Connectivity in a wireless sensor network

Tomáš Mácha, Peter Stančík, Vít Novotný

Dept. of Telecommunications, Faculty of Electrical Engineering and Communication,
Brno University of Technology,
Purkyňova 118, 612 00 Brno, Czech Republic

Summary
In this paper, the issue of full connection probability and network efficiency using a minimum number of nodes in wireless sensor networks is addressed. We investigate the network characteristics through a number of simulations in Matlab. Using various input parameters, we try to approximate four realistic scenarios: a football pitch, a forest, a building and a tunnel. We also examine the impact of different parameters on the full connection probability (sensors scattering model, path loss model, Tx / Rx powers and observer placement). Determining the order of all parameters with respect to the full connection probability is quite difficult, as some of them are dependent on each other. We found out that the environment itself, defined by its radio propagation properties, has the greatest impact on the full connection probability.

Keywords
Sensor network, Path loss, Shadow fading, distribution

1. Introduction

The wireless world began more than a century ago but in the last decade it seems to have become widely known and popular. There are many applications of wireless technology, with the aim to satisfy the desire of modern users to be able to communicate anytime and anywhere.
Wireless sensor networks are a particular kind of ad hoc networks, in which nodes are smart sensors. They exchange information on the environment in order to provide a global view of the monitored region. This information is made accessible to the external user through one or more gateway nodes. Sensors exchange data with their neighboring nodes periodically, in order to improve data collection and detect unusual situations.

The features of a sensor network are listed below:

1. Homogeneous network - sensor networks are composed of the same kind of sensors, but there can be some exceptions and different sensors can sometimes work together.
2. Stationary network - nodes composing a WSN (Wireless Sensor Network) are generally stationary, or at most slowly moving.
3. Dispersed network - generally, nodes composing a WSN are spread over a large region, so that single hop communication between nodes is not possible.
4. Large network size - typically, the number of nodes composing a WSN is from a few tens to thousands [1].

The function of the nodes is to monitor physical or environmental conditions, such as vibration, temperature, pressure, sound, motion and pollutants, at different locations. There is no pre-programmed network topology. The nodes self-organize their networks. This feature leads to a considerable cost reduction concerning the planning.
In the background of wireless sensor network is often mentioned data flow processing. Sensor networks produce multiple data streams of observations from their sensors. Data are coming all the time (on-line) and there is no assuming on the data sequence. Generally they are of unlimited size. Data structure can be changed. After data processing the data are erased or archived.

2. Path loss and shadow fading

The wireless radio propagation environment presents limitations to the performance of radio communications systems. The signal between the transmitter (Tx) and the receiver (Rx) is subject to propagation phenomena, and obstacles generate attenuation of the signal power. Path loss and shadow fading, the main causes of such signal variations, are described. The path loss is the loss range of the power radiated by the Tx. The shadow fading (or shadowing), on the contrary, is caused by the presence of physical obstacles between Tx and Rx, such as buildings or parts of them that obstruct the propagation of electromagnetic waves attenuating the signal. Variations due to the path loss affect the connectivity range typically on a scale of 100 meters, while variations due to shadowing are detected at a distance of meters in outdoor environments and less in indoor environments [1, 2].

Manuscript received December 5, 2008
Manuscript revised December 20, 2008

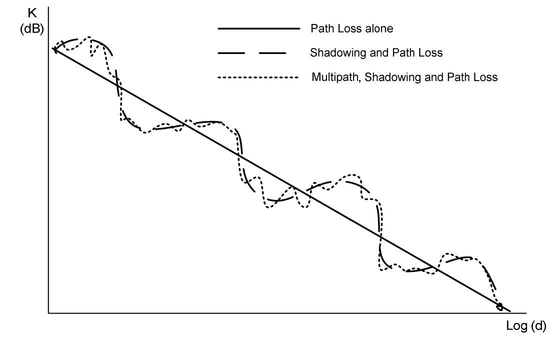


Fig. 1. Pathloss, shadowing and multipath versus distance

Nodes in wireless sensor networks exchange information through transceivers. The nodes Tx and Rx establish a radio connection only if the power of the signal received by Rx is higher than the sensitivity threshold. We can assert that $P_r \geq \beta$, where P_r is the power of the received signal and β is the sensitivity threshold. The value of β depends on both the communication data rate and the wireless transceiver features. The higher the data rate is, the higher β will be. If P_t is the power transmitted by the node u and P_r is the power received by the node v, it can be written that [1]:

$$P_r = \frac{P_t}{PL(u,v)}, \tag{1}$$

where $PL(u, v)$ is the path loss and it is assumed $\frac{P_t}{PL(u,v)} \geq \beta$.

