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The impact of noise on detecting the arrival angle using the root-WSF algorithm

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ABSTRACT

This article discusses three standards of Wi-Fi: traditional, current and next-generation Wi-Fi. These standards have been tested for their ability to detect the arrival angle of a noisy system. In this study, we chose to work with an intelligent system whose noise becomes more and more important to detect the desired angle of arrival. However, the use of the weighted subspace fitting (WSF) algorithm was able to detect all angles even for the 5th generation Wi-Fi without any problem, and therefore proved its robustness against noise.

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1. INTRODUCTION

Most recent studies have an interest in using the 5TH generation in different fields while ensuring the compatibility of the standards used. This new generation brings a significant evolution in terms of higher data rate, reduced latency network accesses, and more energy-efficiency [1, 2]. Wireless communication radios operating at frequencies of approximately 60 GHz offer considerable potential for the support of these 5G communication networks [3]. Figure 1 gives an overview of the global spectrum of 5G [4].

The overall spectrum of 5G is divide into three spectrum bands; each one of them has unique properties, they are as follows; low-band spectrum represents frequencies under 1GHz, it is actually used for 2G, 3G and 4G services for voice, MBB services and the internet of things (IoT) [5]. Intermediate band spectrum corresponds to frequencies between 1 GHz and 6 GHz, also used for 2G, 3G and 4G services. The two Wi-Fi frequencies 2.4 GHz and 5GHz that belong to this band will be treated in this article [5]. High-band spectrum surely offers the expected vault in speed, capacity, quality and low data latency assured by 5G, this spectral band allows the use of frequencies from 24 GHz to 50 GHz, with adjacent bandwidths of more than 100 MHz per network [5].

Current wireless indoor applications typically use Wi-Fi suitable devices to support the connectivity of the wireless network. These devices concern the IEEE 802.11 standards that deploy 2.4 GHz and 5 GHz radio bands. However, the next generation of wireless technologies is facing a spectrum scarcity where the frequency band is below 10 GHz [6]. In accordance with the requirements of 5G, it is more appropriate to use the future IEEE 802.11 standard called Wi-Gig, which operates at the frequency range of 60 GHz [3].

IEEE 802.11 wireless local area networks known as Wi-Fi networks have gained global popularity during the last decade due to their low cost and easy deployment [7]. However, because of the bandwidth limitation in traditional Wi-Fi systems [8], the Wi-Fi indoor positioning system can hardly achieve localization accuracy of the users under harsh conditions such as the non-line-of-sight (NLOS) [8], higher frequencies, and noisy system, which are common for the indoor environment. The analysis of the estimation of the direction of arrival has important value to guide network of the position of the sources to direct the signals toward the proper direction, however, none of these works have addressed the actual conditions as will be discussed in this manuscript [9-11].

In this article, we discussed two issues that are strongly related to the Wi-Fi standards that correspond to the detection of radiation sources when we switch to higher frequencies and the presence of a noisy environment. Therefore, to estimate the direction of arrival, we used the most promising root-WSF algorithm, where these three Wi-Fi standards will be examined according to the following parts:
- We present a comparative study of the three proposed Wi-Fi standards in a perfect case without noise,
- Then we perform a system in a partially noisy case,
- Finally, we introduce a system completely immersed in the noise.

The rest of the article deals with parts that have not been mentioned before, they are distributed as follows. In section 2, we present the search methods by which we use the DOA estimation techniques, then the Wi-Fi networks we worked with. In section 3, we discuss the aspect of the proposed systems. In section 4, we conclude with conclusions.

