

Hybrid Fully Generalized Spatial Modulation for mmWave Vehicular Communications

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Abstract

This article addresses the challenge of achieving high spectral efficiency (SE) in millimeter wave (mmWave) vehicular communications. Traditional approaches using conventional multiple input multiple output (MIMO) systems face complexity and cost issues, compounded by the rapid mobility of vehicles. A promising technique, Fully Generalized Spatial Modulation (FGSM), has been proposed for enhancing SE with low complexity. However, its application in vehicular environments remains limited. To fill this gap this article introduces a novel approach termed Hybrid-Fully Generalized Spatial Modulation (H-FGSM) for vehicular communication. H-FGSM not only boosts spectral efficiency and achievable data rates but also incorporates hybrid beamforming at the transmitter to enhance vehicle connectivity. Our numerical analysis demonstrates that the proposed H-FGSM outperforms baseline schemes, achieving higher data rates and improvements in system error rates, as exhibiting a 2 dB improvement in Bit Error Rate (BER) performance and a 30 bits per channel use (bpcu) disparity in attainable achievable data rate when the Signal-to-Noise Ratio (SNR) is higher.

1. Introduction

Recently, lower frequency bands (e.g., microwave) for cellular communication systems have nearly depleted, implying that future cellular networks will require frequency bands beyond the existing range such as millimeter wave (mmWave) or terahertz [1]. In comparison to the fourth generation network, the (fifth generation (5G)) cellular network is planned to provide 1000 times the system capacity, 10 times the spectral efficiency (SE), energy efficiency (EE), and data rate, and 25 times the average cell throughput [2].

The nature of higher frequency communications will face a loss of orders of magnitude and increased path loss. To combat the substantial path loss and greatly improve system capacity and dependability of higher frequency bands, large-scale antenna MIMO arrays with beamforming must be deployed resulting in greater SE and beamforming advantages [3-5].

Furthermore, the existing digital beamforming MIMO technology necessitates a distinct radio frequency (RF) chain for each antenna. It will therefore be quite expensive and complicated. Incorporating huge MIMO antennas into 5G communication systems poses difficulties and constraints, especially when dealing with mmWave channels and the requirement for full transceivers to support digital beamforming architecture. While hybrid

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analog and digital beamforming MIMO systems claim to simplify the hardware and lower its expense by using fewer RF chains [6-9]. For instance, beamforming enhances signal strength and mitigates interference by directing the signal in precise directions. Nevertheless, traditional analog and digital beamforming techniques may encounter difficulties in coping with the rapid movement and constantly changing conditions of automotive environments. Although hybrid beamforming presents a promising solution for automotive environments, rather it encounters difficulties in achieving optimal beam alignment and managing interference [10, 11].

To date, the use of space modulation techniques (SMTs) like spatial modulation (SM) and fully generalized spatial modulation (FGSM) are potential MIMO approaches in terms of SE, EE, and system complexity [12]. This can be likely accomplished using a simple coding process that generates a one-to-one mapping between transmitted bits and transmits antenna spatial positions. Despite that, SMTs have a significant disadvantage, which is reflected in the logarithmic relationship between the number of transmit antennas (N_t) and the possible data rates [13]. FGSM schemes are created by extending the concept of SM to accommodate only one or multiple active transmit antennas at any given time rather than one.

Thus far, research has demonstrated that FGSM hybrid beamforming is effective in addressing the difficulties presented by unpredictable vehicle situations. FGSM can effectively improve the alignment of beams and minimize interference, resulting in enhanced reliability of communication links [14]. The great spatial selectivity of mmWave channels may be handled by FGSM hybrid beamforming, increasing system throughput overall [11]. The resilience of FGSM hybrid beamforming to different kinds of signal impairments is also highlighted by the research, which makes it a very dependable option for real-world vehicular applications [15].

Against this background, there is a great incentive and interest in investigating an FGSM and MIMO Hybrid beamforming-based solution for vehicular communication systems to benefit from multiple antenna gain with massive MIMO while also minimizing the number of RF chains. Nevertheless, there has not been much focus on the combination of huge MIMO, hybrid beamforming, and FGSM. To the best of the author's knowledge, no systematic investigations in the literature discussing hybrid beamforming with FGSM in vehicular communication until the current authors presented Hybrid fully generalized spatial modulation (H-FGSM).

