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Optimization of Spectral Efficiency of Vehicular Wi-Fi-Ad-hoc Network using Cooperative Relayed Antenna Diversity Scheme

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ABSTRACT

This work focused on optimizing the spectral efficiency of the Wi-Fi-Ad-hoc network connection. A Cooperative Relayed Antenna Diversity (CRD) scheme was employed in actualizing the set objective to improve the received signal strength of the Wi-Fi network hereby enhancing the performance of spectral efficiency of the network. In characterizing the proposed network, a free-space environment and a frequency of 2.4GHz for Wi-Fi network were chosen for the study. The mathematical equation of Friis in free space was adopted to determine the received signal strength of the network under study. This model was simulated in MATLAB platform with parameters of the characterized network to determine the received signal strength and path loss. Results of the simulation were used in the model of the characterized network to observe the effect of received signal strength on the spectral efficiency of the Wi-Fi Ad-hoc mode. However, the aim of the research was realized by utilizing the proposed cooperative relayed antenna diversity scheme. A mathematical model of the technique was used in determining its impact in improving the received signal strength of the network. An integrated mathematical model of the entire scheme was developed by modifying that of the characterized network. This was done by integrating the model of the CRD technique into the model of the characterized network and simulated for behavioral observation of the effect on the network. The results were compared with results gotten when switched diversity was implemented. It showed an average performance improvement of 23.84% in spectral efficiency.

Keywords: Wi-Fi-Ad-hoc network, Cooperative relayed antenna diversity, spectral efficiency, pathloss, free space environment

1. INTRODUCTION

Spectrum is a scarce resource in a wireless communication system that requires proper management to accommodate the ever-increasing demand for its use (Cave et al, 2014). Hence, the efficiency of this limited resource in our communication system is paramount in spheres of the industry particularly, for effective vehicle-to-vehicle (automobile) communication in the transportation system (Belagal, 2019). This will help in minimizing road causalities. There is a need to determine this efficiency to effectively deploy a particular radio frequency spectrum for use in a particular application. For this purpose, parameters such as bandwidth, capacity signal-to-noise ratio, number of demands on the network, and speed of the network are important factors to consider (Brijraj and Cory, (2014). The amount of data delivered with the fewest possible transmission faults over a particular spectrum or bandwidth is referred to as spectral efficiency (Zhu et al, 2022). Spectral efficiency is a good performance parameter used in evaluating the number of data transmitted over a given spectrum or bandwidth with minimized error occurrence.

In transportation system, vehicle-to-vehicle communication requires an effective communication system to enable the vehicles the capability to talk with each other and update each other on information such as safety warnings and traffic information (Khairnar and Kotecha, 2013). The vehicle communication technology combines a dedicated short-range and global positioning system to actualize its set objectives. This technology allows vehicles to exchange information such as safety warnings, and traffic information on their location and speed with one another over the network. The implementation of this system depends on the design, it may be designed to send a warning to the vehicle's driver that there is a risk ahead or the vehicle itself may pre-emptive action such as braking to slow down. It enabled the vehicle user 360-degree awareness of pending threats on the road. (vehicle communication system,2019). Vehicles exchange information using a communication system that requires these limited resources. This range of the spectrum is nothing compared to the number of vehicles on the roads in any country and needs to be managed. Thus if the available spectrum is not properly managed, a high level of traffic congestion and other associated challenges such as interference, loss of information, and delay in transmission of information (low data rate) will continue to be experienced in our communication system (Tan et al, 2020). These challenges will invariably be affecting the effectiveness of communication through call channels and internet connection.

Given these scenarios, it is important to enhance the performance of V2V communication system for effective communication between vehicles at all times to minimize the occurrence of radio traffic congestion and low spectral efficiency. Co-operative antenna diversity based on an amplifier and forward technique was implemented in this work to optimize the use of limited available resources to improve the signal-to-noise ratio and spectral efficiency.

