Deployment Considerations for Reliable Communication in Wireless Sensor Networks

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***Abstract* — When deployed in the real-world, many sensor nodes fail to deliver the expected data or deliver a small percentage of them. The reasons for such failures can be hardware problems, software problems or communication problems. Among the communication problems is the insufficient received signal strength (RSS), which may cause unsuccessful packets delivery. For that reason, during the pre-deployment phase the RF propagation must be considered for predicting the RSS so that it guarantees reliable connectivity level. The present work is devoted to study of the deployment factors and requirements, which can ensure reliable communication links among the sensor network nodes. Subsequently, they are considered by the proposed RF signal propagation-based connectivity algorithm (RFCA). RFCA utilizes an outdoor RF signal propagation model for predicting the RSS in the positions, where sensor nodes are supposed to be deployed. Several factors are considered during RSS prediction, namely RF frequency, transmission power, transmitter–receiver distance, height from the ground and antenna's characteristics (gain, polarization, orientation, etc.). Different outdoor propagation models are discussed and analyzed with respect to their applicability to RSS prediction. Finally, an example illustrates that RFCA is able to find the most appropriate, from the communication point of view, deployment parameters (height, distance, and transmission power) for positioning the sensor nodes in outdoor environment.**

Keywords-WSN deployment; wireless communication; RSS; signal propagation model

I. INTRODUCTION

Sensor nodes' deployment reflects two main aspects of a wireless sensor network (WSN), namely sensing and communication. The deployment process can be considered as consisting of three consequent phases: pre-deployment, actual deployment and post-deployment. The pre-deployment phase includes analysis of the application requirements and of the area environment followed by deployment simulation and planning in order to ensure WSN requirements such as coverage, connectivity, optimal energy budget and low packet loss in the physical layer.

Several deployment algorithms propose solutions for the coverage problems when minimizing the number of deployed nodes [2] and [3] and the connectivity problems with respect to the optimal number of neighbors [4]. However, one communication aspect is not addressed adequately as a deployment prerequisite and that is the RF signal propagation. The knowledge of radio wave propagation and its modeling is essential for deploying a WSN in such a way to ensure reliable communication among the network nodes. A communication link is considered as guaranteed when the received signal strength (RSS) is sufficient.

Different RF propagation models have been introduced in the literature for supporting the wireless communication system design [5-7]. Most of these propagation models have been studied for high-power wireless communication systems, which operate at distances in the range of kilometers and they are not directly applicable to WSNs. However, some of them still could be used in RSS prediction with justification of the environment and conditions for their use. In general, the RF propagation is environment-dependant and the choice of an appropriate propagation model, for a specific environment, is crucial for the success of any RSS prediction.

For predicting the RSS, several parameters of the system have to be considered: the distance between transmitter–receiver pair (T-R), their height from the ground, the antenna's characteristics (gain, polarization, etc) and the terrain specifics.

In some studies, involving WSN, the deployment and the RF propagation are not discussed at all as a factor influencing the communication link between two sensor nodes, but just mentioned that the communication link is good within certain distance. In others [9], [10] and [11] the received power is modeled with log-normal path loss model, which model does not include the influence of the T-R heights and the ground reflection over the RF signal propagation. Such assumptions lead to the common belief that the communication between two sensor nodes is good until certain distance and worsen after it. As we will discuss in the fallowing sections there are several factors that influence the successfulness of the wireless communication and they have to be considered during the pre-deployment planning.

This work discusses the deployment factors that are of importance for ensuring reliable communication among the sensor nodes. It elaborates on the previous work [1], where the RF signal propagation-based Connectivity Algorithm (RFCA) is discussed. RFCA incorporates the signal propagation model and the deployment factors into the pre-deployment WSN planning. It utilizes a RF signal propagation model to predict the RSS within the radio ranges in order to identify the most appropriate communication-based deployment parameters, i.e. T-R distance, height from the ground, and transmission power. It consists of four sequential steps: (1) distance and height prediction; (2) transmission power simulations; (3) non-neighbor interference minimization; (4) deriving the optimal deployment parameters. RFCA is generic enough to be combined with any number-of-nodes optimization algorithm like [2-4] and [8].

In the present work, we motivate the importance of using proper simulation model for a specific environment. For that reason, four propagation models are overviewed and taxonomy for their use in outdoor environments is offered. Real outdoor measurements are compared with the simulation results for verification of the proposed RF propagation models.

The remaining of this paper is organized as follows. In Section II, the pre-deployment simulation framework is outlined and RFCA is presented. Section III presents a detailed description and analysis of the RFCA. Furthermore, an overview of some outdoor propagation models is presented together with simulated and measured results. A classification of the outdoor environments and the corresponding propagation models is also given. In Section IV, the RFCA reasoning is illustrated with an example for an environmental monitoring application scenario in an unobstructed environment. Finally, Section V concludes this work.

II. Pre-Deployment Simulation Framework

The pre-deployment simulation aims at analyzing the application requirements against the deployment environment to satisfy the sensor network's prerequisites for degree of coverage, complete network connectivity, optimal energy budget and low percentage of packet loss due to the physical layer. Therefore, the pre-deployment simulation framework includes three basic simulations: sensing coverage, communication connectivity and in-network localization, as shown in Fig. 1.

The sensing coverage simulation aims at ensuring the application requirement for coverage with the optimal number of sensor nodes. This component provides, along with the number of nodes for the given area, information about the possible heights from the ground of the sensor nodes and the minimum and maximum distance boundaries.

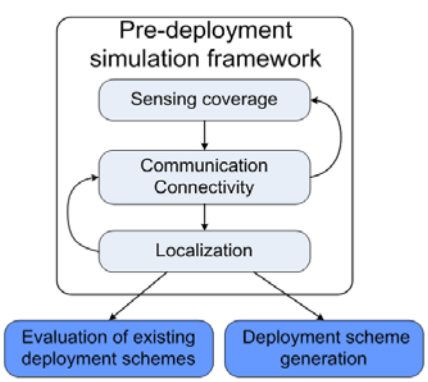


Figure 1. Pre-deployment framework diagram

The communication connectivity simulation extends the simulation process by matching the preferred nodes height and distance with ones proposed by the signal propagation model. The most appropriate height and distance are the output from this component along with suggestions for reducing the transmission power. The last simulation is localization, which uses information about the number of nodes and preferred topology to simulate the nodes localization process based on already known parameters as height, distance and signal propagation. This step may also suggest correction of the nodes height and distances for better localization accuracy. The pre-deployment simulation framework can be used in two directions: (1) to evaluate quality provisioning of existing deployment topologies, and (2) to propose a deployment scheme based on input parameters.

This work focuses mainly on the RFCA as the communication connectivity component, in which the deployment considerations for reliable communication are discussed and implemented.

