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Space-Time Frequency Block Codes in LTE-DSRC Hybrid Vehicular Networks

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Abstract. In vehicular communication systems, Dedicated Short Range Communication (DSRC) is said to provide fast communication and high security between vehicles. Simultaneously, Long-Term Evolution (LTE) is used due to its high bandwidth, low latency, and high spectrum efficiency. The DSRC and LTE hybrid model has gained much attention as it is feasible and simpler in design and deployment. In fact, multiple-input multiple-output (MIMO) systems have been widely used in modern wireless communication systems to enhance data throughput, reliability, and coverage. This paper proposes a MIMO LTE-DSRC hybrid system using space-time frequency block codes (STFBC). This paper focuses on the physical layer performance of the LTE-DSRC hybrid uplink structure. The DSRC Orthogonal Frequency Division Multiplexing (OFDM) transmitter and LTE Single Carrier Frequency Division Multiplexing (SCFDM) receiver are used for the uplink transmission. A study on bit error rate (BER), pairwise error probability (PEP), and channel-to-interference ratio (CIR) of the 2x2 MIMO LTE-DSRC system is conducted. The numerical results show that this proposed method improves the error rate performance with a gradual increase in signal-to-noise ratio (SNR) compared to the baseline systems.

Keywords: Hybrid MIMO; LTE-DSRC; Space time-frequency; Vehicular network

1. Introduction

Information and communication technologies (ICTs) in vehicular networks have enabled immersive communication between vehicles and infrastructures. These networks rapidly evolve, shifting their orientation from the automotive industry to technology and sustainability. Transportation systems become more complex as new technologies emerge to provide new services and functionalities (Leviakangas et al., 2021). This digital transformation has combined various technologies into a single integrated technological platform (Babkin et al., 2021). The primary goal of this research is to optimize passenger safety and provide in-car entertainment by utilizing the internet (Arena & Pau, 2019). (Arena & Pau, 2019). Vehicular Ad-Hoc Network (VANETS) for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications enable transmission of data over a wireless mesh network to send, receive and transmits signals that comprise speed, location, and direction of travel, traffic signals and various stationary devices (Araniti et al., 2013; Prasetijo et al., 2019). The interaction necessitates the exchange of information via a proper

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communication system, such as Dedicated Short-Range Communication (DSRC) (Dar et al., 2010; Amadeo et al., 2012) and Long Term Evolution (LTE) (Bilstrup et al., 2008) standards. For better coverage, data traffic, and capacity, LTE has introduced LTE-Advanced leveraging heterogeneous networks (Summakieh et al., 2019). DSRC is a modified version of the Wireless Local Area Network (WLAN) protocol which is based on IEEE802.11p with a fixed bandwidth of 75Mhz in the 5.850 to 5.925 GHz (Kenney, 2011).

It is effective for high mobility and adverse weather conditions with low latency. However, the drawbacks are limited range (<1km), performance degradation under high mobility nodes, optimal power usage, and low scalability due to the requisite time-probabilistic features while traveling in dense traffic conditions (Chang, 2017). V2V communication capabilities could be enhanced using Long-term Evolution (LTE) by complementing DSRC. LTE, regarded as the fourth generation (4G) of the mobile cellular system, has intrinsic advantages such as large coverage, high penetration rates, high data rates and good quality of service (QoS), and the applications like video streaming, image and information transmission can be provided with high mobility (Hu et al., 2017; Trichias et al., 2012). In addition, 4G LTE is widely used many countries by communication and automotive industries, such as Audi, Mercedes Benz, BMW, Intel, Huawei, and Qualcomm (Chisab et al., 2014). LTE was designed initially for device-to-device (D2D) communication; therefore, it has a huge potential for incorporation in vehicular communications. Since both DSRC and LTE are widely available in the market, a hybrid model of LTE-DSRC is a feasible alternative and can be further explored.