A novel contribution of this article is to expand on the work of a hybrid SM beamforming strategy for high-speed railway (HSR) wireless communication systems operating in the mmWave frequency bands presented in [7] and provide a hybrid beamforming FGSM-based solution that takes advantage of the features of FGSM in a vehicular context. Then, the suggested method is compared to the prevalent hybrid beamforming SM, which can almost attain low computational complexity by using a lower number of RF chains, linear receive processing is considered, and a detailed performance evaluation using several performance measures, such as bit error rate (BER) and achievable data rate as SE, is also provided. This article's contributions can be summarized as follows:

- The Hybrid-Fully Generalized Spatial Modulation (H-FGSM) is a suggested new space modulation technology. The main idea behind the proposed schemes is first to employ a hybrid beamforming technique to reduce the complexity of the antenna model by using fewer RF chains and then use a variable number of transmit antennas to emit information using the FGSM technique. The proposed schemes' system models are also presented.
- A novel mathematical approach is developed and elaborated for evaluating the H-FGSM's achievable data rate (R_{H-FGSM}) performance. This framework attempts to generalize analytical analysis and provide closed-form equations for the (R_{H-SM}) of the H-SM.

The remainder of this article is organized as follows. A synopsis of the literature review is outlined in Section 2. The system model is described in Section 3. The suggested hybrid FGSM beamforming method is described in depth in Section 4. Section 5 discusses the simulation's numerical results and findings. Our concluding remarks are provided in Section 6.

2. Literature Review

In exploring advancements in mmWave communication technologies, several studies have highlighted the integration of spatial modulation (SM) techniques to enhance system performance. A hybrid spatial modulation beamforming scheme was put forth to enhance mmWave railway communication systems. According to the research, hybrid SM beamforming can achieve a compromise between complexity and performance, especially in high-speed rail (HSR) settings. The theoretical and numerical investigations demonstrated substantial enhancements in system efficiency [7].

Likewise, in [16] multi-user massive MIMO mmWave networks were examined hybrid beamforming incorporating spatial modulation. Their model outperformed conventional multi-user SM methods that use a few transmit antennas per array by a substantial margin of 5 dB. This improvement was achieved by integrating hybrid beamforming at the transmitter and digital combining at the receiver. With an emphasis on scalability and efficiency, this performance could be further improved by increasing the number of transmit antennas without requiring additional RF chains.

The connectivity difficulties in mmWave vehicular networks were specifically addressed, recognizing the directional benefits of mmWave technologies that provide beamforming between communication endpoints in [17], nevertheless, they also highlighted notable challenges such as considerable signal attenuation and restricted coverage distances, which are crucial in vehicular communication setting.

Research has proposed a new idea called spatial path index modulation (SPIM) to enhance mmWave hybrid beamforming. The SPIM-mmWave MIMO solution combines mmWave technology with index modulation (IM) techniques to potentially surpass the performance of current mmWave MIMO systems. This novel technique utilizes the information-driven random-switching principle of IM, providing a fresh viewpoint in mmWave MIMO applications [18].

Research has analyzed the error performance of a vehicular Rayleigh fading spatial modulation communication system, in which the variability of the fading channel is affected by the movement of vehicles [15]. Finally, the capability of spatial modulation to support 5G Vehicle-to-Everything (V2X) services was underscored by research concerning the deployment of 5G Cellular Vehicle-to-Everything (C-V2X) via Vehicle-to-Network (V2N) connectivity. The study emphasized the pragmatic viability and advantages of integrating SM into 5G frameworks, specifically in terms of improving communications between vehicles and other objects [19].

The aforementioned studies highlight the revolutionary capacity of hybrid beamforming and spatial modulation methods in diverse mmWave communication environments, ranging from high-speed rail to vehicular systems. They provide valuable perspectives on the prospects and obstacles that lie ahead in this dynamic domain. Nonetheless, neglecting to improve the achievable transmission rate. The insights provided serve as a strong basis for the H-FGSM suggested model, showcasing the advantages of combining spatial modulation with beamforming. By incorporating these strategies, the proposed model seeks to improve the spectral efficiency. It particularly focuses on high mobility where past restrictions can be overcome.

