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Optimal Placement of Wireless Sensor Node for Real Time Fault Monitoring of Secondary Distribution Power Network

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ABSTRACT

This work investigated the optimal placement of wireless sensor nodes for real time fault monitoring of distribution network using Okpanam power network as case study. Implementation was carried out in stages; Mesh topology technique was adopted for the design. The number of wireless sensor network nodes required for deployment between the substations and the control room was determined by simple mathematical tool. Coverage model was developed for node placement. Receive signal strength indicator (RSSI) technique was used to determine the communication range of the ZiGBee module. Result from these experiments was used to determine total number of ZiGBee modules that was needed to cover the dimension of the area under consideration. Genetic algorithm in MATLAB simulator R2015A environment was used to carryout optimization of the network. Result obtained was implemented in network simulator 3 (NS3) environment to show coverage of the ZiGBee networks. Throughput metric was used to check the performance of the network. Findings from the research revealed the following: communication range of ZiGBee node within the area under consideration was 23 m. 784 nodes were required to monitor the dimension of the area under consideration. After optimization, the number reduced to 295. Result from NS3 revealed good throughput with minimal end-to-end delay.

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1. INTRODUCTION

An electrical power system has three main components; generation, transmission and distribution. Among these three components, the distribution systems are most important to the common man Ateh, (2014). In

Nigeria the distribution network has a voltage level of 11/0.415 kV for secondary distribution and 33/11 kV for primary distribution or sub transmission (Caciflo, 2014). According to Sushil and Govind, (2015), distribution systems experience losses more than the transmission side. Also, faults are more frequent in distribution side. A major challenge to electricity distribution in Nigeria today is the inability of distribution Company Engineers to respond quickly to faults because engineers on duty hardly know when faults occur on the line. It is very common to see part of a town or city disconnected from electricity supply for prolong hours and even days without the knowledge of supply authority. This, besides bringing untold hardship on people, also has negative effect on the reliability and efficiency of the power system. There is therefore need for power system to be installed with a device that has the ability to detect faults and also give information on the location of these faults. This will make faults to be detected quickly, reduced time of power outages and hence increase the reliability and redundancy of the system (Daniel et al., 2014).

Wireless sensor network refers to a group of spatially dispersed and dedicated sensors for monitoring and recording the physical conditions of the environment and organizing the collected data at a central location (Bylop, 2012). The recent field of wireless sensor networks combines sensing, computation, and communication into a single tiny device (Cacflio, 2014). Through advanced mesh networking protocols, devices can form various forms of connectivity that can extend to different parts of the physical world. Just as it is possible for water to flows and fill every room of a submerged ship, the mesh networking connectivity will seek out and exploit any possible communication path by hopping data from node to node in search of its destination. Although the capabilities of single device can be limited in terms of the area it can cover, the composition of so many devices offer radical new technological possibilities (Bhakthavathsalam and Ravidrag,2014).

The aim of the study therefore is to determine optimal placement of wireless sensor node for real time fault monitoring.

2. MATERIALS AND METHODS

2.1. Materials

The materials used in the study were Zigbee explorer Board, an Intel Core i5 -5200u laptop, a hundred meter Tape rule, Power Cable, Arduino Uno Development board, an XBee Digi modules with 1 mW wire antenna, 250,000 bps industrial grade (-40 to 85 °C) Xbee series 2 with VCC between 2.8-3.4 VDC, a Transmitter with power and current rating of 2 mW (+3 dBm) and 40 mA (@3.3 V) respectively. The receiver has a current rating of 40 mA (@3.3 V) and sensitivity of -96 dBm.

2.2. RSSI Measurement

Figure 1 shows two ZiGBee nodes which have been configured as coordinator and Router/End device which serve as transmitter and receivers respectively. The transmitter was connected to a computer desktop whereas the receiver was connected to a laptop. The transmitter was fixed in a position while the router was moved away from the transmitter within the tested area in preplanned positions. Packets were transmitted by the transmitter and received by the receiver and the RSSI values recorded. It was ensured that the two nodes were placed at least 1.5 m above ground level to prevent interference caused by Fresnel zone. One hundred packets were transmitted and the RSSI values recorded at each predefined position. This was repeated at twelve locations. The average for each location was considered and recorded.



