

Modelling for Wireless Sensor Network Protocol Design

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Abstract—Protocol design for a Wireless Sensor Network (WSN) must jointly take many aspects into account, owing to the embedded nature of the devices, and the needs for energy efficiency, scalability, self-organisation and robustness to heterogeneous and unplanned environments: all these are cross-layer issues.

As usual for wireless systems, protocol design normally includes a heuristic design phase, followed by validation and optimisation that can be achieved through simulation, mathematical and/or experimental approaches. In the two former cases, models are needed to specify the environment addressed by the researcher: as usual, models should be simple and realistic at the same time, where these two characteristics must be defined according to the target of the evaluation procedure. Models should also be agreed and shared among the scientific world in order to allow the comparability of results achieved by different researchers. In a wider sense, modelling for protocol design should also include the definition of the performance figures that have to be selected to measure protocol optimality, or to benchmark them.

Some models have got in the last year a natural consensus, like for instance the geometrical distribution of nodes, often considered to be (statistically) uniformly distributed over a square area. However, other models for WSN protocol design still need to find consensus. This paper addresses this aspect and discusses the relevance of some of the issues not sufficiently accurate when dealing with modelling for WSN protocol design.

To provide a solid base to this discussion, some results achieved through different means, both via simulation, mathematical or experimental approaches, are reported in the paper; as a common denominator to the different approaches and algorithms discussed, the performance of WSNs is measured in terms of network lifetime (related to energy efficiency), for which a new definition is given in this paper.

I. INTRODUCTION

A. Wireless vs Wired

Wireless Sensor Networks (WSNs) are wireless: this trivial statement emphasises the need to provide suitable wireless channel models able to capture the main characteristics of signal propagation in WSNs, which have not been investigated in the past so accurately as, for instance, for mobile radio systems. Nodes are often displaced in rural, or urban areas, where non-line-of-sight conditions occur, even at short distances. Moreover, the presence of obstacles (humans, animals, objects, ground slopes, trees, etc) makes the prediction of signal strength possible only in a statistical sense. As a consequence, as is usual for wireless systems, received power at a node can be described in terms of transmitted power and a random path loss which might be composed of a statistical and

a deterministic distance-dependent part: the former is usually neglected in many papers about WSNs published over the literature.

Owing to the specific nature of the WSN scenarios, where nodes are often placed on the ground, grass or asphalt, channel modelling can not follow the same rules as for typical mobile radio systems where at least one of the nodes (the base station) is far from the ground. Therefore a suitable model should be defined. Its impact on protocol performance should be estimated in order to assess whether this aspect is of relevance. Section II will address this issue, reporting some of the results of a measurement campaign and their impact over a simulation environment. Only narrowband channel modelling is discussed here. It is shown that first-order description of the statistics of received power often play a very significant role on network performance, measured in terms of network lifetime. On the other hand, one of the simulation results we report, also shows that second-order statistical description can be sometimes neglected.

B. Sensing the World

In most applications, WSNs involve sensor nodes sensing the environment to provide a suitable description of a random process to a remote user. This is accomplished through the collection of sensed data at a sink, or at multiple sinks, connected through evolute communication media that do not use the same paradigms shared by the WSN. As a result of this consideration, the information flow is usually addressed to a specific sink, or set of sinks, and the general network topology can be classified as many-to-one or many-to-few. This clearly impacts on protocol design and makes a clear distinction between the more general concept of ad hoc networking (based on the paradigm of peer-to-peer connection between users) and the particular field of WSNs.

As a result, from the viewpoint of wide-sense system modelling, the performance figures should reflect this aspect and be targeted to the measurement of the error caused by information losses on the estimation of the process realisation, rather than to the evaluation of the packet error rates. Moreover, when dealing with connectivity issues, often oriented in the literature to the description of the amount of resources (number of nodes, power, etc) needed to have a fully-connected network where every node can reach all other nodes, in the case of WSNs models should be found to measure full connectivity as the property of a network where all nodes can provide

their data to a specific sink, or set of sinks. Section III will be dedicated to these issues, recalling results taken from other papers reflecting both the above considerations and the statistical description of channel propagation discussed in Section II.

