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Optimization of Sensor Network Topology in Deployed in Inhomogeneous Lossy Media

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Abstract

This paper presents optimization of wireless sensor network (WSN) topology for forest fire detection. The sensors for this purpose are deployed in forest, grassland and open space, which have different attenuation properties in electromagnetic waves. For this reason, routers which receive signals from sensors and send them to the base station must be deployed considering these differences. In this work, we develop an optimization method for WSN topology based on simulated annealing considering the differences in the attenuation property. The vegetation data are taken from Landsat data. Using the present method, the necessary number of routers for full connection of the sensors deployed in diverse, irregular environments can be estimated.

Keywords*: Wireless Sensor Network, Electromagnetics, Wave Propagation, Simulated Annealing*

1. Introduction

Wildfires caused by lighting, spontaneous combustion, human activities and so on are serious problems especially in North America, Siberia and Indonesia. Wildfires can give rise to significant health, economic and environmental damages. In Kalimantan and Sumatra, a few ten thousand wildfire events are detected a year by MODIS [1]. Because initial detection of wildfires is of importance for effective extinction, a detection system for Indonesian wildfires has been developed [2]-[4]. One of the most promising detection systems is that based on wireless sensor networks (WSNs). In the WSN detection, many sensors are deployed in the target area to measure environmental data such as temperature and humidity. The measured data are then aggregated to the base station through wireless communication.

This system can realize fast and direct detection of wildfires. The WSNs, however have some problems. The major problem is relatively short lifetime of sensors which are usually driven by batteries. Because it needs great efforts to make frequent replacement of the batteries in sensors deployed in wide areas, prolongation of the lifetime is strongly required. For this reason, there have been many studies for extension of WSN lifetimes [5]. In the LEACH communication protocol [6], sensors autonomously constitute clusters each of which has one cluster head. The data measured by sensors are gathered by the cluster heads and transferred to the base station. A cluster head is dynamically selected from sensors in the cluster considering energy load balance.

In the Zigbeetechnology [7], WSNs are composed of sensors, routers and base station. The sensors send the measured data to the nearest router or directly to the base station. The routers send the aggregated data to the base station. Deployments of the sensors and routers have significant influence on lifetime, coverage and connectivity in Zigbee-based WSN systems. The sensors would be deployed to maximize their coverage [8]. On the other hand, the router position should be determined to maximize the lifetime and connectivity. The authors have proposed optimization method of position of the routers to maximize the lifetime and connectivity of WSNs for forest fire detection considering differences in the elevation using genetic algorithm [4].

In this work, we develop an optimization method based on simulated annealing (SA) for deployment of routers of Zigbee-based WSN whose working frequency is in UHF band. In particular, we consider the WSNs located in inhomogeneous lossy media such as forest and grassland, which have not been discussed in other works. We consider the differences in the

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propagation characteristics in the media into account. This paper is organized as follows: propagation of electromagnetic (EM) waves will be discussed in the next section. Then the optimization method will be described in the third section. The conclusion will be followed by the numerical results reported in fourth section.

2. Propagation of EM Waves in Forest

2.1. Propagation Modes in Forest

There are three EM wave contributions to the field [9],[10]: geometric optical waves propagate directly or reflectively from the source to the sink through the tree trunks and canopy. The sky waves have long triangular path whose vertexes are the source, sink and ionosphere. Moreover, the lateral waves propagate along the canopy-air interface. We can discard the second waves for WSNs because they use UHF waves which do not have reflection from the ionosphere. The first and third waves vary with distances as $\exp(-\alpha x)/x$ and $1/x^2$ respectively. Hence it depends on the distance and the attenuation constant α of the medium which wave is dominant. A full wave analysis based on four layer model of the forest concludes that the former is dominant above 100 MHz if the communication distance is shorter than 3 km [11]. In the WSNs for forest fire detection, the communication distance of the sensors and routers would be sufficiently shorter than 3 km. For this reason, we consider only the first waves in this study. Moreover, for simplicity, we only consider the direct waves.

2.2. Electromagnetic Waves in Absorbing Media

Let us consider electromagnetic waves in inhomogeneous lossy dielectric media, which are governed by the Maxwell equations

$$\mathrm{rot}\,\boldsymbol{E} = -j\omega\mu_0\boldsymbol{H}, \tag{1a}$$

$$\mathrm{rot}\boldsymbol{H} = j\omega\dot{\varepsilon}\boldsymbol{E}, \tag{1b}$$

where $\boldsymbol{E}, \boldsymbol{H}, \omega, \mu_0$ are electric field, magnetic field, angular frequency and permeability in vacuum. Moreover $\dot{\varepsilon}$ is the complex permittivity defined by

$$\dot{\varepsilon} \equiv \varepsilon_0\varepsilon_r - j\frac{\sigma}{\omega} \tag{2}$$

where $\varepsilon_0, \varepsilon_r, \sigma$ are permittivity in vacuum, relative permittivity and conductivity, and *j* denotes the imaginary unit.