Figure 1: Coordinator and end device placed at distance apart

2.3. Determination of number of Nodes for Area Covered by Substations

The grid based deployment technique was applied to determine the number of nodes for deployment that will sufficiently cover the area where the distribution substations are located. Equations (1) and (2) represent unit squared grid area and the area covered by the substations under consideration respectively. A number of squared grid makes up the total area covered by the substations. Therefore, the numbers of ZiGBee nodes (N_T) that will be required to cover the substations area is given as shown in Equation (3)

Squared grid Area Ag = Length of grid surface (Lg) X Width of the grid surface (Wg) (1)

Target area covered by substation (AS):

Total number of nodes required:

$$N_{\rm T} = \frac{Length \ \vec{x} \ ||^2 \sin h}{S \lambda} \tag{3}$$

2.4. Optimization of Total Number of Nodes

Problem formulation: Optimize total number of sensor nodes (N_T) ensuring coverage and connectivity between nodes.

Objective function = Minimize
$$\sum (xi)$$
 (4)

Subject to the constrain: $Z \times P \ge \mathbf{b}$

 $\sum (xi) = N_T = Node \text{ count},$

 $Z \ge \mathbf{b}$ represent coverage constrain

Z is a symmetrical Toeplitz matrix that describes the neighbor of the intersections Pij of a grid,

P is the vector Pij of the grid

b is a vector the same size as p of all ones.

Initial population: A randomly generated set of 50 chromosomes

Crossover: A single point crossover function.

Mutation: Adaptive feasible mutation function.

The parameters used for the Optim tool box 7.2 setup were GA-Genetic Algorithm, Fitness Function: - total number of nodes in the region of interest (t), Upper Bound 1, -Lower Bound 0, coverage and connectivity model. Integer Variable Indices: was selected to make integers constrained in the range within the bounds. Double vector was selected because it is required when there are integer constraints. Population size of 50 was selected

2.5. Nodes Placement Model for full Coverage

The 644 by 644 squared area covered by the power substations is represented by a 4 by 4 grid format shown in Figure 2. For coverage to be guaranteed all grid intersection points for the standard system must have one or more neighbour node within communication range in a work area. Positions P11, P12, P13, P14, P21, P22, P23; P24, P31, P32, P33, P34, P41, P42, P43 and P44 are intersections of the grids and represents the possible node positions of the network).

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Figure 2: Grid based wireless sensor network layout

The distance (L) between each grid intersection represent the communication range of sensor nodes. These positions are represented by the matrix:

$$P= \begin{bmatrix} P11 & P12 & P13 & P14 \\ P21 & P22 & P23 & P24 \\ P31 & P32 & P33 & P34 \\ P41 & P42 & P43 & P44 \end{bmatrix}$$
(5)

Equation (6) represents the general forms of node position at the intersection of a grid

$$P = \frac{\begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,ny} \\ \vdots & \ddots & \vdots \\ p_{n=1} & p_{nx,2} & \cdots & p_{nx,ny} \end{bmatrix}}{(6)}$$

Neighbour nodes positions are represented by matrix Nij denoted by Equation (7).

$$\operatorname{Nij} = \begin{bmatrix} P_{i-1,j} & P_{i+1,j} \\ P_{i,j-1} & P_{i,j+1} \end{bmatrix}$$
(7)

. The neighbour elements for all intersections thus become as shown:

				[P0	1	₽2	31]	_	ſŌ		1]							
N1	1=	P11	1 =	Pi	0	₽	12		10		11	=						
Û	₽	12	0	0	P	21	0	θ	0	0	0	0	0	0	θ	0	0	
<u>N1</u>	2=	P12	2 =	$\begin{bmatrix} P0\\ P1 \end{bmatrix}$	12 1	₽2 ₽1	21 31	=	[0 [1			=						
P1	1	0	P:	13	0	Û	P2:	2 1	0 (0	0	0	Û	0	0	0	Û	0
<u>N1</u>	3=	P13	3	된 	203 112	1	P23 P14	=	-	0 1	<u>1</u> 1]	=					
Û	₽	12	0	₽	14	Û	0	\mathbf{P}_{i}	23	0	0	Û	0	0	0	Û	0	0
<u>N1</u>	4=	P14	1	된 	204 13	1	23 P15	=	-	0	1 0]	=					
0	0	P	13	0	0	0	P	23	0	0	0		0	0	0		Û	0
<u>N2</u>	1=	P21	1 =	[P1 [P2	.1 0	P3 P3	31] 22]	=	[1 10		<u>-</u>]	=						
P1	1	0	Û	0	Ð	₽ź	32	0	0	P	31	0	Û	0	0	0	Û	0

