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Enhanced MIMO-OFDM Radar Waveform Designs for Exact Antenna Parameter

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ABSTRACT: This work is focused on predicting the return loss and gain characteristics, develops a novel MIMO-OFDM radar waveform, which is specially designed for a line impedance antenna system on an FR4 substrate. A suggested radar waveform is implemented on an FR4 substrate normally used in microwave applications. It is obtained that, after extensive modelling, the return loss for the MIMO-OFDM radar waveform is -31.7265 dB at a frequency of 6.86 GHz, thereby showing minimum reflection and good impedance matching. At this frequency, the gain for the system comes out to be 7.127 dB, which refers to the fact that this waveform would help enhance the performance of radar systems. These results demonstrate how the MIMO-OFDM radar waveform can be used for advanced radar applications. It gives better return loss and gain, some of the critical specifications required for high-performance radar systems.

1. INTRODUCTION

In the extraordinary development of wireless communication networks, two of the key technologies are orthogonal frequency division multiplexing (OFDM) and multiple input multiple outputs (MIMO). Combined, they form a potent combination known as MIMO-OFDM, which has been utilized in many modern wireless protocols like LTE, 5G, and Wi-Fi. OFDM is a digital multicarrier modulation technique that divides a frequency-selective channel into many narrowband channels at different frequencies called subcarriers [1]. Due to this splitting, OFDM reduces the impact of inter symbol interference (ISI) and multipath fading — two key problems in wireless communications. Because one subcarrier is orthogonal to the other subcarriers, bandwidth can be utilized effectively without the subcarriers interfering with each other, even when they are packed closely together. OFDM can overcome the distortion caused by a lot of signal routes by using multiple subcarriers. Since equalization takes place in the frequency domain in OFDM, it requires low computing power [1–3]. MIMO is a technology that enhances communication performance by using many antennas at both the transmitter and receiver. By combining several signal routes created by different antennas, the resiliency and reliability of the link may increase. Supporting this fact, MIMO can increase data rate effectively without consuming more power or bandwidth by transmitting distinctive data streams on each of many antennas [4, 5]. MIMO greatly improves throughput as data are sent using multiple streams. The use of multiple antennas helps mitigate fading and other constraints.

MIMO systems can use beam-forming techniques to extend coverage [4]. MIMO and OFDM cooperate to yield a robust and high-performance communication system that can meet such challenges in a variety of scenarios for wireless communication [6–9]. MIMO-OFDM has all the potential to be ideal for contemporary wireless systems: achieving high data rates, spectrum efficiency, and durability. For its operation over the wireless channel, which is often frequency-selective, OFDM splits it into several narrowband subcarriers [10–13].

MIMO uses several independent antennas for sending and receiving signals, increasing the capacity and reliability of wireless links. Because of such merits, MIMO-OFDM systems form a cornerstone of both the present and future wireless communication technologies, enabling high-speed transmission of broadband data even under the harshest conditions [14–18]. MIMO-OFDM radar combines the robustness and spectrum efficiency of OFDM with the spatial diversity and the multiplexing benefits brought by MIMO.

These systems have wide applications in automobile radar, remote sensing, and some other applications that require high-resolution imaging with better target recognition and superior resistance to interference [19, 20]. It is still difficult to achieve optimal gain and minimize return loss in such systems. As much as the development of MIMO-OFDM radar technology has gone so far, a few holes are still left to be filled to achieve the desired improvement in gains and return loss performance. Most of the MIMO-OFDM radar waveform designs being used today focus on either minimizing return loss or optimizing gain, but not both at the same time [21].

There are few comprehensive approaches that can optimize these parameters simultaneously and take into account hardware and operating environment constraints. Regarding OFDM

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radar systems, the impact of antenna mutual coupling on gain and return loss in MIMO configurations is not well investigated. For the compact or high-density arrays of antennas, this understanding and mitigation are critical to optimizing radar performance [22].