Multiple-input Multiple-Output (MIMO) is a wireless broadband technology that works well in multipath fading channels with a significant rate of transmission capability and other link disorders (Wang et al., 2017). MIMO system has been proposed with DSRC and LTE in (Ning et al., 2018; Ning et al., 2017a; Rezwan et al., 2018; Wang et al., 2018) and proved some improvement in BER and throughput performance. By using MIMO, existing wireless technology can exploit space, time, and frequency domains, with space-time-frequency block codes (STFBC) being a popular choice (Ansari et al., 2017). STFBC is used to aid the MIMO system by adding time to the space and frequency dimensions (Ning et al., 2017b; Xu et al., 2017). It has also been proposed in the orthogonal frequency-division multiplexing (OFDM) system to alleviate the problem of a high peak-to-average power ratio (PAPR) and to improve error rate performance (Abdullah et al., 2017). An improved STFBC MIMO-OFDM using asymmetric arithmetic coding has also been proposed in 5G mobile networks and beyond due to its error rate and spatial diversity performance (Saleh et al., 2021). MIMO-OFDM systems are popular due to the significant improvement in diversity gain and system capacity. A filtered OFDM has also been proposed for 5G with maximum diversity order by using STFBC approach (Noorazlina et. al., 2021).

Previous papers have shown that MIMO-OFDM has promising potential for future wireless networks. Using the STFBC approach, such systems can further help improve error rate and system performance. To our knowledge, there is no work employing these methods in a hybrid LTE-DSRC, specifically in vehicular networks. In contrast to the previous papers, the authors' contributions in this paper are as follows: i) A general framework for the performance analysis of STFBC for MIMO LTE-DSRC systems with frequency offset (FO) is presented; ii) The BER, PEP, and CIR performances of STFBC in MIMO LTE-DSRC system are analyzed in AWGN and Rayleigh fading channels. Researchers show that the proposed system, which combines STFBC with MIMO, outperforms the conventional LTE-DSRC system and it is easier to implement without further system complexity. The findings also suggest that using space-time-frequency diversity in MIMO can minimize interference with full diversity order.

2. Methods

LTE supports both vehicle and background mobile networks and must fulfill the Quality of Service (QoS) specifications for both. This paper considers a single base station and a single cell (vehicle) and assumes no rebroadcast from neighboring base station. The integrated DSRC vehicles serve as user equipment (UE), transmitting data to the system, base station, or LTE enodeB. Figure 1 illustrates the system model for the LTE-DSRC uplink transmission using MIMO UE antennas and a transmission tower.

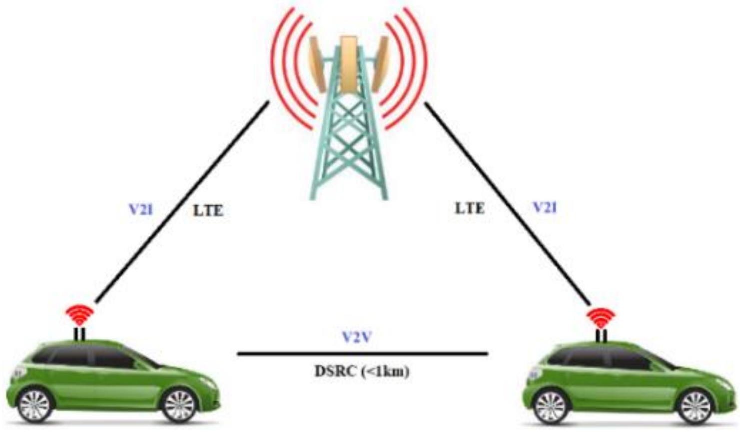

Figure 1 DSRC-LTE heterogeneous vehicular networks uplink transmission

STFBC MIMO in the LTE-DSRC system comprises a DSRC transmitter and an LTE receiver uplink system model that uses 2x2 MIMO. In this case, DSRC-embedded vehicles response to the system or to the LTE eNodeB. The DSRC transmitter transmits 64-point fast Fourier transform (FFT) multicarrier signals and is received by the LTE receiver using a single carrier system. The following is an illustration of the vehicle transmitted signal V_i and is shown by Equation (1):

$$x^v = P_{add} \times D_M^{-1} \times S_T^v \times m^v \tag{1}$$

Where x^v is an $M \times 1$ vector that denotes the transmitted samples after the mapping phase from the v^{th} vehicle. P_{add} is an $(M \times N_c) \times M$ matrix, which introduces the cyclic prefix. D_M^{-1} is an $M \times N$ inverse discrete Fourier transform (IDFT) matrix. S_T^v is an $M \times N$ matrix where $M = QN$ subcarrier analysis of the vth vehicle. Q is the bandwidth capacity factor of the symbol sequence, and N is the number of symbols/blocks. As well as, m^v is an $N \times 1$ vector containing the modulated symbols. At the receiver, assuming perfect time and synchronizing frequency, the received transmission $\overline{Y}$ can be shown in Equation (2) as:

