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Intelligent Reflecting Surfaces: Performance Simulation in Millimeter Wave Channels

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Abstract: The intelligent reflecting surfaces (IRS) can be implemented in radio systems in order to provide the cooperative communication services. In fact, the cooperative communication can increase the received signal strength at the communication receiver. Moreover, it can let transmitters send their signals with low power. The electromagnetic interference (EMI) can degrade the communication system performance. The total interfering power, affecting a communication system, can increase the bit error rate (BER). The large BER value is not good issue as it leads to a low system performance. Therefore, there should be tools and techniques in order to balance and compensate the existing BER. In fact, there are a lot of tools that can compensate the BER effect. We are concerned with the cooperative millimeter wave systems that are based on IRSs which are affected by EMI. Such systems have non-satisfied performance due to the high path losses as well as the existing EMI. These systems will be modeled and simulated. Furthermore, the space time block codes (STBC) are applied in order to compensate the bad performance of such systems. Really, the STBC codes can greatly compensate the bad effects of the high path loss as well as the large interference.

Keywords: Wireless Systems, IRSs, EMI, Millimeter Wave, STBC codes.

1. Introduction

The communication receivers can detect a lot of versions of the originally transmitted signal when the cooperative communication systems are considered. The repeated replicas of the transmitted signals can improve the performance of the communication system. The received signal, at receivers, can be enhanced. Furthermore, the transmitters can send their carriers with low power. In addition, the bit error rate (BER) can be minimized in the radio system due to the cooperative communication operation. In fact, the minimization of the BER can increase the system reliability. The reliability in radio systems is the first priority. In fact, the first standardization for the cooperative communication is the coordinated multipoint transmission and reception (COMP). By application of the COMP technology, the long term evolution (LTE) performance was greatly improved. However, the modern cooperative techniques are depending on both relays and IRSs [1-6].

In fact, both relays and IRSs can provide the cooperative communication facility in modern radio communication systems. The relay can provide amplification for signals as well as noise. The previous disadvantage can limit the usage of relays. The relays are very competitive to IRSs. Each of them has its advantages and disadvantages. There are a lot of relay categories. There are; amplify and forward, decode and forward, adaptive relays, and much more. Decode and forward relays can provide the best performance in communication systems due to their capabilities in noise elimination. The other competing technology to the relays is the IRSs. The IRS is usually a rectangular array that consists of small reflecting elements separated by $\lambda/2$ distance where λ is the wave length of the communication signal. The IRS can provide amplification by constructive reflection of the incident replicas of the communication signal. The constructive directivity can enhance the communication signal without noise amplification. However, the IRS is still suffering from the large size [7-12].

The EMI can have a bad impact on radio systems due to the overcrowding of the electromagnetic environment. The EMI can increase the BER in radio systems. When a digital communication system has large BER values, it may be unreliable for data transmission. It is preferable for a digital communication system to have low BER values. On the contrary to the noise, the EMI is a deterministic signal that may be intentional or non-intentional. The intentional interference can be called jamming. When comparison with the non-intentional interference, the jamming can let the communication system has a bad performance. In general, the EMI can result from natural sources or man-made sources. The interfering power is a valuable parameter that should be continuously evaluated. The interfering power can be affected by two major parameters. The first parameter is the emitted power of the interfering source whereas the second parameter is the path loss between the interfering source and the communication receiver. The path loss, in a communication channel, is dominated by the separation distance. In fact, the path loss, in a communication channel, can be affected by the separation distance as well as the operating frequency. In other words, the propagation channel can affect the total interfering power affecting a communication system. In this paper, our study is carried out by application of the millimeter wave channel models [13-16].

The millimeter wave communication is the promising technology for the 5G networks and beyond. It can provide a high bandwidth which leads to high available data rates. In addition, this band is more secure than radio bands due to the limited number of operating communication systems. On the other side, the high path loss is a still a great problem. Therefore, the millimeter waves can be used only for short range communication [17-20].

In this paper, we try to derive a complete mathematical model for an IRS based cooperative communication system operating at millimeter wave channels. The proposed system is assumed to be affected by EMI. It is predicted that such system has a bad performance due to the high path loss values of the millimeter wave channels. In addition, such system has a non-satisfied performance due to the existing interference. The bad performance will be compensated by applying STBC codes. Really, the application of STBC 3×4 codes can compensate the bad system performance. Furthermore, they can greatly increase the performance of the proposed system.