The proposed Adaptive MIMO-OFDM Radar Waveform Design Framework aims to bridge these research gaps by offering a holistic, efficient, and effective approach toward the possibility of gain maximization and return loss minimization in MIMO-OFDM radar systems. Indeed, the applications of this framework, including joint optimization, adaptive approaches, mutual coupling compensation, and machine learning, may have a great impact on improving performance and reliability in radar systems [23]. The antenna can implemented for the faster transmission of the signal [26], and it can be modified with the increase in the number of elements for MIMO design. The antenna design features a 12-element asymmetric mirror-coupled loop configuration, optimized for integration into 5G smartphones [27]. It consists of six identical asymmetric mirror-coupled (AM) building blocks, each made up of two gap-coupled loop antennas. Each building block measures just $12\times 7\,\text{mm}^2$. This MIMO antenna can be used not only in 5G but also in 6G applications, providing better tolerances by simply changing the dimensions of the 4 elements [28].

Conventional methods in designing the waveform of the radar mainly target maximum energy efficiency or mutual interference. However, these techniques often lead to suboptimal performance when it comes to accurate estimation of the parameters because they have a high side-lobe level, restricted frequency diversity, and limited adaptability to a specific antenna configuration. Such deficiencies can make the system less reliable for detecting objects through radar, as well as degrade its ability to function correctly in dense and cluttered environments.

To overcome this, this paper introduces an enhanced MIMO-OFDM radar waveform design tailored towards optimizing the exact antenna parameters. Our method addresses the issues of conventional methods by utilizing novel waveform generation techniques that reduce side-lobe levels, enhance spatial resolution, and provide improved frequency agility. The proposed design is also amenable to implementation on FR4 substrates, which leads to cost-effective and scalable deployment.

This study mainly consists of four parts. Firstly, there is a MIMO OFDM that summarizes the structure of the antenna. Secondly, there is a MIMO antenna design, including the design specification. Then comes the result analysis, mainly conducting simulation analysis on the research methods. Finally, the conclusion summarizes the research findings and shortcomings.

2. PROPOSED MIMO OFDM METHOD

High Frequency Structure Simulator (HFSS)-based MIMO-OFDM system design and optimization ensures that the final design of the system satisfies the requirements of performance criteria for present wireless communication systems by combining thorough antenna simulations with system-level OFDM analysis. This paper develops a novel MIMO-OFDM radar waveform, which is specially designed for a line impedance antenna system on an FR4 substrate which integrates the advantages of advanced impedance matching and optimized signal processing to attain excellent performance in radar applications. Contrasting with conventional designs, it demonstrates a very low return loss so that the reflected signals will be minimized, thus increasing the efficiency of energy use.

In addition, reflections can occur due to impedance mismatch between the antenna and transmission line that can also add to higher return loss. Impedance mismatch effects are simulated for various OFDM subcarriers and MIMO channels to obtain frequency-dependent return loss profiles. Mutual coupling matrix is included to analyze the effect of closely spaced antennas [24]. Mutual coupling can make the effective impedance of each antenna different from what it would be without the presence of the other antenna. This may affect return loss: Simulations are carried out in order to find the return loss for all the transmitting antennas and OFDM subcarriers. Return loss should be minimized to reduce signal reflections and maximize system efficiency as shown in Figure 1. Therefore, a trade-off has to be made between the maximum gain and minimum return loss, accounting for hardware limitations as well as power consumption. The proposed technique provides a structured approach to the problem of return loss and gain optimization in MIMO-OFDM systems [25]. Incorporating this technique with machine learning, adaptive algorithms, and advanced waveform design improves the real-world performance of MIMO-OFDM systems, thus enhancing the overall radar performance. Due to the increase in data transmission rates, improving the quality of a signal and increasing the capacity of a system, MIMO-OFDM antennas have become indispensable from communication systems to radar. These antennas can also be used in 5G networks as they enable high data rates, low latency, and reliable long-distance communication. Besides, they are critical in other Wi-Fi standards like 802.11n and 802.11ac which increase the data rate by enhancing the connectivity. Moreover, in satellite communications, these MIMO-OFDM antennas play a significant role in the improvement of the spectral efficiency and providing consistent connectivity to broadcasting services as well as the internet services plus remote sensing. Finally, these antennas allow high speed Internet access to