C. The Many Ways to Measure Energy Efficiency

In WSNs, the energy efficiency of communication protocols is a relevant aspect, often estimated through network lifetime, that could be defined, e.g., as the time interval starting with the first transmission and ending when the percentage of nodes still alive (i.e. battery has not expired yet) falls below a given application-dependent threshold. Both the way network lifetime is defined, and the model for battery discharge, play a significant role in protocol optimisation. Section IV will show some simulation results stressing the role on protocol selection of the definition of network lifetime: we also provide a new definition of network lifetime, which is closer to the typical application of WSNs. Then, the simplest (and widely used) approaches used to model energy consumption will be shortly discussed.

D. Nodes' Deployment

In the literature dealing with ad hoc networks in general, a consensus has been reached in terms of the usual reference scenario investigated as for its geometrical lay-out: nodes are often considered to be (statistically) uniformly distributed over a square area. Also many papers dealing with protocol design and assessment of WSNs use this simple scenario. However, while in (homogeneous) ad hoc networks the generic node can be either information source or sink, in WSNs, as already mentioned, sinks are specific nodes. Therefore their displacement over the area has to be defined as part of the model/scenario. In the multi-sink case, it is natural to distribute them uniformly over the same scenario, whereas in the single-sink case, often considered in the literature, the sink might be in the center of the square, or on its border, or outside the area. In Section V, through simulation, it is also shown that this choice has an impact on protocol optimisation or selection procedures.

E. Simulation Tools

The results shown in the following, supporting the concepts whose discussion is the main goal of this paper, are achieved through the use of three different simulation tools, developed over different simulation platforms (Omnet++, Ns2, or C++). These simulators have been described in some cases in previously published papers. As the results itself are not the main objective of this paper, the description of the simulation environments are only given in a short form, in Appendices A, B and C.

The reference scenario considered in these simulators is about the same and it is constituted by a square area of $L \times L$ m^2 , where a fixed number of nodes is uniformly distributed, and these nodes have to transmit the information detected to a sink placed at a distance d from the centre of the area.

The sink, periodically, sends a service request (trigger) to all network nodes, and waits for the reception of data from these. In the following, we will denote as round, the period of time between two successive trigger packets sent by the sink.

II. WIRELESS VS WIRED

A. Experimental Platform, and Procedures

By using an experimental platform, composed of a number of Cross-Bow sensor nodes MICA2 (also denoted hereafter as motes, supporting TinyOS operating system), a wireless channel model for WSNs, based on measures made on the field, is proposed here. Narrowband (i.e. RSSI, Received Signal Strength Indicator) measurements were only made, at a frequency of 433 MHz; consequently all considerations should be limited to this range of frequency, though some more general conclusions can also be drawn.

By considering two motes separated by a distance r , three different measurement scenarios were considered: no obstacles between transmitter and receiver (first Fresnel ellipsoid free), on grass and on asphalt. For each measurement scenario different values of r were considered. By fixing a certain nominal transmit power, $P_{T_{nom}}$, we measured received power, RSSI, at the different distances, through the software tools provided by the experimental platform.

The first aim of the experimentation was to measure the long-term characteristics of path loss, as a function of large-scale phenomena. Having fixed distance r , in a range from 1 to 10-20 m, ten measurements were made changing the position of the transmitter within a radius $R = 20$ centimeters ($R \ll r$), every 10 seconds. Being the wavelength equal to about 60 cm, this did not average out possible multipath effects. On the other hand, the measurements obtained by transmitting about one hundred packets were averaged over the 10 seconds, and thus (possible) fast fluctuations due to the movement of scatterers (foliage, etc) were averaged out. In this way we have developed a channel model that takes into consideration slow fluctuations owing to the movement of obstacles, but not fast fluctuations due to short-range local effects (i.e. multipath), that are averaged out.