2. Related Work

The electromagnetic compatibility refers to the capability of the electric or electronic devices to operate and perform well together without affecting each other even they are coexisting. In fact, wireless communication systems should be electromagnetic compatible with the other coexisted radio systems in the free space. This means that each system should provide reliable communication and reliable services even it coexists with other radio systems in the same geographical area. This requires that each communication system should have great levels of electromagnetic immunity. The EMI can degrade a radio system performance. Moreover, there should be trials to eliminate or at least minimize it as possible [21-23]. Previous work dealt with the mathematical derivations of the EMI in radio systems [24]. Moreover, the same work discussed the impact of the EMI on a radio system. There were two categories of the EMI. One of them considered that the interference may affect a portion of the system bandwidth whereas the other considered that the interference may affect the whole system band.

The EMC regulations were considered through the mathematical analysis carried out in [25]. The EMI regulations were handled during the design of a monitoring system which is applied in high ways. Really, it was critical cases. The authors tried to consider the effect of the EMI in the existence of radio systems. There were other trials that considered the reduction of the EMI in multi-users interfering channels [26]. The authors studied the EMI impact without its nature consideration. In [27], the EMI impact, on spread spectrum techniques, was studied applying the EMC regulation limits. [28] studied the EMI effect of the mobile phones antennas. The interference can have a non-negligible impact on navigation receivers. The authors modeled the single frequency interference as well as the multi-tones one. The authors carried out experiments in order to confirm their analysis [29].

[30] tried to reduce the interference that happens in multi-channel high power amplitude modulation AM radio equipment by usage of the adaptive techniques which were powerful in reduction of coupling among co-existed transceivers. The electromagnetic environment was under control in order to be smart [31]. Really, their proposed system depended on IRSs and scatters. The EMI impact on special types of radars was handled in [32]. Really, the EMI has a bad effect on the pictures detected by the synthesis aperture radar. The interference cancellation was handled in [33]. It was suggested in an OFDM receiver. In [34], the authors assumed two channel impairments which are; the noise as well as the interference. The authors derived a mathematical model for the interference comes from different sources. They already gave the outline of the topic.

In this paper, the effect of the EMI on a cooperative millimeter wave communication system is studied and simulated. The cooperative communication is implemented by using IRSs. The mathematical model is carried out. In addition, the system is simulated by MATLAB. After carrying out the mathematical analysis and the simulation, the diversity techniques especially, STBC codes are applied. These codes can increase the gain of the system that can compensate the loss due to the existing EMI. The main contributions of this manuscript can be concluded as follow;

- The EMI, in a cooperative communication system, is given in a complete mathematical model. In fact, this model was given before. However, our manuscript concluded the complete models that can include both narrow band interference (NBI) and ultra wide band interference (UWBI). Moreover, they are concluded and given in more organized form.
- The millimeter wave channel models are applied. These models are the models of 5G networks and beyond.
- The mathematical models, describing the impact of the EMI on a cooperative communication system, are given in closed formulas.
- The bad impacts of applying millimeter wave models as well as the EMI will be compensated by applying STBC 3×4 codes.

The rest of this paper is organized as follows; the Introduction was given in Section 1 whereas Section 2 concludes the related work. Furthermore, the required mathematical equations are given in Section 3. Subsequently, Section 4 concludes the simulation results. Finally, conclusions are handled in Section 5.

3. Mathematical Model

Before explaining the detailed discussions and the complete mathematical analysis, let us describe the framework and our scenario "working steps" in brief. The framework steps can be stated as follows;-

- Determine the relationship between the received signal and the transmitted signal in existence of noise and interference.
- Categorizing the interference into two models which are; NBI and UWBI.
- Investigating the complete NBI model and also the UWBI model.
- Investigation of the interference "NBI & UWBI" effect on an IRS based cooperative wireless system.

- Optimization of the IRSs' configuration in order to let the IRS be optimized especially when STBC codes are applied assuming that the millimeter wave channels exist.