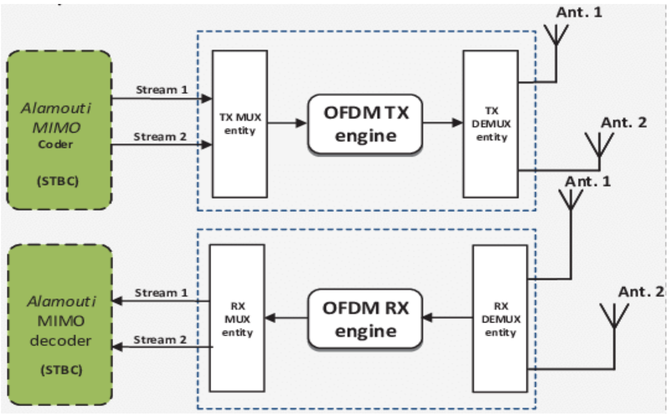

FIGURE 1. Structure of MIMO OFDM.

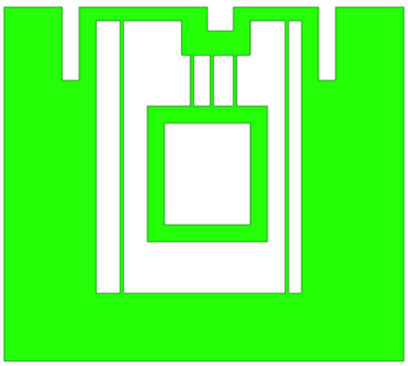

FIGURE 2. Front view of line impedance antenna (42.0 mm∗13.4 mm∗1.4 mm) with FR4 substrate at a frequency of 6.86 GHz.

the most distant un-served areas where no wired infrastructure would otherwise attain access to.

3. MIMO ANTENNA DESIGN

The feeding point of the antenna's radio frequency (RF) signal is strategically placed to achieve the required impedance characteristics. The conductive trace's design and dimensions are optimized to ensure that the antenna operates at 50 ohms impedance at 6.86 GHz, with minimal reflections and increased power transmission, as shown in Figure 2. The trace length of 42.0 mm approximates one wavelength at 6.86 GHz, which contributes to high resonance and radiation efficiency. The radiation patterns are not visible from the front view because of the influence of various design factors related to the shape and orientation of the conductive trace. However, a straight trace produces a dipole-like radiation pattern, and deviations from that design can change the antenna's directivity. Table 1 summarizes the design parameters and essential characteristics that define a line impedance antenna used in the MIMO-OFDM radar system; thus, it serves as a guide toward understanding performance attributes and design decisions of the antenna.

TABLE 1. Line impedance antenna specification.

Antenna Parameters	Specification
Operating Frequency	6.86 GHz
Length	42 mm
Width	13.4 mm
Thickness	1.4 mm
Material	FR4
Substrate Thickness	1.6 mm
Relative Permittivity (ε_r)	~ 4.4

A line impedance antenna may be made as a conductive trace on a substrate with a designed impedance for example 50 ohms for matching to the usual input/output impedance of a radio frequency system. The length, width, and shape of the antenna determine its radiation pattern, impedance, and resonant frequency. FR4 is usually the first option for antenna designers because it is very inexpensive, widely available, and has excellent mechanical properties. However, FR4 suffers from increased dielectric losses at a frequency up to 6.86 GHz, which might decrease the efficiency of the antenna in Figure 3.

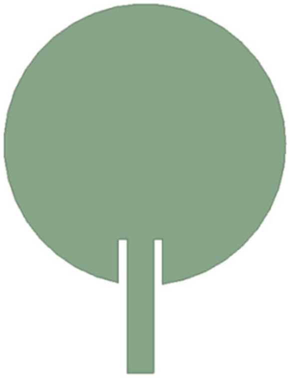

FIGURE 3. Top view of the 6.86 GHz line impedance antenna.

4. RESULTS AND DISCUSSION

4.1. Antenna Parameters

Return loss signifies the efficiency of the power transfer from the transmission line to the antenna. It calculates the power reflected due to impedance mismatch.

$$Return\ loss\ (RL) = -20\log_{10}\frac{V_{reflected}}{V_{incident}}\ \mathrm{dB}$$

An impedance matching of -35 dB is extremely good return loss. The fact that such incident power is reflected so little gives credit to the good matching between the antenna and feed line. The value is perfect for high-performance applications where signal reflection should be at a bare minimum.