III. RF Signal Propagation-based Connectivity Algorithm

In the literature the communication radius is often assumed to be at least twice as the sensing radius to support coverage with minimum number of nodes and complete communication connectivity [6, 7]. In some cases, this assumption might not be valid. For instance, given that the passive infrared (PIR) sensing radius is 10m, then the communication radius should be at least 20m according to the above-mentioned assumption. In this case, distance of 20m cannot be reached, with sufficient RSS level, by sensor nodes such as Tmote Sky [14] and TelosB [15] with internal antenna only, even at the maximum transmission power of 0dBm, if they are placed horizontally on the ground. Therefore, the RF signal propagation and certain deployment factors have to be considered and to go along with the optimal sensing coverage and localization algorithms when a WSN is designed.

A. *Algorithm Overview*

In order to incorporate the signal propagation and the deployment factors into the deployment planning an algorithm named RFCA was developed. Fig. 2 presents its block-diagram. RFCA consists of four steps: (1) Step 1 - distance and height prediction: It aims at discovering the most appropriate heights and distances of the sensor nodes, based on the input parameters; (2) Step 2 - transmission power simulations: Different levels of the transmission (Tx) power are simulated to evaluate the possibility of reduction; (3) Step 3 - non-neighbor interference minimization: In this step simulations are performed to evaluate the RSS level of the non-neighbor nodes in order to discover the best combination of distance, height and Tx power to minimize the interference from the unwelcome nodes; (4) Step 4 - Deriving the optimal deployment parameters: It aims at summarizing the results and at proposing the most appropriate deployment parameters according to initial criteria.

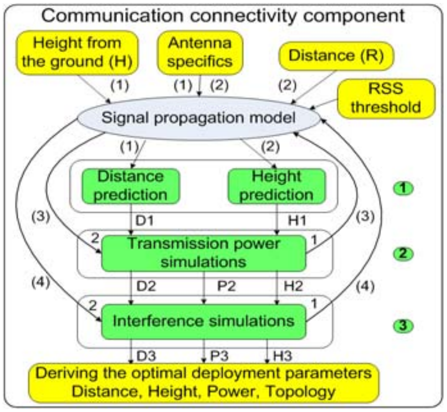


Figure 2. RFCA block diagram

RFCA is applicable for outdoor applications, for manual and for random deployments:

- For manual deployment when one parameter (height or distance) is known, the simulation aims at predicting the other parameter to guarantee sufficient RSS for deployment. For example, path (1) of Fig. 2 uses as input parameter the height from the ground and calculates the appropriate distance for nodes' positioning.
- For random deployment scenario (nodes thrown out from a airplane) the nodes end up on the ground and the height of the antenna is between 2cm and 10cm. Based on the propagation model, on Tx power and on the node's antenna specifics, it is possible to predict the maximum distance, where the signal has sufficient RSS level to guarantee successful communication. Considering this distance as maximum communication radius, the necessary number of nodes per unit area may be calculated to ensure network connectivity and certain degree of coverage.

B. *Algorithm attributes*

The factors that are of importance for successful physical communication are inputs parameters for the RFCA and are discussed in the following Section. As shown in Figure 2, RFCA takes as input height from the ground or the transmitter–receiver (T-R) distance and the RSS threshold. The antenna specifics (gain, polarization orientation) and propagation model need also be known in advance.

1) RF propagation models, height from the ground and distance: The height from the ground and distance between any two sensor nodes are the most important parameters influencing the RSS. These two parameters participate directly in the propagation model equation. The relation between distance, height and RSS forms the propagation of the RF signal.

Many different RF propagation models have been introduced for supporting the wireless communication system design. Most of these propagation models have been studied for high-power wireless communication systems like those for UHF/VHF band, satellite, cellular, etc. [5 - 7]. The assumption made by these models does not take into account some of the most distinctive features of WSNs, i.e. low-power radio, the antenna low height and the feature of omnidirectionality, which render the models unsuitable for WSNs. However, some of them still could be used in RSS prediction when justifying the environment and conditions under use. In general, the RF propagation is environment-dependant and the choice of an appropriate propagation model, for a specific environment, is crucial for the success of any RSS prediction

In the following some propagation models are overviewed and taxonomy for their use in outdoor environments is offered, in conjunction with their dependence on the height.

a) Log-normal Path Loss Model (LPLM): LPLM [5] considers the received power as a function of the T-R distance raised to some power. Since this model is a deterministic propagation model and gives only the average value, another propagation model, known as log-normal shadowing model, defined by (1), was introduced to describe the RSS irregularity [5]. The received power, $P_r(d)$, at distance d is given as:

$$P_r(d)[dBm] = P_0 - 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{1}$$

where X_σ is a Gaussian random variable with zero mean and standard deviation σ, P_0 is the received power at reference distance d_0, and n is the path loss exponent factor. The path loss exponent n is environment-dependant. In general n is 2 in free space model. However, in indoor obstructed environment n may take values between 4 and 6, and for outdoor obstructed – values between 3 and 5 [5].

$P(d_0)$, n and σ describe statistically the path loss model for any location in specific T-R distance. This model is used for computation and simulation of the received power at random locations. In Fig. 3(a) the LPLM model with n=3 is presented.

b) Free-space + Two-ray Ground Reflection Model (FS+GR).

LPLM is actually a simplistic approach as it does not allow obstructions to be taken into account. The greatest and unavoidable obstruction, when the wireless nodes are placed close to the ground is the earth surface. In order to model the ground influence on the signal, the basic Free Space + Ground Reflection (FS+GR) model equation of [5] is adopted for recalculating by including the ground reflection coefficient with its formulation given also in [5]. Thus, the final equation for $P_r(d)$ is given as:

$$P_r(d) = P_r(d_0) + 20\log_{10} d_0 + 10\log_{10}\left(\left(\frac{\cos\Delta\theta}{L_D} - \frac{\Gamma}{L_R}\right)^2 + \left(\frac{\sin\Delta\theta}{L_D}\right)^2\right) \tag{2}$$

where L_D and L_R are the path length of the directed and the path length of the reflected signal, $\Delta\theta$ is phase difference, Γ is the reflection coefficient, which depends on the polarization of the radio waves given in [5] as:

$$\Gamma(\theta)=\frac{\sin(\theta)-X}{\sin(\theta)+X} \tag{3}$$

- for perpendicular polarization: $X_{\perp}=\sqrt{\varepsilon_r-\cos^2(\theta)}$
- for parallel polarization: $X_{\parallel}=\frac{\sqrt{\varepsilon_r-\cos^2(\theta)}}{\varepsilon_r}$

where θ is the angle of incidence and ε_r is the complex permittivity for lossy reflecting surface [5]:

$$\varepsilon_r=\varepsilon_1-j60\sigma_1\lambda \tag{4}$$

where λ is the wavelength, ε_1 is the relative dielectric constant and σ_1 is the conductivity of the reflecting surface material in S/m.