The study of the path loss and the shadowing are two of the main questions in wireless network design. They are consequences of phenomena such as reflection, scattering, and diffraction. Although, they are not considered in this project, a brief description is given:

- Reflection - when the wave signal hits a surface that is very big compared to the wavelength, like the surface of the earth, buildings, walls, etc.
- Scattering - when the wave signal hits several small objects whose size can be compared with the wavelength, like foliage, street signs.
- Diffraction - when the wave signal hits sharp objects edges between the Tx and Rx [1].

Wireless propagation of signals is therefore influenced by many environmental factors. In the following text some of the path loss and shadowing models are described.
The models used are mainly two, log-normal law and attenuation law. The first is based on equation (2). Different values for path loss exponent and shadowing standard deviation were set up, depending on the environment. The second model is based on equation (3). The attenuation constant was set up for this kind of simulations, such as building and tunnel.

Log-normal shadowing

This model takes into consideration practical measurements showing the fact that the average value of the signal between Tx and Rx is very different from the predicted one. The measurements have shown that the value of path loss at any distance d is random and log-normally distributed [3]. This model of path loss can thus be described by the formula:

$$\begin{aligned} PL(d)[dB] &= \overline{PL}(d) + X_\sigma = \\ &= \overline{PL}(d_0) + 10\gamma \log\left(\frac{d}{d_0}\right) + X_\sigma, \end{aligned} \tag{2}$$

where X_σ is the zero-mean Gaussian distributed random variable with standard deviation σ, all expressed in dB, γ is path loss exponent. The log-normal distribution describes the random shadowing effects, occurring over a large number of measurement locations, which have the same distance between the Tx and Rx but different physical obstacles in the middle [3]. Therefore, it is possible to refer to this model as Log-normal shadowing, which means that the measured signal values in dB, between Tx and Rx at a specific distance d, follow the Gaussian distribution [1].

Attenuation factor model

This model studies in-door propagation taking into account a new factor called FAF (Floor Attenuation Factor). It includes the effects of building type and the variations caused by obstacles. In comparison with the log-distance path loss model, it is shown how to reduce the difference in the standard variation between predicted and measured path loss values. The attenuation factor model is described by the following equation:

$$\begin{aligned} PL(d)[dB] &= PL(d_0)[dB] + \\ &+ 20\log\left(\frac{d}{d_0}\right) + \alpha d + FAF[dB], \end{aligned} \tag{3}$$

where α is the attenuation constant with units of dB per meter (dB/m) and FAF is a value which has to be added to calculate the path loss on different floors [1].

3. Simulations

The sensors, thrown onto the area, were scattered according to two probability distributions - uniform and Gaussian. In the first case, the sensors are supposed to be uniformly distributed inside the area, while in the second case they are supposed to follow the typical bivariate Gaussian bell shape distribution. The uniform distribution was chosen for the building and the tunnel, as well as in some of the outdoor simulations, and the Gaussian distribution was used in the outdoor environments.

One of the most important parameters is the sensor connectivity. It depends on two values - the transmitted power and the sensitivity. As they have the same impact on the link budget, it was decided to use them as a single parameter. In fact, increasing the transmitted power and proportionally reducing the sensor sensitivity would result in the same connectivity. The transmitted power and the sensitivity of the sensor are -10 dBm and -90 dBm. The coverage area is an area around the sensor that enables collecting information on the quantity measured, and it is represented as a circular area of a certain radius. The coverage radius is half of the distance between two sensors in the case of ideally distributed nodes.