Graphical return loss representation in Figure 4 for MIMO-OFDM with line impedance antenna at 6.86 GHz shows excellent impedance matching at the frequency of interest, with the return loss of -31.7265 dB. This matching is important so that there is going to be minimal power loss for effective signal transmission and reliability in communication. Looking at the graph provides information about how to understand the bandwidth over which the antenna performs well.

Antenna gain is the measure of the conversion of input power into radio waves in a specified direction relative to a reference antenna, such as a dipole or an isotropic radiator in Table 2. Antenna gain uses decibel units. An antenna's gain combines two factors: the efficiency and directivity of an antenna. Therefore, with a higher gain, that antenna sends more power in one direction. This plays a very important role in the concentration of energy and boosting of signal strength in an application like MIMO-OFDM.

The graphical representation of gain in Figure 5 for the MIMO-OFDM system with a line impedance antenna operating at 5.86 GHz effectively illustrates the antenna's ability to direct energy efficiently. The gain value is 7.1276 dB, highlighting the antenna's strong performance in radiating signals at this frequency. This develops a very essential feature towards fully achieving MIMO-OFDM system performance, and

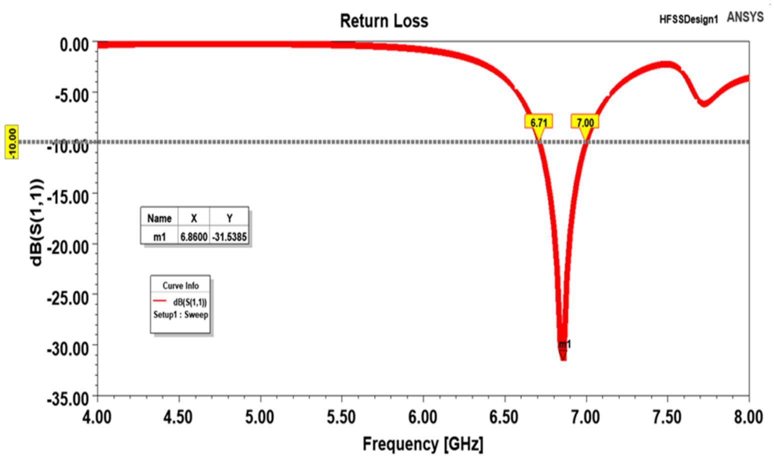

FIGURE 4. Return loss of MIMO-OFDM for line impedance antenna at 6.86 GHz frequency and −31.7265 dB return loss.

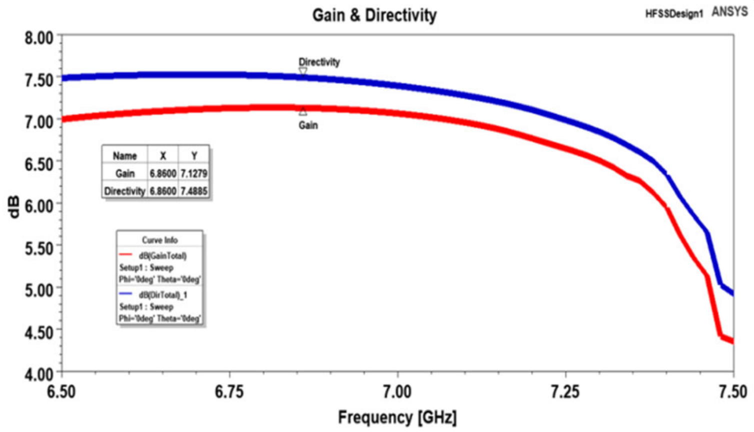

FIGURE 5. Gain of MIMO-OFDM for line impedance of frequency of 5.86 GHz and gain of 7.1276 dB.

TABLE 2. Frequency and return loss of a MIMO-OFDM radar waveform for line impedance antenna operating for frequency from 6.5 to 7.5 GHz.