 $\begin{bmatrix} P32\\P23 \end{bmatrix} = \begin{bmatrix} 0\\1 \end{bmatrix}$ [P12 1] N22= P22 = **P21** 1 = 0 P12 0 0 P21 0 P23 0 0 P32 0 0 0 0 0 $\begin{bmatrix} P13 & P33 \\ P22 & P24 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ $\begin{bmatrix} 1 \\ 1 \end{bmatrix} =$ N23 = P23 = P230 0 P13 0 0 P22 0 P24 0 0 P33 0 0 0 0 0 $\begin{bmatrix} P34\\ P25 \end{bmatrix} = \begin{bmatrix} 1 & 1\\ 1 & 0 \end{bmatrix} =$ [P14] N24 =P24=**P23** 0 0 0 P14 0 0 P23 0 0 0 0 P34 0 0 0 0 $_{N31 = P31 =} \begin{bmatrix} P21 & P41 \\ P30 & P31 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} =$ 0 0 0 0 P21 0 0 0 0 P32 0 0 P41 0 0 $\begin{bmatrix} P22 & P42 \\ P31 & P33 \end{bmatrix} =$ $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} =$ N32 = P32 = P310 0 0 0 0 0 P22 0 0 P31 0 P33 0 0 P42 0 $\begin{bmatrix} 223 & P43 \\ P32 & P34 \end{bmatrix} =$ ſ٥-11 l1 1 = N33 = P33 = |P32|0 0 0 0 0 P23 0 0 P32 0 P34 0 0 0 0 0 [P24] P44 · [1 11 P35 = l_1 N34 = P34 = **P33** 0 =0 0 0 0 0 0 0 P24 0 0 P33 0 0 0 P44 $\begin{bmatrix} P31 & P51 \\ P40 & P42 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ N41= P41 = **P40** 0 0 0 0 0 0 0 0 P31 0 0 0 P42 0 0 $\begin{bmatrix} P32 & P52 \\ P41 & P42 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$ N42= P42 = P41 $_{N43=P43} = \begin{bmatrix} P33 & P53 \\ P42 & P44 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} =$ 0 0 0 0 0 0 0 0 0 0 0 P33 0 0 P42 0 P44 $\begin{bmatrix} P34 & P54 \\ P43 & P45 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ N44= P44 = **P43** ٥l 0 0 0 0 0 0 0 0 0 0 0 0 P34 0 0 P43 0

The neighbour elements are assembled to obtain the whole neighbour. This is denoted in terms of 0's and 1's. Matrix. A '1' indicating the presence of a neighbor node and a '0' indicating the absence of a neighbor node as shown in Equation (8).

010010000000000000 101001000000000000 01010010000000000 0010001000000000 1000010010000000 010010100100000 0001001000010000 0 0 0 0 1 0 0 0 1 0 0 1 0 0 0 0 0 0 0 0 0 1 0 0 1 0 1 0 0 1 0 0 0 0 0 0 1 0 0 1 0 1 0 0 0 0 00000010010001 0000000010000100 0 0 0 0 0 0 0 0 0 1 0 2 1 0 1 0 Pij 0 0 0 0 0 0 0 0 0 0 1 0 0 1 0 (8)

The positions and numbers of neighbour nodes at all intersections is represented in equation (9)

