Exploration of MIMO Systems with a Space-Diversity Technique for Combating Signal Fading in Radio Propagation

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ABSTRACT

Attenuation, fading, distortion, and interference have been age long problems faced by radio communication engineers. These problems arose due to the imperfect nature of the communication channel. Each attempt to solve the problem creates additional cost, resulting from increased complexity in the design or increased RF power requirement. The diversity technique presented in this article is aimed at solving the problem of signal fading and poor reception of radio signals. The results of the previous studies have presented space diversity as a powerful tool for combating signal fading in a radio broadcast station whose studio and transmitting stations are located in a different geographical location, by connecting multiple antennas at both the transmit and the receive ends. Matlab was used to verify the relationship between antenna heights and coverage distance in line of sight transmission. The results were in total compliance with the attenuation square law which states that signal strength is inversely proportional to distance.

Key Words: Space-Diversity Technique, MIMO, Signal Fading, Antennas, Simulation.

1. INTRODUCTION

The block diagram of Fig. 1 symbolically represents any communication system. The information or message from the source is fed to the transmitter for modulation and amplification; after which the modulated signal is transmitted to the receiver through a channel or path. At the receiver, the information is decoded or demodulated and the message signal is reproduced.

The central section of the communication system is the channel, which electrically connects the transmitter and the receiver. A channel may be a pair of wire, a coaxial cable, free space, power line carrier (PLC), a radio wave or even a laser beam. Regardless of the type of medium used, the output of the channel is usually a smeared or distorted version of the input. This deterioration is as a result of the non-ideal nature of the communication channel. This causes certain unwanted and undesirable effects, which invariably corrupt the information-bearing signal [1]. As a result, errors are introduced in the information being transmitted. Factors that degrade system performance are attenuation, which is a progressive decrease in signal power with increasing distance, distortion and interference [1]. The problem of interference is very common in broadcasting, where a radio receiver may pick up two or more signals at the same time.

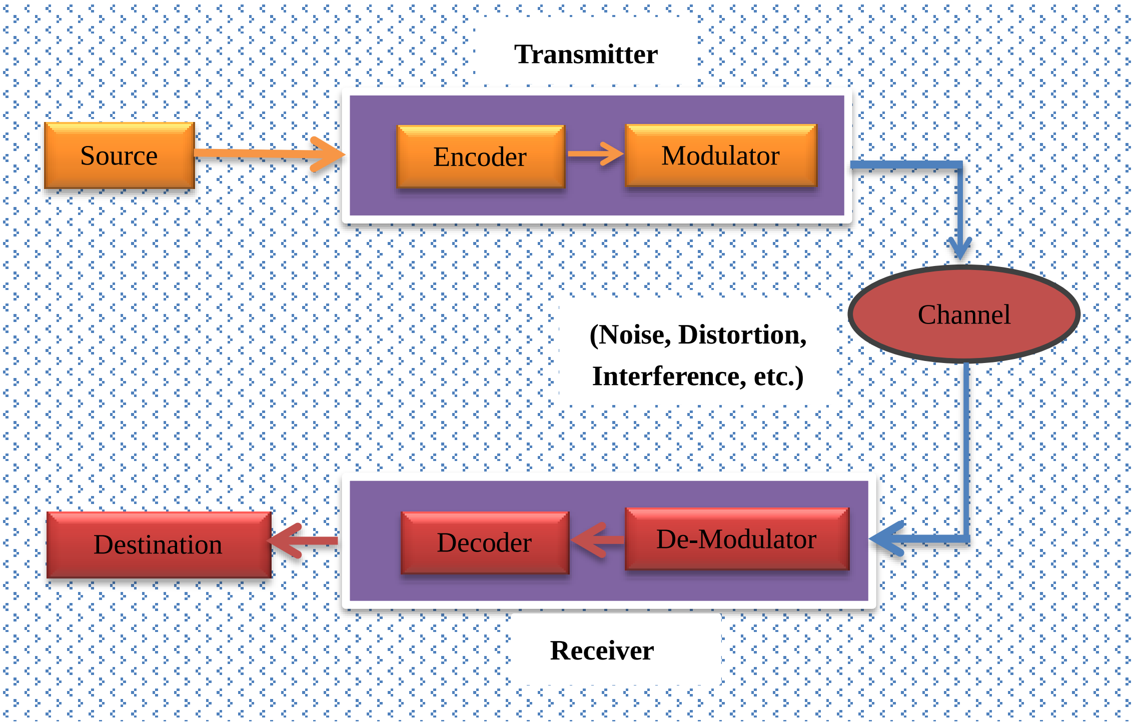

Fig 1: Block Diagram of a General Communication System

Radio network programmes in Nigeria are often associated with intermittent breaks (fast fading) and sometimes degenerate into static noise and total failure (slow fading). This can be traced to daily incidents of high rise of buildings and towers occasioned by the topography of the country with hills, trees and valleys [2]. Again, atmospheric conditions during most part of the year, like rainfall, always pose a great challenge. For instance, during rainy season, most of the newly established FM stations in Nigeria shut down at a slight sign of the rain because of the accompanying lightning, which on many occasions have damaged the power modules of their transmitter and the analogue output cards of their digital console.