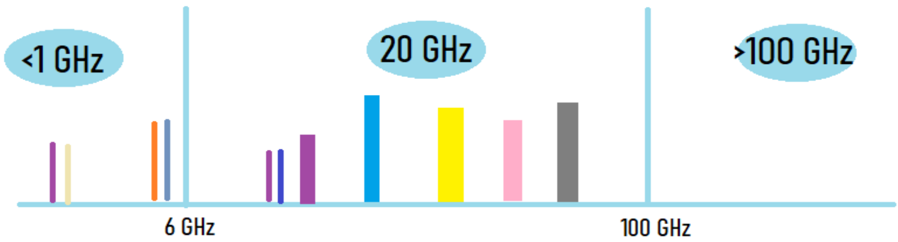

Figure 1. 5G frequencies band [4]

2. RESEARCH METHOD
2.1. DOA estimation

The aim of the DOA estimation is to use the information received at the antenna array to estimate the direction of the signals. Indeed, estimating the direction of the arrival angle presents three major difficulties: an unknown number of signals simultaneously striking the array, unknown directions and amplitudes. Also, the fact that the received signals are constantly corrupted by noise. In this context, we will focus on the problem of a system corrupted by noise. The Figure 2 presents the basic model of DOA [12]. There are several techniques for estimating the direction of arrival, including MUSIC algorithm, ESPRIT algorithm, Capon, and others. In this research, we will use the WSF algorithm that proved its effectiveness in previous works [10, 13, 14].

2.1.1. WSF algorithm

Labelled weighted Subspace Fitting algorithm is an asymptotically efficient parametric method used to estimate the heights of different scatterers in the same azimuth-range resolution cell [15]. This method can detect the direction of arrival by using the weighted version of a matrix whose columns are the steering vectors associated with these directions in close to a data-depending matrix [16]. WSF algorithm is considered as a unified approach to schemes as MUSIC and ESPRIT algorithms, it also requires knowledge of the number of directional sources, and the use of the decomposition technique for the eigenvalues. This approach utilizes the strongest eigenvectors in a diagonal matrix ($\hat{V}_S$) and the matching eigenvectors in the signal subspace matrix ($\hat{U}_S$). The expression of WSF algorithm can be written as:

$$\hat{\theta}wsf = argmax(Tr(\Pi_a(\theta)\hat{U}_S W \hat{U}_S^H)) \quad (1)$$

where $\Pi_a(\theta)$ represent The projection matrix onto the column space of a(θ), and W is a weighting matrix to reduce the impact of the subspace swap [11]. For a better understanding of this expression, we need to know these formulas:

$$\Pi_a(\theta) = a(\theta)a(\theta)^{\dagger} \quad (2)$$

$$a(\theta)^{\dagger} = \left(a(\theta)^H a(\theta)\right)^{-1} a(\theta)^H \quad (3)$$

$$W = (\hat{V}_S - 2\hat{\sigma}^2 I + \hat{\sigma}^2 \hat{V}_S^{-1}) \quad (4)$$

$$\hat{\sigma}^2 = \frac{1}{N-M} \sum_{K=1}^{N-M} \hat{V}_{n,k*} \quad (5)$$

here $a(\theta)^{\dagger}$ Is the pseudo-inverse of a(θ), $\hat{\sigma}^2$ is the noise variance, $\hat{V}_n$ is eigenvectors in a diagonal noise matrix, the M is the number of targets, N is the number of sensors and K is the number of snapshots.

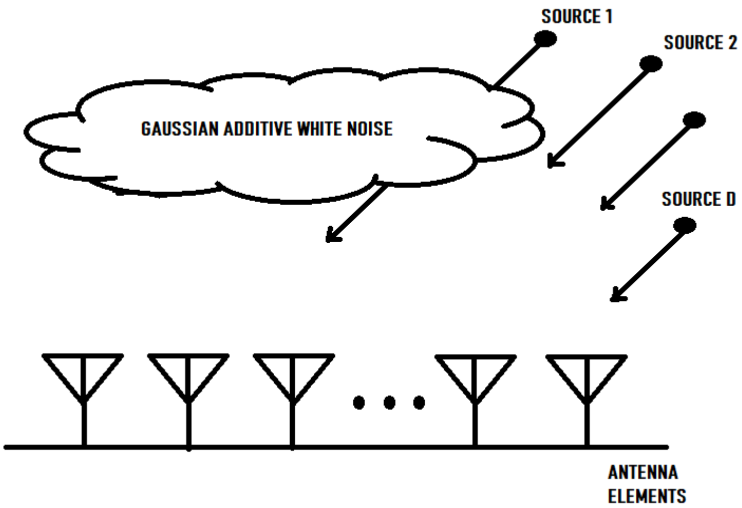

Figure 2. The basic model of DOA estimation [12]