																			[2 neighbor nodes]
																			3 neighbor nodes
0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0.		[P2 + P5,]		3 neighbor nodes
1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0		P1 + P3 + P6		2 neighbor nodes
0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0		P2 + P4 + P7		3 neighbor nodes
0	0	1	Ο.	0	0	1	0	0	0	0	Q	0	0	0	0		P3 + P7		5 Heighbor hodes
1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0		P1 + P6 + P9		4 neighbor nodes
0	1	0	0	1	0	1	0	0	1	0	0	0	0	0	0		P2 + P5 + P7 + P10		4 neighbor nodes
U	Ũ	1	Ο	U	1	U,	1	Ũ	0	1	U	0	U	U	Ø		P3 + P6 + P8 + P11		3 neighbor nodes
0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0		P4 + P7 + P12		3 neighbor nodes
0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0		P5 + P10 + P13		4 neighbor nodes
Û	Ō	0	Ω	Ω	Ũ	1	0	Û	1	0	1	0	0	1	Ű.		P7 + P10 + P12 + P15		3 neighbor nodes
0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0		P6 + P9 + P11		2 modulo en marten
ñ	ñ.	ñ.	ā.	ō.	ō.	ñ.	÷.	Ā.	ñ	÷.	ñ	ñ	ō.	ñ	1				5 neighbor nodes
0	С	<u>v</u>	0	<u>.</u>	0	9 2	1			1	0	<u>.</u>	2	<u>v</u>	T		P0 + P11 + P10		2 neighbor nodes
U	U	U	U	U	U	U	U	T	U	U	U	U	Т	U	Ų,		P10 + P14		2 mainlaine marian
0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0		P10 + P13 + P1		2 treighbor hodes
0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1		P11 + P14 + P16		3 neighbor nodes
lo	Ó	Ó	Ó	0	0	0	0	Ó	0	0	1	0	0	1	0.	=	P12 + P15	=	2 neighbor nodes

Equation (9) thus become Equation (10)

[0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	[P1]		[1]	
1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0		P2		1	
0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0		P3		1	
0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0		P4		1	
1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0		P5		1	
0	1	0	0	1	0	1	0	0	1	0	0	0	0	0	0		P6		1	
0	0	1	0	0	1	0	1	0	0	1	0	0	0	0	0		P7		1	
0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0		P8		1	
0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0		29		1	
0	0	0	0	0	0	1	0	0	1	0	1	0	0	1	0		P10		1	
0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0		P11		1	
0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1		P12		1	
0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0		P13		1	
0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0		P14		1	
0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1		P15		1	
10	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0		P16	>	1	

Equation (10) can be represented by:

(10)

(9)

$$Z \times p \ge \bar{b}$$
 (11)

(11)

Where Z be a symmetrical Toeplitz matrix that describes the neighbour of the intersections \mathcal{P}_{i} of a grid, \mathcal{P}_{i} is the vector whose elements are the intersections Pij of the grid and b is a vector the same size as p, of all ones for full area coverage:

2.6. Implementation of Optimized Nodes in Network Simulator 3

The genetic algorithm runs gave the best results of 295 nodes and this was implemented in NS 3 to show that communication between the nodes is possible and their results are discussed. Figure 3 shows the flow chart for the network simulator 3 implementation. The flow chart involves a summary of the algorithms for each section of the network simulator implementation environment.



Figure 3: Flow chart for implementation in network simulator 3

Figure 4 shows the positions of the optimal 295 nodes within squared area in network simulator 3 environment.



Figure 4: Position of 295 nodes within square area in NS3

4. RESULTS AND DISCUSSION

The result obtained from RSSI Measurement for determining effective communication distance of ZiGBee module is shown in Table 1. The change in distance between the end device and the coordinator causes the RSSI reading and the percentage of transmitted packets received at the receiver to vary. Table 1 reveal a distance of 23 m with RSSI value of -65 dMb. From studies available in literature and measurement, the transmission range of a ZiGBee transmitter falls between 10 m to 100m depending on the environment and the power of the transmitter (Arun, 2016). The minimum signal strength for applications that require very reliable, timely delivery of data packets is 65 dBm (Cadirci, 2006). From the table the corresponding distance between transmitted and receiver that produces -65dBm is 23m. Table 2 shows the dimensions of work area within which all substations are sited, and the total number of sensor nodes required to cover the area.

<u>e 11 10010</u>	monomp occureen	distance resort	araes percent pachet recert
S/N	Distance (m)	RSSI (dBm)	% of Packet received
1	5	-42.2	100
2	10	-52.2	100
3	15	-63.5	100
4	20	-64.1	100
5	23	-65.0	100
5	25	-65.2	100
6	30	-70.4	98.7
7	35	-65.8	99.9
8	40	-72.0	99.9
9	45	-68.1	99.9
10	50	-70.3	99.9
11	55	-76.0	99.89
12	60	-80.0	99 89
13	65	-68.1	99.89
14	70	-74.3	99.87
15	75	-71.8	99.87
16	80	-84.1	99.87
17	85	-79.3	99.87
18	90	-77.8	99.88
19	95	-87.6	99.89
20	100	-76.0	99.89

	able 1: Relationshi	p between distance -	- RSSI Values -	percent packet	t received
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	Table 2: Dimensions of area covered by sul	bstations
S/N	Dimensions of grid/work area	Values
1	Length of work area	644 m
2	Width of work area	644 m
2	Work area	644 m x 644 m
3	Length of each grid	23 m
4	Width of each grid	23 m
5	Each grid Area	23 m x 23 m
6	Total number of nodes required for work area	784 Nodes