$$\overline{Y} = \sum_{v=1}^{i} \times C^v \times \bar{x}^v + \bar{n} \tag{2}$$

Where C^v is an $(M + N_c) \times (M + N_c)$ matrix that defines the channel with channel equalization in order to combat ISI at the receiver antenna of LTE as it is a single carrier. $\bar{n}$ is an $(M + N_c) \times 1$ noise vector. After the removal of prefixing of symbols, the received signal becomes Equation (3),

$$\bar{Y} = \sum_{v=1}^{i} \times C_c^v \times \bar{x}^v + n \tag{3}$$

Where after cyclic prefix elimination, n is the noise. Afterward, the received signal is transformed via an M-point discrete Fourier transform (DFT) into frequency domains as in Equation (4).

$$\bar{Y} = \sum_{v=1}^{i} \times \bar{X}^v + N \tag{4}$$

Where $\bar{X}^v = F_m \times \bar{x}^v$, the transmitted samples from the v^{th} vehicle after the mapping phase are represented by a $M \times 1$ vector. N is the DFT with n. Eventually, the processes of demapping, equalization, IDFT, demodulation, and decoding are carried out.

2.1. Space-Time Frequency Block Codes (STFBC) MIMO

Multiple-input Multiple-output (MIMO) is a wireless network that transfers more data simultaneously by using multiple transmitters and receivers to maximize MIMO. MIMO increases the receiver's signal-capture capacity by allowing antennas to merge data streams from different paths at varying intervals. It is important to enforce signal diversity to provide different versions to the receiver. By taking advantage of the space, time and frequency diversity inherent in the MIMO LTE-DSRC system, STF coding schemes have been used to improve system efficiency and reliability. In the narrowband scenario, the design requirements for STF centered on PEP to achieve maximum spatial diversity. The STFBC mapping can be shown in Equation (5),

$$X_m = \begin{bmatrix} X_1(0) & \cdots\cdots & X_2(0) \\ X_1(0) & \cdots\cdots & -X_2(0) \\ \cdots & \cdots\cdots & \cdots \\ X_1(N-1) & \cdots\cdots & X_2(N-1) \\ X_1(N-1) & \cdots\cdots & X_2(N-1) \end{bmatrix} \tag{5}$$

The transmitted symbols order of size $NI \times NIJ$ is constructed from STFBC codeword in the matrix D and can be written in Equation (6) as

$$D_i = \begin{bmatrix} D_1 & D_2 & \dots & D_I & 0 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 & D_1 & D_2 & \dots & D_1 \end{bmatrix} \tag{6}$$

Every other D matrix is composed of coded transmission from the i antenna and is shown in Equation (7) as

$$D_i = diag[X_i(0), X_i(1), \dots, X_i(k-1)] \tag{7}$$

2.2. Pairwise Error Probability (PEP)

PEP is a critical component in formulating union constraints on the possible outcomes of block and bit malfunction in embedded communication systems. The PEP performance of (Arena & Pau 2019) worked with the adjacent subcarrier mapping scheme on SF diversity for the MIMO LTE-DSRC system. The authors considered systematic design procedures for high-rate full diversity STF codes (Yoshioka et al., 2017) for frequency selective MIMO block fading channels. However, the same assessment and related PEP studies were not considered in the context of the MIMO LTE-DSRC systems. The PEP performance diversity study for STF codes of broadband OFDM systems has been discussed (Bronzi et al., 2016). They illustrated that by minimizing PEP output and using distinct space, time, and frequency, a system could achieve maximum order of diversity. The source data is encoded in three dimensions through space (over multiple antennas), time (over multiple times), and frequency in the STF encoding process (over LTE-DSRC symbol subcarriers), where input data patterns are split into source words of the b-symbol and transformed into frames and translated to code words of STFBC.