2.1.2. Root-WSF algorithm

Root-WSF is the rooting version of weighted subspace fitting. In this study, we chose to use this algorithm for better accuracy. The purpose of this technique is to minimize the cost function with [17]:

$$f_{MODE}(\theta) = Tr(P_{a(\theta)}^{\perp} \hat{U}_S W_{MODE} \hat{U}_S^H) \quad (6)$$

where:

$$P_{a(\theta)}^{\perp} = I_M - a(\theta)\left(a(\theta)^H a(\theta)\right)^{-1} a(\theta)^H \quad (7)$$

$$W_{MODE} = (\hat{V}_S - \hat{\sigma}^2 I)\hat{V}_S^{-1} \quad (8)$$

$$\hat{\sigma}^2 = \frac{1}{N-M} Tr(\hat{V}_n) \quad (9)$$

here $P_{a(\theta)}^{\perp}$ indicate the orthogonal projection matrix of the array steering matrix, W_{MODE} is the asymptotic-optimum weight matrix and same as above, $\hat{\sigma}^2$ represent the noise variance.

2.2. IEEE 802.11 standards: Wi-Fi family

The Institute of electrical and electronics engineers (IEEE) has developed a family of 802.11 compliant specifications for wireless local area network (WLAN) technology, also known as Wi-Fi. These families have many specifications. A letter is added to describe their characteristics such as data rates, frequency band, etc. [7, 18]. This standard is based on two basic protocols, media access control (MAC) and (PHY) [19]. The IEEE 802.11 network includes several basic service sets, in which a number of wireless stations transmit or receive from a single access point shown in Figure 3. The following Table 1 outlines some of these standards in terms of the operating frequency and data rate [20, 21].

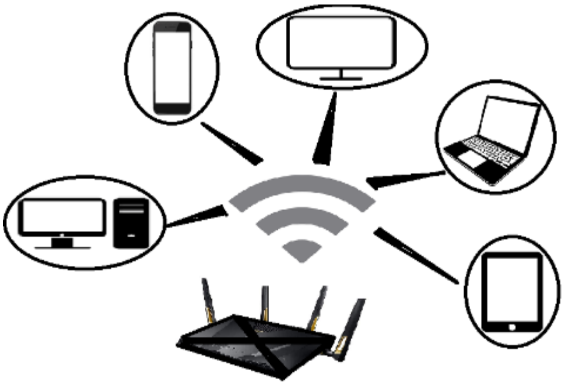

Figure 3. Wi-Fi presentation [18]

Table 1. IEEE 802.11 standards [20]

Protocol	Operating frequency	Data rate (max)
802.11	2.4 GHz	2 Mbit/s
802.11a	5GHz	54 Mbit/s
802.11n	2.4 GHz -5GHz	72 Mbit/s
802.11ad	60 GHz	6.75 Gbit/s

2.2.1. 802.11a

The IEEE 802.11n standard is the first expansion scheme; it operates at a 5 GHz radiofrequency and a 20 MHz bandwidth and corresponds to the use of single-input antenna technologies (SISO) [21].

2.2.2. 802.11b

The IEEE 802.11b standard is considered the first Wi-Fi network that operates around the 2.4 GHz radio frequency. This band was limited to the use of industrial, scientific and medical (ISM) equipment. Fortunately, the FCC (Federal Communications Communication) has deregulated this band to take advantage of wider use. The maximum theoretical data rate that this standard can provide can be up to 11 Mbps. However, in practice, this speed is not achievable, which is why other standards have been proposed to solve this problem and offer better performance [22].