To investigate short-range local phenomena, and whether fast fluctuations should be accounted when characterising the received power on a packet basis, we have also checked for the presence of fast fluctuations, by looking at the samples before averaging; Figure 1 shows RSSI samples measured on asphalt as a function of time (samples, i.e. packet transmissions, are taken every 100 ms). We can see that, once we have fixed the transmitter position, fluctuations are very low (in a maximum range of about 2 dB), whereas they are larger (up to about 10 dB) when we change the position of the transmitter within the circle of radius R . Have in mind that a Rayleigh model would generate deep fades with power fluctuating in a range of up to 30 dB. Owing to the fact that short distances between transmitter and receiver are considered (we have set $r=5$ m in that case), with respect to R (that is about 20 cm), we can argue that these fluctuations are fundamentally due to path loss changes. However, based on these results, one can

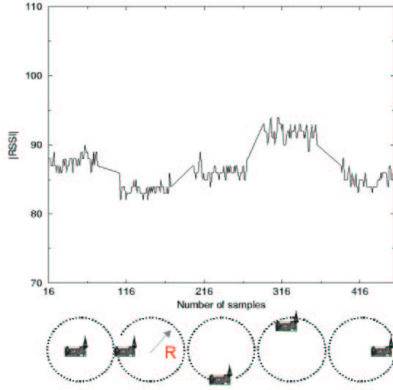


Fig. 1. Inverse of RSSI in dB as a function of time.

argue that fluctuations due to short-range local effects can be neglected, or modelled according to some statistics with very low standard deviation, in the worst case. By looking at the amount of data we have collected for the different three scenarios, the case of Fig. 1 can be considered one of those showing the largest variances. In the following, only short-term average received power (with fast fluctuations averaged out) are considered for discussion.

B. Wireless Channel Model

In the following, all powers and losses are reported in logarithmic scale (dBm or dB, respectively).

The relation, in logarithmic scale, between received power, transmit power and distance, obtained by averaging over all measured samples at fixed r , has been considered, and compared to the following model which is assumed as a reference: the measured power, $P_{R_{meas}}$, which has been considered as the result of the RSSI output measured by the devices, can be written as:

$$P_{R_{meas}} = P_{T_{true}} + \delta_{\varepsilon_m} - s_1 - (K_0 + n \cdot \log(r)) \quad (1)$$

where $P_{T_{true}}$ is the true transmit power used by nodes to transmit a packet; this value can be different from $P_{T_{nom}}$ and is device-dependent. $P_{T_{true}}$ can be considered as a random variable and could be expressed as the sum of an average power value, $P_{T_{avg}}$, and a random variable, δ_{ε} , that (in the absence of other information) could be considered Gaussian distributed, with zero mean and standard deviation σ_{ε} (we are neglecting here the need to truncate it in order to take for maximum power limits into account): $P_{T_{true}} = P_{T_{avg}} - \delta_{\varepsilon}$. δ_{ε_m} is an error modelling RSSI output accuracy with respect to the true received power; this factor is due to measurement errors. This is usually considered as a Gaussian variable, with zero mean and standard deviation σ_{ε_m} ; data sheets report a maximum error of plus or minus 6 dB. The error is device-dependent.

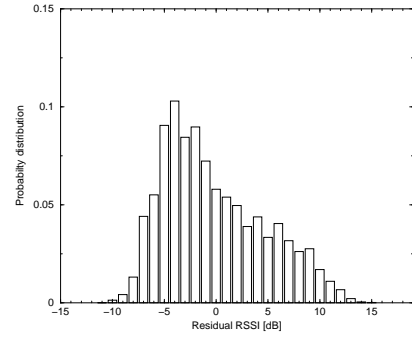


Fig. 2. Statistical distribution of the residual RSSI samples measured.

The shadowing sample, s_1 , is assumed to be Gaussian distributed, with zero mean and standard deviation σ_1 and the different shadowing samples, competing to different links, can be assumed to be independent as they depend on the particular path, different for each link. Finally, K_0 is a constant, different for the different scenarios considered and n is the path loss coefficient.