2. LITERATURE REVIEW

Several works have been carried out over the years as developments continue in this innovative technology. The Newell model was proposed in 1961 taking into account the velocity-headway relations in actual traffic (Newell, (1961). Based of the Newell model, several classical car-following models were developed, including the optimal velocity model (OVM) (Bando et al, 1995) and the whole velocity difference model (FVDM) (Jiang et al, 2001). To look at the dynamical evolution of traffic congestion, Bando et al. proposed the OVM in 1995. Sugiyama and Nagatani (2012), investigated the dynamic process of multiple-vehicle crashes when a vehicle abruptly stopped in the flow of traffic using the OVM. The FVDM, which is used to investigate traffic problems like traffic jams and vehicle collisions, was developed in 2001 by Jiang et al as already cited. An Early Collision Warning Algorithm (ECWA) and the Global Positioning System (GPS) are used to measure the distance between vehicles and send warning signals to the driver in Huang and Lin's proposed system (Huang et al, 2012). This system does not require specialized infrastructure and can track people, motorcycles, and stationary objects. To improve the early braking safety feature, particularly in the case of rapid braking phenomena, Chen et al (2012) presented the critical safe distance model in V2V communication. They came to the conclusion that the essential safe distance model performs better, particularly when diverse vehicle speeds are present or when an obstruction emerges in front of the leading vehicle that is invisible to the following vehicles.

2.1 Theory of the Technique

A cooperative relayed diversity scheme was proposed for use in the optimization of the spectral efficiency of vehicular Wi-Fi-adhoc network. This technique employs a multiple antenna scheme that uses distributed antennas belonging to each node in a wireless network for maximizing total network channel capacities for any given set of bandwidths. This technique utilizes user diversity by decoding the combination of the relayed signal and the direct signal in wireless multi-hop networks, thus considering the other signal as a contribution ("Cooperative diversity", 2022). It is also known as multi-user MIMO technique. A cooperative relaying network is made up of three or more nodes with three fundamental items namely source, destination, and a relay node or nodes supporting the direct communication between source and destination. Considering a scenario when the direct transmission of a message from source to destination is not fully successful, the overheard information from the source to the relay can get to the destination via a different path. The concepts of time diversity and space diversity are implemented in this scheme since the propagation of signals in the communications network takes a different path to reach the destination directly from the source.

The following are the relaying strategies;

i. Amplify-and-Forward: In this strategy, a relay node(s) has the capacity to amplify the signal received directly from the source node and forward it to the destination node.

ii. Decode-and-Forward: This strategy allows relay in the communication network to get information from the source, decode, and forward correct information to the destination. If unrecoverable errors are present in the information received, the relay will not contribute to the cooperative transmission. Compress-and-Forward Strategies: In the compress-and-forward strategy, relay stations are allowed to compress the signal received from the source node and send it to the destination node without decoding the signal.

2.2 Topology of Relay Transmission.

There are two topologies used in relay transmission, namely;

i. Serial Relay: This type of topology uses power gain it provides for long distance communication as well as for range extension in regions seen to be shadowy. In this relay transmission topology, signals are propagated from one relay to another relay using orthogonal channels of neighboring hop to avoid any interference.

Parallel Relay: Power gain and diversity gain are provided simultaneously by this type of topology. Its robustness against multi-path fading where serial relay transmission is constrained by the multi-path fading is an advantage over serial relay topology. Propagation of signal is done through multiple relay paths using the same hop and the destination node of the network utilizes combining capability in summing the received signals in this topology. It can be used for radio signal propagation through non-line-of-sight and out door settings where the installation of multiple antenna devices is not viable ("Cooperative diversity", July, 2021).

3 METHOD

In actualizing the aim of this work, Friis transmission model was adopted and used in this work to observe the behavior of the system studied. The behavior of the system was observed by simulating the adopted model for each node represented by a single antenna assumed to be a dipole antenna. This antenna model was assumed to operate with the frequency of Wi-Fi (2.4 GHz). The simulation and observation were done using MATLAB tools.

3.1 Evaluation of Received Signal Strength of the Network under Study for a Free Space Environment.

Friss free space model was utilized in this work to represent the Wi-Fi system operating at the frequencies of 2.4 GHz for free space environment with nodes (Wi-Fi devices) having a direct line of sight communication with one another. The behavior of the system was observed by simulating the model as represented in Equation 2 below. This was done to determine the signal strength of the system represented by the model with respect to distance. Assuming the power of the transmitter is 100 milliwatts. Representing the free space formula using Friis transmission equation, the relationship between the power of the signal received and the power of the signal transmitted is expressed as;

$$\frac{\mathrm{Pr}}{\mathrm{Pt}} = \mathrm{G_r G_t}\left(\frac{\lambda}{4\pi d}\right)^2 \qquad 1$$

Rearranging Equation 1, then

$$\mathrm{Pr} = \mathrm{Pt} * \mathrm{G_r} * \mathrm{G_t} * \left(\frac{\lambda}{4\pi d}\right)^2 \qquad 2$$