3. System Model

The suggested H-FGSM for vehicular communication networks was investigated using the system model depicted in Fig. 1. which presents an H-FGSM-based MIMO communication system with four RF , and N_t transmit antennas. The digital precoder consists of four baseband processing units, which are in charge of power allocation. The four RF symbols are created after digital baseband processing. Following the processing of data streams by RF chains, the spatial-domain data stream selects RF at random to send symbols using FGSM technology. The remaining RF antenna groups are deactivated in this situation.

As illustrated in Fig. 1, the forthcoming input data streams to be communicated at a given moment are divided into two portions user bits' data streams and an additional space-domain data stream as spatial bits. The initial set of bits incorporates the modulation symbol ($\log_2 M$) bits, commonly known as data bits. The subsequent set of bits incorporates ($RF - 1$) bits known as the spatial bits. The aforementioned set of bits is employed to select the specific subset of RF that will be utilized in the transmission of the data constellation symbol. The modulation symbol is then sent by antennas that are connected to the selected activated analog RF beam. As a result, (1) gives the total number of valid antenna group combinations [13]. The modulation symbol and the transmitted RF index are matched using the first and second portions, respectively.

$$\begin{aligned}
 R_{FGSM} &= \log_2 M + \left\lceil \log_2 \left(\sum_{K=1}^{RF} \binom{RF}{K} \right) \right\rceil \\
 R_{FGSM} &= \log_2 M + \lfloor \log_2 (2^{RF} - 1) \rfloor \\
 R_{FGSM} &= \log_2 M + (RF - 1)
 \end{aligned} \tag{1}$$

Where M stands for the modulation order and k is the possibilities of activated RF . The antenna subsets within the F-GSM exhibit variability, ranging from a configuration where only one transmit antenna is active to a configuration where several or all transmit antennas are active. The manipulation of the number of transmit antennas within the subsets of antennas improves the effectiveness of the communication channel, streamlines the identification of distinct pathways within the channel, and consequently reduces the degradation in the performance of the bit error rate (BER).

For the sake of simplicity, each RF at the BS and the vehicle is considered to have equal antenna elements and interelement spacing. Our further assumption is that each vehicle user (N_U) is served by a single RF beam with an individual data stream (i.e., $N_U = N_B = N_S$), whereas N_B and N_S are the numbers of activated beams and transmitted data streams, respectively. Note that this article considers only downlinks in suburban areas as shown in Fig. 2, which depicts the extent of coverage provided by a (BS) using four distinct beams (red, blue, green, and yellow). It emphasizes the spatial connections and interactions within a suburban area. This visualization helps the optimization of network planning.

The sampled transmitted signal $X \in \mathbb{C}^{N_T \times 1}$ is denoted by (2)

$$X = F_{RF}S \tag{2}$$

where $F_{RF} = [f_{RF}^1, f_{RF}^2, \dots, f_{RF}^{N_U}]$, the analog transmit beamforming weight vectors are denoted by $\mathbb{C}^{N_T \times N_U}$. There are modulation symbols for each data stream, that are determined by the modulation order being exploited (e.g, M-QAM). In $S = [S_{j,q}^1, S_{j,q}^2, \dots, S_{j,q}^{N_U}]^T \in \mathbb{C}^{N_U \times 1}$, where $S_{j,q}^i$ represents the modulation symbol S_q of the i th data stream broadcast by the j th RF at the BS, where $i = 1, 2, \dots, N_U$ and $j \in \{1, 2, \dots, N_{RF}\}$. Consequently, it is feasible to specify the received signal for the i -th data stream processed by the N_{RF} receive beamforming weight vector as (3)

$$r_i = \sqrt{p_i} \sum_{n=1}^{N_U} (w_{RF}^n)^H H_{i,j} f_{RF}^n S_n + (w_{RF}^i)^H n_i \tag{3}$$

where p_i stands for average received power, a path loss-dependent quantity [20]. It is decided to use a Rayleigh fading channel model $H_{i,j}$ in this system, with L_i scatterers between the j -th active N_T at the BS and the i -th vehicle user. $H_{i,j} \in \mathbb{C}^{N_T \times N_U}$ written as (4), where w_{RF}^i is the analog receive beamforming weight vector. $n_i \in \mathbb{C}^{N_U \times 1}$ are independent identically distributed (i.i.d) complex Gaussian variables with zeros mean and variance σ^2 .