Assume that there is an IRS based cooperative communication system that is affected by the EMI coming from different sources. The EMI, affecting the victim receiver, is the summation of interferences coming from different sources; each of them has its unique characteristics. Assume that y can represent the received signal at an IRS from a transmitted one S at the source. Then, the received signal y can be expressed as;

$$y = h_1 s + n \tag{1}$$

where n refers to the noise in the channel. h gives an indication of the channel parameter "channel impulse response". The destination can receive a replica that can be written as follows;

$$y = g_2^H x + h_d s + w \tag{2}$$

y refers to the received signal at the destination. g is the channel impulse response. w is the noise in the path from the source to destination whereas h_d represents the direct link channel parameter "direct link channel impulse response". x refers to the reflected signal from an IRS whereas H is the Hermitian transpose.

The EMI can be divided into two categories which are; narrow band interference (NBI) and the ultra-wide band one (UWBI). The NBI can represent the interference comes from remote interferers. Moreover, it always affect portion of the intended communication band "victim receivers". The total average effective NBI power, affecting a communication system can be given by;

$$\sigma^2 = \sum_{k=1}^{\infty} \sigma_k^2 P_k = X \sum_{k=1}^{\infty} k P_k \tag{3}$$

where k is the number of interferers and σ_k^2 is the effective NBI power for given k interferers.

On the other side, the UWBI can represent the interference that can affect the communication system bandwidth as whole. The impulse response of the UWBI interference sources can be modeled as follows;

$$h_i(t) = X_i \sum_{l=0}^{L-1} \sum_{k=0}^{K-1} \alpha_{k,l}^i \delta(t - T_l^i - \tau_{k,l}^i) \tag{4}$$

where $\alpha_{k,l}^i$ represents the multipath gain coefficients, T_l^i is the delay of the l^{th} cluster, $\tau_{k,l}^i$ is the delay of the k^{th} multipath component relative to the l^{th} cluster arrival time (T_l^i). X_i represents the log normal shadowing and i is the i^{th} realization.

The interference can affect the received signal strength as well as the signal to noise ratio (*SNR*). The *SNR* can be given by the following equation;

$$SNR = \frac{P\left|g_2^H h_1 + h_d\right|^2}{A\sigma^2 g_2^H R g_2 + \sigma_w^2} \tag{5}$$

- **Millimeter Wave Channel Models**

The millimeter wave channel models can be used for high data rate short range communication. The millimeter waves can be considered as the promising channels of the 5G networks and beyond [35].

Thanks to the high available bandwidth, the achievable data rates can be very large. Moreover, these bands can provide a great level of security. However, they can provide a high path loss. Therefore, they are applied for short range communications only [35].

There are a lot of mathematical models for the millimeter wave channels, however the most obvious model is that provided by Rappaport [35]. This model is the easiest one and it is obvious in Table 1. The path loss values, of millimeter wave channels, can be calculated according to Eq. 6 [35]. The millimeter wave path loss models, *PL*, in decibels, can be expressed as follow;

$$PL = \alpha + 10\beta \times Log_{10}(d) + \zeta \tag{6}$$

The values of α, β, and ζ are constants and they can differ according to the operating frequency 28 GHz or 73 GHz. Moreover, they can also differ according to the type of operation. In fact, there are two categories of operation which are; line of sight (LOS) and non-line of sight (NLOS). The values of the constants α, β, and ζ are summarized in Table 1 as follow;

Table 1. The values of the constants of path loss equation of the millimeter wave channels [35].

	Frequency				
	28 GHz		**73 GHz**		
	LOS	**NLOS**	**LOS**	**NLOS (First Model)**	**NLOS (Second Model)**
α	61.4	72	69.8	86.6	82.7
β	2	2.92	2	2.45	2.69
ζ ~ N (0, σ²)	σ = 5.8 dB	σ = 8.7 dB	σ = 5.8 dB	σ = 8 dB	σ = 7.7 dB

Table 1 can be replaced by a graphical form of Figure 1. This Figure can show the propagation millimeter wave channels. The scatter plot of the different millimeter wave channels are displayed in this Figure.

