WCOT: A REALISTIC LIFETIME METRIC FOR THE PERFORMANCE EVALUATION OF WIRELESS SENSOR NETWORKS

Atay Ozgovde Cem Ersoy
NETLAB
Department of Computer Engineering
Bogazici University,34342 Bebek, Istanbul, Turkey
{ozgovde,ersoy}@boun.edu.tr

ABSTRACT

Wireless Sensor Networks (WSNs) give rise to a new networking paradigm in which energy efficiency is a high priority goal. A direct measure of the energy efficiency is the *network lifetime* which WSN proposals strive to extend. To correctly quantify the lifetime, the metric must be defined in an application dependent manner. In this paper, we propose a generic lifetime measurement framework called Weighted Cumulative Operational Time (WCOT) for the performance evaluation of the WSNs. Novelty brought by WCOT is twofold: First, it defines a utility based interface for the diverse WSN applications to incorporate their scenario specific requirements into the metric itself. Second, WCOT assigns different weights to the operational durations that have different utilities and perform a weighted summation to calculate the cumulative lifetime thereafter. With this mechanism, a more representative lifetime metric which maps the complete network behavior into a numeric value is obtained. This is in contrast with metrics which focus solely on certain milestones of the network functionality to quantify the lifetime which include the first node death, the last node death.

I INTRODUCTION

Wireless Sensor Network (WSN) research has one ultimate performance objective: prolonging the *network lifetime*. Being the decisive performance evaluation criteria, how the network lifetime is defined deserves extra attention. Basic functionality of a WSN is to *monitor* a region of interest. Therefore, a natural definition of the lifetime of a WSN is the time between the deployed sensor nodes start collecting data and the instance where the *monitoring quality* drops below an *acceptable threshold level*. Here, the terms monitoring quality and acceptable threshold level have different interpretations for different application scenarios. For instance, for a WSN application that monitors the humidity of an agricultural area, the acceptable threshold might correspond to regular data being collected from at least 85% of the crops, whereas for a military video-surveillance application, the maximum latency of 2 seconds for video packets may set the threshold for the monitoring quality. Given the wide range of WSN applications, it is not possible to give definitions for the *monitoring quality* and the *acceptable level of operation* that is generally applicable, therefore the network lifetime should be examined in an application dependent context.

Existing lifetime metrics in the WSN literature, however, disregard the application dependence of the network lifetime and offer a single definition to be used for the whole range of WSN applications, which is simply not realistic. A lifetime metric that is not compatible with the specific application requirements causes two major problems: (i) lifetime measured would be incorrect, (ii) trying to optimize the network performance based on such a lifetime metric would result in a misallocation of the resources. Let us consider, as an example, the frequently used lifetime metric, *the time till the first node dies* [1, 2, 3, 4, 5]. A lifetime optimization based on this metric does not necessarily lead to the maximum lifetime for an application scenario that can tolerate a predefined percentage of loss of the initially deployed sensor nodes. Such an effort would dedicate all the network resources to delay the first node death without caring about what would happen at later stages which may lead to inefficiencies, hence shorter lifetimes, for the original scenario. Therefore, suitable lifetime definition that is in accordance with the application requirements is a must for correctly quantifying the useful lifetime so that it can further be optimized.

In this paper, our aim is twofold: First, we propose a novel lifetime metric called *Weighted Cumulative Operational Time* (WCOT) for the realistic performance evaluation of the WSNs in an application dependent context. Second, with the help of WCOT, we show how a lifetime metric incompatible with the application requirements might result in misleading results. To achieve this, we focused on a specific WSN application area and conducted a series of simulation experiments whose performance is evaluated both by WCOT and the metric the time till the *First Node Death* (FND). We chose FND as the rival metric since it is widely used in works that optimize and/or compare WSN performances. The lifetime values obtained by the two metrics were either discrepant or contradictory for the cases studied. It is observed that FND values measured does not capture the actual lifetime behavior of the networks, whereas, WCOT realistically characterizes the application dependent operational lifetime of the networks involved. We believe that, with these results, it becomes evident that more care should be exercised on the lifetime metric which currently lacks in the WSN community.

The rest of this paper is organized as follows: the relevant work in the WSN literature is summarized in Section II. WCOT is explained in detail in Section III. The simulation setup and a comparative evaluation of WCOT with the other lifetime metric

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is presented in Section IV and Section V. Finally, Section VI concludes the paper.

II EXISTING LIFETIME METRICS

Previous lifetime definitions proposed for WSNs shall be examined in this section. The most common lifetime definition encountered in the WSN literature is the time till the first sensor node death occurs [1-7]. Rationale behind such a lifetime definition is twofold. Firstly, it is a lower bound on any possible lifetime definition - i.e. this lifetime definition cannot overestimate the operational lifetime of a WSN. Secondly, it can easily be incorporated into LP style problem formulations. [1, 2]. Despite its popularity, confining the lifetime with the initial node death does not reflect the actual operational lifetime of a WSN, since in virtually all WSN applications, initial sensor death causes only negligible deformation on the network functionality.