The purpose of this work is to analyze and explore the performance applications of Multiple-Input Multiple-Output (MIMO) systems with focus on a Space-Diversity Technique for combating signal fading, so that broadcasting media in Nigeria can tap from its gains to improve on the reception quality of their signals with an increased coverage area. Again, the study also aims at analyzing the relationship between antenna heights and maximum coverage distances in line-of-sight propagation and signal strength of the received signal using simulation.

This study: Exploration of MIMO Systems with a Space-Diversity Technique for Combating Signal Fading will focus mainly on radio broadcasting network signals in Nigeria. However, the result of the study will still be applicable to other communication systems.

This paper is organized into five Sections. The introductory part in Section 1 deals with the general perspectives and objectives of the work. Section 2 reviews relevant work in MIMO systems, combating signal fading with a space-diversity technique and exploitation of diversity techniques in multi-path propagation. Section 3 gives a detailed step-by-step approach in carrying out the study, which includes research methodology, data collection and presentation. The relationship between antenna heights/distances and electric field strength simulated using Matlab is presented in Section 4. Also included in this section is the analysis of signal strength when the number of receiving antennas connected in the circuit is varied. Finally, Section 5 discusses the conclusion and future work to be carried out.

2. REVIEW OF RELEVANT WORKS IN MIMO SYSTEMS

Since the invention of the radio telegraph by Marconi in 1895, wireless communication has attracted great interest and is now one of the most rapidly developing technologies [3]. From narrow-band voice communications to broadband multimedia communications, the data rate of the wireless communications has been increased dramatically, from kilobits per second to megabits per second [4]. According to [3], the last two decades witnessed an explosion in the advancements of wireless systems and hence future wireless networks face challenges of supporting data rates higher than one gigabit per second.

Among numerous factors that limit the data rate of wireless communications, multipath propagation plays an important role [5]. In wireless communications, the radio signals may arrive at the receiver through multiple paths because of reflection, diffraction, and scattering. This phenomenon is called multipath propagation, which causes constructive and destructive effects due to signal phase shifting. Channels with multipath fading fluctuate randomly, resulting in significant degradation of signal quality. When the bandwidth of the signal is greater than the coherence bandwidth of the fading channel, different frequency components of the signals experience different fading. This frequency-selective fading may further limit the data rate of wireless communications.

In order to mitigate multipath fading, Code Division Multiple Access (CDMA) and Orthogonal Frequency-Division Multiplexing (OFDM) were developed [4]. While CDMA mitigates multipath fading by transmitting signals which occupy a wider bandwidth, OFDMA splits the channel into many small bandwidth carriers, each of which occupies a narrowband channel [4]. Though a small percentage of this wideband channel may undergo deep fading, the overall channel could still be in good shape. The lost signals could be recovered with the help of a Rake receiver and/or maximum-ratio combining [6]. Although these two schemes are effective in mitigating multipath fading, they have the limitation of providing a higher data rate compared to other techniques [4].

The last decade witnessed the deployment of multi-antenna systems, which are also referred to as multiple-input multiple-output (MIMO) systems. These technologies are undoubtedly the most promising to achieve higher data rates. MIMO is a method of transmitting multiple data beams on multiple transmitters to multiple receivers [7].

The benefits of these arise from the use of extra spatial dimension, which involves the use of multiple antennas at the transmitter and/or receiver ends. With this technique, the rich scattering channel is exploited to create a multiplicity of parallel links over the same radio band, thus providing MIMO with several advantages such as array gain, spatial diversity gain, and spatial multiplexing gain [8].