Expressing Equation 2 in log form,

$$\mathrm{Pr(dB)} = \mathrm{Pt(dB)} - \left(20\log_{10}(\mathrm{d}) + 20\log_{10}(\mathrm{f_c}) + 20\log_{10}\left(\frac{4\pi}{c}\right)\right) + \mathrm{G_t(dBi)} + \mathrm{G_r(dBi)} \qquad 3$$

Where $Pr(dB)$ = recieved power in decibel, $Pt(dB)$ = tranmitted power in decibel, d= distance (Meters) between transmitter and receiver antenna, λ = Wavelength, d= distance between the antennas. Note that d must be greater than the wavelength for far-field (d> λ). f_c = operating frequency (GHz), $G_t = G_r$= antenna gain in dBi, c = wave length(m/s).Distance of 0- 200m was used with an interval of 10m apart, for reciprocity the gain of the antenna was assumed to be equal to that of the receiver, while Gt was assumed to be equal to the gain of a dipole antenna which is 2.15dB (1.64).

3.2. Evaluation of the Model of the Spectral Efficiency of the Proposed Network under Study

Spectral efficiency was represented as a Mathematical equation and was used to study the behavior of the proposed network as the received signal strength was varied. This parameter is defined as,

$$\text{Spectral Efficiency}(\eta) = \frac{\text{throuput (mbps)}}{\text{bandwidth(mbps)}} \quad 4$$

The equation 4 can be written as;

$$\eta = \log_2\left(1 + \frac{s}{n}\right) \quad 5$$

Where s= Pr and n= noise (Add White Gaussian Noise). The model of spectral efficiency (Equation 5) was simulated in MATLAB platform. The result of the received signal strength evaluation was used in the simulation of of Equation 5 to observe the behavior of the network in terms of its spectral efficiency and signal-to-noise ratio. The result of the simulation was represented in Figure 2 in Section 4.

3.3. Development of Cooperative Relayed Diversity technique

In developing the model of the overall system, the model of the technique proposed for this work was evaluated putting into consideration some conditions and assumptions made on the two scenarios considered in this work.

3.3.1 Some conditions and assumptions made were;

i. Transmitting and receiving antennas of equal height, sighted within the same lane of the road and having signal received to be from the line of sight, and a single reflected signal or relayed signal.

ii. Transmitting and receiving antennas of equal height, sighted within the same lane of the road, and having signal received to be from the line of sight and multiple reflections or relayed signals.

iii. Transmitting and receiving antennas are of the same height, located on different lanes of the road and having signal received to be from the line of sight and a single reflection or relayed signal.

iv. Transmitting and receiving antennas are of different heights, located within the same lane of the road and having signal received to be from the line of sight and single reflection or relayed signal.

v. Transmitting and receiving antennas are of different heights, located on different lanes of the road and having signal received to be from the line of sight and multiple reflections or relayed signal.

vi. It was assumed that all the antennae used for all the nodes are of phase array antenna of N=5 with adaptive equalizer combiner.

vii. Also it was assumed that signal received at the destination from the source is equal to the signal received at the relay from the source and from the relay to the destination with the same channel coefficient for simplicity purpose.

viii. Also it was assumed that signal received at the destination from the source is equal to the signal received at the relay from the source and from the relay to the destination with the same channel coefficient for simplicity purpose.

ix. Transmit antenna gain is equal to that of the receive antenna gain following the law of reciprocity as mentioned earlier. Gr=Gt.

x. Transmit/Receiver antenna gain is the gain of the antenna array.

xi. Channel gain is directly proportional to the root square mean of the signal power level and inversely proportional to the square mean of the noise power level.

xii. Constant of proportionality varies from one channel to another.

Sampling the transmit signal arriving at the designed antenna with the adaptive combiner equalizer, the received signal was estimated using Equation 9. This was used in the study of the system using the model developed for this work