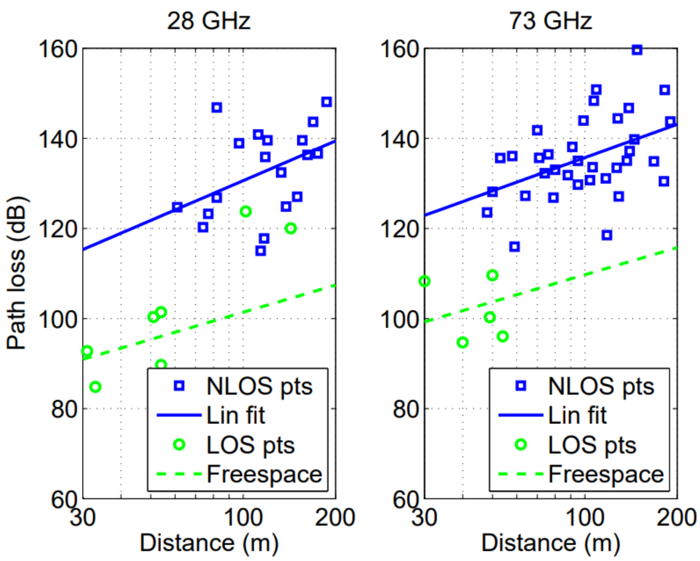

Figure 1. Scatter plot along with a linear fit of the estimated omnidirectional path losses as a function of the TX-RX separation [35].

- **3×4 STBC**

The STBC is a wireless communication technique that can be used in order to transmit a lot of copies of the same signal to a receiver. When a receiver receives a lot of versions of the same signal, it can use the best of them or it may combine them in order to get benefit of them. This technique can fit well in the radio environment that is dominated by; fading, scattering, and much more [36].

The Alamouti codes belong to the space time block codes (STBC) that can provide diversity gain. In general, the diversity codes can mitigate the bad channel effects on the basis that there are a lot of versions of the transmitted signal. Each version is transmitted with a different code. In this manuscript, the 3×4 STBC codes are applied. The transmission strategy of the applied 3×4 STBC code is shown in Figure 2 [36].

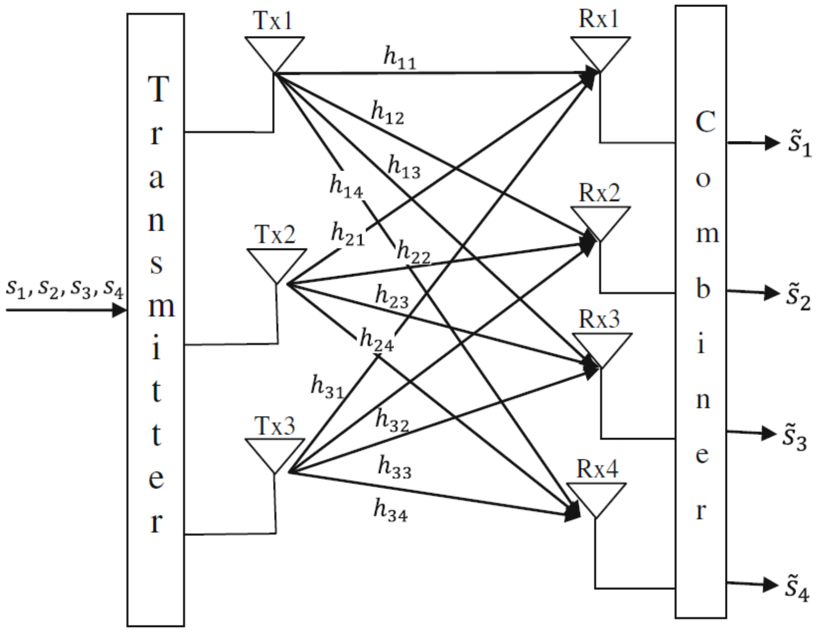

Figure 2. The transmission and reception strategy in 3×4 STBC codes [36].

