Enhancing Topology Control Algorithms in Wireless Sensor Network using Non-Isotropic Radio Models

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Summary

In reality, radio range of any wireless communication device does not emulate an isotropic behavior or as modeled by theory. An isotropic antenna is a hypothetical lossless antenna having equal energy being radiated or transmitted in all directions. Along with wireless sensor networks, any wireless network suffered propagation complications including multipath propagation, shadowing and path loss to name a few which are vital factors to consider in a wireless environment. Radio irregularity is ubiquitous in every wireless sensor network that it should be constituted in every protocol or algorithm design. As per some other studies, radio propagation can be evaluated by statistical means therefore, making it an easier and general way to characterize radio irregularity without being dependent to any specific environment. Furthermore, it could be very flexible in varying network conditions like mobility. In this paper, we develop both linear and non-linear models to capture radio irregularity using regression analysis on distance and received signal strength. These models are assessed by implementing a simple middleware to be added to topology control algorithms.

Key words:

Radio Irregularity, Non-isotropic Antenna, Topology Control, Regression.

1. Introduction

The presence of radio irregularity in wireless sensor networks and its effect on network performance makes it a protocol design variable which cannot be ignored. Simplistic radio model assumes a perfect spherical radio range among all nodes in the network. Studies show, that most of the proposed protocols developed before which were based on isotropic radio range model had ignored this phenomenon and thus lead to flawed protocols. Simulation results which utilized a simplistic model may not be valid in the real world. Radio irregularity was proven to have an impact on both the routing layer and the MAC layer [1]. Former topology control protocol design only accounts for power consumption in non-radio irregularity environment and thus in reality, performance suffers. This paper attempts to design a mechanism for topology control with consideration of radio irregularity.

This study has two major objectives. First, to model radio irregularity statistically based on distance and received signal strength from a set of data gathered an experiment and second, to propose a solution for topology control algorithms.

Radio irregularity inevitably exists in wireless sensor networks as investigated by [1]. The paper explained some notable causes of radio irregularity namely: non-isotropy, continuous variation and difference in sending power. From empirical data gathered from MICA2 motes, they were able to establish a Radio Irregularity Model (RIM). Furthermore, their results showed that radio irregularity has a considerable impact on routing layer and MAC layer protocols. They also proposed possible solutions for problems caused by radio irregularity. However, the suggested solutions were not examined specifically on performance parameters for localization algorithms and topology control. The researchers in [2] investigated a practical realistic radio range irregularity (RRI) model and described how it affected localization algorithms in sensor networks. A constrained–greedy forwarding radio propagation method is used to achieve localization performance in a realistic radio range environment. Surveyed causes of attenuation of radio range are limited and environmental dependent that makes the model difficult to apply in different system conditions.

There are numerous topology control algorithms proposed which largely depends on conserving power and varying performance. A fault tolerant topology control [3] uses higher vertex connectivity while making use of the little power consumption in the sleeping state to extend the lifetime of sensor networks. As it might be a good solution in conserving energy, it was not yet tested in a highly dynamic topology. On the other hand, an efficient on-demand topology control [4] applies a specific technique where and when the wireless node needs it. This is to minimize overhead on every node at a given time. Aside from saving energy, it keeps some other properties like: connectivity, power spanner, bounded-degree, localized construction and guaranteed packet delivery. Although, it has the nice properties of a topology control, it still needs full investigation on mobility and throughput. Another scheme [5], categorized energy saving methods, i.e. topology control, into two types: active subnetwork and short hops. They combined these two to create a two-level topology control to further save energy. Together with [6],

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change in topology, energy remaining in nodes and transmission range determines the coordinator selection process among nodes. Similarly, in [7], ASCENT is formulated wherein certain nodes remain active as routers while others are allowed to conserve energy in their sleep state. The decision to become an active router is based on node connectivity and observed data loss rates, providing the network with an option to trade energy consumption for connection reliability.

Although, there are a number of topology algorithms currently known in this research field, they however, are missing a link to various real world scenarios. Previous studies show discrepancies between experimentally observed to widely used simulation models [8]. Another important issue which can be deduced from their study is that one must also take into account the non-uniform communication quality of network nodes at all times. In [9], the researchers did a comprehensive review of common assumptions being done in ad hoc network simulations. These are jumpstart studies in bridging the gap between real and simulation models. Thus, these are the key points which motivated this research. [1] and [2] are some of the studies which identify real radio range irregularity in wireless sensor networks.