We make here following assumptions on the dielectric property of the medium:

(a) The loss is dominant so that $\sigma/(\varepsilon_0\varepsilon_r\omega) \ll 1$.

(b) The relative permittivity ε_r is uniform while conductivity σ varies with position.

(c) The spatial scale of σ is sufficiently smaller than the wavelength of UHF wave $2\pi/k_r$. That is, assuming that σ varies sinusoidally, $\sigma = \sigma_0\exp(jk_\sigma r)$, the magnitude of $d\sigma/dr$ is expressed by $\sigma_0 k_\sigma$ which is sufficiently smaller than $\sigma_0 k_r$.

Now introducing vector potential, satisfying $\boldsymbol{H} = \mathrm{rot}\,\boldsymbol{A}$, which obeys the Lorentz gauge, the vector Helmholtz equation

$$\nabla^2\boldsymbol{A} + \dot{k}^2\boldsymbol{A} = 0, \tag{3}$$

can be derived from (1), where $\dot{k}$ is the complex wave number defined by

$$\dot{k} = \sqrt{\omega^2\mu_0\dot{\varepsilon}}. \tag{4}$$

Due to the assumption (a), $\dot{k}$ can be approximated as

$$\dot{k} \approx k_0\sqrt{\varepsilon_r}\left(1 - \frac{j}{2}\frac{\sigma}{\varepsilon_r\varepsilon_0\omega}\right)$$

$$\equiv k_r - j\alpha \tag{5}$$

For simplicity, we here consider a wave radiated from a dipole in *z* direction perpendicular to ground, which is governed by the one-dimensional scalar Helmholtz equation given by

$$\frac{d^2 f}{dr^2} + \left[k_r^2 - 2jk_r\alpha(r)\right]f = 0 \tag{6}$$

where $f(r) = rA_z$. It can be shown that the damped wave solution

$$f(r) = Ce^{-jk_r r}e^{-\int \alpha(r)dr} \tag{7}$$

satisfies (6) under the assumptions (a)-(c). Note that (7) is an exact solution to (6) when α is constant. It is therefore concluded that the vector potential is given by

$$A = \frac{Ce^{-jk_r r}e^{-\int \alpha(r)dr}}{r}\hat{z} \tag{8}$$

It can also find that $\boldsymbol{E}$ and $\boldsymbol{H}$ also have the spatial attenuation of the form $\exp\left(-\int \alpha(r)dr\right)/r$.

3. Optimization Method

3.1. Formation of Wireless Sensor Networks

In the optimization, we adopt the following assumptions for determination of WSN topology for simplicity.

(a) The sensors, routers and base station have a common threshold in electric field E_0 above which they communicate with others.

(b) The multi-hop transmission is available for the routers but not for sensors.The magnitude of electric field which is generated by node i and received by node j, and vice versa, is expressed by $E_{ij} = \exp\left(-\int_{C_{ij}} \alpha(r)dr\right)/d_{ij}$, where $C_{ij}$and d_{ij} denote a straight line connecting these points and their distance.

3.2. Wireless Sensor Networks Deployment Algorithm

The WSN topology is determined from the following algorithm.

(1) The tentative layer level, say -1, is given for all the routers.

(2) The sensor i and its nearest node j which is either a router or base station are connected if $E_{ij} \geq E_0$.

(3) The router i and its nearest base station j are connected if $E_{ij} \geq E_0$. The layer level of the connected router is set to 1 and the current layer level L is set to 1. Then the following procedure is repeated until there are no routers which can be connected to the other routers.

(4) The router i of level -1 and its nearest router j of level L are connected if $E_{ij} \geq E_0$. If router i is connected, then its layer is set to $L+1$.

(5) $L = L+1$. Return to (4).

3.3. Optimization Using Simulated Annealing

The objective function to be maximized is just equal to the number of connected sensors, ***N***. For optimization of WSN topology, we employ the simple simulated annealing whose algorithm is described below.