$$H_{i,j} = \sqrt{\frac{N_t N_r}{L_i}} \sum_{l=1}^{L_i} (\alpha_{i,l} A_r(\phi_{i,l}^r, \theta_{i,l}^r) A_t(\phi_{i,l}^t, \theta_{i,l}^t)^H) \tag{4}$$

where $\alpha_{i,l}$ denotes the complex gain with $\sum_{l=1}^{L_i} \alpha_{i,l} = 1$. $\phi_{i,l}^r, \theta_{i,l}^r$ where the azimuth (elevation) arrival and departure angles are, respectively, $\phi_{i,l}^r, \theta_{i,l}^r$. The received and transmitted steering vectors, or array responses, are denoted by $A_r(\phi_{i,l}^r, \theta_{i,l}^r)$ and $A_t(\phi_{i,l}^t, \theta_{i,l}^t)^H$ at the appropriate arrival and departure angle.

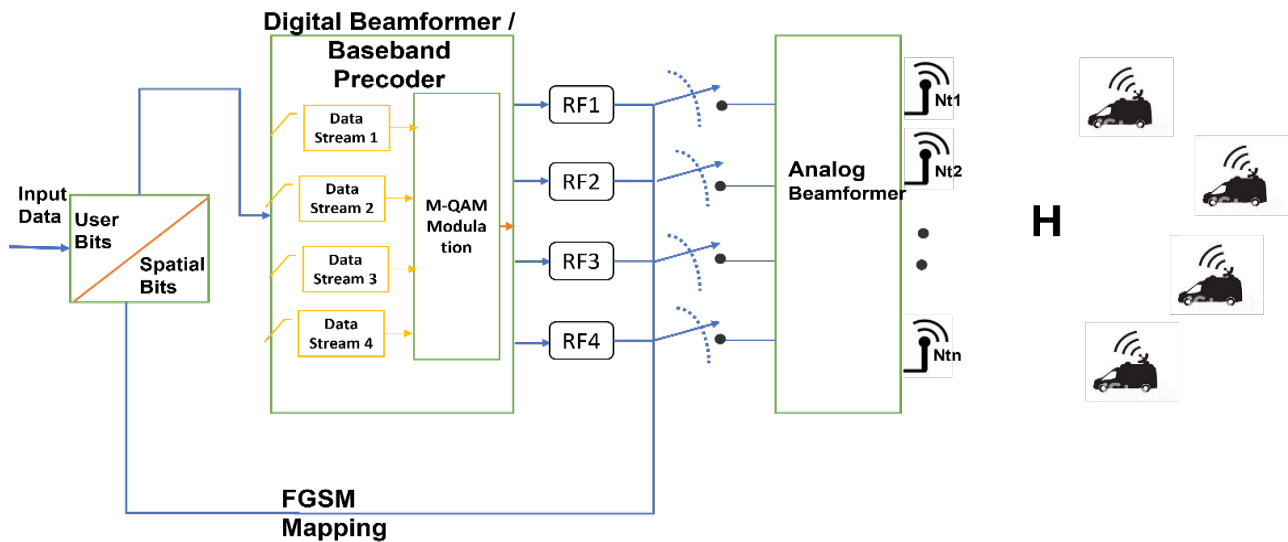


Fig. 1 Proposed system model of hybrid beamforming with FGSM

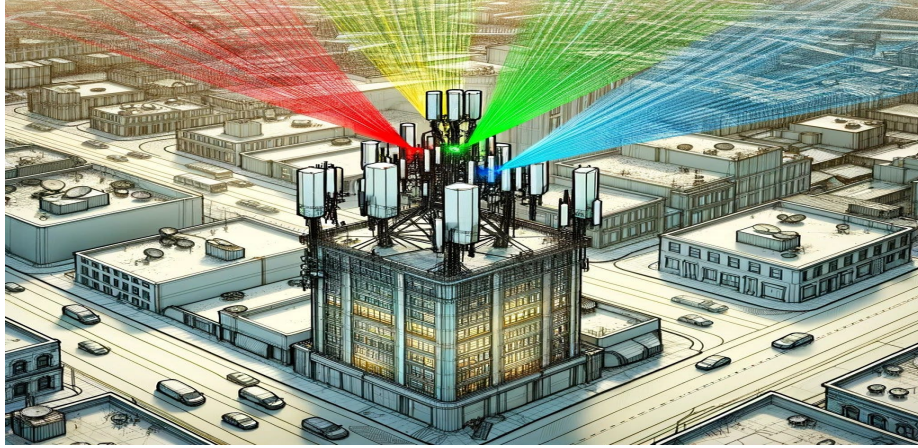


Fig. 2 Network structure of mmWave vehicular system

4. Hybrid FGSM Beamforming Scheme

As indicated in Fig. 1, four RF ($RF = 4$) are provided with four data stream transmissions ($N_s = 4$) at the BS . When the beams are reactivated, the channel state information (CSI) is adaptively assessed using beam-dedicated reference signals. Explicitly, in the suggested hybrid design, in the digital domain, the active RF index is selected using FGSM based on the information bits. Since RF in this instance equals 4, the amount of information bits transmitted by the active RF 's index is equal to $(RF - 1)$.

Table 1 defines a proposed H-FGSM mapping between information bits and transmits RF index. In the analog domain, based on selection criteria such as vehicle velocity and the length of time the vehicle is in the coverage area, the best beams are chosen from a collection of candidate RF beams spanned on a respective service region.

In this scenario, by using FGSM various RF 's are enabled an example is shown in TABLE 1. Throughout this article, the mapping index follows to activate which RF position has $q^{(n)} = [q^1 q^2 q^3]$. For instance, if the incoming spatial bits data sequence $q^{(n)} = [001]$ is mapped to activate RF^3 and RF^4 which sends the data stream through all the connected N_t 's to that RF , and the other RF 's are deactivated. In the second time instance, if the incoming data sequence $q^{(n)} = [011]$ is mapped to RF^2 , RF^3 and RF^4 which will transmit the symbol to all RF except RF^1 will be off.

