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Study of Electromagnetic Interference Effects in Intelligent Reflecting Surfaces Aided Communication in Alamouti Coded 5G Networks

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Abstract: The cooperative communication techniques, wherein several transmitters and one receiver are implemented, can greatly increase the performance of a communication system. In fact, the cooperative communication has been launched since the fourth generation mobile systems. The two competing cooperative techniques are; relays and intelligent reflecting surfaces (IRS). It is known that the electromagnetic interference (EMI) can degrade a radio system performance. In this paper, the EMI, affecting an IRS-based communication system, is mathematically modeled and simulated. The interference level can be affected by the channel parameters which are the 5G path loss models. In order to improve the communication system performance, Alamouti codes are applied. The gain, offered by diversity codes "Alamouti", can reduce the degradation of the performance due to the EMI existence. The complete mathematical model is carried out as well as the simulation model. The simulation results show that the cooperative Alamouti-coded 5G radio systems have a satisfying performance even the EMI exists.

Keywords: Radio Systems, EMI, 5G Models, MIMO, Alamouti Codes.

1. Introduction

The theory of cooperative communication was launched in 2010, in such a way that, a communication receiver can receive a lot of versions of the transmitted signal. In brief, the communication performance can be greatly improved when the communication receiver receives the transmitted signal a lot of time. In other words, the cooperative theory depends on transmission of the intended signal to an intended receiver a lot of times. The cooperative communication appeared in the 4G systems in a form called coordinated multipoint transmission and reception (COMP). In a COMP technique, the cooperative communication occurred among a lot of transmitters and a lot of receivers [1-3]. In fact, these techniques could greatly increase a radio system performance.

There are two major categories of the cooperative communication. One of them is the relay deployment whereas the other is the IRS implementation. These categories are very competing. In fact, the relay can provide a satisfied cooperative performance. However, it can amplify both the intended signals and the noise. In other words, the noise amplification, in relays, is still a great challenge. On the other side, the IRS can also provide an acceptable performance. However, they occupy a large space size. Up till now, the two techniques still work well. However, there are a lot of trials in order to reduce their disadvantages [4-7].

The electromagnetic interference (EMI) can badly affect a radio communication system. In fact, both of noise and EMI can reduce a radio system performance. However, the noise can be defined as random signals that badly affect the performance whereas the EMI is a deterministic signal that may be intentional or non-intentional. The EMI can be affected by a lot of parameters which include; transmission power, noise margin, receiver sensitivity, and much more [8-11].

In this paper, the EMI, affecting a radio communication system, is modeled and simulated. It's effect is studied on a cooperative communication system. The considered cooperative mechanism is an IRS-based one. The EMI effects are considered assuming that the 5G path loss models are applied.

2. Related Work

The EMI is a vital phenomenon in communication systems and equipment in general. In fact, each system and component should follow the electromagnetic compatibility regulations. These regulations can confirm the acceptable performance of a system or a component when they exist in an electromagnetic environment. In brief, each component should not emit a radiation that can badly affect the neighboring systems and also it should not be affected by the surrounding electromagnetic environment. A component or a system should have a high immunity to electromagnetic radiations [12-14]. The EMI was modeled and it's performance was simulated in radio systems in [15]. There were two types of interference which were; the narrow band and the ultra-wide band. The authors studied the effect of two types of interference as well as noise on the bit error rate (BER) of a digital radio communication system. The noise as well as interference can increase the BER of a digital communication system.

In [16], the authors tried to apply the electromagnetic compatibility (EMC) regulations and they carried out a mathematical model for the EMI. They studied its effects on a radio communication system. The fore-mentioned communication system is a subsystem that was used for control signaling between a base station and a rail way train. They carried out their model in order to consider the open-air environment, the existing Wi-Fi networks, cellular networks, and much more. [17] considered the trials to reduce the interference in multi-users interfering channels. The suggested scheme was completely independent of prior knowledge on the nature of the interference. In [18], the effect of the switched mode spread spectrum system was considered in order to mitigate the interference affecting equipment and systems. The authors considered the EMC regulations in their analysis. The authors gave practical recommendations about how to apply the spread spectrum modulations with a general reflection on the EMC requirements. [19] discussed the electromagnetic properties "radiation" of the front-end receiver of the mobile phones. They tried to reduce the interference effect by reducing the harmonics effects of the electronic transistors. [20] tried to carry out a mathematical model for the EMI on a navigation receiver. They considered the single frequency interference as well as the multi frequencies one. They assured their performance by carrying out experiments on multi-frequencies interference by using Beidou navigation receiver.