According to [9], some of the performance improvements and potential applications of MIMO technology include:

- ✓ Array Gain – improves system robustness to the noise thereby increasing coverage and quality of service (QoS)
- ✓ Diversity Gain – MIMO achieves spatial diversity by providing the receiver with multiple identical copies of the transmitted signal to mitigate multipath fading, increase coverage and to improve the quality and reliability of the reception. Diversity is maximized to mitigate channel fading and decrease the bit error rate (BER)
- ✓ Multiplexing Gain – is achieved by transmitting independent data signals from different antennas to increase throughput and spectral efficiency.
- ✓ Co-channel interference mitigation – increases cellular capacity.

For MIMO to be effective, the paths need to be de-correlated. That is, the signals travelling need to behave differently from each other, so that if any one part experiences fading, there is a high probability that the other parts will not undergo fading and hence the signal can still get through [7]. This can be possible with proper exploitation of techniques such as spatial separation (space-diversity) of the antennas or separation of the transmitted waveforms via time separation, polarization separation, frequency separation, etc.

Radio Frequency (RF) signal transmission between two antennas commonly suffers from power loss in the space. This power loss between transmitter and receiver is as a result of three different phenomena: **distance-dependent decrease in power density** called path loss or free space attenuation, **absorption due to the molecules in the atmosphere of the earth** and **signal fading** caused by terrain and weather conditions in the propagation path [2]. Path loss is the attenuation which occurs under free-line-of-sight conditions and which increases with the distance between base station and mobile. Atmospheric absorption is due to the electrons, uncondensed water vapor and molecules of two quite high peaks, 60GHz and 21GHz for oxygen and water respectively. Fading is an attenuation that varies in an irregular way. Signals move through areas with obstacles of various sizes, surrounded by mountains, buildings and tunnels. Occasionally, these obstacles will shadow or completely cut off the signal. Although the consequences of such shadowing effect depend on the size of an obstacle and the distance to it, the received signal strength inevitably varies. This type of fading is referred to as shadow fading. Rayleigh fading, Short-term fading or Multi-path fading is a completely different kind of fading involving irregular signal strength variations as a result of several signals at the receiver. Rayleigh fading is a form of fading that is often experienced in an environment where a large number of reflections are present. Rayleigh fading is a result of a reception of several signals at the receiver. These signals are reflected from different objects and directions in the area. The received signals are usually not in phase, reinforcing or extinguishing each other. The movement of the terminal causes continuous and unpredictable variations of the signal phases over time, making the attenuation variable and extremely high at some points (fading dips).

Rayleigh fading is a model that can be used to describe the form of fading that occurs when multipath propagation exists. In any terrestrial environment, a radio signal will travel via a number of different paths from the transmitter to the receiver. The most obvious path is the direct or line-of-sight path. However, there will be very many objects around the direct path. These objects may serve to reflect, refract, etc. the signal. As a result, the signals can now travel through different paths to reach the receiver. When this occurs, the overall signal is a combination of all the signals that have travelled through various paths to reach the receiver. Rayleigh fading is most perceptible in urban areas. Dips will occur more frequently at higher frequencies in a more rapid mobile movement. The performance degradation can be solved by increasing the transmitted power and resizing the antenna. However, this solution is not economically attractive, hence the need for deployment of special reception techniques such as the space-diversity technique (multiple receiver combining technique), which can be used to overcome these challenges.

In telecommunication, a diversity technique refers to a method for improving the reliability of a message signal by utilizing two or more communication channels with different characteristics. Diversity is important especially in mitigating fading and co-channel interference [2]. In wireless communications, diversity techniques are primarily employed to improve performance over a fading radio channel. According to [10], this technique can be used to mitigate the problems caused by multipath fading channels. Diversity therefore plays a vital role in combating fading and co-channel interference, and avoiding bursts. It is based on the fact that individual channels experience different levels of fading and interference.

Fig. 2 shows a wireless communication system that undergoes attenuation, distortion, delays and phase shifts. The signal strength is severely degraded as shown at point 10 along the horizontal axis. The channel suffers from much impairment such as thermal noise which is modelled as Additive White Gaussian Noise (AWGN) as shown in the diagram. The signal undergoes shadowing effect due to the presence of fixed obstacles in the path. Due to the distance and height of propagation, the signal power is reduced and signal strength is affected. As a result of the path loss in power, noise, and shadowing effect of obstacles, the overall performance of the signal becomes severely affected, and eventually the signal is faded (undergoes Rayleigh fading) as shown at point 25 along the horizontal in Fig. 2.