More precisely one analog RF beam is used to transmit each data stream, Consequently, the number of chosen beams equals the number of data streams. Each data stream is considered to be an essentially independent user, and indeed the total amount of simultaneously serviced vehicles, after that the signals are added together to obtain multiplexing gain, in contrast to traditional MIMO, all antennas are utilized to receive all signals sent by the BS .

In the proposed method, FGSM replaces baseband precoding in the digital domain, which significantly increases the achievable data rate compared to H-SM. Refer to [7] the achievable data rate for H-SM (RH-SM) is calculated as (5) follows.

$$R_{H-SM} = \frac{1}{Nt} \sum_{j=1}^{Nt} \log_2 \left(1 + \frac{p_i \left\| (w_{RF}^i)^H H_{i,j} f_{RF}^i \right\|^2}{\sum_{n \neq i} \left\| (w_{RF}^n)^H H_{i,j} f_{RF}^n \right\|^2 + \sigma^2} \right) + \log_2 Nt \quad (5)$$

In which, The channel matrix, denoted as $H_{i,j} \in \mathbb{C}^{N_T \times N_U}$ belongs to the set of complex numbers. It represents the communication channel between the j th active antenna at the base station (BS) and the i th vehicle user, as was pointed out in the system model to this article. Where (w_{RF}^i) and (f_{RF}^i) is the analog and digital beamforming weight vector respectively.

Studies of the achievable data rates for SM and FGSM can be found in [13] and defined as (6) and (7) follows.

$$R_{SM} = \log_2 M + \log_2 Nt \quad (6)$$

$$R_{SFGM} = \log_2 M + (Nt - 1) \quad (7)$$

Table 1 The proposed F-GSM mapping table for vehicular communication

Transmitted Data				
Spatial Bits (q^n)	Activated RF Index			
RF mapping	RF ¹	RF ²	RF ³	RF ⁴
000	0	0	0	1
001	0	0	1	1
010	0	1	0	1
011	0	1	1	1
100	1	0	0	1
101	1	0	1	1
110	1	1	0	1
111	1	1	1	1

In light of this, we can derive the theoretically achievable data rate of the proposed H-FGSM in the following manner (8)

$$R_{H-FGSM} = \frac{1}{RF} \sum_{j=1}^{RF} \log_2 \left(1 + \frac{p_i \|(w_{RF}^i)^H H_{i,j} f_{RF}^i\|^2}{\sum_{n \neq i} \|(w_{RF}^n)^H H_{i,j} f_{RF}^n\|^2 + \sigma^2} \right) + (RF - 1) \tag{8}$$

5. Simulation Results and Discussion

This section analyses and performs thorough Monte Carlo simulations to assess the performance of the proposed H-FGSM utilizing a range of system metrics. The detailed values of the simulation parameters setting are listed in TABLE 2.

