence of Doppler spread on effective speed, v_{eff} ($v_{eff} = \sqrt{v_R^2 + v_T^2}$) is obtained as [19]

$$f_D = \left(\frac{0.428}{\lambda\sqrt{2}}\right) v_{eff} + 11.5 \tag{2}$$

where λ is the wavelength of the carrier signal. Doppler spread largely depends on the environment type, such as rural, highway, or suburban. Another parameter directly related to the performance of vehicular communication channels is the coherence time. The coherence time is defined as the time interval over which the channel impulse responses are invariant. Coherence time also assists in determining whether the time-variant nature of the channel can be regarded as fast fading or slow fading. The inverse relationship between the coherence time and the Doppler spread was demonstrated in cellular studies, and a rule of thumb relation between the coherence time and the Doppler spread is provided by [20]

$$T_c \approx \frac{0.423}{f_D} \tag{3}$$

where T_c is the coherence time. However, the proportionality constant that relates the two parameters is not determined completely in the V2X environment. Therefore, we prefer to use the coherence time given by [21, 22]

$$T_c = \frac{M}{f_D} \tag{4}$$

where M varies between 0.25 and 1. In several research papers [14, 19], an autocorrelation function has been utilized to compute the coherence time directly from the measured time-domain signal. To guarantee slow fading, symbol duration must be shorter than coherence time.

For vehicular communication systems, the IEEE 802.11p standard is derived from the IEEE 802.11a standard, which is based on OFDM. In wireless communications, one of the significant problems is multipath delay, which degrades the desired signal with time-delay and causes ISI (Inter-Symbol-Interference). To completely prevent this in OFDM systems, a guard interval is introduced at the beginning of each time-domain symbol. The duration of the guard interval depends on the delay spread, and it should be approximately two to four times the RMS delay spread [23]. A cyclic prefix, which is a repetition of the OFDM signal, is also used in the guard interval to prevent ICI. In the frequency domain, the signal can suffer frequency selective fading. To overcome frequency selective fading, an OFDM system modulates data on multiple subcarriers. Additionally, the OFDM symbol duration should be at least five times the guard time, which implies a 1 dB SNR loss because of guard time [23]. The subcarrier spacing, defined by spacing between adjacent subcarriers, is half of each subcarrier bandwidth as

$$\Delta f = \frac{B_s}{2N_s} \tag{5}$$

where B_s is the system bandwidth and N_s is the total number of subcarriers. It is important to note that subcarrier spacing must be much larger than the maximum Doppler spread, otherwise Doppler spread may cause ICI. It can be reasonably assumed that the channel is flat if the coherence bandwidth is greater than the total system bandwidth and the coherence bandwidth is estimated as [17]

$$B_{coh} \approx \frac{1}{2\pi\tau_{rms}} \tag{6}$$

where τ_{rms} is the RMS delay spread of the channel.

IV. Performance Analysis of OFDM-based Scheme

To verify the proposed OFDM-based scheme for V2X communication, consider different scenarios in vehicular environments. In every scenario, system design parameters are analyzed for the OFDM-based scheme. In the first scenario, vehicles are moving in an urban region, the speeds of the vehicles are less than 20 km/h (or 6 m/s). In this scenario, vehicular communication suffers primarily from multipath effects caused by the urban area's infrastructure and the movement of other vehicles around the Tx and Rx vehicles. The second scenario is set in a rural area, where the vehicles are moving at moderate speeds, such as 55 km/h to 60 km/h (or 16.67 m/s). In this scenario, the communication signal suffers from both multipath and Doppler spread. The third scenario represents a highway environment where vehicles are moving at high speeds above 130 km/h (or 36 m/s). In highway vehicular communication, signals mainly suffer from Doppler spread, which depends on vehicle speed as well as separation distance between the Tx and Rx vehicles. At high speeds observed in the highway environment, vehicular communication system performance decreases because of both short coherence time and large Doppler spread. By analyzing system parameters of the OFDM-based scheme, we can optimize the requirements for vehicular communication, and establish a more reliable, secure, and efficient scheme for V2X communication.

Table 1 presents parameter symbols employed for performance analysis. Table 2 and Table 3 present parameter analysis results to investigate the satisfaction of four requirements when the data rate is 1 Mbps and 10 Mbps, respectively.

TABLE 1. SYMBOLS OF PARAMETERS USED FOR PERFORMANCE ANALYSIS.