The PEP is a standard measure for ST or SF code design (Bronzi et al., 2016). The ICI can be reduced by designing a code that minimizes the PEP, and the diversity and coding gain can be maximized simultaneously [28]. The overall coded symbol sequence D is expressed based on assumptions. Based on the realization of the interface H through OFDM block, the PEP mistakenly decided in favor of the coded sequence $\bar{D}$. Suppose that D and $\bar{D}$ are two distinct STF that can be higher bound as defined by the PEP between D and $\bar{D}$, which has been proposed in Ning et al. (2018) and this relation is given by Equation (8),

$$P(D \to \bar{D}) \leq \ell \binom{2\Gamma J - 1}{\Gamma J} (\prod_{i=1}^{\Gamma} \lambda_i)^{-J} \xi^{-\Gamma J} \tag{8}$$

$P(D \to \bar{D}$)is the probability of inappropriately decoding in favour of codeword $\bar{D}$ (decoded codeword in error) when D is transmitted, ℓ is the performance loss, $\prod$ is product criterion, λ_i is non-zero Eigen value of $(\Delta D \cdot R)$ and ξ is the average (E_b/N_0). Equation (8) shows that $\Gamma = rank(\Delta D \cdot R)$ where R is the correlation of the channel and is uncertain, D is the transmitted codeword and $\bar{D}$ is the wrongly decoded codeword $\Delta D = (D - \bar{D})(D - \bar{D})^H$. Superscript H stands for (Hermitian matrix). The upper limit of PEP can be reduced by formulating the STFBC parameters for better results.

1. *Diversity rank criterion:* The minimum rank of $(\Delta D \cdot R)$ should be as high as possible over all pairs of separate codewords (different D and $\bar{D}$), improving the system's efficiency.
2. *Product criterion*: The minimum value of the product $\left(\prod_{i=1}^{\Gamma} \lambda_I\right)$ should also be maximized over all pairs of distinct codewords (different D and $\bar{D}$*).* To generate a system with low PEP, the value of λ_i and $(\Delta D \cdot R)$ must be at the minimum value.

The challenge is that R is a link to the channel and is highly unpredictable. In general, various fading channels seem to have different R correlations, and a method designed for one channel may not be suitable for another. Therefore, the above STFBC design requirements are not accurate. On the other hand, the maximum attainable diversity, can be found. In comparison, based on the rank distributions of Hadamard products and tensor products which is shown in Equation (9);

$$rank(\Delta D \cdot R) \leq rank(\Delta D) rank(R) \leq LI \tag{9}$$

As the rank of ΔD is at most I, the rank of R is at most L (path), and that of $(\Delta D \cdot R)$ is at most N, thus Equation (9) reduces to Equation (10) as

$$rank(\Delta D \cdot R) \leq min\{LI, N\} \tag{10}$$

The overall achievable diversity from the above analysis is at most min $\{LIJ, NJ\}$, which is in accordance with the outcomes in Bronzi et al. (2016).

2.3. Channel to Interference Ratio (CIR)

The carrier-to-interference ratio (C/I, CIR) also known as the signal-to-interference ratio (S/I or SIR), is the ratio between the average modulated carrier power obtained S or C and the average co-channel interference power received, i.e., cross-talk, from transmitters other than the useful signal. The difference is that radio resource management can regulate interfering radio transmitters that contribute to I, while N requires noise power from other sources, usually additive white Gaussian noise (AWGN). Channels have a common flat frequency response along two paths to evaluate frequency offset (FO) individually, like $H_l^1 = H_l^2 = 1$, and CIR is written in Equation (11) as follows,

$$CIR = \frac{E[|C_k|^2]}{E[|ICI_k|^2]} \tag{11}$$

Where C_k means the desired kth carrier component, ICI_k means the ICI component of the kth carrier.

3. Results and Discussion

Table 1 shows the parameters used in this simulation, which was run on MATLAB simulation software version 2017b. The subsection discusses the bit error rate (BER), Pairwise error probability (PEP), and channel-to-interference ratio (CIR) performance. In this simulation work, the researchers assume a single carrier FDMA signal is generated from a high-level perspective at the receiver side. DFT block appears before the subcarrier mapping at the LTE uplink. The LTE receiver will receive the multicarrier signals via channel type COST 207 and be detected using channel equalization schemes. The signals are then transferred into the OFDM block to remove a cyclic prefix, 64-point IDFT, and subcarrier demapping. The decoded signal with 1024-point FFT is processed for digital demodulation, deinterleaving, channel decoding, and decryption. Eventually, the transmitted data is retrieved. The researchers compare this simulation work with the result of Ansari et al. (2017) contrasting the proposed research and framework characteristics. Table 1 depicts the typical parameters used for this simulation work.