2.2.3. 802.11n

The IEEE 802.11n standard refers to Wi-Fi 4 or dual-band Wi-Fi, or Wi-Fi Alliance uses two frequencies band 2.4 GHz and 5 GHz. This is an improvement of both standards 802.11 a, b. it is considered the first standard acknowledging MIMO technology [11, 23].

2.2.4. 802.11ad

The IEEE 802.11ad standard, also known as Wi-Gig for Wireless Gigabit Alliance, certified by Wi-Fi, operates in the 60 GHz frequency range, which is suitable for 5G applications. This technology uses much larger ultra-wideband channels, much higher spectrum band, fast data transmission rate, antenna array, beamforming, and so on. However, it is limited by its short distance [24, 25].

2.3. Number of users in Wi-Fi networks

The number of users of Wi-Fi access point effects on signal power and throughput. Devices such as computers and smartphones need to share limited resource capacity on a network, each device connected to the wireless network uses a little more bandwidth and must be generated somewhere once the maximum bandwidth is reached [26]. In theory, a wireless router can support 250 devices connected to the Wi-Fi network. In practice, some mobile providers consider that the maximum number of users can reach up to 125 users. However, there is a formula for calculating the number of users based on data rate and Wi-Fi throughput as follows [26]:

$$Speed\ of\ data\ rate = \frac{WiFi\ rate}{number\ of\ device} \tag{10}$$

the number of users in a home who use the Internet with multiple devices at the same time is a critical factor in determining the Internet speeds needed at the point of maximum use. Based on this formula, we can also determine the limits of the data transmission rate that a user can benefit from shown in Table 2. For basic use of Wi-Fi 2.4 GHz, six users share the connection with a low bit rate of one Mbit/s.

Table 2. Maximum number of users based on the data rate

	Wi-Fi a	Wi-Fi b	Wi-Fi n	Wi-Fi ad
Minimum (1Mbps)	27 users	6 users	72 users	3375 users
Basic (3Mbps)	9 users	2 users	24 users	1125 users
Moderate (10 Mbps)	3 users	0 users	7 users	337 users
Ideal (35 Mbps)	0 users	0 users	2 users	96 users
Heavy (75 Mbps)	0 users	0 users	1 user	45 users

3. RESULTS AND ANALYSIS

The purpose of this study is to evaluate the performance of the WSF algorithm to detect the arrival angles in a noisy system, where it is difficult to distinguish the received signals. To do so, we consider a uniform linear array of 10 elements with interspacing of λ/2, six received signals with the respective angles of arrival (AOA) Θ_1=-60°; Θ_2=-50°; Θ_3=-30°; Θ_4=5°; Θ_5= 20°; Θ_6=30°; Θ_7=50°; Θ_8=60°. Since we are in a critical situation where the system emerges with white Gaussian noise, some angles of arrival are too close, which creates a new constraint for the detection of the angles of arrival, such as the 10° separation between Θ_1 and Θ_2, same with Θ_5 and Θ_6, Θ_7 and Θ_8.

This research is based on Wi-Fi applications using different frequencies bands from 2.4 GHz to 60 GHz and a basic model of data rate with eight users. In the following section, we will investigate the impact of all these criteria. First, regarding a perfect case without noise, then increasing significantly the noise value, and finally, with a system in which noise is dominant. The simulations presented in this article were made with MATLAB and SIMULINK R2018a.

3.1. A perfect system without noise

Based on the system described above, we will evaluate the proposed DOA algorithm (root-WSF) in a perfect system without noise. The result of this work is given in the following table. According to Table 3, we can clearly notice that all angles of arrival are well detected in the three Wi-Fi applications, which is quite logical in the absence of noise. This system will be considered as a reference for the studies established in the following sections.

Table 3. System without noise

Angles	Wi-Fi 2.4 GHz	Wi-Fi 5GHz	Wi-Gig 60GHz
-60°	-60.21°	-60.31°	-60.18°
-50°	-55.65°	-53.75°	-48.93°
-30°	-29.99°	-30.1°	-30.01°
5°	5.21°	5.06°	5.19°
20°	19.49°	14.89°	15.19°
30°	27.41°	27.42°	28.7°
50°	49.78°	49.68°	49.77°
60°	59.72°	59.82°	59.93°

3.2. System with partial noise

The same system is used as before, adding an additive Gaussian noise to each of the received signals to provide a near-real world system. In this context, we will evaluate the system's response in terms of detecting the angles of arrival using the root-WSF algorithm, while adding the AWGN noise.