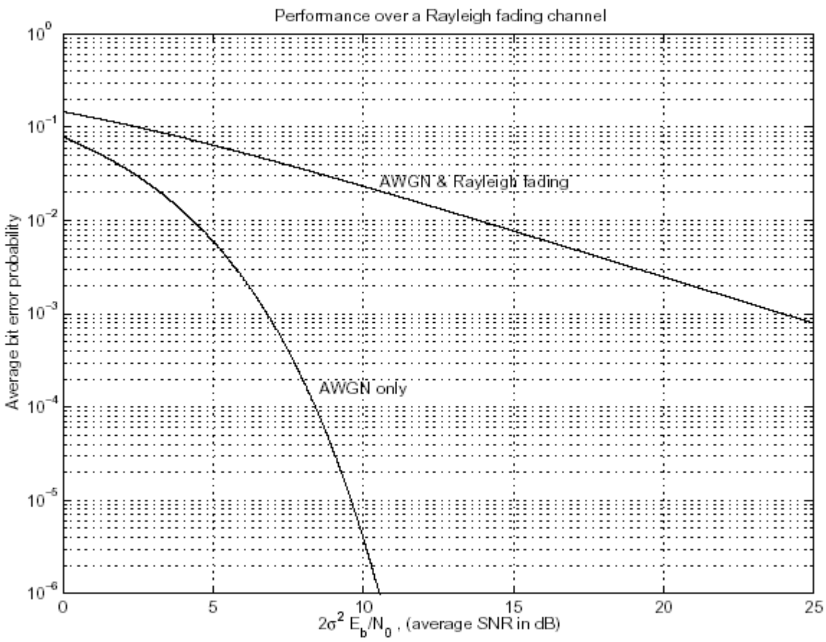

Fig. 2: System Performance Degradation due to Fading

To combat the problem of signal fading, [11] suggested the use of several diversity schemes, which could be improved by deploying multiple transmit and receive antennas.

2.1 Types of Diversity Schemes

This section presents the various methods of reducing signal fading and the types of diversity combiner.

2.1.1 Frequency Diversity

This involves sending of the same information using two or more different frequencies of transmission or different transmitters set to different frequencies. The arrangement is such that the receiver (s) selects the frequency with better signal and uses that as its preferred signal [12]. This is however difficult to implement as the task of generating severally transmitted signals and combining signals received at different frequencies is quite enormous. There is also the problem of powering as many transmitters as the number of redundant channels to generate the information at the different frequencies, coupled with the fact that the scheme demands a large space to site the receivers and their antennas. Again, the scheme requires commercial FM and TV stations to obtain as many licenses as the number of frequencies they intend to use. This factor alone makes it unattractive to broadcasting stations. However, the scheme is applied in Orthogonal Frequency Division Multiplexing (OFDM), which is efficient for combating frequency selective channels.

2.1.2 Time Diversity

This involves the transmission of multiple versions of the same signal at different time intervals. Essentially, a redundant forward error-correction code is added and the message is spread in time by means of bit-interleaving before it is transmitted. This is predicated on the perception that the obstacles blocking signal paths are not stationary, hence the essence of transmitting the same information at different time intervals [13]. However, time is wasted while the receiver evaluates the received signals to determine the best to use. Moreover, while the scheme may be better in data transmission, it is out of need in a radio and TV transmission where a live broadcast may be required. Also, in the event where the obstacles are permanent, transmitting the same information even a couple of times will not yield any better reception. However, time diversity may be better applied in conjunction with other diversity schemes such as space and pattern diversities.

2.1.3 Pattern Diversity

Pattern diversity involves two or more co-located antennas with different radiation patterns. In this case, directional antennas are used to create independent copies of the transmitted signals over multiple paths. At the receiver, the signals arriving at the antennas are from different directions and are uncorrelated. It occurs in many instances at the mobile terminals because the antennas will select signals coming from different angles. And the antenna with the strongest signal is selected at a time by the combiner, or alternatively, the combiner may add the signals from the antennas coherently. This type of diversity scheme is never applied alone but in conjunction with space diversity, and is limited by the fact that only directive antennas can be used. Again, it is more complex than space diversity scheme.

2.1.4 Rake Receiver

A rake receiver is a radio receiver designed to counter the effects of multipath fading [14]. This is achieved by utilizing several sub-receivers called fingers. Each finger independently decodes a single multi-path component, which is later combined to make the most use of the different transmission characteristics of each transmission path. Rake receivers are common in a wide variety of CDMA radio devices such as mobile phones and wireless Local Area Network (LAN) equipment.