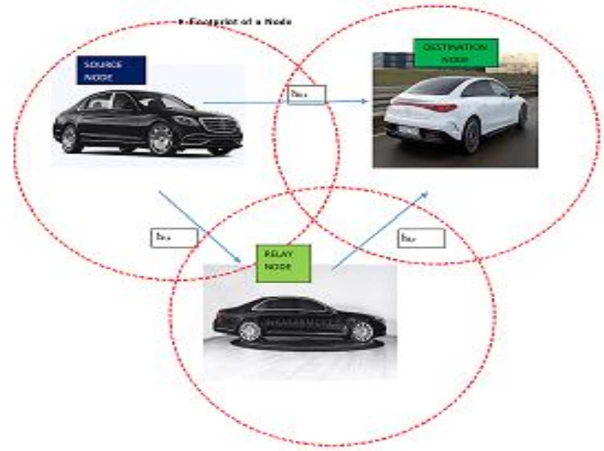

Figure 1: Architectural diagram for demonstration of the network scenario

The scenario as illustrated in Figure1, was assumed to be of two phases through which the signal can get to the destination. The transmitted signal got to the receiver through two nodes (direct and relayed). In this context, each vehicle was considered a node. The combination of signals from direct and relay nodes was used to improve spectral efficiency for the given set of bandwidths using a diversity scheme. Serial relay topology was employed in establishing a cooperative relay communication network as proposed in this work. The relayed signal received at the destination node was determined using Equation 5.

In the first stage, the transmitted signal gets to the destination and the relay node directly from the source node. The signals received by the two nodes were represented as;

$$r_{d,s} = h_{d,s}x_s + n_{d,s} \quad 6$$

$$r_{r,s} = h_{r,s}x_s + n_{r,s} \quad 7$$

Where $h_{d,s}$= Channel from the source to the destination node, $h_{r,s}$=Channel from source to the relay node, $n_{d,s}$= noise added to the channels $h_{d,s}$ and $h_{r,s}$ respectively.

For the second phase, the destination gets the signal transmitted to it through the relay. In this phase, no signal was received from the source.

The signal received by the destination from the relay was represented as;

$$r_{d,r} = h_{d,r}x_s + n_{d,r} \quad 8$$

Then the total signal received by the destination was expressed as

$$r = [r_{ds}, \quad r_{dr}]^T \quad 9$$

$$r = [h_{d,s} \quad h_{rs}, h_{d,r}]^T x_s + \left[1 \quad \sqrt{|h_{d,r}|^2 + 1}\right]^T n_d \quad 10$$

$$r = hx_s + qn_d \quad 11$$

Representing the received signal in vector form,

$$y = w^H r \quad 12$$

Where w = linear combining weight which is used to improve the signal received.

Spectral efficiency was estimated by modifying Equation 5 above by integrating Equation 12 into Equation 5. Estimating spectral efficiency for adaptive antenna array antenna,

$$\eta = \log_2\left(1 + \frac{y}{n}\right) \quad 13$$

Equation 13 was used for the simulation of spectral efficiency and the results were recorded in Table 2 analyzed using Figures (4.1and 4.2). Also behaviour of the system when switched diversity was implemented was observed. The CRD algorithm was presented in the section 3.3.1, while the flow chart was reported in the appendix A. The spectral efficiency of the WiFi network was observed when the proposed technique and switched diversity were implemented. Switched Diversity Scheme (SWD) utilized received signal strength with the highest value to determine the spectral efficiency of the network under study.

3.3.2 Algorithm of the Cooperative Relayed Diversity

Step 1: Initiate Process.
Step 2: Activate Device
Step 4a: Process the message sensed
Step 4b: If any node is sensed Go to step 7
Step 4c: If No Go to step 5
Step 5: Keep Device Active
Step 6a: Is there any sensed Node
Step 6b: If any node is sensed Go to step 7
Step 6c: If No Go to step 5
Step 7: Broadcast Signal.
Step 3a: Sensed any Information?
Step 3b: If Yes Go to step 4
Step 3c: If No Go to step 5

Step 8: Is signal sensed by Receiving Node?
Step 8b: If Yes Go to step 9
Step 8c: If No Go to step 5
Step 9: Align receiving antenna elements.
Step 10a: Are signals from more than one source?
Step 10b: If Yes Go to step 12
Step 10c: If No Go to step 11
Step 11: Wait for result interpretation.
Step 12: Combine, process and prioritize.
Step 13a: Is there any node sensed?
Step 13b: If any node is sensed Go to step 14
Step 13c: If No Go to step 5
Step 14: Broadcast Sensed Signal.
Step 15a: Any signal sensed by receiving node?
Step 15b: If Yes Go to step 16
Step 15c: If No Go to step 9
Step 16a: Is Destination Reached?
Step 16b: If Yes Go to step 17
Step 16c: If No Go to step 3
Step 17: end all If statement; Stop

In this section of this work, the results of measurements, simulations and observation of mathematical models were presented in tables and analyzed using graphical representations.