Now, according to the above model, received power is the sum of a deterministic value, $P_r = P_{T_{avg}} - K_0 - n \cdot \log(r)$, and three Gaussian random variables (δ_{ε} , δ_{ε_m} , s_1), that are statistically independent; thus we can define a Gaussian random variable, $s = \delta_{\varepsilon} - \delta_{\varepsilon_m} + s_1$, with zero mean and variance, σ^2 , given by: $\sigma^2 = \sigma_{\varepsilon}^2 + \sigma_{\varepsilon_m}^2 + \sigma_1^2$. Then, we have

$$P_{R_{meas}} = P_r - s. \quad (2)$$

C. Comparison to Experimental Results

According to the measurements performed, the following considerations were made as for the deterministic components of short-term average received power. Values for K_0 are 39.3 dB for the first scenario, 48.4 dB for the second scenario, and 43 dB for the third scenario.

Concerning the statistical part of the model, it is difficult to provide reference values that can be used in general. We have observed that, even if the designer set a nominal value, $P_{T_{nom}}$, for packet transmission, the true transmit power used is different from the nominal value and it varies statistically when changing mote. Differences in the order of 2-4 dB were measured.

Figure 2, at a fixed distance, shows the statistical distribution of the RSSI samples measured, once the average value has been subtracted: the Figure shows that the observed distribution is not symmetrical. Clearly, it is not easy to draw conclusions from this campaign; if one wants to stick to the simple Gaussian model for s , according to Fig. 2 the standard deviation of s should be in the range [2-6]. The simple Gaussian model, given by (2), will be used in the following.

D. First and Second Order Statistics

In this subsection we underline the importance of considering the first order statistics of the received power, but also the independence of the network performance on the second order statistics. What we want to prove is that when we have to

develop an accurate model of the radio channel, it is important to consider the first order statistics, because of this role on performance.

To prove this we report the results obtained with two different simulators, that show the dependence of network performance on standard deviation of received power, but also its basic independence from the autocorrelation function of the same process.

In Figure 3, network lifetime (see Section V) obtained with the simulator described in Appendix A, is shown; the Figure illustrates the number of nodes still alive as a function of time, expressed in terms of rounds, by varying the standard deviation σ of the received power variance (see curves with $d = 100$ m). As we can see the energy spent in a network strongly depends on this parameter; in fact, by increasing σ , performance worsens significantly.

Figure 4 shows the performance, once again in terms of network lifetime, obtained with the simulator described in Appendix C. Here the residual energy of two particular nodes as a function of time, by considering a correlated and a uncorrelated Gaussian variable, is shown. The case with correlated shadowing has been developed by assuming a Two-State Markov Model to describe the random process $s(t)$; this choice is in agreement with the observation of the measured samples. As we can see for both nodes, performance obtained in the two cases is roughly the same.

III. SENSING THE WORLD

In many applications, the WSN aims at estimating a given physical phenomenon, which can be modelled as a bi-dimensional random process (generally non stationary) denoted as $Z(s)$, where $s = (s_1, \dots, s_l)$ is the point coordinate in the real space. Hence, $Z(s)$ represents the target process (or signal); nodes generate samples of $Z(s)$ and, via a self-organizing clustered communication protocol, transmit them to the sink, which is in charge of the signal processing and the estimation [1], [2]. Owing to communication failure, a probability, p , exists that a node is unable to send its information to the sink; in this case the corresponding sample does not contribute to the signal estimation (sample loss) and the process will be estimated with a certain error ε , given by [2]:

$$\varepsilon = \frac{\beta\zeta}{q\rho} \quad (3)$$

where $\beta = \text{size}(\mathcal{S})$, and \mathcal{S} is the frequency space in which the more significant spectral components of the signal are included; $\zeta = \text{size}(\mathcal{S}^*)/\text{size}(\mathcal{S})$, and $\mathcal{S}^* \supseteq \mathcal{S}$; $q = 1 - p$ is the probability of correct sample transmission and ρ is the nodes density.