In [21], the authors tried to reduce and eliminate the EMI in multi-channels for full-duplex high power AM Radios by adaptive techniques. The applied adaptive technique was powerful in eliminating the interference in collocated radio systems and it was already successful in reducing the coupling among coexisted transmitters and receivers. In [22], the authors tried to make control on the electromagnetic environment. They introduced the formation of smart radio environment considering efficient utilization of radio spectrum in a given geographical area. They totally depended on IRSs as well as ambient backscatter communication technologies. [23] studied the EMI effects on synthesis aperture radars (SAR). The EMI from different sources, which are close to the radar, can badly affect the detected image displayed on the radar. The EMI level can false alarm the radar with faulty high resolution images. In [24], the successive interference cancellation was suggested in an OFDM receiver by the GNU radio. [25] studied the IRSs cooperative radio communication system wherein the noise and interference exist. They assumed that the EMI comes from different sources. Thanks to the authors, they already modeled the EMI in a cooperative radio network and their model can be considered as a base line for the topic.

Our paper handles the EMI from a different point of view. This paper is concerned with the EMI study in a cooperative communication system wherein advanced channel models are employed. In this paper, the cooperative communication systems, based on IRSs, is mathematically analyzed as an extension of the work proposed in [25]. The main contribution of this paper can be stated as follows;

- The EMI is mathematically modeled in an IRS-based cooperative communication system.
- The 5G path loss models are applied in the proposed cooperative communication system. The 5G models are considered as the current generation models.
- The EMI effect on a cooperative radio communication system is modeled and simulated. In order to reduce the impact of the EMI on the proposed cooperative communication system, Alamouti 2×2 codes are applied in order to improve the performance of the system.

This paper is organized as follows; Section 1 handled the introduction of the paper. In section 2, the related work was clarified. Subsequently, the system mathematical model is explained in Section 3. After that, the simulation results are given in Section 4 whereas Section 5 summarizes the conclusions of the paper.

3. Mathematical Model

The EMI is a vital phenomenon in communication systems and equipment in general. In fact, each system and component should follow the electromagnetic compatibility regulations. These regulations can confirm the acceptable performance of a system or a component even they exist in electromagnetic environment. The system model is shown in Figure 1. Assume that the transmitted signal is *S*, the received signal *y* can be expressed as;

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

The *y* gives the symbol refers to the received signal at an *IRS* whereas the *n* is the noise. Moreover, h_1 gives an indication of the channel parameter between the signal source and an *IRS*. The received signal, at the destination, can be given by;

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

The *y* refers to the received signal at the destination. *w* refers to the noise in the direct link path between a source and a destination. h_d refers to the direct link gain "between source and destination". *x* refers to the reflected signal from an IRS. *g* is the channel gain between the reflected signal *x* from an *IRS* whereas *H* refers to the Hermetian transpose of a matrix. From the previous two equations, it can be said that;

$$y = \left(g_2^H h_1 + h_d\right) \times s + g_2^H n + w \tag{3}$$

The statistical model for the *EMI* can be given, as in [15], as;

- **Narrow Band Interference (NBI) Model**

The most famous narrow band interference model was stated before in [15]. This model considered that the NBI can come from independent sources. The probability of a certain number of *k* interferers, P_k , on a system spectrum can have Poisson distribution as follows;

$$P_k = \frac{\eta^k}{k!} e^{-\eta} \tag{4}$$

where η refers to the average number of occurrence of certain events whereas *k* gives an indication of the number of interferers. In addition, the average of bandwidth occupied by NBI, λ , can be obtained by applying the following relation;

$$\lambda = \frac{\eta \Omega}{W} \tag{5}$$

where *W* is the system bandwidth, and Ω is the average bandwidth of interference occurrence. The interfering power which affects a subcarrier at f_m , in a multicarrier submission system, is denoted by *X* and it can be calculated by;

$$X = \int_0^{\Omega} P \left| X_y(f_m) \right|^2 dy = \frac{2\Omega}{W} \int_0^{\Omega} \left| X_y(f_m) \right|^2 dy \tag{6}$$

where *y* is the different frequency values (spectrum positions) at which the interference can affect. Therefore, the power contribution due to the *k* interferers is;

$$\sigma_k^2 = k.X \tag{7}$$

where σ_k^2 is the effective NBI power for given *k* interferers. Therefore, the total average effective NBI power in the system is;

$$\sigma^2 = \sum_{k=1}^{\infty} \sigma_k^2 P_k = X \sum_{k=1}^{\infty} k P_k = X\eta \tag{8}$$

The NBI, due to *k* interferers, can be represented by a random variable with Gaussian (*pdf)* and it can have a value of *z* with mean μ and variance σ_k^2. Therefore, the probability distribution function (*pdf*) can be described as follows;

$$P_Z(z|k) = \sum_{k=1}^{\infty} \frac{P_k}{\sqrt{2\pi\sigma_k^2}} * e^{-(\frac{(z-\mu)^2}{2\sigma_k^2})} \tag{9}$$

- **Ultra Wide Band (UWB) Channel Model**

There may be wide band interference or ultra wide band interference that can affect system band as whole not a portion of band only. [15] applied a most common UWB interference model, in such a way that, the UWB channel has an impulse response as follow;

$$h_i(t) = X_i \sum_{l=0}^{L-1} \sum_{k=0}^{K-1} \alpha_{k,l}^i \delta(t - T_l^i - \tau_{k,l}^i) \tag{10}$$

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.