The two-ray ground reflection model is useful to predict the RSS variance concerning the ground reflection over distances. It also could be used to calculate the most appropriate height from the ground of the T-R pair for certain T-R distance.

c) Free-space Outdoor Model (*FOM*): This model was introduced firstly in our previous work [13]. Various RF signal-influencing factors, such as free-space path loss, ground reflection path loss, RSS uncertainty, variation of the transceivers, radio frequency gain inequality and antenna pattern irregularity are included in the model. The FOM formulation is given as :

$$\overline{P_R}(d)=P_T\left(\frac{\lambda}{4\pi d}\right)^2\left(K_1^2+K_2^2\Gamma^2+2K_2\Gamma\cos\left(\frac{2\pi}{\lambda}\Delta L\right)\right) \tag{5}$$

where $\overline{P_R}(d)$ is the average value.

If P_R is expressed in decibels with RSS uncertainty included as $X_{\sigma(\overline{P_R})}$, then the formulation is:

$$P_R=\overline{P_R}(d)+X_{\sigma(\overline{P_R})} \tag{6}$$

where P_R is the received power, P_T is the transmission power, d is T-R distance, λ is the wavelength, Γ is the ground reflection coefficient given with (3), ΔL is path length difference between the direct and the reflected signals, coefficients K_1 and K_2 are antenna specifics representing the gain in particular antenna orientation. The RSS uncertainty is given as a Gaussian random variable X with distribution $\sigma(\overline{P_R})$ [10]. A simulation performed with (5) is presented in Figure 3(b).

d) Tree-obstructed Outdoor Model (TOM): In a tree-obstructed environment the trees can be located in any order -random, line, or grid. The impact factors of the RF signal propagation through forest environment, apart from the common ones like height from the ground, T-R distance, ground reflection, antenna radiation pattern, and RSS variance, are also the trunk and vegetation diffraction and scattering.

For sparse tree environment the base model could be FOM (equation (6)) with counting additionally the single-tree effects over the RF signal such as: trunk diffraction and vegetation scattering. Considering the total propagation loss in decibels as $L_{TOT}= L_M + L_{veg}$, where L_M is the basic signal propagation loss in the media and L_{veg} is the propagation loss because of vegetation, we recalculate the P_R trough L_M and L_{veg}. Consequently, the final equation for the received power P_R in decibels is:

$$\begin{aligned}&P_R[dBm]=P_T[dBm]-L_{TOT}[dBm]=\\&=P_T-L_M-L_{veg}=P_{R_M}-L_{veg}\Rightarrow\\&\Rightarrow P_R[dBm]=P_{R_M}[dBm]-L_{veg}[dBm]\end{aligned} \tag{7}$$

where P_{R_M} is the received power in the transmission media.

A simulation, utilizing TOM, is presented in Fig. 4, where RF propagation in an area of 20m x 30m is simulated with one transmitter located at height of 0.70m. Here L_{veg} is the signal propagation loss due to the trunk diffraction, obtained with the diffraction equations given in [5].

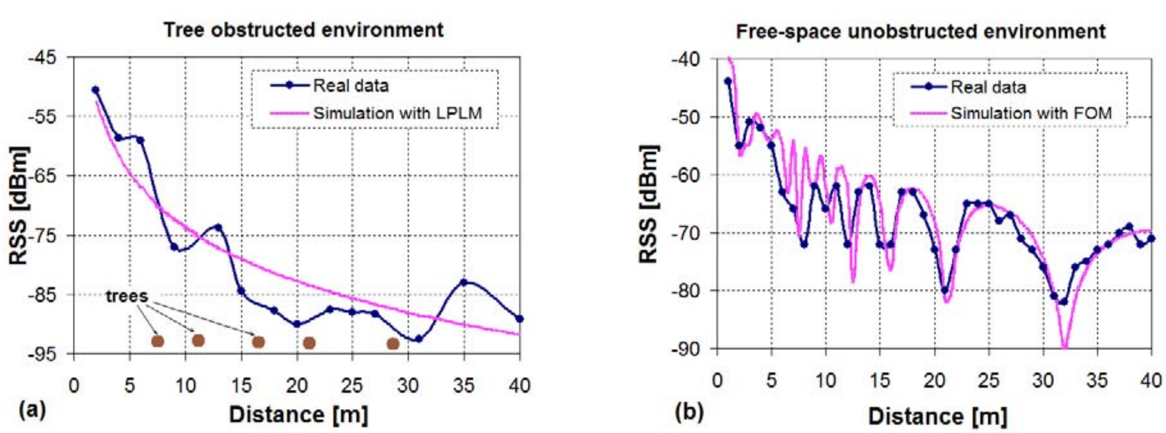


Figure 3.Real-field measurements in tree environment (a) and free space (b) and simulations with LPLM (a) and FOM (b).

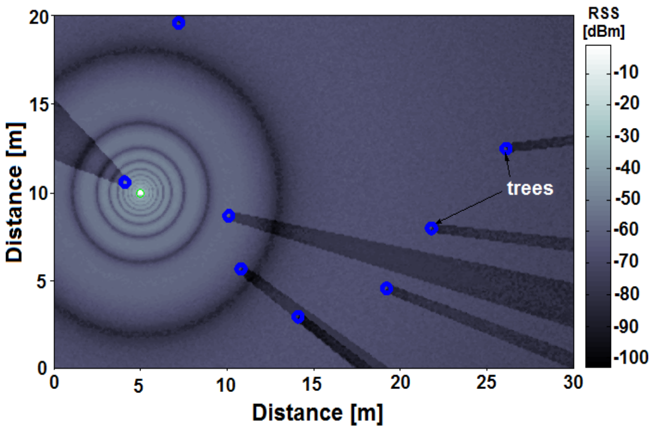


Figure 4. Simulation with TOM

When the trees are located close to each other, as it is in the thick forest environment, their influence over the RSS of the radio signal have to be examined as a whole, and the TOM may not be the best suited model. As it is shown in Fig. 3(a) the LPLM with n=3 successfully could be used to model the propagation in thick forest environment.

e) Classification of the outdoor models: Based on the WSN application scenarios three outdoor types are identified depending on the presence of trees: thick forest, sparse garden and free space. A specific RF propagation model corresponds to each environment, predicting the RSS at any T-R distance. Fig. 5 depicts the three outdoor environments and the corresponding propagation models. The choice of the appropriate propagation model for a specific environment is crutial for the success of any RSS prediction. As shown in Fig. 3, where the measured and simulated results are compared, when using inappropriate RF propagation model and not taking into consideration the deployment factors during the pre-deployment phase, may lead to communication and data loss.