(a) We set the values of δ, $0 \leq P_{tk} \leq 1$, $0 \leq \gamma \leq 1$, initial temperature T_0 and maximum iteration count M.$N_s$sensors andN_r routers are randomly deployed in the target field Ω.

(b) One router is randomly chosen and its position $x = (x, y)$ is modified to $x' = (x + \delta a, y + \delta b)$, where $0 \le a, b \le 1$ are random numbers and δ is a given constant. If x' is outside of Ω, this modification is discarded. The topology of both WSNs is determined using the algorithm described in 3.2, and the numbers of connected sensors, N, N', are computed.

(c) If $\Delta N = N' - N$ is positive, then this modification is accepted. Otherwise, we compute $P = \exp(\Delta N / T)$. If $P \ge P_{th}$ ($P < P_{th}$), then the modification is accepted (rejected).

(d) The temperature is decreased by $T = \gamma T$. If iteration count is smaller than M, then return to (b).

4. Analysis of Experimental Results

4.1. Artificial Test Problem

We apply the present optimization method to an artificial test problem, where an area of highly attenuation with $\alpha = 1/100$ is located near the base station. In all the optimization mentioned below, the optimization parameters are set as follows: $E_0 = 1/300$, $N_s = 30$, $\delta = 20$, $P_{th} = 0.5$, $\gamma = 0.98$, $M = 1000$, $T_0 = 100$. It is expected that the WSN topology would be formed avoiding the attenuation area. Figure 1 shows the optimization result. We can see that all the sensors are successfully connected to their parent nodes and their communication routes detour around the attenuation area, as expected.

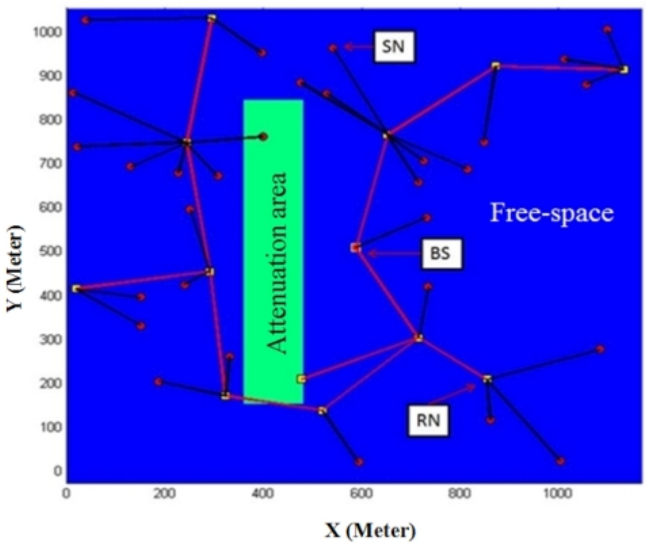

Figure 1. Artificial test problem with attenuation area with $\alpha = 1/100$ near base station, RN=12.**BS, RN SN** representBase Station, Router and Sensor nodes

4.2. Optimization of WSNs for assumed attenuation constants

In this simulation, we choose the tropical rain forest in Central Kalimantan, Indonesia for a case study of the simulation. The map of the location is obtained from Landsat images. There are forest, grassland and free space. We use the system for automated geoscientific analyses (SAGA) [13] to extract the information about forest and vegetation from Landsat images. We also perform optimization of a free space with the same area for comparison. In these models, the sensors and router nodes are placed randomly and the latter positions are optimized. We use the same random seed for both optimizations.We utilize a linear interpolation based method to estimate the information about forest, vegetation and free-space.

To evaluate the electric field received by the nodes, which depends on α defined in (5), we need the values of the homogenized permittivity ε_r and electric conductivity σ for forest and grassland. According to [7], their ranges are $1.01 \le \varepsilon_r \le 1.5$, $10^{-5} \le \sigma \le 10^{-3}$ S/m. In [8], ε_r is assumed to be unity. Hence α would range from about 0.2 to 1.5×10^{-3}. Thus we assume here that $\alpha = 1/600$ for forest.

In [9], the received power P is assume to be of the form $P = P_0 - n\log(d_{ij})$ in dBm, and the values of n, determined by experiments, are compared for forest and grassland. At 2.45 GHz, the resultant value is 2.89 for pine forest, and it ranges from 3.55 to 4.13 for grassland in long communication. Since their decay model is different from our exponential model, we cannot evaluate α from these results for grassland. We assume that the decay for grassland is two times stronger than that for forest, that is $\alpha = 1/300$ (Figure 2). Note that the present optimization can be executed for arbitrary values of α.