4. RESULTS AND DISCUSSION

4.1 Evaluation Results of Received Signal Strength for a Free Space Environment

The simulation results of the evaluation of the model of the network under study in a free-space environment was represented in Table 1.

Table 1: Relationship between Distance, Pathloss, and Received Signal Strength

Distance(m)	Pathloss (dB) at Frequency of 2.4 GHz	Received Signal Power (dBm) for Frequency of 2.4 GHz
0.00	0.00	0.00
10.00	55.75	-35.75
20.00	61.77	-41.77
30.00	65.29	-45.29
40.00	67.79	-47.79
50.00	69.73	-49.73
60.00	71.31	-51.31
70.00	72.65	-52.65
80.00	73.81	-53.81
90.00	74.83	-54.83
100.00	75.75	-55.75
110.00	76.58	-56.57
120.00	77.33	-57.33
130.00	78.03	-58.03
140.00	78.66	-58.67
150.00	79.27	-59.27
160.00	79.83	-59.83
170.00	80.36	-60.36
180.00	80.85	-60.85
190.00	81.32	-61.32
200.00	81.77	-61.77

Table1 showed the results of the evaluation of the pathloss and distance for 2.4 GHz frequency of WiFi capability at distance between 0-200 Meters. At distance zero, there was no loss recorded in the path of communication. As the distance between the nodes changes in the positive direction away from zero, a loss of 55.75dB for an operating frequency of 2.4GHz was detected in the path at 10m. In addition the result also revealed that increase in pathloss continued along the path as distance increased in the positive direction, furthermore, it so for the distance between 10 and 200 meters, the loss on the propagation path increases, showing that the Higher the distance between nodes, the higher the losses along the propagation path. Table 1 also showed the result of an evaluation of the characterized model of Equation 2 to ascertain the behaviour of the Wi-Fi network for the operating frequency of 2.4 GHz in terms of distance and received signal strength. At 10m, the signal strength was the best. The strength of the signal decreases as the node moves away from the source. The received signal strength at 200meters falls below the minimum value for all services that required smooth and reliable data traffic which is -68.14dBm. Between 100-200meters the signal is not very good but mostly sufficient. It portrayed the effect of distance on the received signal of the Wi-Fi network. Beyond this distance, signal strength will continue to diminish and will be very unlikely to connect and use the services.

4.2 Result of the network performance

This section discussed the result of the network performance, considering the spectral efficiency impact of the CRD developed and signal strength on the signal to noise ratio of the Wi-Fi network. The figure 2 presented the relationship between the spectral efficiency of the network against signal to noise ratio.