Table 1 The Simulation Parameters

DFT, IDFT Size	64, 1024
Modulation	64 QAM
Bandwidth (MHz)	10
Channel Type	COST 207 Typical Urban
Channel Equalizer	MMSE

3.1. BER Performance Result

According to Figure 2, the BER curves for 2x2 MIMO LTE-DSRC outperform the LTE-DSRC technique by about 2dB. At BER $=10^{-3}$, the BER performance for LTE-DSRC is better than conventional LTE (the performance loss is about 9.5dB), whereas for the LTE technique, the performance loss is about 2.5dB compared to DSRC. This result shows that the system using the STFBC technique can reduce BER with a lower value of $S_{i,j}(k)$ from Equation (5) and as compared with the system without the STFBC technique, even though there is interference in the system. The system with the STFBC technique results in lower BER and higher SNR with maximum frequency diversity gain, less noise, and interference. This system shows less bandwidth efficiency interference than the other systems.

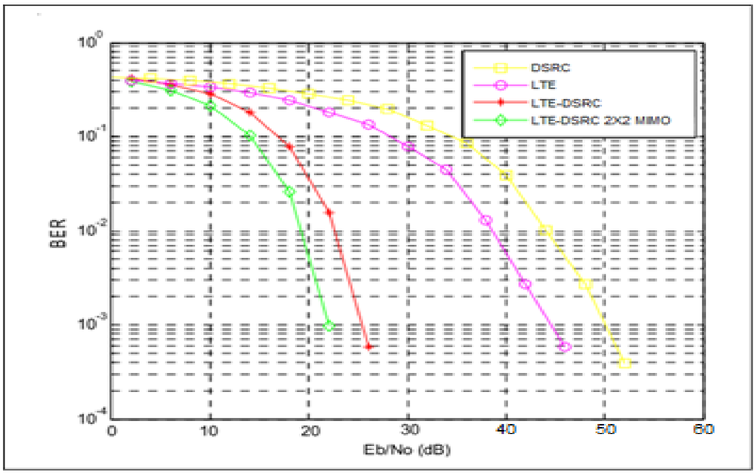

Figure 2 BER vs SNR for MIMO LTE-DSRC hybrid system

Table 2 The performance of LTE-DSRC hybrid using MIMO at BER

Method	SNR	Improvement (%)
DSRC	25	-
LTE	22.5	10
LTE-DSRC	13	48
2x2 MIMO LTE-DSRC	11	56

3.2. PEP Performance Result

The PEP of the 2x2 MIMO LTE-DSRC system is displayed in Figure 3 compared to the baseline systems. The simulated PEPs are plotted from 0 to 30dB. Table 3 shows PEP improvement over the baseline DSRC. At PEP $=1 \times 10^{-3}$, 2x2 MIMO LTE-DSRC system has outperformed the conventional LTE-DSRC system with 37.1%. As shown in Equation (5), MIMO adaptation with space-time frequency can increase the system due to multipath propagation. LTE-DSRC also is better than the conventional LTE and DSRC by 3dB and 5.5dB.