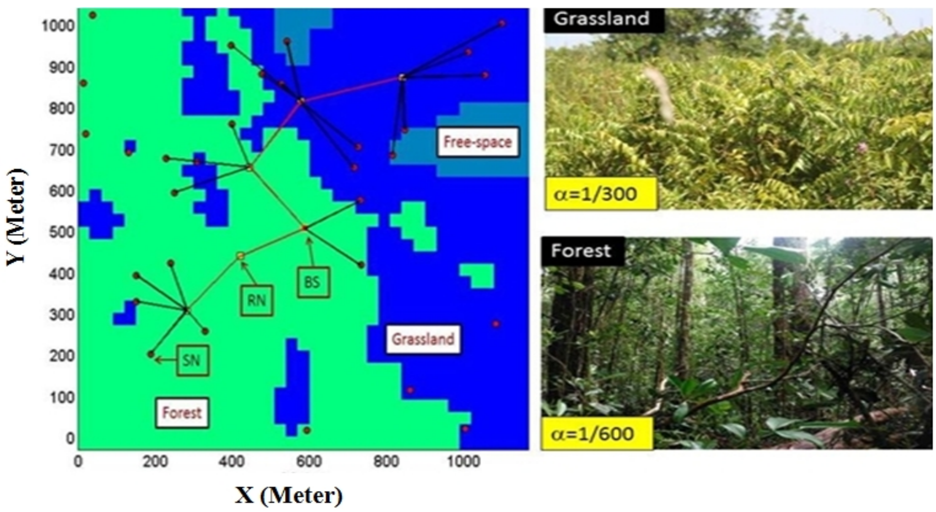

Figure 2. Sensing field in grassland and forest

In WSNs consider a sensor network to detect forest fires. The sensor nodes are assumed to be randomly deployed in the forest. Moreover, it assumes that the sensor and router nodes have the communication distance R_0 in free space. It is clear that the number of the sensors which can communicate with the nearest parent node depends on the router deployment. The sensor is judged to be connected if the condition.

$$\frac{e^{-\int_0^R \alpha(r)dr}}{R} > \frac{1}{R_0} \quad (9)$$

is satisfied, where R is the distance from the sensor to the nearest router including the base station. We optimize the router positions to maximize the number of connected sensors using the simulated annealing (SA). The optimization problem is defined by]

$$N_c \rightarrow \max. \quad (10)$$

whereN_c denotes the number of the connected sensors.

Figure 3 shows the optimized WSNs when RN=5. We find that the numbers of connected sensors are 26 and 22 for the free space and inhomogeneous area composed of forest, grassland and free space. Because of the stronger attenuations in the forest and grassland, the numbers of connected sensors are reduced for the latter case. Moreover, we find the optimized network topology is different from each other.

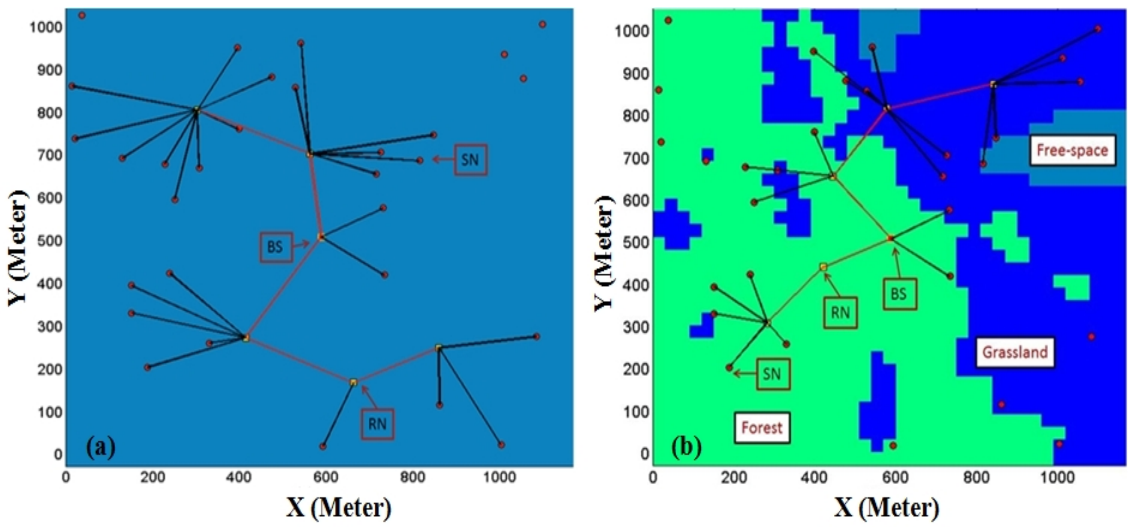

Figure 3. Optimized results for RN=5, (a) free-space environment, (b) Inhomogeneous field composed of forest, grassland and free space

Figure 4 shows the convergence histories of SA for both cases. After the initial fluctuations due to random search at high temperature, the values of the objective function (number of connected sensors) almost monotonously increase and converge to the final values.