Table 2 Parameter setting

Parameters		Values
Transmission power	P_{tx}	20 dBm
Path-Loss exponent,	n	2.1
Channel attenuation	$Catt$	70 dB
Noise Floor	N_{floor}	-174 dBm
Bandwidth	B	50 MHz
Carrier frequency	fc	28 GHz
Noise figure	NF	6 dB
Max. Velocity	$vmax$	120 Km/H
BS coverage angle	Φ_{BS}	120 degrees
BS-Road distance	d	100 m

First, analytical-numerical simulations are used to assess the BER performance of the suggested H-FGSM. For each BER value, the average of at least 10^{-5} symbol transmissions over an uncorrelated Rayleigh fading channel is evaluated. It is validated with the performance of conventional H-SM, with SEs of 7 bpcu, 9 bpcu, and 11 bpcu, respectively, adopting the same number of RF chains and various modulation orders M-QAM. Multiple modulation orders of M-QAM are utilized to meet the previously specified spectral efficiency (SE) while using the same number of (RF) chains, this is because each SE necessitates a specific modulation scheme to guarantee precise comparison. We observe in Fig. 3 that a 2 dB SNR enhancement over the standard H-SM is provided by the suggested H-FGSM technique even though both achieve the same SE, due to a lower modulation order used in H-FGSM rather than all other schemes are taken into consideration. For instance, the suggested approach attains a BER of 10^{-5} at 3 dB SNR while achieving SE = 7 bpcu, as opposed to the 6 dB SNR needed by the traditional approach. This notable enhancement highlights the potential of the suggested technique for improving communication system performance by demonstrating its ability to sustain low BER at higher SEs.

Fig. 4 presents the impact of the vehicle's velocity on SE as achievable data rates for H-FGSM and H-SM. Due to the beamforming gain, the rate in both systems initially rises with the number of activated RF. The most obvious finding compared to H-SM is that the proposed technique H-FGSM has a better success rate. Specifically, when increasing the number of activated RF, for instance, while jumping from 6 dB SNR to 20 dB SNR the proposed technique's data rate jumps from 25 bpcu to 45 bpcu, while the traditional method only reaches 15 bpcu, indicating a notable improvement. This superior performance of the proposed technique is attributed to its more efficient utilization of the beamforming gain, which optimizes signal strength and data throughput. However, at greater velocities, there is a noticeable rate that decreases as the number of RF grows and the increase in SNR. Additionally, because of the LoS configuration, fluctuations in the achievable rate owing to changes in velocity are minimal. Overall, the analysis shows that the suggested beamforming technology surpasses previous methods in terms of data rates while also providing improved dependability and stability, making it an appealing alternative for modern communication systems.

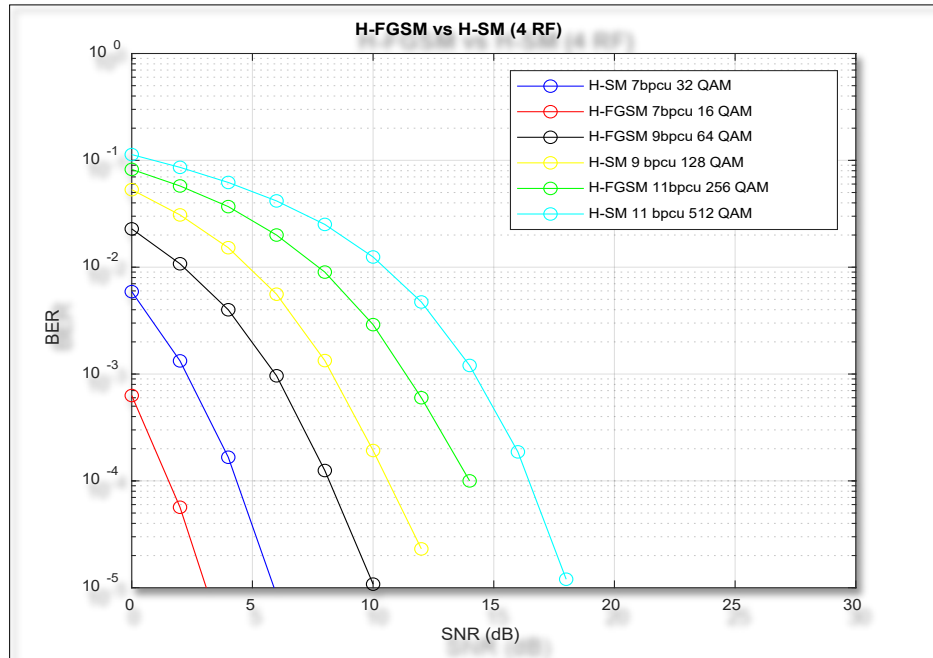


Fig. 3 BER performance comparison between the proposed H-FGSM and H-SM for a spectral efficiency of 7,9,11 bpcu