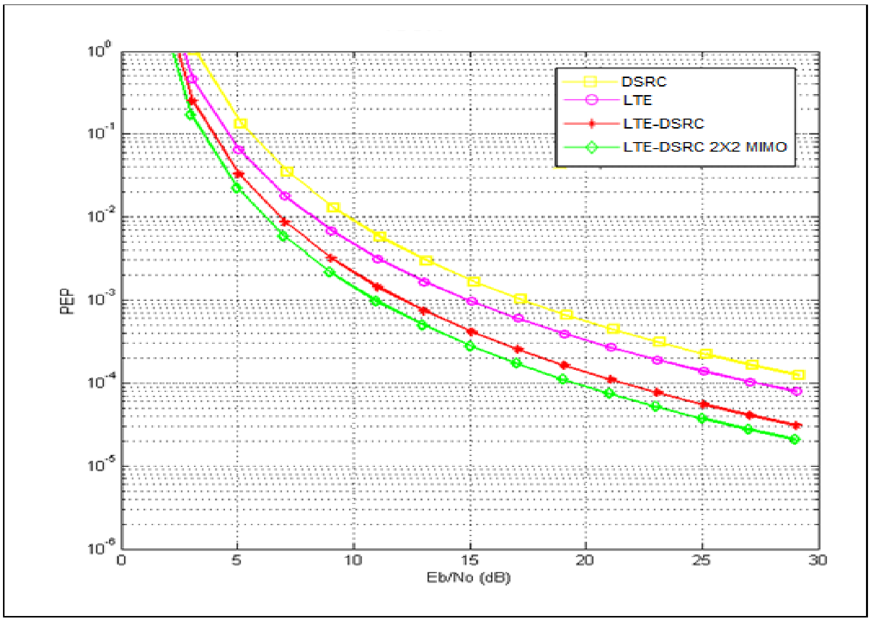

Figure 3 PEP vs SNR for MIMO LTE-DSRC hybrid system

Table 3 The performance of MIMO LTE-DSRC hybrid using MIMO at PEP 1×10^{-3}

Methods	SNR	Improvement (%)
DSRC	17.5	-
LTE	15	14.3
LTE-DSRC	12	28.6
2X2 MIMO LTE-DSRC	11	37.1

3.3. CIR Performance Result

Figure 4 depicts the simulation result of CIR performance for the LTE-DSRC system using 2x2 MIMO and without MIMO compared to conventional DSRC and LTE systems using Equation (11). The proposed 2x2 MIMO LTE-DSRC system in Equation (5) shows the highest SNR value which are 38 dB, 21dB, and 16dB at FO= 0.05,0.25, 0.4. Whereas, the LTE-DSRC system without MIMO has lower SNR values of 33dB, 18dB, and 13dB compared to the conventional DSRC system, with the lowest SNR values of 22 dB, 7.5 dB, and 2.5 dB, respectively. Therefore, LTE-DSRC with 2x2 MIMO with full diversity technique has shown promising results as this method simultaneously enables the transmission of the subcarriers in full space, time, and frequency diversity.

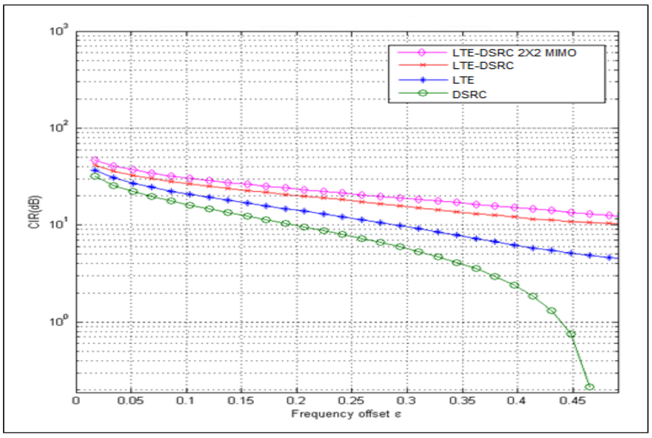

Figure 4 CIR performance of MIMO LTE-DSRC hybrid system

Table 4 The performance of MIMO LTE-DSRC hybrid using MIMO at frequency offset (FO) = (0.05, 0.25, 0.4)

Method	SNR (dB)		
	FO = 0.05	FO = 0.25	FO=0.4
DSRC	22	7.5	2.5
LTE	28	12	6
LTE-DSRC	33	18	13
2x2 MIMO LTE-DSRC	38	21	16

4. Conclusions

The authors proposed using the STFBC approach in MIMO hybrid LTE-DSRC vehicular networks. Moreover, the authors examined the proposed system's performance while considering the frequency offset. The proposed method provides an excellent BER performance for minor frequency offset over the MIMO LTE-DSRC system using STFBC techniques in fading channels. The proposed MIMO-based system outperforms the conventional LTE-DSRC system and is easier to implement without increasing system complexity. The results also suggest that by using space-time-frequency diversity in MIMO, the system becomes more robust to interference with maximum diversity order.

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