The rest of the paper is organized as follows. Section 2 describes the proposed model and is further divided into three subsections. The first subsection illustrates the non-isotropic radio range in reality, the second subsection defines non-isotropic radio range model using linear regression and finally, the third subsection defines a non-isotropic radio range model using non-linear regression. In Section 3, a way to enhance topology control schemes will be formulated. Finally, the conclusion will be drawn from the models and solution described.

2. Proposed Model

2.1 Non-Isotropic Radio Range Model

To show the existence of non-isotropic property of wireless sensor networks using Chipcon 2430, the received signal strength in dBm is recorded in 12 different directions. One node is assigned as the fixed sending node that continuously sends packets at constant sending power and mains powered while another node is assigned as the receiving node that is being moved around 12 different directions. Both nodes are at ground level and have no physical obstructions directly between them as shown in Fig. 1.

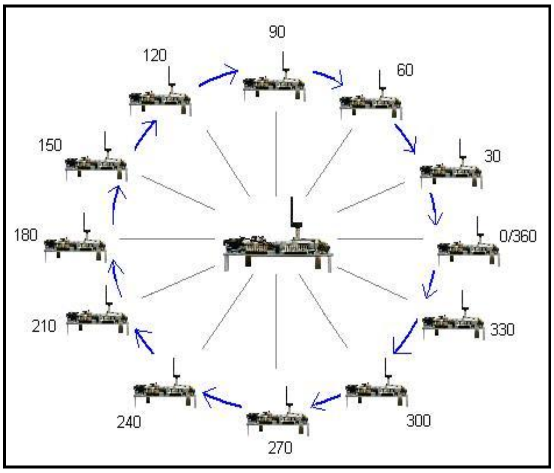

Fig. 1 A simple experiment setup using 2 nodes with varying direction of the receiving node.

The output of the simple experiment above demonstrates that while changing directions at a certain distance, the received signal strength varies randomly, as shown in Fig. 2. We recorded observations from 30cm. and 60cm. distance away from the sending node (middle node). The graph denotes that even at a short distance (30 cm. and 60 cm. away from the sending node); the signal strength being detected from 12 different directions at the same distance from the sending node varies at different level. We repeat the same experiment, but this time varying the distance in a single direction, as shown in Fig. 3. Similar from the first experiment, the sending node (Node 1) is mains powered while the receiving node (Node 2) is being moved away from the sending node and is battery powered. After recording the received signal strength on the receiving end, we were able to draw a scatterplot of the data, as shown in Fig. 4.

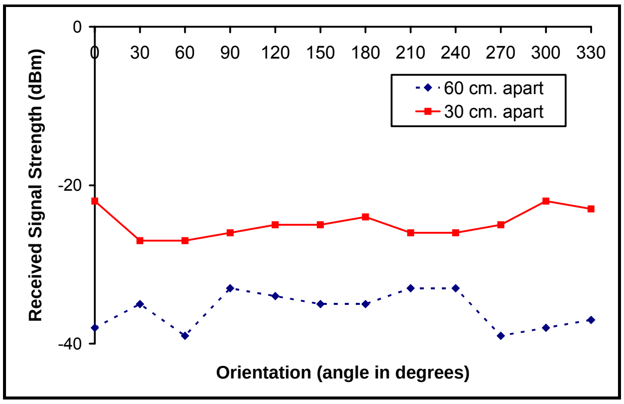

Fig. 2 Received signal strength from 12 different directions.

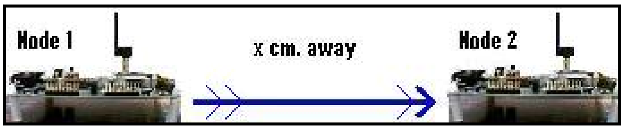

Fig. 3 An experiment setup of two nodes with varying distance of the receiving node (Node 2).

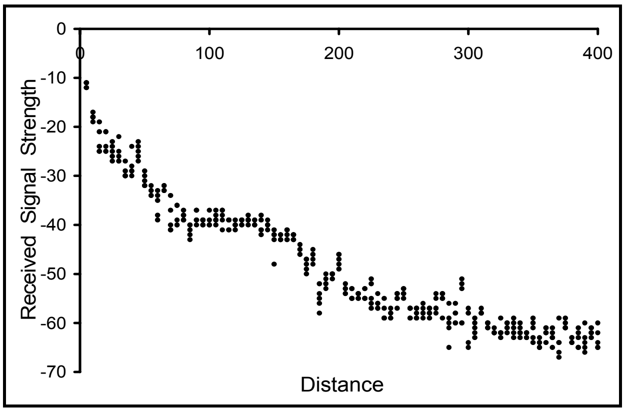

Fig. 4 A scatterplot of distance vs. signal strength.