S.NO.	FREQUENCY (GHz)	RETURN LOSS (dB)
1	6.25	−3
2	6.45	−4
3	6.50	−5
4	6.75	−25
5	6.85	−31.7265
6	6.95	−25
7	7.00	−10
8	7.25	−12
9	7.50	−4
10	7.75	−6
11	7.95	−5
12	8.00	−4

it assures good quality in the transmission and reception of the signal, thereby allowing general improvement in the grade of communication. In Table 3, the operating frequency and gain of the line impedance antenna for the proposed system are shown. The performance of an antenna across a range of frequencies offers crucial insights into its operating bandwidth and efficiency. The gain curve effectively represents these characteristics, serving as a dependable measure of the antenna's capabilities.

$$Gain(G) = 10\log_{10}\left(\frac{4\pi A_e}{\lambda^2}\right)$$

Figure 6 indicates that the radiation efficiency is quite high, at 0.9203, at the frequency of 6.86 GHz, hence proving that the antenna works within this particular frequency. It ensures that most of the fed power to the antenna would be conveniently converted into electromagnetic radiation, thereby minimizing losses for good signal transmission as revealed by the communication in Table 4. Its efficiency further suggests that line impedance antenna is generally properly tuned for this specific 6.86 GHz of operation to meet the requirements placed there against the several specifications used on MIMO-OFDM systems. The slight fall in the efficiency for frequencies other than at this point does, however, provide some areas where further optimization could be carried out, especially when the system demands consistent performance over a wider range of band-

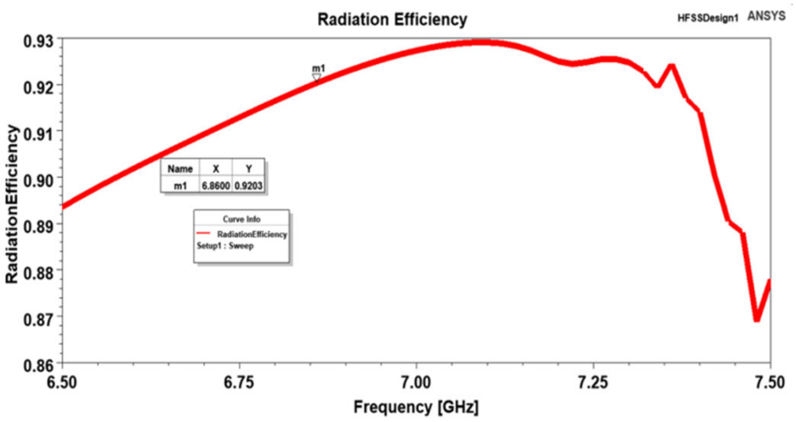

FIGURE 6. Radiation efficiency (0.9203) of MIMO-OFDM at a frequency of 6.86 GHz.

TABLE 3. Frequency and gain of a MIMO-OFDM radar waveform for line impedance antenna operating for frequency from 6.5 to 7.5 GHz.

S.NO.	FREQUENCY (GHz)	GAIN (dB)
1	6.50	7
2	6.55	7
3	6.60	7
4	6.65	7.01
5	6.70	7.04
6	6.75	7.05
7	6.80	7.08
8	6.85	7.1276
9	6.90	7.125
10	6.95	7.05
11	7.00	7.05
12	7.05	7.01
13	7.10	7.01
14	7.15	7.01
15	7.20	7
16	7.25	7
17	7.30	6.9
18	7.35	6
19	7.45	5.5
20	7.50	4.5

TABLE 4. Frequency and radiation efficiency of a conventional-OFDM radar waveform for line impedance antenna operating for frequency from 6.5 to 7.5 GHz.

S.NO.	FREQUENCY (GHz)	Radiation efficiency
1	6.50	0.86
2	6.55	0.86
3	6.60	0.86
4	6.65	0.865
5	6.70	0.866
6	6.75	0.867
7	6.80	0.868
8	6.85	0.8742
9	6.90	0.875
10	6.95	0.87
11	7.00	0.87
12	7.05	0.88
13	7.10	0.885
14	7.15	0.89
15	7.20	0.88
16	7.25	0.87
17	7.30	0.875
18	7.35	0.87
19	7.45	0.865
20	7.50	0.88

TABLE 5. Frequency and VSWR of a conventional OFDM for line impedance antenna operating for frequency from 4 to 8 GHz.