- **Signal to Interference plus Noise Ratio (SINR) Calculations**

The *SINR* refers to the signal divided by two terms which are; interference and noise. The interference can include the fore-mentioned two categories which are; narrow band interference and the ultra-wide band one. The *SINR* can be given by;

$$SINR = \frac{P\left|g_2^H h_1 + h_d\right|^2}{A\sigma^2 g_2^H R g_2 + \sigma_w^2} \tag{11}$$

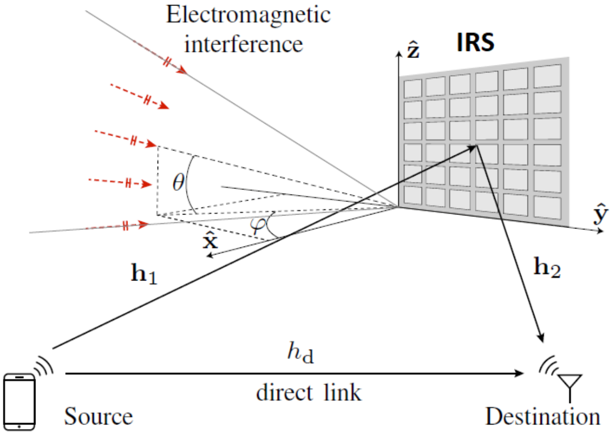


Figure 1. The cooperative communication system.

- **Alamouti 2×2 Codes**

The Alamouti codes are special types of space time block codes that can be used for diversity purpose. The diversity can be applied in order to mitigate the channel effects on the basis that the transmitted signal can have a lot different independent paths to the receiver. If one channel path is not suitable for reliable data transmission, there will be a lot of different reliable paths. Moreover, the receiver can select the best channel one or it can combine the different received signals. Alamouti code is a form of codes that can confirm reliable channel transmission even there is noise, fading, interference, and other channel impairments. The Alamouti 2×2 code can be mathematically modeled as follow;

$$\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix} + \begin{bmatrix} \eta_{11} & \eta_{12} \\ \eta_{21} & \eta_{22} \end{bmatrix}$$

$$= \begin{bmatrix} h_{11}s_1 + h_{12}s_2 + \eta_{11} & -h_{11}s_2^* + h_{12}s_1^* + \eta_{21} \\ h_{21}s_1 + h_{22}s_2 + \eta_{21} & -h_{21}s_2^* + h_{22}s_1^* + \eta_{22} \end{bmatrix} \tag{12}$$

When the receiver applies a combiner technique, the combined signal can be expressed as;

$$\tilde{s}_1 = h_{11}^* y_{11} + h_{12} y_{12}^* + h_{21}^* y_{21} + h_{22} y_{22}^* \quad (13)$$

$$\tilde{s}_2 = h_{12}^* y_{11} - h_{11} y_{12}^* + h_{22}^* y_{21} - h_{22} y_{22}^* \quad (14)$$

4. Simulation Result

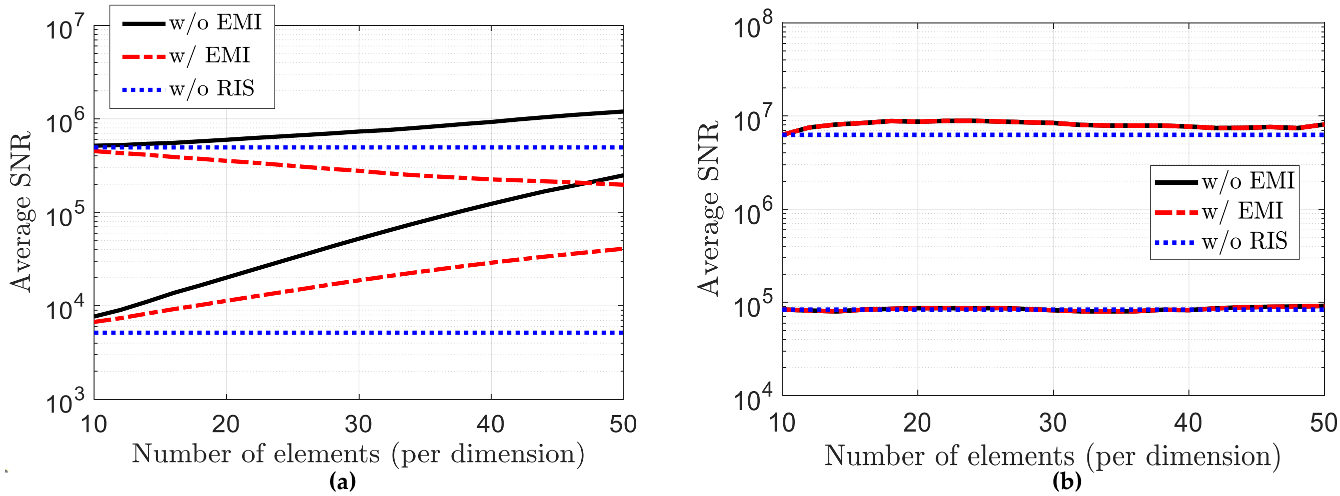
In this section, the cooperative radio communication system, affected by EMI, is simulated. The simulation parameters are given in Table 1. The simulation parameters are chosen in order to be compatible with the previously carried out work which is in [25].