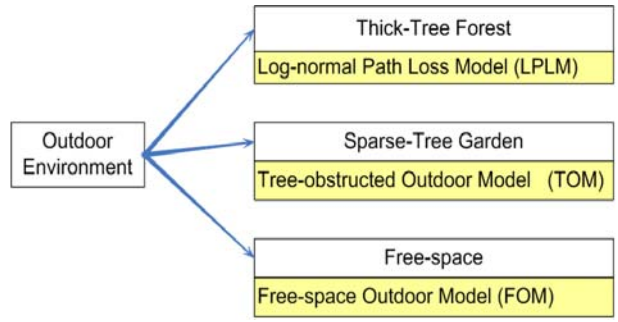


Figure 5. Classification of the outdoor models

f) Measured and simulated results: In order to investigate the eligibility of the proposed models, measurements and simulations have been conducted. The results presented in Fig. 3, Fig. 6 and Fig. 7 confirm that the propagation model is environment-dependent.

Real-field experiments have been conducted in a free space area of 100m x 50m, using Tmote Sky nodes [13], operating in the band of 2.4GHz with internal antenna and Tx power at the maximum of 0dBm. The process of measuring the RSS consists of the following steps: Every 100msec the transmitter sends to the receiver a packet of length 21 Bytes, including one counter holding the number of packets sent. The counter reaches a maximum of 150,

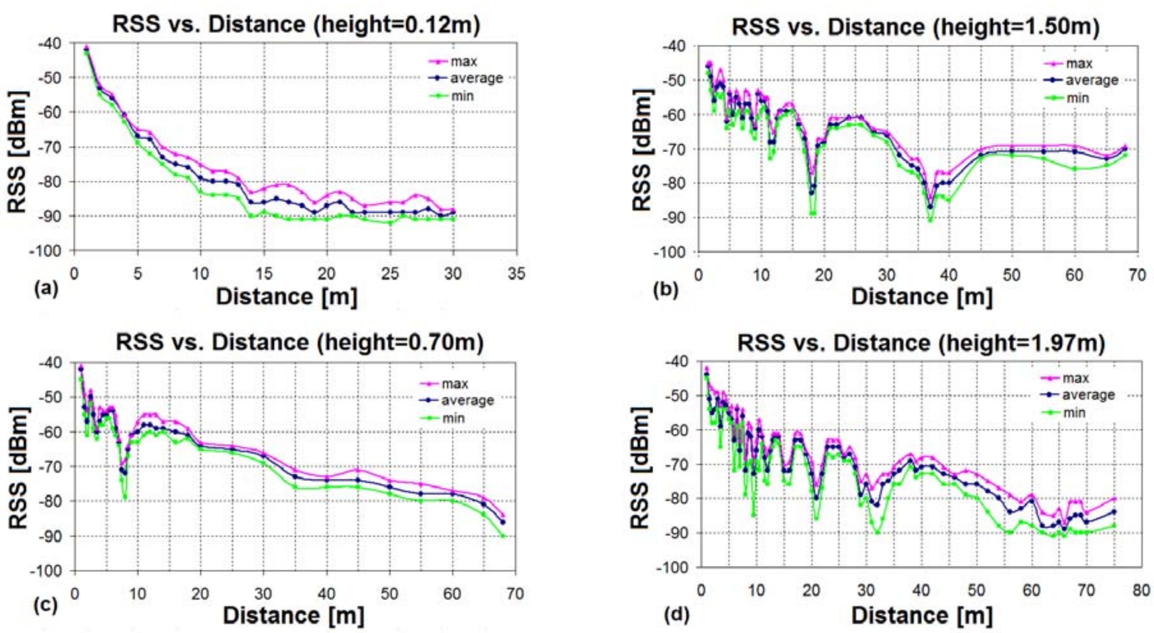


Figure 6. Real outdoor measured results in free space (min, average, max) for T-R heights of the ground: (a) 0.12m, (b) 1.50m, (c) 0.70m and (d) 1.97m

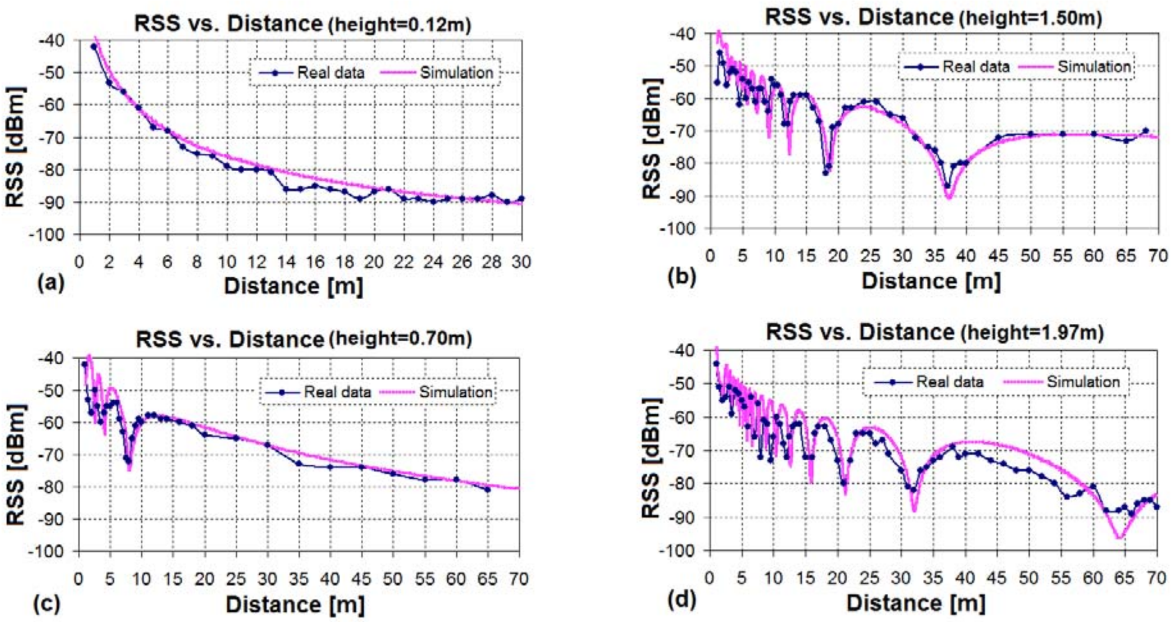


Figure 7. Real outdoor measured results and simulation results with FOM for T-R heights of the ground: (a) 0.12m, (b) 1.50m, (c) 0.70m and (d) 1.97m

indicating that at most 150 packets are sent for each distance. The receiver incorporates the RSS of the received packet in a 1-Byte field to the received packet and forwards it to the base station, connected through USB to a laptop.

Fig. 3 shows that a thick tree obstructed environment, with trees located every 4-5m, is best modeled using LPLM with n=3 (Fig. 3(a)), while a free space without trees is adequately modeled with FOM, shown in Fig. 3(b). Both measurements are taken for T-R height of 1.97m.