By fixing the target quality in the estimation process, leading to a target value of ε , one can obtain useful information on the minimum nodes density needed to satisfy these requirements.

Concerning p , it generally depends on multiple access and the communication protocol used, and on physical layer issues related to connectivity, i.e. the property describing how the nodes of the network are connected each other. Connectivity

for WSNs has been studied in the recent literature, and it is also addressed by the companion paper presented at this Workshop [3]. In [3], a model to describe the connectivity between nodes and uniformly distributed sinks, through a hierarchical strategy, is proposed, taking a wireless channel characterisation like the one proposed in this paper into account. We let the reader refer to [3] for this issue.

IV. THE MANY WAYS TO MEASURE ENERGY EFFICIENCY

Network lifetime of a sensor network depends on lifetime of individual nodes, which, in its turn, depends on the amount of sensing, processing, communication, and sleeping performed at each node.

A formal definition of network lifetime is not easy and may depend on the application scenario in which the network is used [4]. In the literature, network lifetime has often been defined as the time elapsing between network deployment and the moment when the first node dies [5], or a certain percentage of network nodes die [6]. This percentage depends on the application: for instance, in case we consider an event triggered monitoring application, it is not very important that all nodes in the network are alive, because to detect an event, a low percentage of alive nodes could be enough, to satisfy the service request; whereas, if we consider a spatial and time random process estimation application, it is important that a large number of nodes are alive, because samples losses from a lot of nodes cause high estimation errors.

Having in mind the latter definition, and using the C++ simulator (see Appendix B), in Figure 5 we show the number of nodes still alive as a function of time, by varying some protocol parameters. The aim is to show how these parameters can impact on network lifetime; in particular, we have considered the performance by varying x , that is the probability that a node elects itself Cluster Head (see Appendix B), and the MAC protocol used: we consider the cases in which GTSs are allocated or not. As we can see, the Guaranteed Time Slots (see Appendix B) allocation improves performance only in case we consider large values of x ; in fact thanks to these allocations, CHs save energy, because they can reduce the sensing time. However if the number of CHs in the network is low (px is low) this benefit regards only a small part of nodes. We can note also that the more x increases, the more the curve is steep; in fact, by increasing the CH density, the variance of distances between CHs and non CHs decreases and the transmit powers used by nodes are very similar; in this case nodes tends to die about at the same time. Therefore, it is clear that, for different applications, protocol optimisation brings to different parameter choices.

Moving forward with network lifetime definitions, in [4] it is underlined that in WSNs the requirement for connectivity must be complemented with the requirement for coverage; all the monitored region must be covered by the sensors. To this aim the new definition introduced in that paper, that takes into account connectivity and coverage together, refers to the time of the first loss of coverage or connectivity.

Having in mind this definition, to take into account simultaneously connectivity and coverage, we could observe the process estimation error, as a function of time. This parameter, in fact, gives a measure of network connectivity and also, if we consider it as a function of time, it takes into consideration the energy life of the network. Hence, by fixing a threshold value for ε , ε_0 , we can define network lifetime as the time elapsing between network deployment and the instant in which the error ε goes above ε_0 . Therefore, we need a curve $\varepsilon = \varepsilon(t)$.

To obtain this curve, as an example, we can consider (3) and put $q = (1 - p) = P_{alive} \cdot P_{trigger} \cdot P_{no-coll}$. Where P_{alive} is the probability for a node to be alive (node has not consumed all its energy), $P_{trigger}$ is the probability that the node receives correctly the trigger and, finally, $P_{no-coll}$ is the probability that a packet does not collide. In this way, being P_{alive} a function of time, we can express ε as a function of time. We must underline, however, that the application of this formula is possible only in case we suppose that nodes die uniformly in the space, which is not true in general, as this assumption lays behind expression (3).