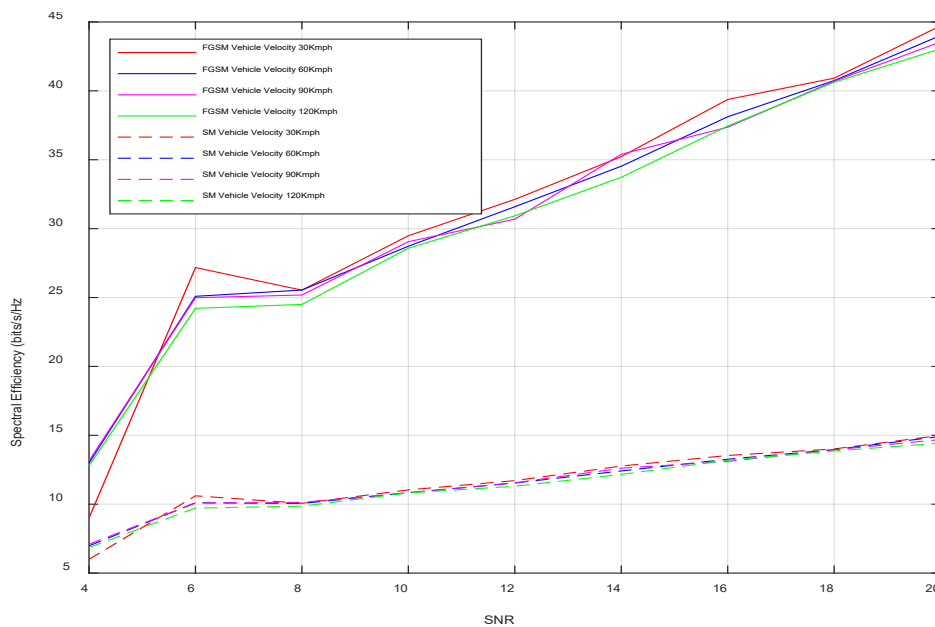


Fig. 4 Impact of vehicle's velocity on achievable data rates for H-FGSM and H-SM

The simulation for Fig. 3 and Fig. 4 was performed using the settings outlined in TABLE 2, involving 4 RF chains. The aforementioned parameters were utilized to implement FGSM hybrid beamforming in a mmWave vehicular setting for the purpose of assessing performance metrics such as spectral efficiency (SE) and bit error rate (BER). The comparison of (SE) and (BER) before and after adopting the proposed model showed a statistically significant improvement, thus demonstrating the usefulness of the proposed strategy.

6. Conclusion

This article presents a hybrid fully generalized spatial modulation (H-FGSM) beamforming method at mmWave frequency ranges under vehicular communication scenarios. In this article, the suggested framework is highlighted as the first significant effort to generalize a mathematical framework for rating the R_{H-FGSM} . The simulation results demonstrated that each formula employed a realistic range of signal-to-noise ratio (SNR) values, and these results were consistent with each other. Additionally, compared to the standard H-SM, the suggested H-FGSM offers a significant improvement in BER demonstrating a 2 dB enhancement in BER performance and 30 bpcu difference in achievable data rate at higher SNR, which is supported by the simulation findings. This quantitative proof demonstrates the proposed technique's effectiveness in increasing communication system efficiency and dependability.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Sheemaa Ali; **data collection:** Sheemaa Ali, Rudzidatul Akmam Dziyauddin, Mohd Azri Bin Mohd Izhar **analysis and interpretation of results:** Sheemaa Ali, Rudzidatul Akmam Dziyauddin, Mohd Azri Bin Mohd Izhar, Budi Prasetya **draft manuscript preparation:** Sheemaa Ali, Rudzidatul Akmam Dziyauddin, Mohd Azri Bin Mohd Izhar, Budi Prasetya. All authors reviewed the results and approved the final version of the manuscript.

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