2.1.5 Space Diversity

This is also known as antenna diversity. It is one of the diversity schemes that utilize two or more antennas to improve the quality and reliability of a wireless link. In urban and indoor environments, there is usually no clear line-of-sight between the transmitter and the receiver; rather the signal is reflected along multiple paths before finally being received. Each of these bounces can introduce phase shifts, time delays, attenuations, and even distortions that can destructively interfere with one another at the apertures of the receiving antenna [2]. Space diversity is effective at mitigating these multipath situations because multiple antennas afford a receiver several copies of the same signal. Each antenna experiences a different interference environment. Thus, if one is experiencing a deep fade, it is likely that another has a sufficient signal. Signals received from the various antennas are then fed to a diversity combiner, which either selects the antenna with the best signal strength or adds the signals coherently.

Application of space diversity to combat signal fading is not new to mobile and fixed wireless telecommunication providers. In this research work where the scheme will be helpful in radio broadcasting was explored. Radio Nigeria, like some older radio and television stations whose studios and transmitting stations are located at afar distance, could make use of this scheme. A microwave transmitter and receiver called studio-transmitter link (STL) is used to couple the studio output to the main transmitter through the line-of-sight propagation. The signal suffers a lot of degradation before reaching the microwave receiver at the main transmitting station.

The usability of this scheme was tested at Federal Radio Corporation of Nigeria (FRCN) transmitting station Shogunle Lagos state, and it was found that multiple antennas spaced out provided increased signal strength. The space diversity scheme tested in this research work is reception diversity.

2.1.5.1 Advantages of Space Diversity

The following are some of the advantages of space diversity technique as outlined in [15]:

- ✓ Improvement in uplink performance for reception of both mobiles and portables
- ✓ It is flexible as it can be applied either at the transmitting station (transmit diversity) or at the receiver end (diversity reception).
- ✓ It is very simple and can be used independently unlike pattern and polarization diversity schemes.
- ✓ It is cheaper than frequency diversity that requires several transmitters to generate the required frequencies.

The disadvantage of space diversity is that it requires large structures and thereby occupies space.

2.1.5.2 Diversity Combiner

This is an electronic device used to combine the multiple received signals of diversity reception device into a single improved signal. According to [11], the idea is to combine several copies of the transmitted signal undergoing independent fading; so that the overall received signal power will be increased. Several diversity combining methods as shown in [16] include:

- ✓ Switching – the signal from one antenna is fed to the receiver for as long as the quality of that signal remains above some prescribed threshold. As soon as the signal degrades, another antenna is switched in. Of the antenna diversity processing techniques, switching is the easiest and the least power consuming.
- ✓ Selection – selection combining presents only one antenna signal to the receiver at any given time. The antenna selected is the one with the best signal-to-noise ratio (SNR) among the received signals.
- ✓ Combining – here, all antennas maintain established connections at all times. The signals are then combined and presented to the receiver. Depending on the nature of system, the received can be summed up directly (i.e. equal gain combining) or summed up coherently (maximum-ratio combining). This technique provides the greatest resistance to fading. But since all the receive paths must remain energized, it also consumes the most power.
- ✓ Dynamic Control – Dynamically controlled receivers are capable of choosing from the above processing schemes for whenever the situation arises. While much more complex, they optimize the power versus performance trade-off. Transitions are signaled by a change in the perceived quality of the link. In situations of low fading, the receiver can employ no diversity and use the signal presented by a single antenna. As conditions degrade, the receiver can then assume the more highly reliable but power-consuming modes described above.

3. RESEARCH PROCEDURES

Space diversity technique was applied at reception in radio broadcast station at FRCN Lagos operations main transmitting station using three antennas. The strength of the received signal was displayed on the STL receiver metering unit. After which, a second antenna was mounted on the mast with a space of 0.5m from the first one. Since there was unavailability of an electronic combiner, an RF multi-switch connector was used to parallel the outputs of the antennas. With the second antenna in circuit, a change in the signal strength reading was observed and noted. Finally, a third antenna was introduced and the new signal strength noted. The STL receiver metering unit served as the spectrum analyzer for measuring signal strengths.

Again, because of the important roles antenna heights play in bypassing obstacles that cause fading and other interference effects, Mat-Lab was used to verify its effects to maximum coverage distances in line-of-sight transmission and field strength of the received signal. Approximate value for the maximum distance between transmitter and receiver over a reasonably level terrain was calculated using:

$$\mathrm{d} = \sqrt{(17\mathrm{ht} + 17\mathrm{hr})} \quad (1)$$

Where

$\mathrm{d} = \mathrm{max.\,distance(km)}, \mathrm{ht} = \text{ transmitting antennaheight (m)}, \text{and hr} = \text{receiving antenna height (m)}$

The power density of the signal was calculated using the power density formula

$$\mathrm{P}_D = \frac{\mathrm{p}_t}{4\pi r^2} \quad (2)$$

Where$\mathrm{P_D}$ = power density of the signal, $\mathrm{p_t}$ = transmitted power and r = maximum distance in metres.