The STBC can be represented in a matrix form where each row represents a time slot and each column can represent one antenna's transmission over time. The matrix form can be given as follow;

$$\begin{bmatrix} y_{11} & y_{12} & y_{13} & y_{14} & y_{15} & y_{16} & y_{17} & y_{18} \\ y_{21} & y_{22} & y_{23} & y_{24} & y_{25} & y_{26} & y_{27} & y_{28} \\ y_{31} & y_{32} & y_{33} & y_{34} & y_{35} & y_{36} & y_{37} & y_{38} \\ y_{41} & y_{42} & y_{43} & y_{44} & y_{45} & y_{46} & y_{47} & y_{48} \end{bmatrix}$$
$$= \begin{bmatrix} h_{11} & h_{21} & h_{31} \\ h_{12} & h_{22} & h_{32} \\ h_{13} & h_{23} & h_{33} \\ h_{14} & h_{24} & h_{34} \end{bmatrix} \begin{bmatrix} S_1 & -S_2 & -S_3 & -S_4 & S_1^* & -S_2^* & -S_3^* & -S_4^* \\ S_2 & S_1 & S_4 & -S_3 & S_2^* & S_1^* & S_4^* & -S_3^* \\ S_3 & -S_4 & S_1 & S_2 & S_3^* & -S_4^* & S_1^* & S_2^* \end{bmatrix} \tag{7}$$
$$+ \begin{bmatrix} \eta_{11} & \eta_{12} & \eta_{13} & \eta_{14} & \eta_{15} & \eta_{16} & \eta_{17} & \eta_{18} \\ \eta_{21} & \eta_{22} & \eta_{23} & \eta_{24} & \eta_{25} & \eta_{26} & \eta_{27} & \eta_{28} \\ \eta_{31} & \eta_{32} & \eta_{33} & \eta_{34} & \eta_{35} & \eta_{36} & \eta_{37} & \eta_{38} \\ \eta_{41} & \eta_{42} & \eta_{43} & \eta_{44} & \eta_{45} & \eta_{46} & \eta_{47} & \eta_{48} \end{bmatrix}$$

The STBC decoding can be carried out according to linear combining techniques. The symbols are transmitted simultaneously from antennas one, two, and three, respectively. Then, ML detection amounts to minimizing the decision metric [36].

$$\begin{aligned}\sum_{j=1}^{m}\Big(&\left|y_{1j}-h_{1j}s_1-h_{2j}s_2-h_{3j}s_3\right|^2+\left|y_{2j}+h_{1j}s_2-h_{2j}s_1+h_{3j}s_4\right|^2\\&+\left|y_{3j}+h_{1j}s_3-h_{2j}s_4-h_{3j}s_1\right|^2+\left|y_{4j}+h_{1j}s_4+h_{2j}s_3-h_{3j}s_2\right|^2\\&+\left|y_{1j}-h_{1j}s_1^*-h_{2j}s_2^*-h_{3j}s_3^*\right|^2+\left|y_{6j}+h_{1j}s_2^*-h_{2j}s_1^*+h_{3j}s_4^*\right|^2\\&+\left|y_{7j}+h_{1j}s_3^*-h_{2j}s_4^*-h_{3j}s_1^*\right|^2+\left|y_{8j}+h_{1j}s_4^*+h_{2j}s_3^*-h_{3j}s_2^*\right|^2\Big)\end{aligned} \tag{8}$$

Then, each symbol can be detected individually [36].

4. Simulation Results

The simulation results are explained in this section. The simulation parameters are concluded in Table 2. They are chosen as stated before in Ref. [34] in order to have a fair comparison with already published work. In fact, the simulation parameters are stated in details in order to allow the others to repeat the same results. Moreover, the specifications of the machine that is used in the simulation are stated as it is related to the processing time. After that, the simulation results are explained and analyzed in details.

In this section, the simulation results are shown. Moreover, simple discussions are given about the existing figures and tables.

In Figure 3, the variation of the SINR with the number of elements "square grid" of an IRS is plotted. In this Figure, there is a comparison between Figure 3(a) that represents the results given in [34] and Figure 3(b) that shows the results of the proposed system. For more clarifications, Figure 3(a) can show the performance of the related work that was considered in [34]. This figure is repeated in order to have a fair comparison with the proposed work. By the same way, Figure 3(b) displays the average SINR in the proposed system. In other words, this figure displays the relation between the average SINR with the number of elements for an IRS system operating in the millimeter wave frequency band. From Figure 3(a) and Figure 3(b), it can be observed that the implementation of the STBC (4×3) codes can compensate the effect of millimeter wave high path loss and the effect of the EMI.