The observer performs an important role, that of the data collector. Different placements of the observer are expected to affect the results of the simulation significantly. Two different observer models were chosen in this work. In the first one, all the perimeter of the area is covered and is referred to as ‘perimeter observer’. The second presents the observer as a single spot in a corner, in the middle of one of the longer sides or in the center of the area. It is referred to as ‘point observer’ (Fig. 2.). The point observer was used in office, forest, and tunnel simulations. The perimeter observer was chosen, by contrast, for the football pitch, because it represents a mobile observer which moves around the area. It would be quite difficult in the case of a forest or a tunnel.

Fig. 2. Observer positions

Table 1. The simulation setup for different environments

Parameter	**Office**	**Forest**	**Football pitch**	**Tunnel**
Area dimensions [m]	[110 75]	[110 75]	[110 75]	[5000 10]
Observer type	point	point	perimeter	point
Observer coordinates [m]	[55 37]	[55 0]	-	[0 0]
Sensor Tx power [dBm]	-10	-10	-10	-10
Sensor sensitivity [dBm]	-90	-90	-90	-90
Path loss model	Log-normal	Log-normal	Log-normal	Attenuation law
Path loss exponent	3.0	4.5	3.0	-
Path loss st. deviation [dB]	20	6	8	-
Attenuation constant α [dB/m]	-	-	-	1
Coverage radius [m]	6	6	6	10
Sensor distribution	uniform	Gaussian	uniform	uniform

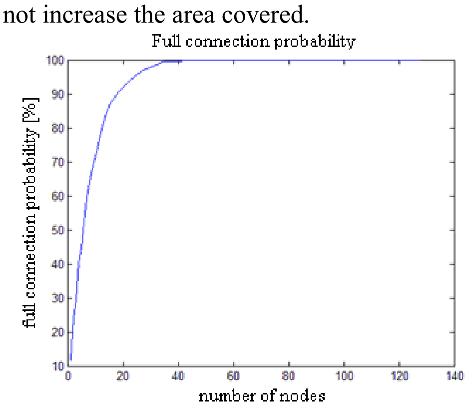
3.1 Office with soft partitions

In order to run this simulation, it is necessary to set up the important variables characterizing this kind of environment. The main shadowing sources are soft and hard walls as well as people, furniture, devices, etc.

The full connection probability value increases a lot with a small number of sensors. It depends on the small path loss exponent of an office building with soft partitions. No hard divisions are able to reflect big quantities of energy. As a consequence, the approximated connectivity radius is quite high in comparison with the whole area, and just a few nodes are enough to produce a good probability of full connection.

The coverage curve is always rising and an interesting point is its shape. The first part of the curve presents a particular result. It is characterized by a positive second derivative. It is due to the fact that only the connected nodes are being considered. When the number of nodes connected to the observer is small, the coverage by connected nodes is low and the rate of the curve is slow. As the number of nodes thrown increases, the number of nodes connected to the observer rises and the full connection probability rises.

The efficiency curve is a direct consequence of the coverage curve. As the coverage increases steeply, the efficiency curve dramatically rises until a point placed between 10 and 20 sensors is reached. Then, its slope is negative. As can also be seen from the pictures, the break-point of the efficiency curve corresponds to the flex point of the coverage curve. After this point, adding more nodes does not increase the area covered.



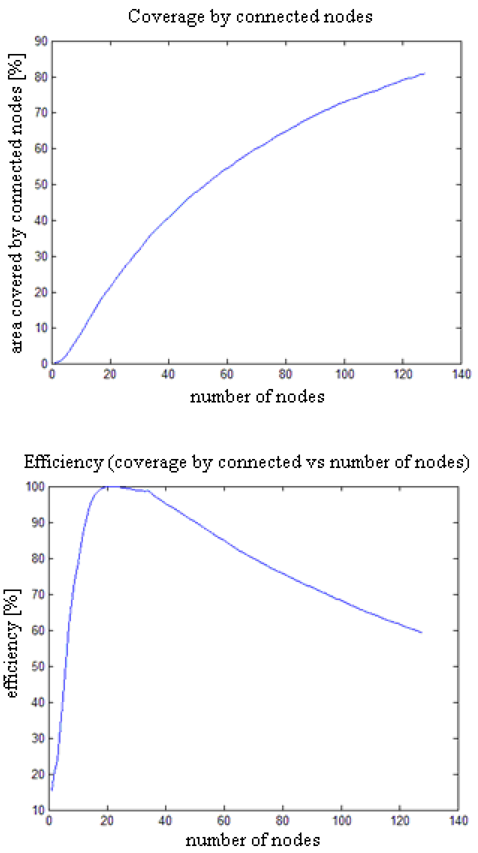


Fig. 3. Final simulation curves of the office environment

3.2 Tropical forest

In outdoor environments, the choice of a WSN in a forest represents an interesting application illustrating the fading wireless channel since trees cause a significant path loss.