The final calculation made in the simulation was to calculate the electric field strength (signal strength) using

$$\in = \sqrt{377 P_D} \quad (3)$$

3.1 Data Collection and Presentation

The applicability of space diversity technique was tested at radio Nigeria Metro FM station located in Lagos state. At the Ikoyi broadcasting house, the output of the studio was fed to a 250w, 450.15MHz STL transmitter located in the control room. The output of the studio transmission link (STL), through 50 ohms coaxial cable is terminated in an antenna mounted on a 120ft mast. At the Ikeja GRA, an STL receiver of the same frequency was installed. A receiving antenna mounted on 100ft mast through line of sight propagation receives signal of 450.15MHz frequency. Through a 50 ohms coaxial cable, the received signal is fed to the STL receiver. The output of the receiver passes through audio processors to a 20KW BE transmitter for terrestrial transmission.

With the original connection of one receiving antenna at the Ikeja GRA station, the received signal strength as displayed on the STL receiver metering unit was 8dB. When the second antenna was connected and the output paralleled, the STL receiver reading increased to 12dB. A third antenna was introduced and the received signal strength further increased to 15dB. These antennas were spaced at 0.5m apart and were mounted facing different positions. Because of the unavailability of an electronic diversity combiner within the broadcasting station, an RF multi-switch connector was used to parallel the outputs of the antennas. The STL receiver meter served as the spectrum analyzer for measuring the signal strength. The summary of the results is presented in Table 1.

Table 1: Signal strengths for various numbers of antennas.

S/N	Number of antennas	Signal strength
1.	One	8dB
2.	Two	12dB
3.	Three	15dB

4.0 SIMULATION RESULTS AND ANALYSIS

To verify the relationship between antenna heights and signal strength, which is one of the objectives of this research, some conversions were made from feet to meters in S.I units and simulation was carried out using MATLAB.

Transmitting antenna height ht $= 120 \times 0.3048\text{m} = 36.576\text{m}$

Receiving antenna hr $= 100 \times 0.3048\text{m} = 30.480\text{m}$

In the simulated results shown below, the transmitting antenna height ht was kept constant while the receiving antenna height hr was varied to take 15m, 20m, 30.48m, 35m, and 40m. The STL transmitter rated power Pt was maintained at 250w. Equations (1), (2), and (3) were used to evaluate the maximum coverage distances d, power density P_D and electric field strength $\in$ respectively. The following are the analysis of the results from simulation:

4.1 Relationship between Distance and Antenna Heights

Fig. 3 is a simulation result showing the effect of antenna heights to coverage distances. It is observed that the receiving antenna height is directly proportional to the maximum coverage distance in the line of transmission. This is because as the receiving antenna height increases, the maximum coverage distance also increases. It is therefore evident that, if all other factors remain constant, the receiving antenna height hr increases equally with the maximum coverage distance d at which a signal transmitted through line-of-sight propagation will be received.

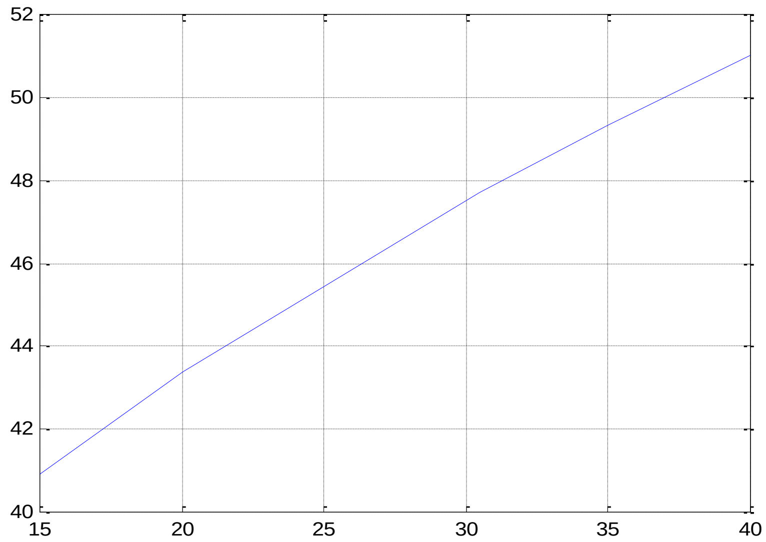

Fig. 3: Graph of Maximum distance against Antenna height

4.2. Relationship between Power Density and Antenna Heights

Fig. 4 shows that although the maximum coverage distance increases with increase in receiving antenna height, the power density of the received signal tends to decrease. This graph has placed a limit to the increase of antenna heights to achieve wider coverage. For instance, beyond 40m high, the power density of the signal tends to zero.