Fig. 6 shows the measured RSS max, average and min value when the T-R pair is deployed at four different heights from the ground, 1.97m, 1.50m, 0.70m and 0.12m respectively. One important observation regarding the influence of the ground reflection phenomenon over the RSS is that the reflected and the direct signals interact and create regions, called ‘nulls’, with very low and unstable RSS. The plots in Fig. 6 present that the RSS is more variable in the areas with low RSS value, below -80dBm, and in the areas with ‘nulls’.

Fig. 7 shows the average value of the real-field measured RSS for the fourth T-R heights from Fig. 6 compared with simulated RSS with FOM. All plots clearly demonstrate that data measured are in conformance with the simulation results.

2) Antenna specifics: The antenna orientation, polarization and gain also influence the RSS. The antenna gain participates directly in the propagation model equation as coefficient K_1 and K_2 in (5), while the antenna polarization predetermines the reflection coefficient, as presented in (3). In the simulations, the coefficients ε_1 and σ_1 take values according to material parameters given in [3][4], that is ε_1 = 15 and σ_1 =0.008S/m. The importance of the antenna particularities for the RSS prediction is described in detail in [12] and [13].

3) RSS threshold: A major communication consideration is the correct message reception. It is assumed that a packet sent by a transmitter can be received by a receiver with certain confidence, only if the intensity of the received power is above a given threshold. The relation between the intensity of the received power and the packet loss was empirically investigated to find whether such a threshold exists. The results are presented in Fig. 8 and the following conclusions can be drawn:

- For RSS above -80dBm, packet loss is less than 5%
- For RSS between -80dBm and -87dBm, packet loss rises to 10%.
- For RSS approximately -90dBm, which corresponds to the sensitivity threshold of the CC2420 radio, packet loss can reach 100%.

From the results in Fig. 8, we can conclude that the RSS value of -80dBm is an acceptable threshold level. It indicates that signals with RSS above -80dBm will be received with probability over 95%. Similar results have been presented in [8].

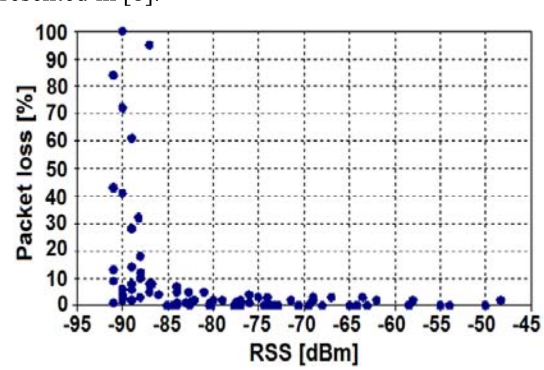


Figure 8. Packet loss versus RSS

C. RFCA Definition

This section presents a comprehensive description and analysis of the four steps of RFCA. The four steps are subsequent and the results of one task are inputs to the subsequent one.

1) Step1 - Discovering the most appropriate heights and distances of the sensor nodes: The most important task for the first step is the selection of the propagation model that corresponds to the target environment. When assuming unobstructed environment, the appropriate model is FOM. Using FOM, the relation among RSS, height from the ground and distance are determined by simulation. During this simulation all practical heights from the ground and distances are combined to produce the RSS for the maximum Tx power of 0dBm. Fig. 9 presents the results of the simulation, where heights vary from 0m to 3m and the distance from 1m to 100m. The gray-scale bar is marked with numbers indentifying RSS areas. For instance, the area marked as 4 designates RSS values between -70dBm and -80dBm. In general, Fig. 9 gives an idea about which heights and distances can be combined to achieve sufficient RSS for reliable communication.

Based on the real-field measurements and simulation results presented in Fig.6, Fig.7 and Fig.9, the following constraints for choosing heights and distances are formulated:

- the sensor node should not be placed in area with deep and wide 'nulls' due to the high variability of the signal and high possibility of signal and packet loss,
- the sensor node should not be placed in areas with RSS lower then -80dBm due to great variance of RSS and higher probability of packet loss.

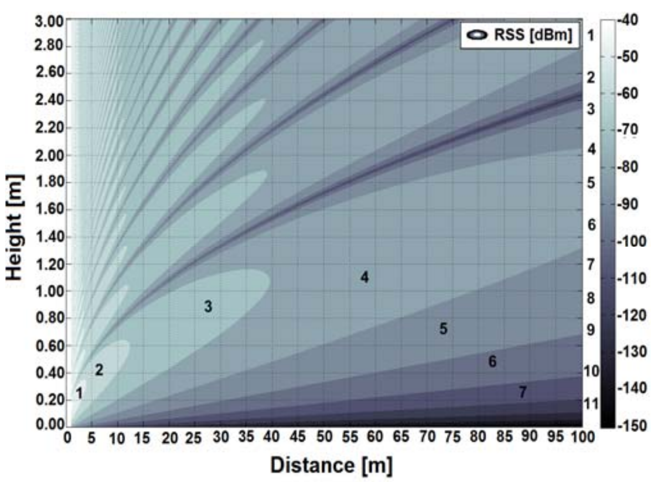


Figure 9. Simulation of the RSS

2) Step 2-Reducing Tx power. The RSS simulation may also help to reduce the Tx power. Referring to Fig. 7, power simulations are performed for three heights from the ground (1.97m, 1.5m and 0.70m) and for distances of 25m and 50m for each height case. These distances were chosen according to Fig. 7, cases (b), (c) and (d), so that the RSS, at 25m, has the maximum value after a 'null' at maximum Tx power of 0dBm. The power simulation results, presented in Fig. 10, illustrate that the Tx power could be reduced and still the RSS be above the threshold of -80dBm, as shown in Table I.

TABLE I. REDUCTION OF TX POWER

Height	Distance 25m	Distance 50m
1.97m	up to -16dBm	up to -8dBm
1.50m	up to -16dBm	up to -8dBm
0.70m	up to -15dBm	up to -4dBm

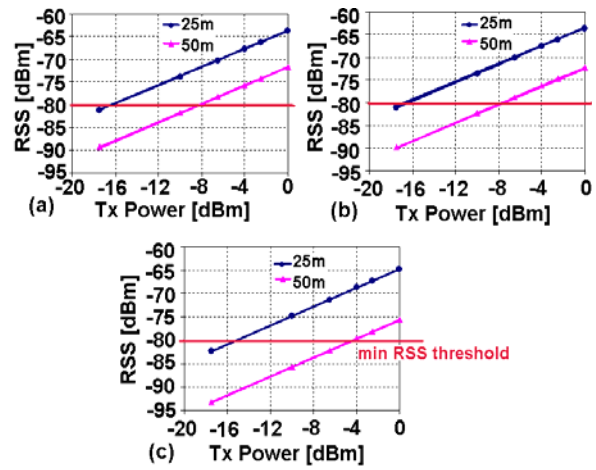


Figure 10. Power simulation for heights:
(a) 1.97m (b) 1.50m and (c) 0.70m

3) Step 3-Minimizing the interference from non-neighbor nodes:

The neighborhood nodes should lie at distance where the RSS is more than -80dBm to guarantee min allowed percentage of packet loss, while the non-neighbor nodes should lie at distance where the RSS is about -90dBm, low enough to guarantee maximum percentage of packet loss.