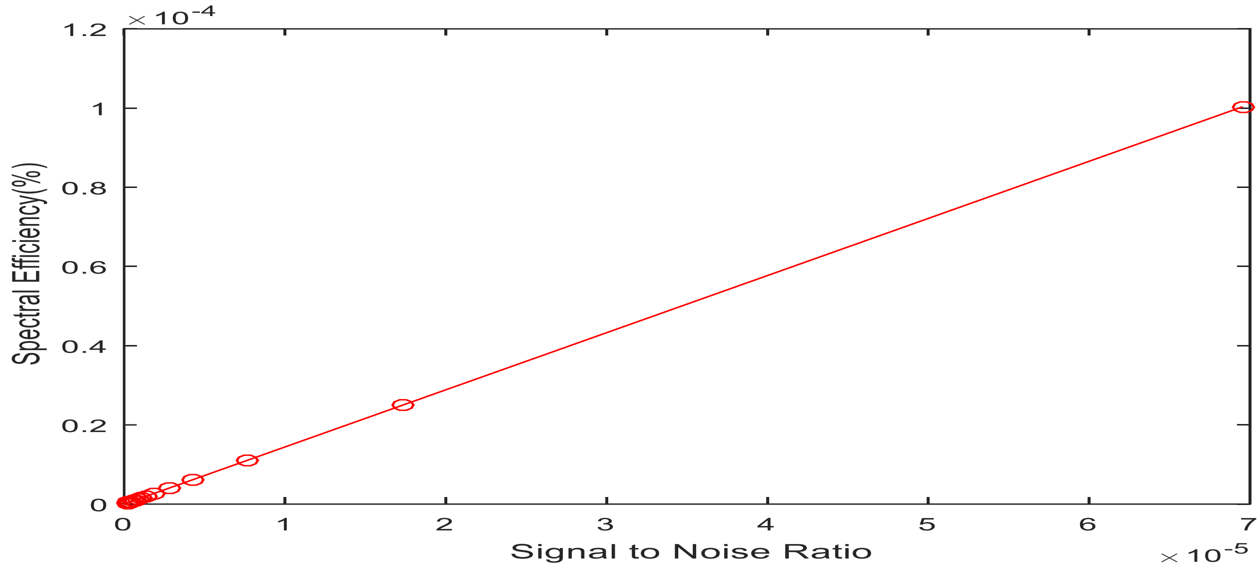

Figure 2. Spectral Efficiency versus Signal to Noise ratio

Figure 2 showed the efficiency of the proposed network between two nodes as the distance between the nodes increases at the distance mentioned above. As the distance between the nodes increases, the received signal strength decreases resulting into decrease in the signal-to-noise ratio and as the signal to noise ratio decreases, the spectral efficiency of the network also decreases. From the graph, the spectral efficiency and the signal-to-noise ratio of the network are very poor.

4.3 Results from of Overall Model of the Network Studied

This section consists of the table showing the result evaluation of the technique to determine the total signal received at the destination through the source and relayed path. Also the presentation and analysis of results gotten from the simulation of a model of the overall network and when switch diversity was implemented.

Table2: Showing the Average Result of Simulation of the Model of Equations 9 and 13.

Signal with Maximum Amplitude Received and Used for Switched Diversity (dBm).	Total Signal Received with CRD (dBm).	Spectral Efficiency with (CRD) (%)	Spectral Efficiency Switched Diversity (SWD) (%)
-64.92	-48.22	67.76	53.00
-62.77	-44.62	70.27	54.20
-61.23	-43.52	72.79	55.39
-60.23	-42.61	75.31	56.66
-59.32	-41.83	76.15	56.94

Results from the simulation of the model of the proposed technique (Equation 9), spectral efficiencies from the simulation of the overall model of the network when the technique and switched diversity were implemented were represented in Table 2. The spectral efficiency increases as the received signal strength increases. There wasan average of 36.64% improvement in the spectral efficiency of the network when the technique was implemented compared to the switch diversity.

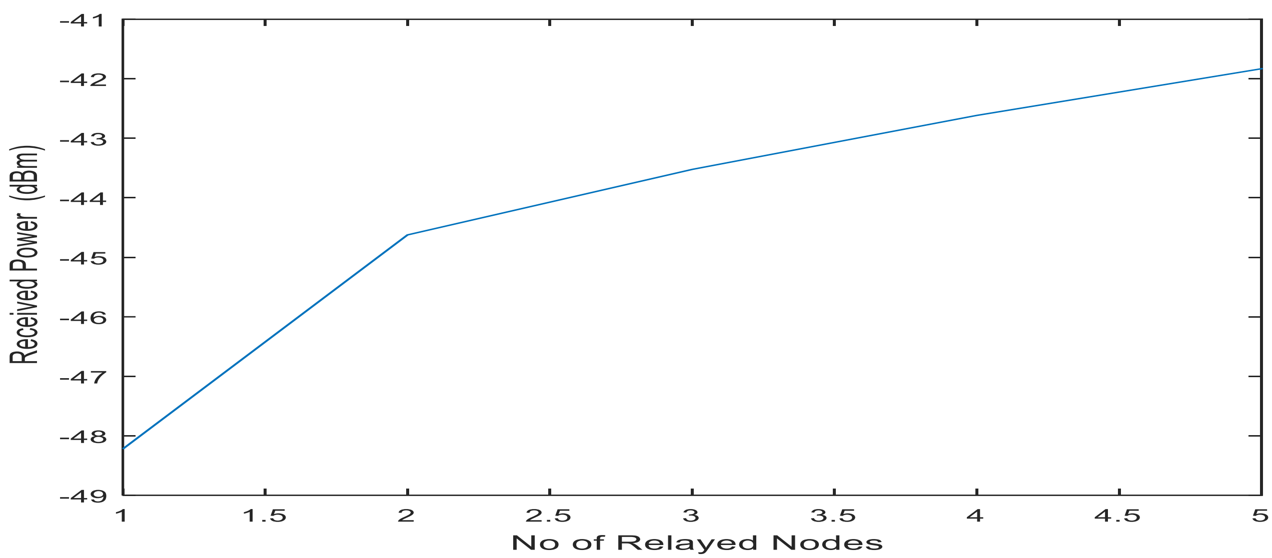

Figure 3: Received Signal Strength (dBm) with the new Technique

Figure 3 shows that the received signal strength increases in a positive direction as the no of relayed nodes increases. Comparing the results gotten from the simulation; when the relay node was 1, the signal strength of the network was about -48.22dBm with the technique implemented. Comparing the results in Table 2, signal strength received for both techniques improved in a positive direction but is better with the proposed technique.