Table 1. The simulation parameters.

Parameter	Value
Frequency of Operation	2 GHz
Number of IRS elements	50
IRS	Square Grid
Number of channel realizations	1000
Bandwidth	1 MHz
Transmitted Power	23 dBm
Path Loss	5G models
Diversity Codes	Alamouti 2×2
MATLAB	Version R2020a
Operating System	Win 10 – 64-bit operating system, x64-based processor
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
OS build	19044.2130
Experience	Windows Feature Experience Pack 120.2212.4180.0

Figure 2 presents the variation of the *SINR* levels with the applied number of elements in the *IRS*. Figure 2(a) shows the figure displayed in [25] whereas Figure 2 (b) clarifies the results in our proposed work. It can be concluded that the Alamouti codes can neglect the *EMI* effect in the *5G* systems. In fact, the Alamouti codes are not used for interference mitigation. However, in the proposed work, these codes are applied in order to reduce the effect of the *EMI* and the increased path loss values due to the application of *5G* models. They really can provide a gain in the system as whole. The average *SINR* for a cooperative communication system applying Alamouti 2×2 codes can have a satisfied performance.

Table 2, Table 3, and Table 4 concludes the *SINR* levels for the cooperative communication system, based on *IRS*, that applies Alamouti 2×2 codes in comparisons with the results discussed before in [25]. It can be stated that the *IRS* cooperative radio systems with Alamouti 2×2 codes have a god performance even there is severe interference.



(a) **(b)**

Figure 2. The average *SINR* level comparisons between [25] which is in (a) and the proposed work which is in (b).

Table 2. The average of *SINR* comparisons of the proposed system and the work in [25].

N	**Average *SINR* [25]**					**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	3160	3160	3160	3160	3160
100	400	300	300	300	300	12640	9480	9480	9480	9480
150	1000	750	750	750	950	31600	23700	23700	23700	30020
200	1600	1100	1200	1200	1500	50560	34760	37920	37920	47400
250	2400	1500	1600	1600	2100	75840	47400	50560	50560	66360
300	3200	2000	2150	2250	2800	101120	63200	67940	71100	88480
350	4000	2400	2600	2700	3500	126400	75840	82160	85320	110600
400	5000	3000	3200	3400	4300	158000	94800	101120	107440	135880

Table 3. The average of *SINR* comparisons of the proposed system and the work in [25].

N	**Capacity (bps / Hz) [25]**					**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	13.5	13.5	13.5	13.5	13.5
200	10.5	10	10.1	10.1	10.4	15.5	15	15.1	15.1	15.4
300	11.6	11	11.1	11.2	11.5	16.6	16	16.1	16.2	16.5
400	12.2	11.5	11.6	11.7	12	17.2	16.5	16.5	16.7	17
500	13	12	12.1	12.2	12.8	18	17	17.1	17.2	17.8

Table 4. The average of *SINR* comparisons of the proposed system and the work in [25] after applying an optimization algorithm.

N	Average SINR [25]				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	9480	9480	9480	9480
200	1600	1500	1000	1000	50560	47400	31600	31600
300	3000	2500	2000	2000	94800	79000	63200	63200
400	5500	4000	3000	3000	173800	126400	94800	94800
500	8000	5600	4100	4100	252800	176960	129560	129560
600	11000	7000	5500	5500	347600	221200	173800	173800

5. Conclusions

The *EMI* in a cooperative communication system, based on IRSs, was modeled and simulated. There were two types of interference which were the narrow band interference and the wide band one. The path loss of the 5G was applied. The *EMI* has a negative impact on a radio communication system performance. The performance was improved by applying Alamouti codes. It can be concluded that the application of Alamouti codes in an IRS aided radio interfering system can improve the system *SINR* and the link capacity even there are severe interference.

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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