Table 2. The simulation parameters.

Parameter	Value
Frequency of Operation	Millimeter Wave Bands (28 GHz & 73 GHz)
Number of IRS elements	50
Number of channel realizations	1000
Bandwidth	1 MHz
Transmitted Power	23 dBm
IRS	Square Grid
Processor	Intel(R) Core(TM) i7-4600U CPU @ 2.10GHz 2.69 GHz
Installed RAM	8.00 GB (7.88 GB usable)
Product ID	00329-10330-00000-AA651
Edition	Windows 10 Enterprise
Version	21H2

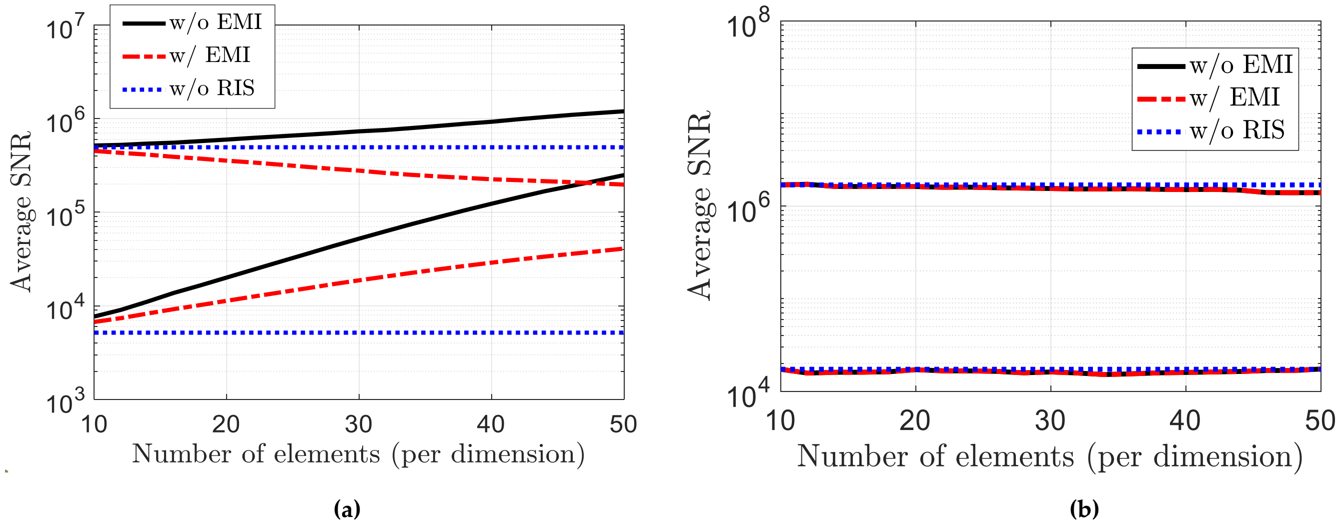

Figure 3. The average *SINR* level comparisons between [34] which is in (a) and the proposed work which is in (b).

Table 3, Table 4, and Table 5 can hold comparisons among the related work and the proposed work. The left section of Table 3 compares between the averages of SINR for an IRS without interference, with isotropic radiator, for directive IRS that has different directive angles. On the other side, the right section of the same Table can clarify the average SINR for an IRS that operates in the millimeter wave channel models, without interference, with isotropic radiator, and for directive IRS that has different directive angles. From this table, it can be concluded that, the applied STBC codes can increase the directivity gain of the IRS regardless the high path loss values given from the millimeter wave channel models. In brief, the application of the STBC codes can compensate the loss degradation in the cooperative system performance due to the high path loss resulted from the millimeter wave channels. Moreover, the gain acquired from STBC application can increase the system performance. In other words, the gain acquired by STBC application can overcome the loss acquired by millimeter wave path loss values. This gain is obvious in the average SINR comparison which is shown in Table 3.

Table 3. The average of SINR comparisons of the proposed system and the work in Ref. [34].