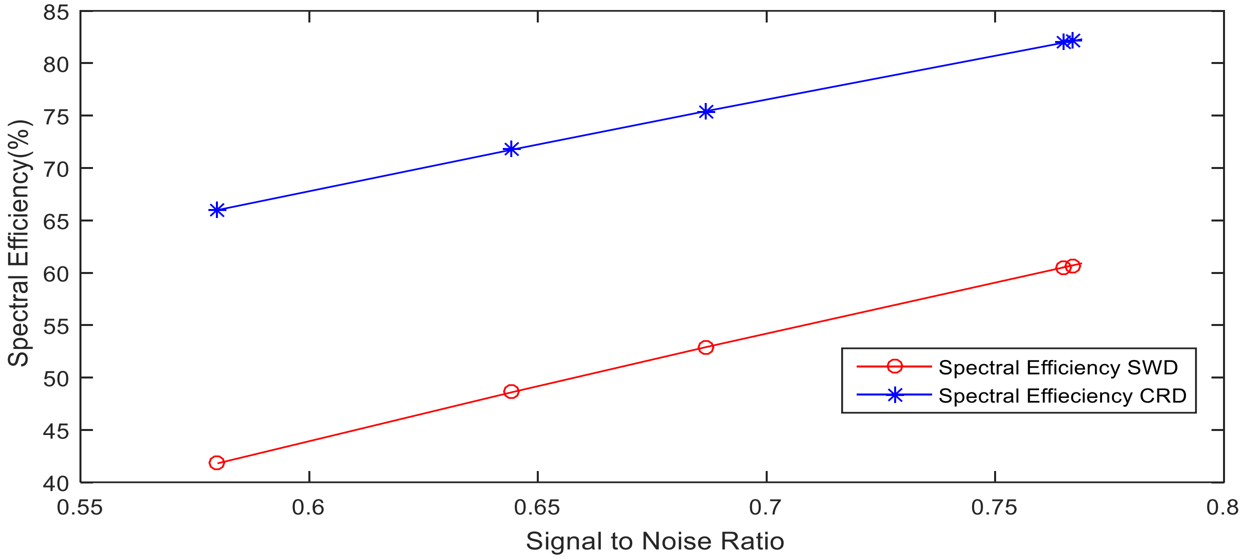

Figure 4: Spectral Efficiency Versus Signal-to-Noise Ratio

The result showed that the spectral efficiency of the network increased with an increase in transmitted power as in Table 2. From Figure 4, spectral efficiency increases as the signal-to-noise ratio increases when switch diversity and the technique was Implemented, but was higher when the technique was implemented compared to switched diversity. Comparing the results gotten from the technique employed in this work and switch diversity, it showed about 36.64% improvement for the average of the power sampled. This implies that the use of the cooperative relayed antenna diversity scheme in improving this parameter observed in this work for vehicle-to-vehicle communication system will enhance its performance effectively if implemented.

5. CONCLUSION.

Communication among road users could be made effective by maximizing the limited available spectrum to accommodate users demand on the network. Cooperative relayed antenna diversity scheme has proven to be effective in improving the performance of vehicle to vehicle communication by improving on the signal power, signal to noise ratio, hence enhancing the spectral efficiency of the Wi-fi-ad-hoc network connection. From the results gotten, the spectral efficiency was over 36.64percent better than that of the switched diversity. Co-operative relayed antenna diversity scheme if implemented properly in wireless communication system can help overcome the challenges resulting from radio traffic congestion thus, enhance on the performance of our vehicle to vehicle communication in our transportation system effectively.