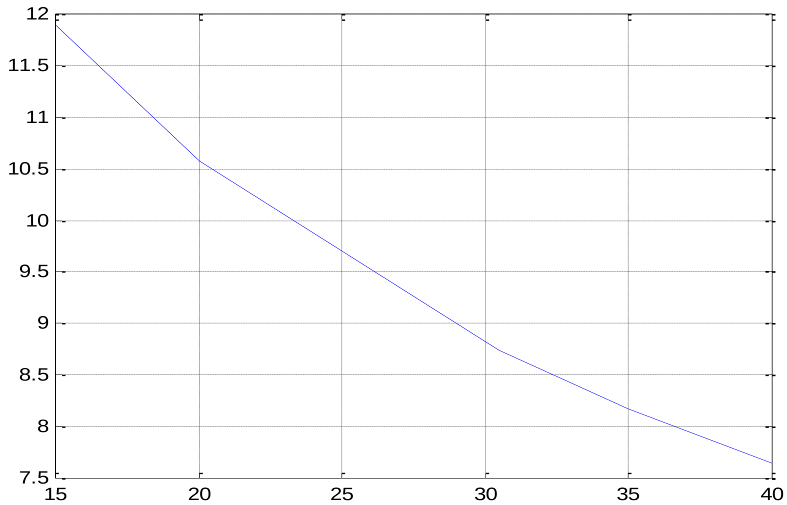

Fig. 4: Graph of Power Density against Antenna Height.

4.3 Relationship between Power Density and Maximum Distance

Fig. 5 shows that power density decreases with increasing maximum coverage distance. At the distance d = 42km, the power density of the signal Pd = 11.25nW/m^2 approximately. As d increases to 50km, Pd drops below 8nW/m^2, showing that maximum distance varies inversely with power density. To ensure that the signal level did not degenerate into a static noise, repeater or transceiver station can be sited at d = 46km.

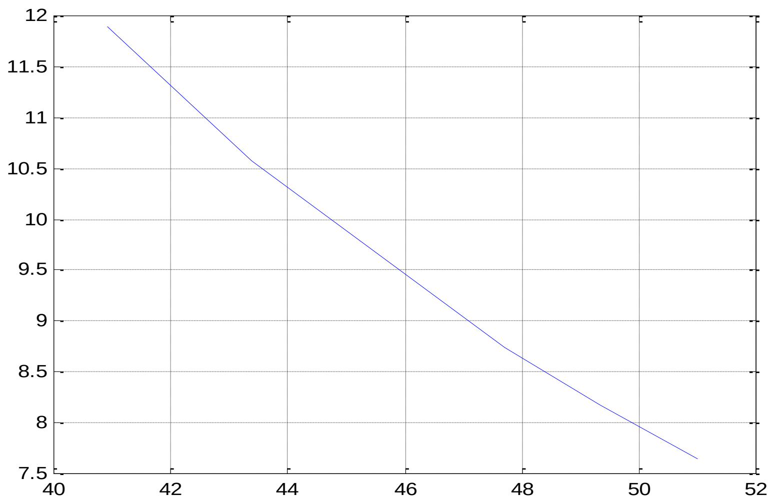

Fig. 5: Graph of power density against maximum distance.

4.4. Relationship between Electric Field Intensity and Antenna Height

Fig. 6 shows a graph of signal strength against receiving antenna height. The signal steadily decreased as the receiving antenna height was increased to obtain a new maximum distance. Between 30.48m and 35m, constant signal strength was erroneously displayed as a result of approximations done on the close values of the field intensity using Matlab programme. In general, it is observed that the receiving antenna height cannot be increased without limit to obtain an increased maximum distance, since the signal strength will deteriorate.