S.NO.	FREQUENCY (GHz)	VSWR
1	6.75	2
2	6.85	1.23
3	6.95	1.40
4	7.00	2

width.

$$\eta_r = \frac{P_{rad}}{P_{input}}$$

Figure 7 shows voltage standing wave ratio (VSWR), at 0.258, which is very low at 6.86 GHz and is very helpful in designing the antenna. Normally, a VSWR close to $1:1$ represents almost perfect impedance matching between the transmission line and the antenna. With a value of 0.258, there is the likelihood that the frequency is very well matched to the antenna and the transmission line, perhaps well below the reflection losses, thus ensuring that most of the power gets transferred from the source to the antenna in Table 5. A low VSWR like this directly supports effective power transfer, necessary for MIMO-OFDM systems to sustain robust signal strength and quality. Impedance mismatch distortions and losses decrease,

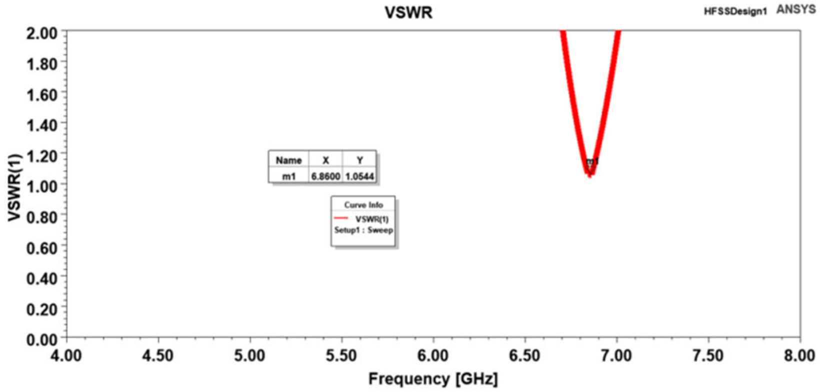

FIGURE 7. VSWR of MIMO-OFDM for line impedance antenna at a frequency of 6.86 GHz the VSWR is 0.258.

TABLE 6. MIMO OFDM antenna metrics.

Antenna Metrics	
Returns Loss	−31.7265 dB
Gain	7.1276 dB
Radiation efficiency	0.9203
VSWR	0.258

thus giving an overall improvement in the communication system performance.

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|}$$

$$\Gamma = 10^{\frac{-RL}{20}}$$

The antenna metrics required for the MIMO OFDM model include return loss, gain, radiation efficiency, and VSWR, as outlined in Table 6. These parameters are critical for evaluating the antenna's performance in the system.

Contrasting with conventional designs, a very low return loss is demonstrated so that the reflected signals will be minimized, thus increasing the efficiency of energy use. It further ensures a high gain of 7.1276 dB and high radiation efficiency of 92.03% at the operational frequency of 6.86 GHz, providing high accuracy in detecting and tracking the signal without compromise. In addition to features such as a high signal-to-noise ratio, low return loss, and high gain, the system achieves an exceptionally low VSWR of 0.258. This establishes a benchmark for a highly precise radar system, delivering enhanced resolution, extended range, and reliable performance under diverse conditions. This promises to close the gap between theory and practice in next-generation radar technologies.

5. CONCLUSION

The novel MIMO-OFDM radar waveform was designed on an FR4 substrate optimized for a line impedance antenna system. This design minimizes the signal reflection and increases performance. The return loss of the system is very low, showing good impedance matching. Its gain at 6.86 GHz was high with 7.1276 dB, thus with great capability to radiate the signal. Furthermore, the radiation efficiency of the antenna is found to be 92.03%, and its VSWR value is found to be 0.258, showing how efficiently it transforms input power into electromagnetic waves with fewer losses. This will contribute to higher quality detection, tracking, and identification features, thereby suitable for precision radar systems in which the aspect of clearness, distance, and dependability is necessary. This shows that the proposed MIMO-OFDM radar system satisfies all the requirements of modern radar technologies, which have inherent advanced signal processing and optimization of their performance.

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