The value of full connection probability increases very slowly with respect to the number of distributed sensors. It is possible to observe that the curve raises and reaches a probability of 50% with about 100 sensors deployed, and it reaches the 100% probability with approximately 900 sensors. This trend of the curve is caused by the relatively high path loss exponent of the tropical forest environment. Therefore, even though the connectivity radius of the sensor is quite large compared to the area considered, a significant number of nodes are required to obtain full connectivity.

The coverage curve shows an interesting trend. The curve remains almost flat until about 100 sensors are deployed. With more added nodes, the number of connected nodes increases and the covered area increases faster. After this, we have a lot of sensors already connected and the covered area increases more slowly.

The efficiency curve and the coverage curve correlate. When the number of sensors is between 0 and 100, the curve shows a slight slope and therefore low efficiency. With increasing number of sensors, the area covered grows faster and then the efficiency curve becomes steeper. Between 300 and 400 nodes the curve reaches its maximum value and after this it begins to decline. With a few extra sensors added, the covered area does not grow as before, so the efficiency decreases.

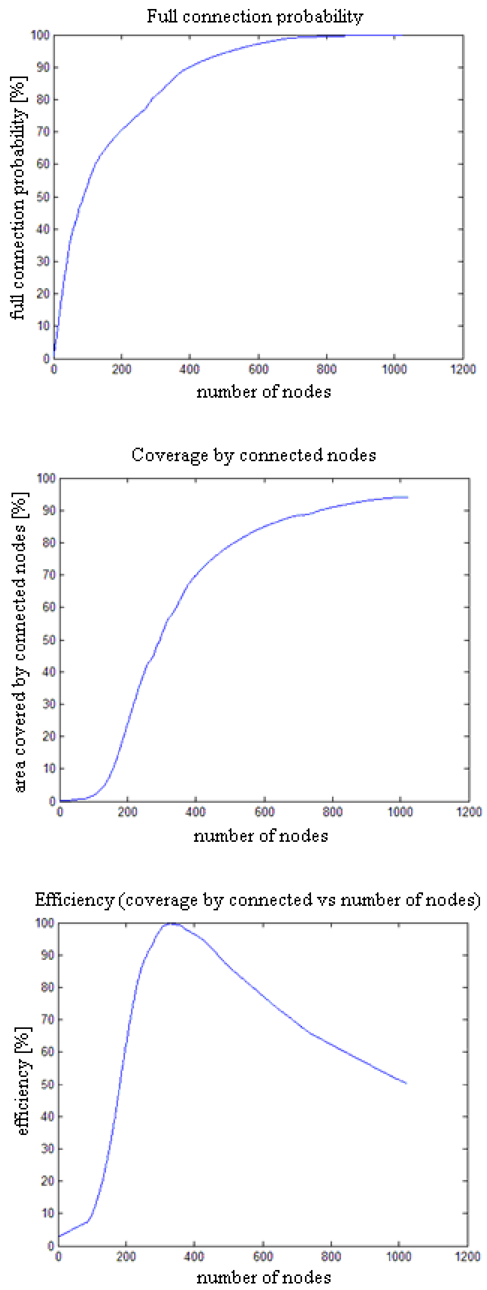
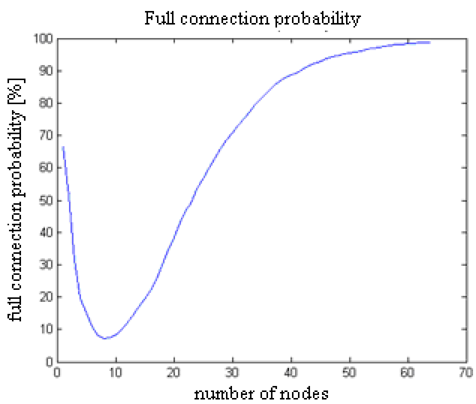
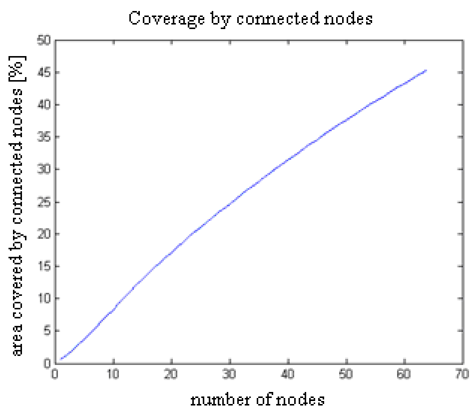