The simulation results about height and distance of *Step1* and the power simulations of *Step 2* are input parameters for *Step 3,* where nodes' height, T-R distance and power are combined in order to satisfy the following requirement:

- the RSS of a neighbor node should be above the min RSS threshold of -80dBm in order to guarantee that the messages will be received with packet loss below 5%.
- the RSS of a non-neighbor node should be below the sensitivity threshold of -90dBm, in order to minimize the possibility to receive and send signals and thus to interfere the neighboring communication.

For instance, let us assume the simple line topology of Fig. 11, where the distance between any two neighbor nodes is 25m and node 1 has to communicate with node 2 but should not communicate with node 3. In order to satisfy the above requirements, the T-R height is selected at 0.70m and the Tx power at -15dBm according to Fig. 10 (c). For this combination, the RSS is predicted as -80dBm at 25m for the neighbor node and as -91dBm at 50m for non-neighbor node, as shown with the ellipse in Fig. 12.

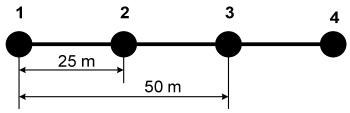


Figure 11. Packet loss versus RSS

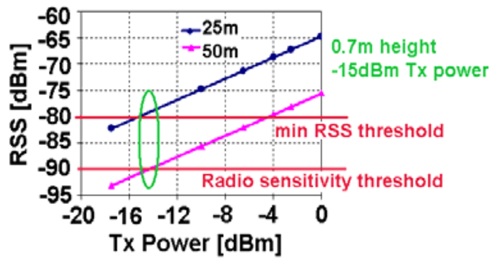


Figure 12. T-R height 0.70m (extracted from Fig. 10(c))

4) *Step 4-Deriving the optimal deployment parameters*: The final step aims at summarizing results and proposing the most appropriate deployment parameters according to initial criteria i.e. minimum node numbers, less neighbor nodes, minimum disturbance from the non-neighbors, etc.

D. *RFCA implementation*

The pseudo code of the RFCA implementation is shown in Fig. 13, consisting of four sequential tasks. Results of one task are inputs to the subsequent one. The final output is a vector with the optimal $h/P_{TX}/d$ combination or a matrix with a series of $h/P_{TX}/d$ satisfying the criteria. Input parameters are, the minimum and maximum height from the ground, H_{min} and H_{max}, the smallest and biggest neighbor distance, d_b and d_e, the minimum and maximum Tx power, P_{TXmin} and P_{TXmax}, the velocity of light, c, the radio frequency, f, and the permittivity of the reflecting surface, ε_r.

IV. Case Study: Application of RFCA to a Real Deployment Example

In this section, the RFCA is illustrated through an example for an environmental monitoring application in unobstructed environment, where environmental parameters such as temperature and humidity are under observation.

A. *Application Requirements*

Application scenario: Environment monitoring
Area type and size: 200m x 200m, open space
Sensor nodes: Tmote Sky or Telos B
Antenna type: Internal, inverted-F
Deployment criteria: minimum disturbance from the non-neighbor nodes with minimum Tx power

B. *Application Analysis*

The environmental parameters do not change in short distance. Therefore, the sensing radius is not decisive for the area coverage and the number of nodes. Referring to the RF propagation, shown in Fig. 7 and the requirements that the RSS should be more than -80dBm we can assume that one node per 50m - 70m would provide an acceptable degree of sensing coverage and reliable communication. Based on that, the distance as the input parameter is already known: d = 50m. The first simulation assumes maximum Tx power of the Tmote Sky sensor nodes at 0dBm and distance for the neighbor nodes of approximately 50m.

RFCA_Step1

Input parameters: H_{min}, H_{max}, d_b, d_e, c, f, ε_r
for $\forall\ d \in \{d_b$: step : $d_e\}$ and $\forall\ h \in \{H_{min}$: step : $H_{max}\}$
    Compute RSS (d, h, λ, ε_r, P_{TX}(0dBm))
    if RSS < min_RSS_treshold than
        Save h in $\{h_{step1}\}$, d in $\{d_{step1}\}$
    end if
  end for
end for

RFCA_Step2

Input parameters: $\{\{h_{step1}\},\{d_{step1}\}\},c,f,\varepsilon_r,P_{TXmin},P_{TXmax}$
for $P_{TX} \in \{P_{TXmin}$: step : $P_{TXmax}\}$
  Compute RSS($d,h,\lambda,\varepsilon_r,P_{TX}$) for $\forall\ d/h$ combination, where $d \in \{d_{step1}\}$ and $h \in \{h_{step1}\}$
  if RSS < (min_RSS_treshold) than
    Save h in $\{h_{step2}\}$, d in $\{d_{step2}\}$, P_{TX} in $\{P_{TXstep2}\}$
  end if
end for

RFCA_Step3

Input parameters: $\{\{h_{step2}\},\{d_{step2}\},\{P_{TXstep2}\}\}$, c, f, ε_r
Compute the non-neighbor node distance: d_{non}
for $\forall\ d/h/P_{TX}$ combination
  Compute RSS($d_{non},h,\lambda,\varepsilon_r,P_{TX}$) for $d_{non} \in \{d_{non}\pm5\}$, $h \in \{h_{step2}\}$ and $P_{TX} \in \{P_{TXstep2}\}$
  if RSS < (radio_sensitivity_treshold) than
    Save h in $\{h_{step3}\}$, d in $\{d_{step3}\}$, P_{TX} in $\{P_{TXstep3}\}$
  end if
end for

RFCA_Step4

Input parameters: Deployment array $D(h, P_{TX}, d) \in \{\{h_{step3}\},\{P_{TXstep3}\},\{d_{step3}\}\}$
Define deployment criterion: minimum disturbance from the non-neighbors; min Tx power, etc.
Sort $\{\{h_{step3}\},\{P_{TXstep3}\},\{d_{step3}\}\}$ according to the Deployment criterion 1
Sort $\{\{h_{step3}\},\{P_{TXstep3}\},\{d_{step3}\}\}$ according to the Deployment criterion 2
Sort $\{\{h_{step3}\},\{P_{TXstep3}\},\{d_{step3}\}\}$ according to the Deployment criterion N
Obtain the final deployment parameters: h, P_{TX}, d

Figure 13. RFCA pseudo code

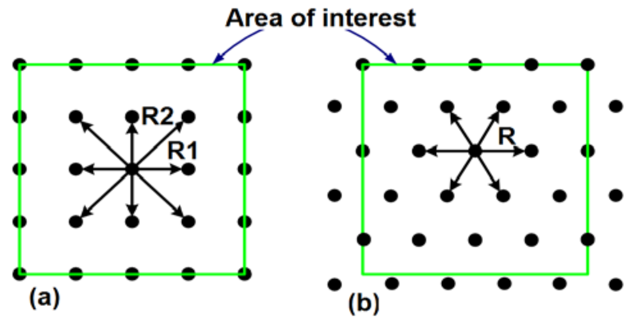


Figure 14. Deployment schemes:
(a) square grid, (b) triangular grid

One of the deployment goals is to optimize the number of nodes, which supposes manual deployment in grid topology [3]. The two most widely used deployment schemes for manual deployment are: square grid and triangular grid as shown in Fig. 14. While the triangular grid uses equal communication ranges among all six 1-hop neighbors, for the square grid a stable communication must be guaranteed in two radii R1 and R2 in order for a sensor node to communicate with its eight 1-hop neighbors. Assuming that the preferred communication range is 50m, then the communication range with complete connectivity is between R1=45m and R2=75m for square grid deployment, and R=45m–55m for triangular deployment with 5m deployment tolerance.