N	**Average *SINR* Ref. [34]**					**Average *SINR* "proposed work"**				
	Without *EMI*	Isotropic *R*	2π/3	π/4	π/8	Without *EMI*	Isotropic *R*	2π/3	π/4	π/8
50	100	100	100	100	100	11200	11200	11200	11200	11200
100	400	300	300	300	300	44800	33600	33600	33600	33600
150	1000	750	750	750	950	112000	84000	84000	84000	106400
200	1600	1100	1200	1200	1500	179200	123200	134400	134400	168000
250	2400	1500	1600	1600	2100	268800	168000	179200	179200	235200
300	3200	2000	2150	2250	2800	358400	224000	240800	252000	313600
350	4000	2400	2600	2700	3500	448000	268800	291200	302400	392000
400	5000	3000	3200	3400	4300	560000	336000	358400	380800	481600

The left section of Table 4 compares between the averages of capacity "bps" for an IRS without interference, with isotropic radiator, for directive IRS that has different directive angles. On the other side, the right section of the same Table can clarify the average capacity "bits per second (bps)" for an IRS that operates in the millimeter wave channel models, without interference, with isotropic radiator, and for directive IRS that has different directive angles. From this table, it can be concluded that, the applied STBC codes can increase the capacity of the IRS regardless the high path loss values given from the millimeter wave channel models. In brief, the application of the STBC codes can compensate the loss degradation in the cooperative system performance due to the high path loss resulted from the millimeter wave channels. Moreover, the capacity gain acquired from STBC application can increase the system performance. In other words, the capacity gain acquired by STBC application can overcome the loss acquired by millimeter wave path loss values. This capacity gain is obvious in the average bps comparison which is shown in Table 4.

Table 4. The average of bps comparisons of the proposed system and the work in Ref. [34].

N	**Capacity "bps / Hz" Ref [34]**					**Capacity "bps / Hz" proposed work**				
	Without *EMI*	Isotropic *R*	2π/3	π/4	π/8	Without *EMI*	Isotropic *R*	2π/3	π/4	π/8
100	8.5	8.5	8.5	8.5	8.5	15	15	15	15	15
200	10.5	10	10.1	10.1	10.4	17	16.5	16.6	16.6	16.9
300	11.6	11	11.1	11.2	11.5	18.1	17.5	17.6	17.7	18
400	12.2	11.5	11.6	11.7	12	18.7	18	18.1	18.2	18.5
500	13	12	12.1	12.2	12.8	19.5	18.5	18.6	18.7	19.3

The left section of Table 4 compares between the averages of optimized SINR for an IRS without interference, with isotropic radiator, for directive IRS that has different directive angles. On the other side, the right section of the same Table can clarify the average optimized SINR for an IRS that operates in the millimeter wave channel models, without interference, with isotropic radiator, and for directive IRS that has different directive angles. It can be concluded that, the proposed system can provide high optimized SINR gain than the related work [34].

Table 5. The average of SINR comparisons of the proposed system and the work in Ref. [34] after applying an optimization algorithm.

N	Average SINR Ref. [34]				Average SINR "proposed work"			
	Without *EMI*	Upper Bound	Iterative Algorithm	Optimized Thermal Noise	Without *EMI*	Upper Bound	Iterative Algorithm	Optimized Thermal Noise
0	0	0	0	0	0	0	0	0
100	300	300	300	300	33600	33600	33600	33600
200	1600	1500	1000	1000	179200	168000	112000	112000
300	3000	2500	2000	2000	336000	280000	224000	224000
400	5500	4000	3000	3000	616000	448000	336000	336000
500	8000	5600	4100	4100	896000	627200	459200	459200
600	11000	7000	5500	5500	1232000	784000	616000	616000

5. Conclusions

Our manuscript considered the EMI impact on a cooperative radio system that employs the IRS. The considered channels are millimeter wave ones. The EMI is organized well and its mathematical formulas are given in more clarified form. The most EMI competing models are considered which were; NBI and UWBI. The propagation channels were considered millimeter waves as they are the competing bands for the 5G networks and beyond. After that, there was a trial to employ the STBC codes in order to eliminate the bad impact of the EMI as well as the high path loss of the millimeter wave channels. Really, the STBC codes compensated the fore-mentioned bad effects. Moreover, they could provide gain in the SINR as well as throughput "bps".

Declarations

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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There is no conflict between this work and other published work.

The Matlab code is available on reasonable request.

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