3.2.1. System with SNR = 20

In this section, we consider that our system introduces noise with a signal-to-noise ratio of 20 dB while respecting the same specifications previously used. We must also take into account that one of the Wi-Fi applications used (Wi-Gig) operates in a high-frequency band up to 60 GHz. The following table provides the results of this simulation. Table 4 shows the effect of using 20 dB noise on the three Wi-Fi applications. We can obviously notice that the root-WSF algorithm allows perfect detection even in the presence of noise for all frequency bands. Indeed, the signal is much more important than the noise, which results in the positive value of the SNR.

Table 4. System with partial noise of SNR = 20

Angles	Wi-Fi 2.4 GHz	Wi-Fi 5GHz	Wi-Gig 60GHz
-60°	-59.89°	-60.93°	-60.06°
-50°	-43.5°	-54.19°	-48.64°
-30°	-30.02°	-29.97°	-30°
5°	5.18°	5.60°	5.30°
20°	21.32°	20.97°	12.85°
30°	34.12°	32.17°	28.33°
50°	50.41°	55.72°	49.82°
60°	60.36°	59.07°	59.83°

3.2.2. System with SNR = -50

In order to evaluate the impact of the noise in the system we used, we opted for a signal whose input noise is much important than the incoming signal with a value of -50dB. Table 5 shows the results obtained for the three proposed Wi-Fi applications. According to Table 5, the WSF algorithm has once again proved its effectiveness in detecting arrival angles even in the presence of noise. However, there is a small difference between the three Wi-Fi applications in terms of accuracy. This difference will be discussed further in the precision and precision part.

Table 5. System partial noise of SNR = -50

Angles	Wi-Fi 2.4 GHz	Wi-Fi 5GHz	Wi-Gig 60GHz
-60°	-60.1°	-59.84°	-60.08°
-50°	-47.4°	-45.44°	-47.1°
-30°	-29.99°	-30. 44°	-29.99°
5°	5.49°	4.80°	5.48°
20°	11.73°	21.24°	12.37°
30°	28.44°	33.78°	28.61°
50°	49.81°	41.07°	49.82°
60°	59.83°	58.79°	59.86°

3.3. System with massive noise

In this part, we evaluate our system in critical cases, where it emerges completely in noise. This study will be divided into two parts; the first will treat an SNR of 20dB and the second one of -50dB.

3.3.1. System with SNR = 20

The signal-to-noise ratio (SNR) varies from a positive value to a negative one, in this analyses, we chose to evaluate the performance of the noise when the signal is more powerful than the proposed noise. The results of this study are given in the following Table 6. It is obvious that the impact of noise cannot affect the performance of the suggested system. However, it is also true that the operating frequency plays an important role in determining the arrival angle detection. The higher the frequency the more the system becomes more sensitive to noise but in an insignificant way. Which shows the efficiency of our root-WSF algorithm.

Table 6. System with total noise of SNR = 20

Angles	Wi-Fi 2.4 GHz	Wi-Fi 5GHz	Wi-Gig 60GHz
-60°	-60.01°	-59.7°	-60.5°
-50°	-48.93°	-49.36°	-53.22°
-30°	-29.99°	-30.04°	-29.99°
5°	5.15°	5.42°	5.02°
20°	16.26°	19.54°	12.09°
30°	28.94°	25.31°	27.27°
50°	49.92°	43.26°	49.56°
60°	59.84°	58.86°	59.7°

3.3.2. System with SNR = -50

In order to complete our study, it is necessary to take into account the case where the noise is more powerful than the input signal. The result of this simulation is interpreted in Table 7. The result achieved in Table 7 shows the impact of noise on detecting the arrival signals in three different frequency bands of the Wi-Fi, the ROOT-WSF algorithm gives almost identical results in almost all cases, with a minor margin of error.