The number of nodes N, where complete coverage and connectivity is assured, can be calculated as:

- For the square grid

$$N = \left(\frac{L}{R}+1\right)\left(\frac{W}{R}+1\right) \tag{7}$$

- For the triangular grid

$$N = \left(\frac{L}{R}+1\right)\left(\left(\underbrace{\frac{W}{R\sqrt{3/4}}}_{RoundUP}\right)+1\right)+\left(\underbrace{\frac{W}{2R\sqrt{3/4}}}_{RoundUP}\right) \tag{8}$$

where W is the area width, L is the area length, R is the communication range. Consequently, for the square grid topology the number of nodes is N=25, and for the triangular grid is N=33.

1) Step 1-Discovering the most appropriate heights and distances of the sensor nodes

The most appropriate T-R heights, after the first simulation step are listed in Table II for square grid and Table III for triangular grid, respectively. Table II and Table III show only those heights, where the RSS is above -80dBm for the whole range of 45m–75m for the square grid and range of 45m–55m for triangular grid, as -80dBm is considered as an acceptable RSS threshold. The simulated T-R heights are between 0m and 3m.

2) Step 2-Reducing the transmission power

This step uses the results for T-R heights discovered in *Step 1* to investigate the possibility of reducing the Tx power. Simulations are performed for both the square and triangular grids for the T-R heights depicted in Table II and Table III as follows: (a) for square grid: distance range 45m–75m, T-R height range 1m–1.5m and (b) for triangular grid: distance range 45m–55m, T-R height ranges 0.70m–1.50m; 2.00m–2.20m; and 2.70m.

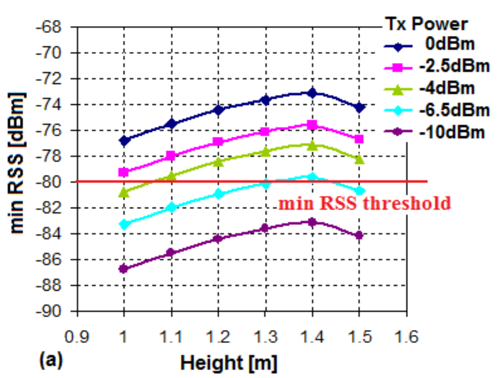
TABLE II. SQUIRE GRID SCHEME

Height range	RSS range for the 45m÷75m interval
1.00m – 1.50m	-68dBm – -77dBm

TABLE III.TRIANGULAR GRID SCHEME

Height range	RSS range for the 45m÷55m interval
0.70m – 1.50m	-68dBm – -77dBm
2.00m – 2.20m	-68dBm – -75dBm
2.70m	-69dBm – -76dBm

Results presented in Fig. 15 show the minimum RSS value for the whole distance range at specific T-R height, for five levels of Tx power. The conclusions based on the results are:



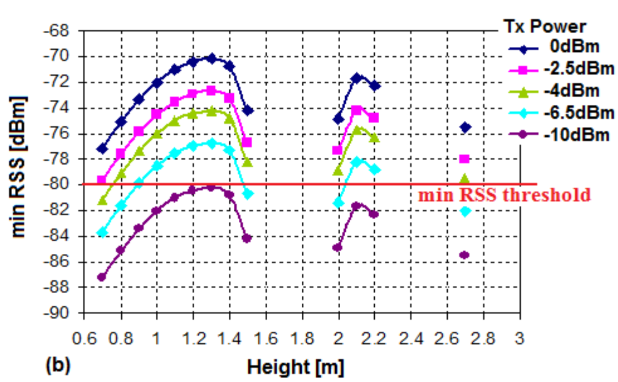


Figure 15. Power simulations for: (a) square and (b) triangular grid

- the most energy efficient combination of T-R height and Tx power for square grid is 1.4m and -6.5dBm, respectively.
- the most energy efficient combination of T-R height and Tx power for the triangular grid is 1.3m and -10dBm, respectively.

3) Step 3-Minimizing non-neighbor nodes interference

Step 3 aims at satisfying the requirements discussed in Section III C, which are:

- the RSS of a neighbor node should be above the min RSS threshold of -80dBm in order to guarantee that the sent messages will be received with packet loss less than 5%.
- the RSS of a non-neighbor node should be below the sensitivity threshold of -90dBm, in order to minimize the possibility to receive and send signals and thus to interfere the neighboring communication and to create huge data flow.

For the square and triangular grid schemes, the distance to non-neighbor node is about double R and R1, i.e. 90m–110m. Simulations are performed for the T-R heights and the Tx powers determined in *Step 2*, presented in Fig. 15 and listed in Table IV.

The simulation results for thus step are presented in Fig. 16 and Fig. 17, where the simulated RF signal propagation for distances between 45m and 110m for the T-R heights and Tx power taken from Table IV is shown. Based on this results the following conclusions are derived:

(a) The square grid scheme cannot fulfill the requirement for minimizing the interference from non-neighbor nodes. For the chosen T-R heights and Tx powers of Table IV at distance 90m–110m the RSS still has value significantly above the radio sensitivity threshold of -90dBm, as shown in Fig. 16.

(b) The triangular grid scheme can fulfill the requirement for minimizing the interference from non-neighbor nodes while ensuring good communication with the neighbor nodes only for the following heights and Tx power levels: 0.7m with -2.5dBm; 0.8m with -4dBm, 0.9m with -6.5dBm and 2.7m with -4dBm. This is presented in Fig. 17(a) and (b) with ellipses. The optimal combination for energy saving and reliable communication is T-R height at 0.9m and Tx power of -6.5dBm.