In Figure 6 a possible behaviour for this curve is obtained by putting $P_{trigger} = 1$, $P_{no-coll} = 1$ and considering the curve of Figure 3 with $\sigma = 4$ dB and $d = 100$ m. As we can see, when varying t , ε increases, because nodes die and they could not transmit their data to the sink. As we said, this curve is obtained, by making strong assumptions: all nodes are triggered by the sink, no collisions occur and nodes die uniformly in space. Hence this simply intends to be an example of application of the new network lifetime definition.

Finally, the use of different models to describe the battery discharge can impact on lifetime performance. The simplest model, used in all simulators considered in this paper, refers to a battery that, at every transmission, reception, or when the node senses the channel, discharges. But other models could be considered: batteries in many cases can be more efficiently used when active periods are interrupted by inactive intervals; during inactive periods batteries restore part of their energy and provide better utilisation than in case of continuous use. This is known as relaxation effect [7]. As a result, the usual assumption that an initial amount of energy is available, and that its use is to be considered as a simple sum of events, is not realistic. This aspect deserves attention, since it could drive suitable design of some communication protocols (e.g. at MAC layer).

V. NODES' DEPLOYMENT

To show the impact of the choice of sink position, we consider the performance, in terms of network lifetime, obtained with the simulator described in Appendix A, where a single-sink scenario is developed. In Figure 3, if we look at the curves with $\sigma = 4$ dB, network lifetime is obtained for three different sink positions: the centre of the area ($d = 0$ m), the border of the area ($d = 50$ m) and outside the area ($d = 100$ m). As we can see, by putting the sink away from the centre of the area, network lifetime diminishes, because nodes have to transmit with higher power to reach it.

VI. CONCLUSIONS

In this paper some models useful for protocol design of WSNs have been discussed. The two main contributions are the following. First, a model to describe wireless channel fluctuations has been proposed and motivated through experimental results; more importantly, its relevant impact on some example networks has been shown. Then, concepts related to the definition of network lifetime to be used when WSNs are exploited to estimate a given random spatial process (a typical application of WSNs), have been introduced.

Acknowledgments - This work is performed within NEWCOM (Network of Excellence in Wireless COMMunication). The authors thank D. Sangiorgi, A. Giorgetti, A. Conti and D. Dardari for useful discussions on the topic.

APPENDIX A – OMNET++ SIMULATOR

An Omnet++ platform is used to simulate a WSN composed of several tens of nodes randomly and uniformly distributed over a square area, accounting for routing, MAC, physical, energy and propagation aspects [8]. The routing protocol considered is a new version of Low Energy Adaptive Clustering Hierarchy (denoted as LEACH B) [9], a cluster based algorithm, which enables self-organization of large numbers of nodes with one node per cluster acting as Cluster Head (CH) and where nodes forward their data to the sink through the CH according to a two-hop strategy. CHs are elected through a self-election algorithm and rotations of CHs roles are introduced, to evenly distribute the energy load among all nodes. Each node selects its CH by evaluating the energy dissipated in the complete path between itself and the final sink, via the CH, for the transmission of its packet: it will select the CH, which corresponds the lowest loss. As far as MAC protocol, a Carrier Sense Multiple Access (CSMA), based on IEEE 802.11, is developed. The relevant energy waste in CSMA protocols, owed to idle listening that occurs when nodes are sensing the channel, is avoided by introducing an ON/OFF modality which consists in turning off and on periodically radio components. The Figures shown in this paper are obtained by considering an area of side $L = 100m$, with 30 nodes.