Table 7. System with total noise of SNR = -50

Angles	Wi-Fi 2.4 GHz	Wi-Fi 5GHz	Wi-Gig 60GHz
-60°	-60.1°	-60.2°	-60.72°
-50°	-47.42°	-52.82°	-55.6°
-30°	-29.99°	-29.99°	-30.01°
5°	5.48°	5.91°	5.17°
20°	11.73°	12.14°	13.73°
30°	28.43°	23.84°	26.84°
50°	49.81°	45.92°	49.56°
60°	59.83°	59.56°	59.76°

3.4. Accuracy and precision

The accuracy of our results is an important criterion in the detection of arrival angles. Each study treated previously gave a negligible margin of error in terms of precision. However, to evaluate the performance of our system we proposed to calculate the percent error of each case. Table 8 announce the work done in this field. Table 8 presents five different cases for each Wi-Fi application, grouped as follows: noise-free system, partial signal-to-noise ratio system of 20 dB and -50 dB, and finally, a system with a total signal-to-noise ratio of 20dB and -50 dB. We can see that for Wi-Fi of 2.4 GHz, the accuracy is 96.51% with a percent error of 3.49%. This value increases with the presence of noises; it goes from 4.82% to 7.80% for partial noise. Same for the case of total noise where the percent error goes from 5.18% to 7.77%.

Similar to the 5 GHz Wi-Fi, the accuracy of a system without noise is 94.42% with a percent error of 5.58%. This value increases with the presence of noises; and goes from 5.89% to 6.67% for partial noise, and from same 5.46% to 11.63% in a system with total noise. The process is the same for Wi-Gig. A perfect system has an accuracy of 95.6% with an error percentage of 4.40%. This value increases very slightly with the presence of noises; and goes from 6.34% to 7.36% for partial noise, and from 7.21% to 7.37% in a system with total noise, which proves the robustness of our system in a noisy environment.

Table 8. Accuracy of our system based on the percent error

	Wi-Fi 2,4	Wi-Fi 5	Wi-Fi 60
System without noise	3.49%	5.58%	4.40%
Partially noisy 20	4.82%	5.89%	6.34%
Partially noisy -50	7.80%	6.67%	7.36%
totally noisy 20	5.18%	5.46%	7.21%
totally noisy- 50	7.77%	11.63%	7.37%

4. CONCLUSION

This study investigates the impact of noise on detecting the arrival angle using the root-WSF algorithm. In order to achieve this objective, we relied on the alliance between the number of users sharing the same Wi-Fi Access point at the same time, signal strength versus the noise and throughput of a basic mode of use at 3Mbps. To carry out this study, we developed a system consisting of a uniform linear array (ULA) of 10 antenna elements with a spacing of $\lambda/2$, and where all the sources are assumed uncorrelated.

Several measurements were performed to ensure the proper functioning of our system, as a reference, we first evaluated the performance of a perfect system without the presence of noise. In this case, the proposed root-WSF, DOA algorithm gave the best results in terms of detecting the arrival angles in the three application of Wi-Fi: 2.4 GHz, 5 GHz, and 60GHz. Then, we started to investigate two other promising cases, close to reality, in which the noise appears in the partially noisy system and in a very noisy system. Compared to the reference, the root-WSF algorithm stood out by proving the best result in almost every situations and for the different Wi-Fi applications.

Regarding accuracy, for each of the proposed Wi-Fi applications, we calculate the percent error from five different perspectives to determine the robustness of our system. These conditions are analyzed based on noise-free system, partial signal-to-noise ratio system of 20 dB and -50 dB, and system with a total signal-to-noise ratio of 20 dB and -50 dB. As a conclusion, the value of the percent error increases slightly with the presence of noises, Changing the operating frequency does not affect the robustness of the system, and thus provides better performance in the detection of the angles of arrival using the root-WSF algorithm.

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