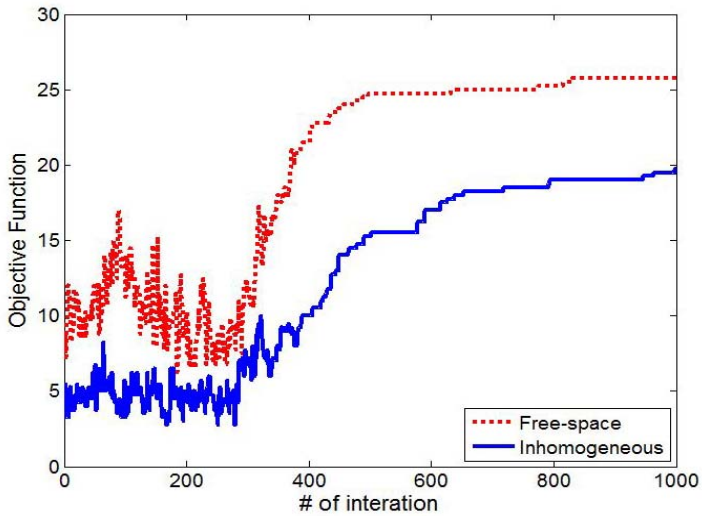

Figure 4. Optimization histories for RN=5

Figure 5 and 6 show the corresponding results for RN=12. All the sensors are connected to the network for the free space, while there are still 3 unconnected sensors in the inhomogeneous field. To evaluate the necessary number of routers or full connections of the sensors to WSNs, we perform optimizations changing the number of routers and random seeds.

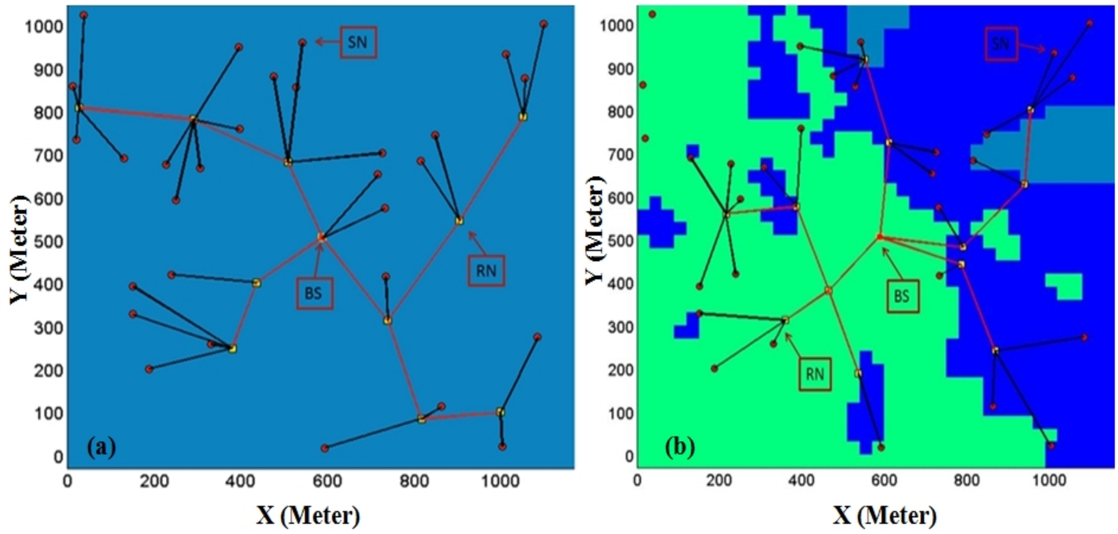

Figure 5. Optimized topology for inhomogeneous RN=12, (a) Free space, (b) Inhomogeneous field composed of forest, grassland and free space