The scatterplot illustrates a graph of the relationship between the distance and the received signal strength between sending and receiving nodes. From this scatterplot, we can derive a model using linear or non-linear regression. Regression is a process of finding a mathematical model that best fits the data.

2.2 Linear Regression

The straight line model for the response, that is, received signal strength in terms of distance can be written as:

$$\mathrm{y} = \beta_0 + \beta_1 \mathrm{x} + \varepsilon , \tag{1}$$

where *y* is the received signal strength, *x* is the distance, ε is estimation error and β_s are weights. The fitted line of the deterministic part of the equation is:

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x . \tag{2}$$

The weights $\hat{\beta}_0$ and $\hat{\beta}_1$ corresponds to y-intercept and the slope of the fitted line, respectively. Using the least square method:

The slope of the fitted line is defined as:

$$\hat{\beta}_1 = \frac{SS_{xy}}{SS_{xx}} , \tag{3}$$

and y-intercept is defined as:

$$\hat{\beta}_0 = \bar{y} - \beta_1 \bar{x} ; \tag{4}$$

Where

$$SS_{xy} = \sum_{i=1}^{n} x_i y_i - n \bar{x} \bar{y} , \tag{5}$$

$$SS_{xx} = \sum_{i=1}^{n} x_i^2 - n (\bar{x})^2 , \tag{6}$$

$$SS_{yy} = \sum_{i=1}^{n} y_i^2 - n (\bar{y})^2 . \tag{7}$$

SS_{xy}, SS_{xx} and SS_{yy} are the sum of squares error along the corresponding axes. Also, $\bar{x}$ and $\bar{y}$ are mean values of x and y, respectively. The least square line that would approximate the data in the scatterplot is:

$$\hat{y} = -26.31981 - .1076 x .$$

The resulting line that would approximate the relationship between the received signal strength and distance for the given set of data is shown in Fig. 5.

The least square line must satisfy:

$$SE = \sum_{i=1}^{n} [y_i - \hat{y}_i] = 0 \tag{8}$$

Where SE is the sum of errors and for our case, we get:

$$SE = \sum_{i=1}^{n} [y_i - \hat{y}_i] = 0.0026$$

This value is acceptable, since we are trying to minimize the value of the sum of error. The best and ideal approximation is when *SE = 0*, that is the points lie on a straight line and that line is the best approximate of the set of those points. We also test the accuracy of the approximation by Pearson product of moment coefficient of correlation, *r*, where:

$$r = \frac{SS_{xy}}{\sqrt{SS_{xx} SS_{yy}}} = -.948493$$

This means that *r* is close to -1 and a linear trend may exist between *y* and *x*; that is received signal strength is inversely proportional to distance. The value *r* ranges from -1 to 1. A value of 1 shows that the linear equation describes the relationship perfectly and positively, with all the points lying on the same line and with *y* increasing with *x*. A value of -1 means that the linear equation describes the relationship perfectly and negatively, with all the point lying on the same line and with *y* decrease as *x* increases. This is similar as what we have seen in our result. Lastly, a value of 0 means that the linear model is inappropriate and thus there is no linear relationship between the two variables (x and y).

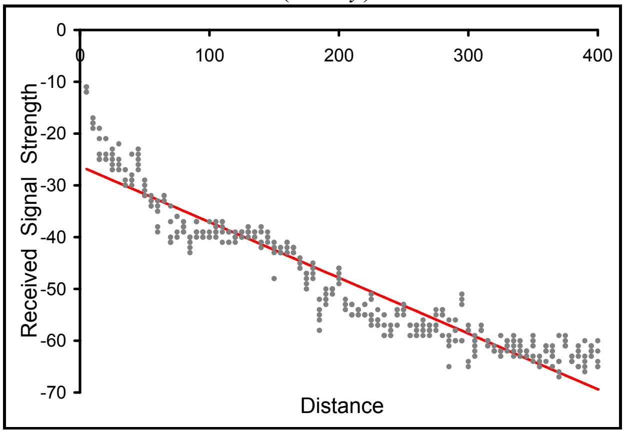

Fig. 5 A graph of the scatterplot with superimposed least square line.