Fig. 4. Final simulation curves of the forest environment

3.3 Football pitch

In this case, no clutter types such as buildings or foliage are considered. However, the presence of grass between transmitter and receiver must be taken into account.
For the case of perimeter observer the full connection probability curve has a negative slope with a small number of nodes because one sensor has a higher probability to be connected than several nodes have. The situation changes after dropping some extra nodes. The probability of the network to be fully connected is increasing because the average number of clusters will converge to one and the number of nodes will rise.
It can be seen that the coverage curve is almost straight line because the coverage grows slowly. It depends mostly on the small coverage radius chosen. The slope is a little less steep after a threshold around the twentieth node. After adding more nodes, the increase in area coverage gained by each additional node will be smaller.
Simulations show good results in terms of percentage of efficiency as a function of the number of nodes. The efficiency curve increases with rising number of nodes until the threshold point between the tenth and the twentieth node. After this point, no significant gain of covered area can be expected by deploying more nodes.





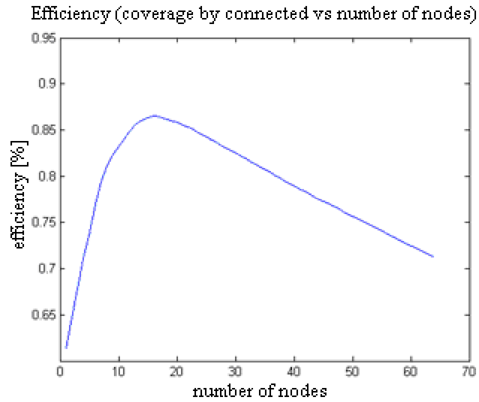
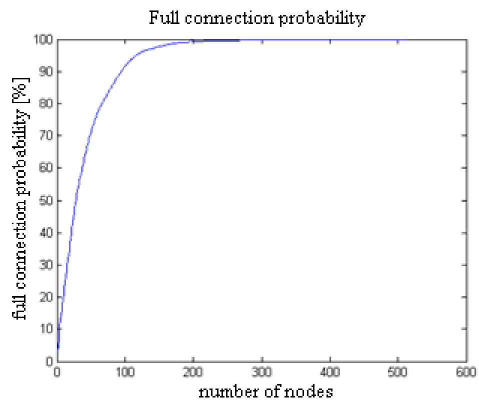
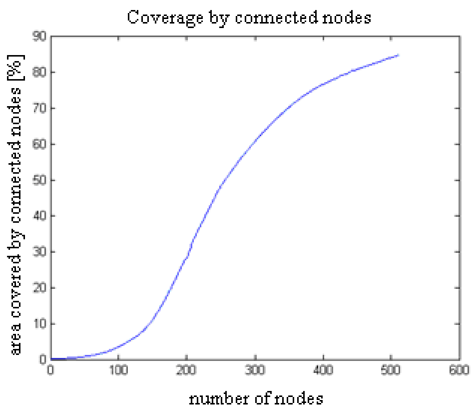


Fig. 5. Final simulation curves of the football pitch environment

3.4 Tunnel

This environment was chosen because of its specific radio wave propagation properties. The tunnel model is expected to be an environment with good connectivity qualities resulting in a relatively small number of sensors needed to be scattered in the area to guarantee full connectivity.
The full connection probability curve has a steep slope caused by the uniform distribution of nodes and good connectivity conditions (small attenuation constant), in particular until approximately 120 nodes have been scattered. After this point, where the area got ‘saturated’, the slope became softer because the probability of adding a new node to an already connected part of the area became higher.
Using 270 sensors, which are needed to guarantee full connection, the network will be able to provide information on measured quantity only from approximately 50% of the area.
The efficiency curve reaches its peak with 300 sensors. This value can be obtained from the previous coverage curve by determining its flex point. It means that adding more nodes than 300 will not bring any efficiency increase.