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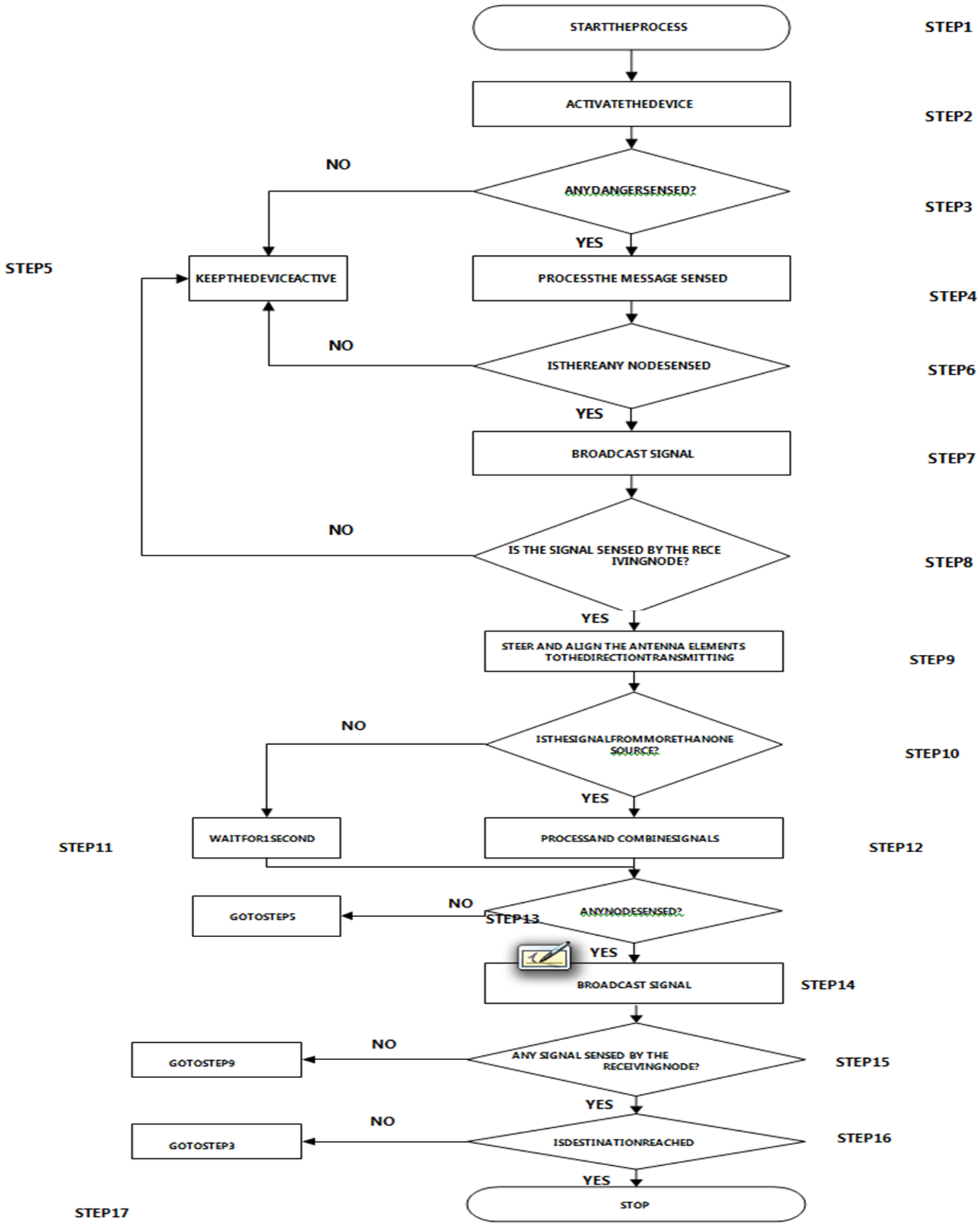
APPENDIX A (flow chart of the CRD algorithm)


STARTTHEPROCESS
STEP1
ACTIVATETHEDEVICE
STEP2
NO
ANYDANGERSENSED?
STEP3
YES
STEP5
KEEPTHEDEVICEACTIVE
PROCESSTHE MESSAGE SENSED
STEP4
NO
ISTHEREANY NODESENSED
STEP6
YES
BROADCAST SIGNAL
STEP7
NO
IS THE SIGNAL SENSED BY THE RECE IVINGNODE?
STEP8
YES
STEER AND ALIGN THE ANTENNA ELEMENTS TOTHEDIRECTIONTRANSMITTING
STEP9
NO
ISTHESIGNALFROMMORETHANONE SOURCE?
STEP10
YES
STEP11
WAITFOR1SECOND
PROCESSAND COMBINESIGNALS
STEP12
GOTOSTEP5
NO
STEP13
ANYNODESENSED?
YES
BROADCAST SIGNAL
STEP14
NO
GOTOSTEP9
ANY SIGNAL SENSED BY THE RECEIVINGNODE?
STEP15
YES
NO
GOTOSTEP3
ISDESTINATIONREACHED
STEP16
YES
STEP17
STOP