Symbol	Parameter	Symbol	Parameter
N_s	Number of sub-carriers	f_D	Doppler spread
τ_{RMS}	RMS Delay spread	Δf	Sub-carrier spacing
R_D	Data rate	T_c	Coherence time
T_{GI}	Guard time	T_s	OFDM Symbol duration
B_{coh}	Coherence bandwidth	T_p	Packet length

TABLE 2. PARAMETER ANALYSIS FOR SCENARIO. (HIGHWAY-NLOS, R_D = 1Mbps)

Symbol	Case 1	Case 2	Case 3	Case 4	Remarks
N_s	1024	256	128	64	
τ_{RMS} [ns]	500	500	500	500	Ref. [15]
T_{GI} [ns]	2000	2000	2000	2000	Vehicular
B_{coh} [kHz]	318	318	318	318	$B_{coh} \approx \frac{1}{2\pi\tau_{rms}}$
T_{GI} [MHz]	1	1	1	1	$B_{coh} = \frac{1}{2\tau_{rms}}$ Ref. [20]
f_D [Hz]	710	710	710	710	cellular
	1000	1000	1000	1000	Vehicular Ref. [15]
Δf [Hz]	0.49	1.95	3.91	7.81	
T_c [µs]	595.77	595.77	595.77	595.77	rule of thumb for cellular
	250	250	250	250	$T_c = \frac{M}{f_D}, M = 0.25$
T_s [µs]	1024	256	128	64	$T_s = \frac{N_s}{Data\_rate}$
T_p			< 2	< 4	No. of OFDM symbols

TABLE 3. PARAMETERS ANALYSIS FOR SCENARIO. (HIGHWAY-NLOS, R_D = 10Mbps).

Symbol	Case 1	Case 2	Case 3	Case 4	Remarks
N_s	1024	256	128	64	
τ_{RMS} [ns]	500	500	500	500	Ref. [15]
T_{GI} [ns]	2000	2000	2000	2000	Vehicular
B_{coh} [kHz]	318	318	318	318	$B_{coh} \approx \frac{1}{2\pi\tau_{rms}}$
T_{GI} [MHz]	1	1	1	1	$B_{coh} = \frac{1}{2\tau_{rms}}$ Ref. [20]
f_D [Hz]	710	710	710	710	cellular
	1000	1000	1000	1000	Vehicular Ref. [15]
Δf [Hz]	4.9	19.5	39.1	78.1	
T_c [µs]	595.77	595.77	595.77	595.77	rule of thumb for cellular
	250	250	250	250	$T_c = \frac{M}{f_D}, M = 0.25$
T_s [µs]	102.4	25.6	12.8	6.4	$T_s = \frac{N_s}{Data\_rate}$
T_p	< 3	< 10	< 20	< 40	No. of OFDM symbols

From Fig. 1, we can observe that Doppler range (or coherence time) increases (or decreases) when the relative speed increases. When the relative speed is 200 km/h, Doppler range (or coherence time) has a value of 1000 Hz (or 250 µs). Fig. 2 presents the sub-carrier bandwidth versus data rate and Fig. 3 presents the OFDM symbol time versus data rate for various number of sub-carriers. From Fig. 2, we may prefer to decrease the number of sub-carriers to minimize ICI when the data rate is increasing. It is important to note that Fig. 3 can be useful for determining the number of sub-carriers, to guarantee frequency non-selective fading and slow fading, depending on the data rate.

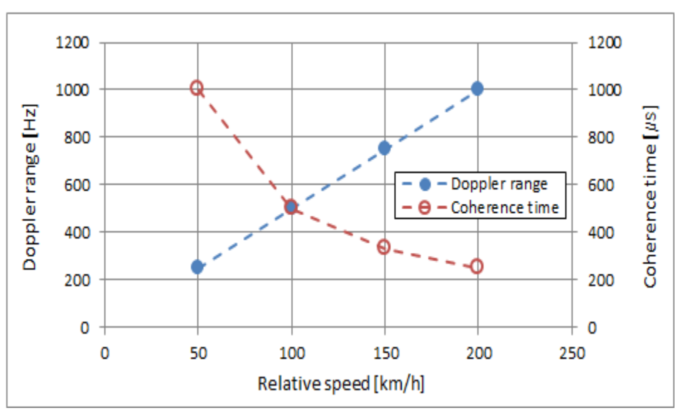

Fig. 1. Doppler range (Coherence time) vs. Relative speed.