Another lifetime definition, on the other extreme, is the time till the last sensor node dies. Although not as common as the previous definition, there are studies that depend on this definition of network lifetime [3, 4, 6]. This definition implies that a WSN is functional even in the presence of a single sensor node. This is clearly an overestimation of the useful lifetime as the monitoring quality of a sensor network drops below acceptable threshold long before the number of remaining sensors is one.

Another class of lifetime definitions rely on the percentage of alive sensors [7]. Here, the network is assumed functional when the ratio of alive sensors to the initially deployed sensors is above a predetermined threshold. This definition better suits the needs of WSN when compared to the other two definitions, however the way the threshold is chosen is arbitrary and does not necessarily reflect the constraints of the application scenario.

Yet another approach to quantify the network lifetime is in terms of coverage [8]. In general, the term coverage can be interpreted as sensing coverage or networking coverage. However, assuming $r_{sensing} \leq \frac{1}{2} r_{comm}$, sensing coverage implies networking coverage [9].

III WCOT (WEIGHTED CUMULATIVE OPERATIONAL TIME)

To measure the lifetime, WCOT takes the reverse approach and instead of trying to give a single lifetime definition, it lets users to incorporate application specific requirements into the metric itself. WCOT is a utility based method, in which we abstract away the application dependent term *monitoring quality* with the notion of *utility*. Utility, as used in this context, denotes the extent of the collaborative monitoring activity performed by the sensors in a WSN. The dynamic utility of the network is captured by the user supplied *utility function*. The utility function, therefore, not only denotes the application specific threshold point after which the network is assumed to be dead, but also it specifies the continuous degradation of the network functionality that occurs due to eventual sensor deaths.

One major difference of WCOT from the current lifetime metrics is in the way it handles the degrading functionality of a WSN. Existing metrics, assume that the network is fully and equally functional throughout its lifetime, therefore they tend to measure the lifetime as the time between the initial and a final state. WCOT, on the other hand, divides the time into smaller durations and assigns different weights to operational intervals which have different utilities. The weighted lifetime calculation method reflects the changing utility of the network in time into the lifetime value. This approach gives rise to an increased lifetime measurement accuracy, meaning that WCOT is able to assign different lifetime values to the WSN performances which cannot be differentiated by the existing measures.

A Formal Definition

Definition *Lifetime of a WSN is the sum of weighted subintervals of operation time where the weights are the utility offered by the network for the subinterval at hand.*

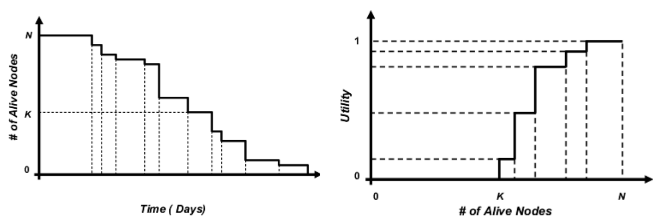
Let Δt_i denote the duration in which the utility offered by the network is U_i and let us assume that the utility can take D different discrete levels. The network lifetime as defined above can be formulated as:

$$Network\ Lifetime\ (WCOT) \equiv \sum_{i=1}^{D} U_i \Delta t_i \tag{1}$$

Assuming discrete utility levels is based on the fact that a decrease in the utility of the network occurs only due to sensor deaths which is discrete in nature.

B The Graphical Interpretation of WCOT

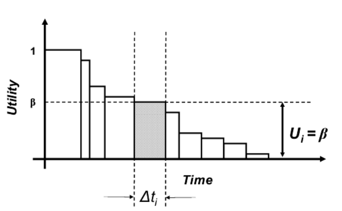
Traditionally the performances of the WSNs are shown in terms of the consecutive network states in time. An example graph is given in Fig. 1(a) which shows the performance in terms of the number of alive sensors in time. Let us assume that the utility function specific to the WSN application in question is as depicted in Fig. 1(b).



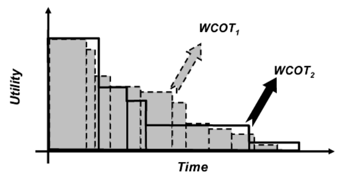
(a) (b)

Figure 1: (a) Performance in terms of alive sensors in time. (b) The utility function

The network has initially N sensors deployed and is assumed to be functional at various levels till $(N - K)$ of its sensors die out. To calculate the lifetime of this WSN performance via WCOT, firstly, the graphs in Fig. 1 need to be transformed into a *utility vs. time* graph. This is achieved by replacing the alive node numbers in Fig. 1(a) with the corresponding utility values obtained from Fig. 1(b). Fig. 2(a) shows the resulting *utility vs. time* graph. The shaded region in the graph depicts the weighted lifetime calculation step for the duration Δt_i. Each duration is weighted with the utility value specific to the duration to obtain the effective resulting time. When all intervals are considered, WCOT actually performs a discrete integration over the graph. In Fig. 2(b) two different WSN performances are quantified by the resulting areas computed by WCOT. The magnitude of the area is determined by the changing utility till the instance utility drops to zero. Therefore, the lifetime value obtained by WCOT is a reflection of the whole history of a WSN performance. To compare the performances of two sensor networks, we do the integration on each graph and compare the areas computed, as shown in Fig. 2(b)



(a)



(b)

Figure 2: (a) WCOT calculation shown graphically. (b) WCOT lifetime values for two different WSN performances.