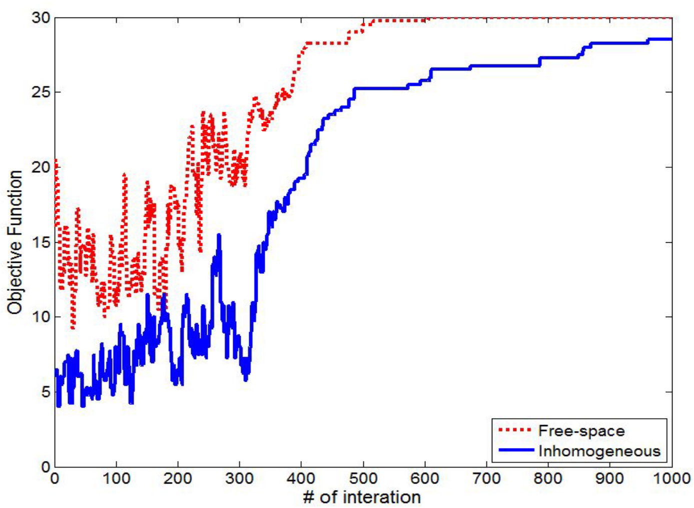

Figure 6. Optimization histories for RN=12

The results are shown in Figure 7 and Figure 8, where we can conclude that we need at least 8 and 11 routers are needed for the free space and inhomogeneous field respectively. This number depends on the vegetation. We can evaluate the necessary number of the routers for inhomogeneous field with arbitrary distribution.

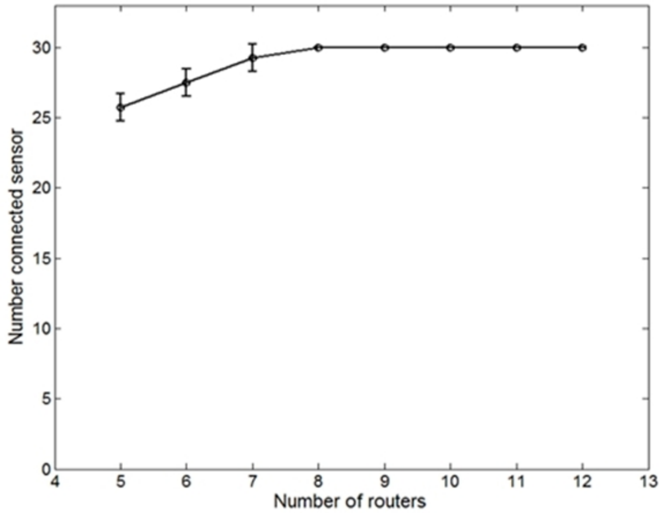

Figure 7. Number of connected sensors in free space field

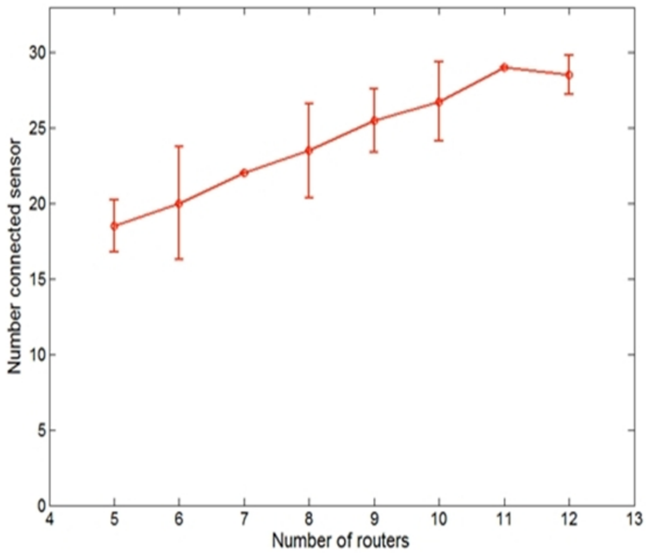

Figure 8. Number of connected sensors In Inhomogeneous field composed of forest, grassland and free space

5. Conclusions

We have presented optimization of WSNs placed in inhomogeneous lossy field composed of rain forest, grassland and free space. We optimize the router deployment using the SA. The wave attenuation in the inhomogeneous fields is taken into account in the optimization. We can evaluate the necessary number of the routers for full connection of the sensors to WSN.

We have applied the present method to the artificial test field with rectangular lossy area near the base station and real inhomogeneous field composed of rain forest, grassland and free space in Kalimantan. The network has been formed avoiding the lossy area as expected.

For the latter problem, we have found that we need at least 11 routers for full connection of sensors. For future work, we will evaluate the reliability of the present method by measuring the performance of the optimized WSN in real field.

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