APPENDIX B – C++ SIMULATOR

In this simulator, a LEACH routing protocol is applied to Zigbee standard. LEACH differs from LEACH B only for cluster formation: nodes select the clusters to belong to, on the basis of the power received by CHs itself. In particular, each non-CH selects the CH which corresponds to the highest received power. Concerning physical and MAC layers, Zigbee standard is considered. The access to the channel is managed by organizing the transmit packets into a super-frame: time axis is divided into sixteen slots that constitute a super-frame structure. Super-frame begins with the transmission of a control packet (Beacon), that could be sent only by the network coordinator and it is used to manage the network. The Beacon function is to synchronize devices and to create the super frame structure. After the Beacon transmission, there is a Contention Access Period (CAP), where devices can access

to the channel, by using a slotted CSMA-CA protocol; a Contention Free Period (CFP) follows, where dedicated time slots (Guaranteed Time Slot, GTS) are allocated. In each GTS only the device to which the slot has been allocated, can transmit, without collisions. Finally, there is an inactive zone, where transmissions may not occur. The Beacon packets contain information about sizes of the above periods and the addresses of the devices to which GTSs belong to. The Figures shown in this case are obtained by considering an area of side $L = 50m$, with 300 nodes and the sink set in the centre of the area.

APPENDIX C – NS2 SIMULATOR

In this simulator a Destination Sequence Distance Vector (DSDV) routing protocol, together with a CSMA MAC protocol are developed. DSDV is a proactive protocol, where nodes constantly update routing tables; each node has a routing table, where all the possible destinations that it can reach and the correspondent number of hops necessary to reach them, are recorded. The protocol uses also a sequence of numbers to allow nodes to distinguish a new from an old route; sequence number is generated by destination nodes and it is used to read tables. The information updating, made by each node by sending in broadcast the routing table, can be developed in two different ways: timer driven, in which transmission of tables is made periodically and event driven, where each node sends its table each time this table changes. As far as MAC protocol is concerned, a CSMA protocol, based on IEEE 802.11, is considered. The Figures shown in this paper is obtained by considering an area of side 550m, with 100 nodes and the sink is set on the border of the area.

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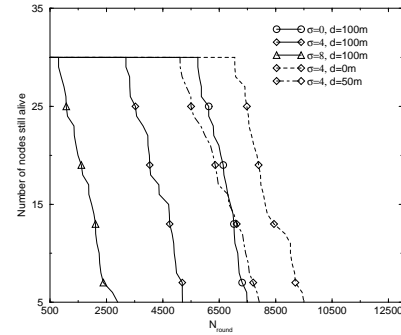


Fig. 3. Number of nodes still alive as a function of time, expressed in number of rounds, by varying σ and d .

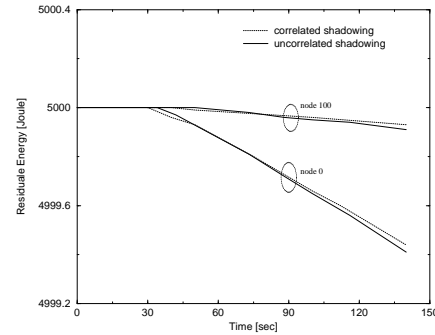


Fig. 4. Residual energy for two specific nodes of the network as a function of time, by considering uncorrelated and correlated shadowing samples.

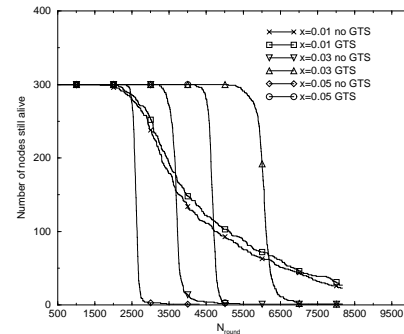


Fig. 5. Number of nodes still alive as a function of time, expressed in number of rounds, by varying x and the MAC protocol.

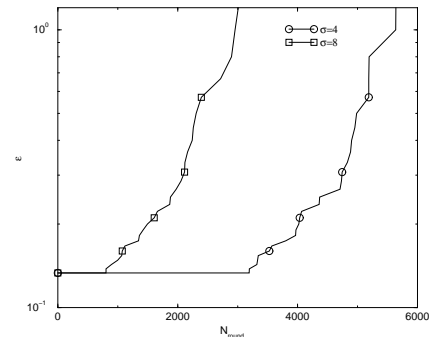


Fig. 6. Normalized process estimation error as a function of time.