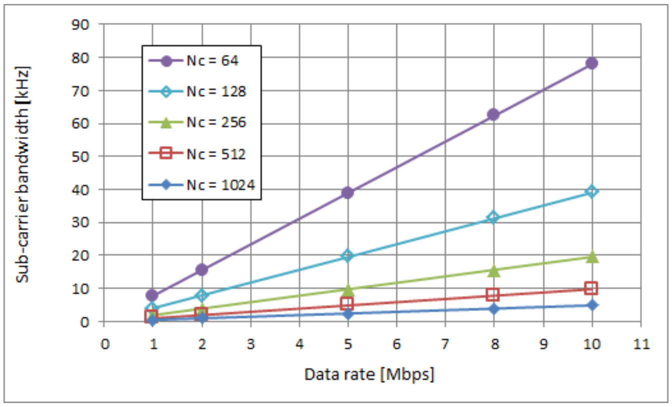

Fig. 2. Sub-carrier bandwidth vs. Data rate.

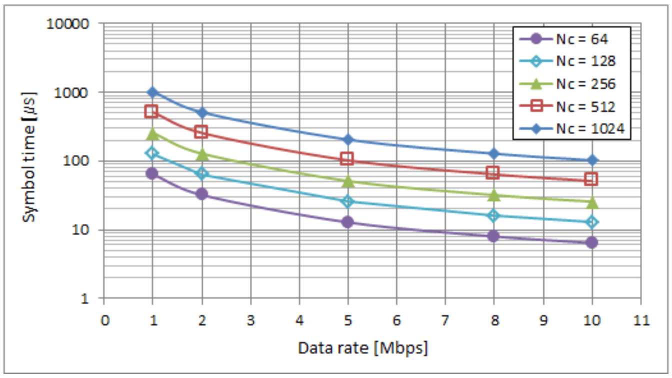

Fig. 3. OFDM symbol time vs. Data rate.

If we are compelled to reduce the number of sub-carriers to prevent fast fading, while maintaining the total number of users as the case of $N_s = 1024$, we may consider the OFDM-based structure of Fig. 4. In this instance, the total number of users is derived by multiplying the number of sub-carriers by the processing gain of DSSS (Direct Sequence Spread Spectrum).

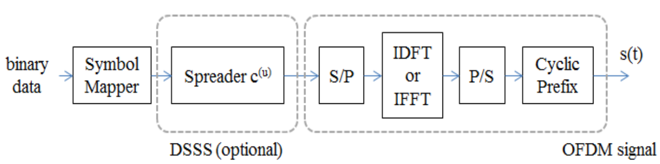

Fig. 4. Hybrid DSSS-OFDM structure.

Scenario example for numerical analysis: The scenario represents the highway-NLOS environment where a vehicle accelerates, increasing its relative speed from 50 to 200 km/h while maintaining a constant data rate of 1 Mbps. Subsequently, while driving 200 km/h of relative speed, data rate is increased from 1 Mbps to 10 Mbps.

To demonstrate a possible solution, the results of the performance analysis to optimize the requirements are summarized in Tables 4 and 5. Based on these results, we can easily know that the smaller number of subcarriers is preferred to guarantee slow fading and minimum ICI when the relative speed is increasing from 50 to 200 km/h, while maintaining the constant data rate of 1 Mbps. When the data rate is increasing from 1 Mbps to 10 Mbps under a relative speed of 200 km/h, the larger number of subcarriers is preferred to satisfy the requirements, especially to prevent frequency selective fading.

TABLE 4. PERFORMANCE ANALYSIS RESULTS FOR SCENARIO EXAMPLE. (DATA RATE = 1 Mbps, RELATIVE SPEED = 200 km/h)

	64	128	256	512	1024
Req. (1)	Y	Y	Y	Y	Y
Req. (2)	Y	Y	M	N	N
Req. (3)	Y	Y	M	N	N
Req. (4)	Y	M	N	N	N

Y: Yes, N: No, M: Marginal

TABLE 5. PERFORMANCE ANALYSIS RESULTS FOR SCENARIO EXAMPLE. (DATA RATE = 10 Mbps, RELATIVE SPEED = 200 km/h)

	64	128	256	512	1024
Req. (1)	N	N	M	Y	**Y**
Req. (2)	Y	Y	Y	Y	**Y**
Req. (3)	Y	Y	Y	Y	**Y**
Req. (4)	Y	Y	Y	Y	**Y**

V. CONCLUSION

We presented the performance analysis results of an OFDM-based scheme for V2X, which was designed to optimize requirements such as frequency non-selective fading, slow fading, minimum ICI, and valid channel estimation. These results provided the information needed to further refine the OFDM-based system to guarantee more reliable, secure, and efficient V2X communication. The validity of our analysis was demonstrated through numerical analysis combined with scenario examples.

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