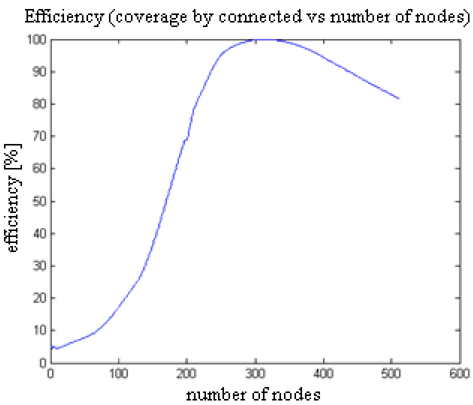


Fig. 6. Final simulation curves of the tunnel environment

4. Conclusion

We have investigated the issues of coverage and connectivity by keeping a minimum number of sensor nodes to operate in a wireless sensor network.
It can be concluded that the value of shadowing standard deviation has an important impact on the link budget. A strong influence can be noticed when comparison of two different simulations changing the model of scattering the sensors in the area. When a uniform distribution is used, the sensors are spread all over the area and a large number of clusters can be generated with a few nodes. This phenomenon can lead to a drop in the probability curve in its first part. On the other hand, using a Gaussian distribution, the sensors are concentrated around the center of the area (expected value of the Gaussian variable) and, generally, are always connected to each other.
We found out that the environment itself, defined by its radio propagation properties, has the greatest impact on the full connection probability.

References

[1] P. SANTI *Topology Control in Wireless Ad Hoc and Sensor Networks*. WILEY, 2005, ISBN-13: 978-0470094532.
[2] A. GOLDSMITH *Wireless Communications*. s.l.: Cambridge University Press, 2005, ISBN: 978-0521837163.
[3] T. RAPPAPORT *Wireless Communication principle and practice*. s.l.: Prentice Hall, 2001, ISBN: 978-0130422323.
[4] Crossbow [online]. 2008 [2008-11-06]. WWW: <http://www.xbow.com/Products/productdetails.aspx?sid=164>.
[5] S. RAJEEV, et al. *Mobile, Wireless and Sensor Networks: Technology, Applications, and Future Directions*. s.l.: WILEY, 2006, ISBN-13: 978-0471718161.
[6] K. HOLGER, *Protocols and Architectures for Wireless Sensor Networks*. WILEY, 2007, ISBN-13: 978-0470519233

Acknowledgements:

This paper has been supported by Grant Agency of the Czech Republic, project no GA CR 102/06/1569.

Tomáš Mácha - received BSc at the Department of Telecommunications at the Faculty of Electrical Engineering and Communication at Brno University of Technology in 2006. He received Ing. (MSc) at the same department in 2008. The areas of his professional interests are convergence of telecommunication networks and services and VoIP technology. His dissertation pursues multimedia services support for IMS (IP Multimedia Subsystem).

Peter Stančík - received BSc at the Department of Telecommunications at the Faculty of Electrical Engineering and Communication at Brno University of Technology in c2006. He received Ing. (MSc) at the same department in 2008. The current areas of his professional interests are cryptography and broadband connection over power lines. His dissertation pursues broadband connection over metallic leadings.

Vít Novotný - received MSc at the Department of Telecommunications at the Faculty of Electrical Engineering and Computer Science at Brno University of Technology in 1992. In the same year he entered the Department as an assistant professor. In 2001 he received the PhD degree. The areas of his professional interests are applications of modern active circuit elements, electrical network analysis, telecommunication and computer networks and terminals. In the 2005 he submitted Assoc. Prof. thesis on the topic “Filtering Circuit Structures with Modern Active Elements”.