A convenient way of measuring how well the least square line equation performs as a predictor of y is to compute the reduction in the sum of squares of deviations that can be attributed to x, expressed as a proportion of SS_{yy}. This is through coefficient of determination, given by:

$$r^2 = 1 - \frac{SSE}{SS_{yy}} = 1 - \frac{6891.2222}{68664.71} = .8996, \tag{9}$$

where the sum of square error (SSE) is given by:

$$SSE = \sum_{i=1}^{n} [y_i - \hat{y}_i]^2 . \tag{10}$$

The total sum of squares of deviations of the 400 samples of received signal strength values about their predicted values has been reduced by 89.96%. That is, 89.96% of the sample variation of the received signal strength can be "explained" by the least square line.

2.3 Non-Linear Regression

Similarly, we could describe the scatterplot by non-linear regression. This process is carried out repeatedly to minimize the value of the squared sum of difference between the data and the fitted line, as defined by Eq. (10).

Therefore, we need to maximize the correlation index or coefficient of determination, r^2:

We maximize:

$$r^2 = 1 - \frac{\sum_{i=1}^{n} [y_i - \hat{y}_i]^2}{\sum_{i=1}^{n} [y_i - \bar{y}]^2} \tag{11}$$

Subject to:

$$\hat{y} = A + B \log(1 + x)$$

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}$$

By maximizing, r^2 and varying the values of A and B, we would be able to produce a non-linear regression between y and x. Fig. 6 shows the non-linear regression between received signal strength and distance. Note that Eq. (1) has a ε term added to the deterministic part of the equation. This term accounts for the error. We assumed that the ε has a mean of zero with an estimated variance of:

$$s^2 = \frac{SSE}{n-2} \tag{12}$$

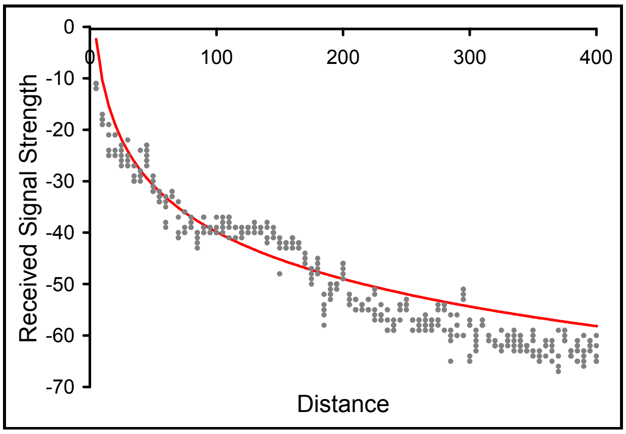

Fig. 6 A graph of the scatterplot with superimposed non-linear regression curve.

The square root of Eq. (12) is the estimated standard deviation, s.

Table 1 shows the estimated variance and standard deviation or ε. The $n-2$ is the degrees of freedom for error and is denoted by number of weights subtracted from number of samples.

Table 1 Estimated values for variance and standard deviation for ε from Eq. (1).

Estimates for ε	
s^2	17.3146
s	4.1611

3. Topology Control

The design for topology control considers minimum power consumption but should still maintain the connectivity of the whole network.

Limited power is one of the constraint and characteristic of a wireless sensor network. The ability of each node to conserve energy is an important aspect in prolonging the network lifetime. There are two significant factors to consider in designing a topology control algorithm: 1) the selection of representative nodes to form a network backbone and 2) the maintenance of the network backbone. The first one involves designing a set of criteria in selecting which node would qualify as a representative node for a particular group of nodes and that would join other representative nodes to form the network backbone. On the other hand, the second consideration involves keeping the network functional while the role of being a representative is distributed among other nodes for a particular time. In the following subsection, we apply what we designed so far in Geographic Adaptive Fidelity (GAF), as an example.