Applying the grid based deployment technique and Equation (3), the number of nodes required for the squared area of interest (644 x 644 squared area) was found to be 784 nodes. Table 3 shows the mean number of nodes for different crossover and mutation functions when genetic algorithm optimization technique was carried out on 784 nodes. From the results it can be seen that Single Point crossover function with Constraint dependent mutation function had the lowest optimization value of 295 and converging at the 70th generation, consequently giving the optimal solution. Thus, number of nodes was reduced from the initial 784 to 295 nodes. The implication of this is that cost and power consumption of the network is also minimized

Table 3: genetic algorithm optimization for different crossover and mutation functions

I ut	sie 5. genetie algoritani optimization for anterent crossover and matation function	15
GAs	Different crossover and mutation functions	Mean no
GA01	Constraint dependent crossover function with constraint dependent mutation	313
GA02	Constraint dependent crossover function with Gaussian mutation function	311
GA03	Constraint dependent crossover function with uniform mutation function	295
GA04	Constraint dependent crossover function with adaptive feasible mutation	320
GA05	Scattered crossover function with constraint dependent mutation function	318
GA06	Scattered crossover function with Gaussian mutation function	304
GA07	Scattered crossover function with uniform mutation function	306
GA08	Scattered crossover function with adaptive feasible mutation function	295
GA09	Single point crossover function with constraint dependent mutation function	295
GA10	Single Point crossover function with Gaussian mutation function	320
GA11	Single Point crossover function with uniform mutation function	328
GA12	Single Point crossover function with adaptive feasible mutation function	295
GA13	Two Point crossover function with constraint dependent mutation function	320
GA14	Two Point crossover function with Gaussian mutation function	311
GA15	Two Point crossover function with uniform mutation function	328
GA16	Two Point crossover function with adaptive feasible mutation function	301
GA17	Intermediate crossover function with constraint dependent mutation function	307
GA18	Intermediate crossover function with Gaussian mutation function	298
GA19	Intermediate crossover function with uniform mutation function	304
GA20	Intermediate crossover function with adaptive feasible mutation function	304
GA21	Heuristic crossover function with constraint dependent mutation function	307
GA22	Heuristic crossover function with Gaussian mutation function	321
GA23	Heuristic crossover function with uniform mutation function	309
GA24	Heuristic crossover function with adaptive feasible mutation function	307
GA25	Arithmetic crossover function with constraint dependent mutation function	318
GA26	Arithmetic crossover function with Gaussian mutation function	320
GA27	Arithmetic crossover function with uniform mutation function	298
GA28	Arithmetic crossover function with adaptive feasible mutation function	304

Figures 5 and 6 shows result for implementing 295 nodes in network simulator 3. The result reveals that at nodes in the network can communicate with other nodes from different positions "X" and "Y". Figure 7 shows the plot of throughput versus number of nodes. The graph reveals that throughput decreases as the number of nodes in the network

increases. From available literature as the number of nodes increases, collisions increases and this brings about throughput reduction(Boaz et al., 2014). In general terms, throughput of a network decreases as (1/nhops), where n hops are the number of hops transverse by a packet to reach its destination. Equation (8) represent the placement pattern of wireless sensor nodes on the grid network. A "1" and "0" indicates that sensor nodes are present and absent respectively at the grid intersection. Across rows and columns of each intersection there is at least a "1" which represent a neighbour node. From studies available in related literature, a wireless sensor network can only attain coverage over a given area if there is at least one neighbour node from an intersection node (Anagha, 2014).







Figure 7: Throughput vs numbers of nodes

5. CONCLUSION

Seven hundred and eighty four wireless sensor nodes (ZiGBee modules) were require to cover the area under consideration. This number was reduced using genetic algorithm techniques to 295 nodes. Grid deployment technique was used for deployment or placement of these nodes with at least one or more neighbour node present to ensure coverage and connectivity of the sensor network.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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