TABLE IV. T-R HEIGHTS AND TX POWERS

Square grid		Triangular grid	
T-R height	Tx Power	T-R height	Tx Power
1.00m	-2.5dBm	0.7m	-2.5dBm
1.10m	-4dBm	0.8m	-4dBm
1.20m	-4dBm	0.9m	-6.5dBm
1.30m	-4dBm	1.00m	-6.5dBm
1.40m	-6.5dBm	1.10m	-6.5dBm
1.50m	-4dBm	1.30m	-10dBm
		2.00m	-4dBm
		2.10m	-6.5dBm
		2.20m	-6.5dBm
		2.70m	-4dBm

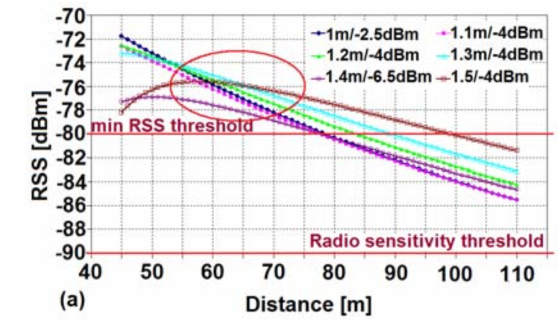


Figure 16. Non-neighbor interference simulations for squire grid scheme

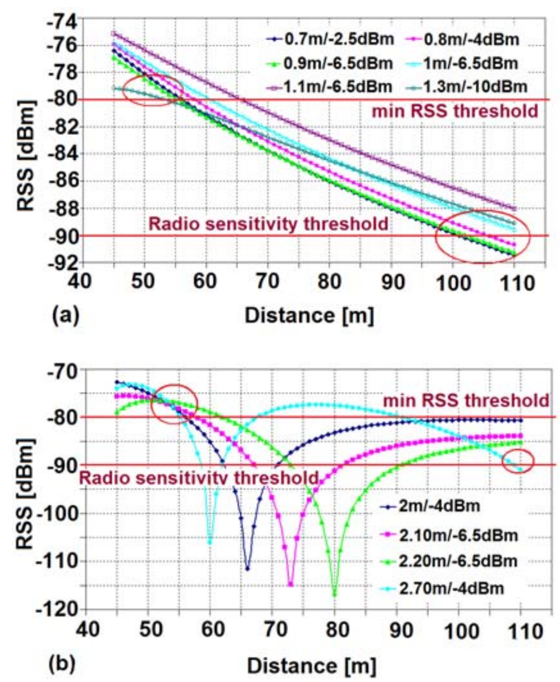


Figure 17. Non-neighbor interference simulations for triangular grid scheme: (a) for heights 0.7m–1.5m and (b) for heights 2m–3m

C. Deriving the final deployment parameters

Step 4 of RFCA aims at summarizing the results and at proposing the most appropriate deployment parameters. In this step, the evaluation of results from *Step 3* is according to the initial criteria defined as application requirement. For the described example those are minimum disturbance from the non-neighbors nodes with minimum Tx power. Base on that are the following conclusions:

1) Square grid scheme:

- The necessary number of nodes is N=25, neighbor nodes=8,
- The most energy efficient height-power combination is T-R height of 1.4m and Tx power of -6.5dBm,
- Cannot fulfill the requirement for minimizing the interference from non-neighbor nodes.

2) *Triangular grid scheme:*

- The necessary number of nodes is *N*=33, neighbor nodes=6,
- The most energy efficient height-power combination is T-R height of 1.3m and Tx power of -10dBm,
- The height-power combinations, which satisfy the criterion of minimum disturbance from non-neighbor nodes, are: 0.7m/-2.5dBm, 0.8m/-4dBm, 0.9m/-6.5dBm and 2.7m/-4dBm.

3) *Deployment parameters:*

The final deployment parameters for reliable communication, which satisfy all the initial criteria, are determined as follows:

- *Height:* 0.9m,
- *T-R distance:* 50–55m,
- *Tx power:* -6.5dBm,
- *Preferred deployment scheme:* triangular grid,
- *Number of nodes:* 33.

The proposed methodology could be used also to scale down the topology in applications where the network performance is studied, when adjust the deployment parameters: height, distance and transmission power. For instance, the deployment parameters from the example above require distance between the sensors about 50m and number of sensors 33, which is quite a big area for coverage. In order to form the same topology, but in smaller area the deployment parameters are recalculated as follows: for distance 5m, the height from the ground is 12cm with transmission power of -11dBm. These parameters' values ensure that the 1-hope neighbors can transmit and receive packets with RSS above -80dBm, when in the same time the RSS of the non-neighbor nodes transmission is approximately -90dBm. This approach is used in [16] when the topology is formed in order to be tested the network performance expressed as message delivery delay, network throughput and packets dropping percentage due to multi-hopping.

V. Discussion and Conclusion

This work discusses the importance of employing an algorithm, which can evaluate the sensor nodes deployment locations against communication-aware deployment criteria, into the pre-deployment phase. In addition, a pre-deployment simulation framework has been introduced and in its context a RF signal propagation-based connectivity algorithm (RFCA) has been developed to fulfill three deployment provisions: discovering the most appropriate height and distances for the sensor nodes, reducing the transmission power and minimizing the interference from non-neighbor nodes.

RFCA uses the RF signal propagation model to predict the received signal strength (RSS) in order to identify the most appropriate communication-based deployment parameters, i.e. T-R distance, height from the ground, and transmission power. The choice of the RF propagation models is crucial for the success of the prediction procedure, which is our motivation to study the importance of using proper simulation model for a specific environment. Since our work is focused on outdoor environment, we differentiate three types of outdoor environments: free unobstructed space, thick-tree forest and sparse-tree garden. In addition, four propagation models are overviewed and classified for their applicability to these three environments. Furthermore, real outdoor measurements are compared with the simulation results to confirm the applicability of an RF propagation model to a particular environment.

Another important factor, which was considered during the pre-deployment phase, is the criteria that distinguish the radio range for neighbors and non-neighbors. It is common belief that the communication between two sensor nodes is good until certain distance and gets worsen after it. To investigate how reasonable this statement is, we performed a set of measurements. From the results we concluded that a packet sent by a transmitter can be received by a receiver with certain confidence, only if the intensity of the received power is above a given threshold. In addition, it was also determined that the RSS in closer distance is not always stronger. For instance, in Fig. 3(b) the RSS at 32m is -82dBm, but at 40m is -70dBm. Thus, the threshold was empirically investigated as relation between the intensity of the received power and the packet loss. As a conclusion, the criteria for neighbor node distance should not be the distance as maximum value, but the distance where the RSS is high enough to guarantee min allowed percentage of packet loss and for non-neighbors - the distance where the RSS is low enough to maximize the probability for packet loss.

Finally, a deployment case study illustrated the RFCA functionality in deriving the optimal deployment parameters, consisting of height, distance, and Tx power, for reliable communication. RFCA is generic enough to be combined with any topology optimization algorithm such as min number of nodes deployment, maximum battery life deployment, power-aware deployment, etc.

Analysis of the results presented in this work has shown that a communication-aware pre-deployment simulation for preliminary planning of the deployment can significantly reduce the link quality problems due to the physical layer communication loss.

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