3.1 Geographic Adaptive Fidelity (GAF)

GAF is a topology control algorithm that divides the network into virtual grids/cells and assigns a single node on each grid as the designated router/leader that would stay awake for a given time. The nodes in the network periodically wake up and become the router to distribute the work load equally among the nodes. GAF has 3 states: sleep, discovery and active states. Initially, the nodes enter a discovery state and listens for messages for other nodes in the grid, if another node is already designated as the router all other nodes in the grid will enter sleep state and conserve energy. Nodes in the active state participate in routing and then enter discovery state after a specified time. The dimension of the grid, r, in GAF is dictated by transmission range, R:

$$r \le \frac{R}{\sqrt{5}}$$

3.2 Modified Bounded Distance Forwarding

For the purpose of minimizing problems caused by radio irregularity in GAF, we may use *Modified Bounded Distance Forwarding* in the network. Originally, the distance in Bounded Distance Forwarding, over which a node can forward a message to a single hop, is restricted. The *modified* bounded distance will now be dictated by half the radio range of a sensor device and within $2s$ or two standard deviation of ε for that specific radio range.

We define $R' = R/2 \pm \varepsilon$, so that the new equation is:

$$r \le \frac{R'}{\sqrt{5}}. \qquad (13)$$

Therefore, resulting to a topology control algorithm wherein the transmission range is restricted but also considers the variance in transmission range. Fig. 7 shows the summary of the solution for topology control algorithms using regression. The first step is to determine

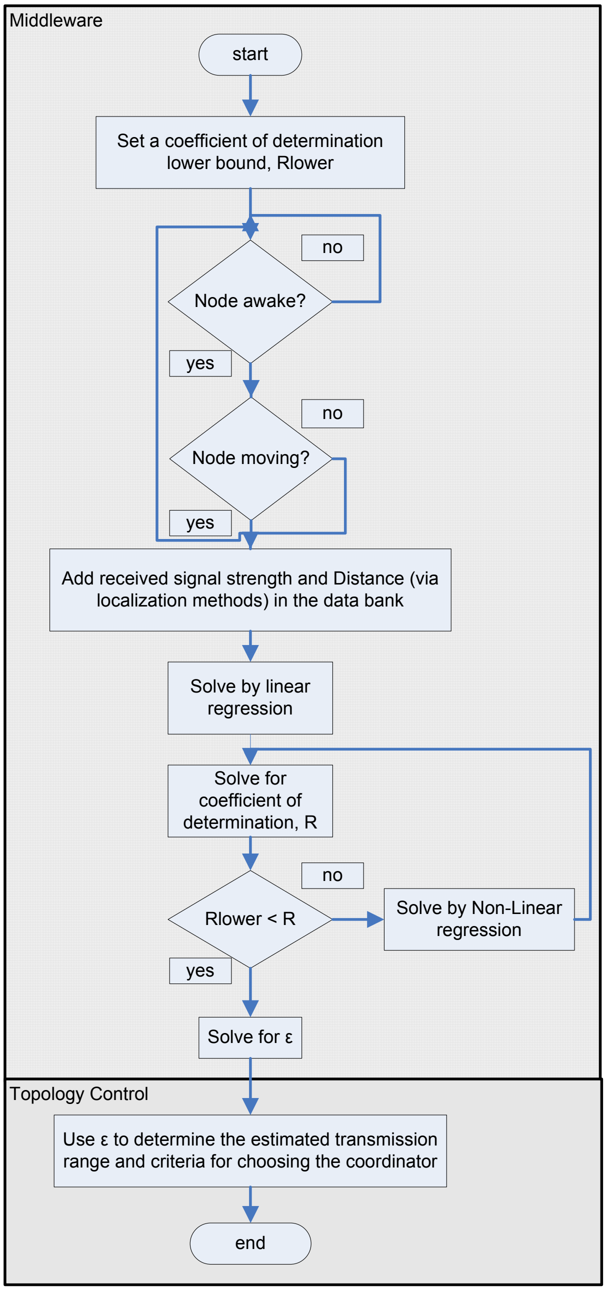

Fig. 7 The summary of the middleware mechanism incorporated with topology control.

how strict the coefficient of determination should be or how much error is allowable in the process. We leave this choice to the topology control designer, but we recommend that this value should be close to 1. The following steps are similar as to what was described in the previous sections. Consequently, the amount of data to be stored in the databank on each node may create a big overhead; therefore, it is mandatory to have a limit on how much data can be stored.

4. CONCLUSION

This paper attempts to mathematically and statistically model radio irregularity using linear and non-linear regression on a representative dataset of distance and received signal strength. We test the approximation by using Pearson product of moment coefficient of correlation and coefficient of determination to determine how well the regression describes the relationship between two parameters. Finally, we give a solution on how to solve radio irregularity problem on topology algorithms (e.g. GAF) by adding a middleware called Modified Bounded Distance Forwarding.

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