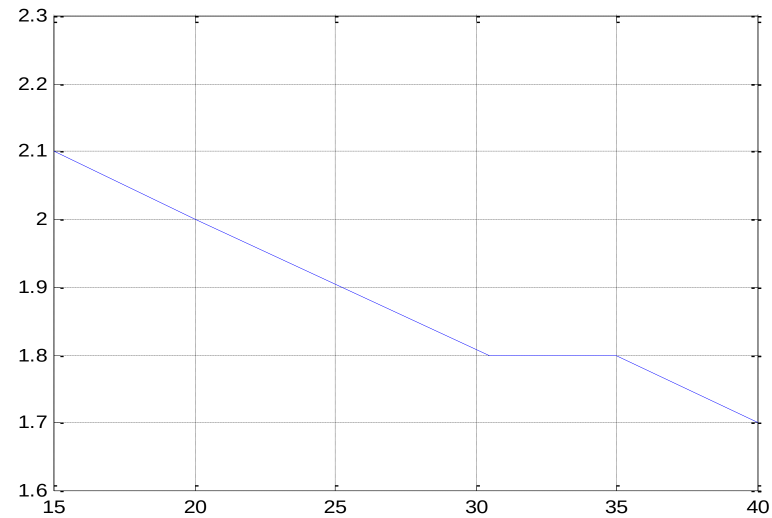

Fig. 6: Graph of Field intensity against Antenna height.

4.5 Relationship between Field Intensity and Maximum Distance

Regardless of the approximation error of the field intensity around 48km maximum distance, signal strength is inversely proportional to the maximum distance of line-of-sight coverage. From Fig. 7, we observe that signal field intensity decreases with increasing distance. So, increasing antenna height to achieve wider coverage has a limit because the signal power will be reducing. Because of this fact, if the main transmitter must be sited very far away from the information source (studio), there may be need to have a repeater station or transceiver in order to maintain the signal quality.

These results are in total compliance with the attenuation law, which states that signal strength is inversely proportional to distance.

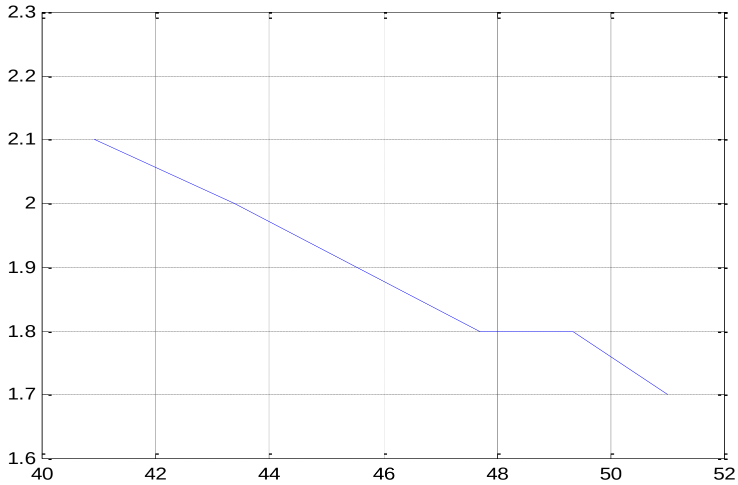

Fig. 7: Graph of Field Intensity against Maximum distance.

5. CONCLUSION

Having seen that with the connection of three receiving antennas, the FRCN STL marti-receiver signal strength increased from 8dB to 15dB, it is evident enough that space diversity technique can be utilized by radio broadcasting stations to improve on their signal quality. This space-diversity scheme is very important in radio broadcasting stations where studio transmission link (STL) is used to couple the studio output to the transmitting station sited in a different geographical location. The resulting graphs of the simulation showed that antenna heights determine to a great extent the maximum coverage distance in the line of sight propagation. It is then concluded that: space diversity technique can be utilized by broadcasting stations to improve their signal quality and invariably combat signal fading, and the scheme would be much more helpful if applied at reception and with a standard combiner; increasing the number of receiving antennas also increases the signal strength; With multiple antennas spaced out, there will be improvement in signal quality while signal drop-outs or signal failure will be greatly minimized; Although increasing the antenna heights also increases the maximum coverage distance in line-of-sight propagation, this cannot be increased indefinitely since there will be corresponding decrease in signal power resulting in fading.

With these, it is recommended that: Transmitters must not be sited very far away from the information source (i.e. studio), but if it becomes unavoidable, a repeater station or transceiver may be required to maintain the signal quality; Frequency allocation should be properly planned to prevent interference between RF channels, and two or more stations in close geographical range should not operate on close RF carrier frequency; Broadcasting houses should be properly earthed to prevent damage of equipment often caused by thunder and lightning and to guarantee longer life span of digital broadcasting equipment as well as safety of workers.

In the nearest future, we intend to focus more on designing an affordable and less power consuming combiner. This will help radio broadcasting stations and other small communication outfits to exploit the advantages of diversity schemes to improve the quality of their signals.

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