IV System Description

In this section, we will introduce the application specific details of the WSN scenario that will be used in the performance evaluation experiments.

A Application Scenario

We will focus on environmental monitoring [10, 11] as our basic application scenario. The characteristics of the scenario are: periodic traffic with low generation rate, delay insensitive communication, spatial and temporal redundancy of the data and sensor deaths being tolerable to some extent.

In Section III-B, the utility is studied as a function of the number alive sensor nodes. However, a better choice for the utility mapping is to use the sensing coverage. Coverage is a more direct indicator of the utility of a sensor network, as it measures the monitoring quality performed. Utility function that we will adopt in all of the WCOT calculations in the rest of this paper is given in Fig. 3. Here, sensing coverage is mapped to utility in a linearly degrading fashion such that coverage between 0.7 and 1.0 corresponds to utility values in [0.5,1]. Coverage below 0.7 indicates a nonfunctional environmental monitoring sensor network for our case.

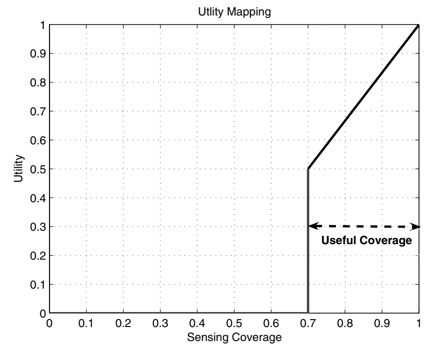


Figure 3: Utility function to represent the environmental monitoring application scenario considered

B System Model and Assumptions

The network is assumed to be comprised of a single sink node and numerous sensor nodes. Exact number of sensor nodes deployed depends on the targeted node density for the deployment. Sensor nodes are uniformly deployed on a square geographic area with lateral length being l. Sink node is placed in the middle $(l/2, l/2)$. Nodes are assumed to have identical hardware including transmission capabilities and initial battery energies they posses. Also, nodes have the ability to individually adjust their transmission powers - thus their transmission ranges. We adopt the energy model given in [3] and [8] which can be expressed as:

$$E_{tx} = \kappa_1 + \kappa_2.d^{\alpha} \tag{2}$$

$$E_{rx} = \kappa_3 \tag{3}$$

Here, E_{tx} and E_{rx} denote the energy per bit required for transmission and reception respectively. κ_1 is the distance independent part of the transmission energy, d is the distance between communicating sensor nodes and α is the *path loss index* which is assumed to be 2 in our model. Energy required for the reception is independent of the distance d and κ_1 and κ_3 are assumed to be identical [3]. In this work κ values are taken as $50nJ/bit$ for κ_1 and κ_3, and $100pJ/bit/m^2$ for κ_2.

In the simulation experiments *Minimum Energy Routing* (MER) and *Basic Probabilistic Routing* (BPR) are used to guide the multihop communication between the sensor nodes and the sink node. MER is a static routing protocol in which the least energy paths are formed during the setup period and are used throughout the WSN operation. BPR belongs to a class of routing algorithms called *Probabilistic Routing* which try to even out the load on the nodes by using alternate paths [5].

The choice of the routing algorithms is based on clarity rather than performance. Here, we want to concentrate on the effect of the network lifetime metric on the performance evaluation for a WSN scenario. In this context, a more advanced routing algorithm, such as LEACH [3] or TEEN [12] would complicate the discussion with their operational details. In the simulations, a perfect MAC layer in which nodes do not contend for the medium is assumed.

V QUANTIFYING THE LIFETIME IN AN APPLICATION DEPENDENT CONTEXT

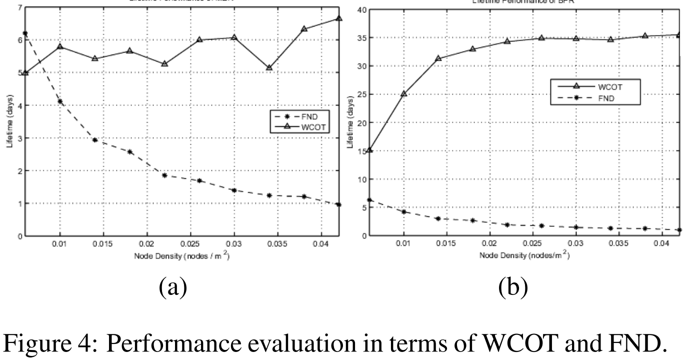
In this section, our aim is to measure the network lifetime with the two metrics involved and try to understand the dependency of the results on the metrics themselves and discuss implications.

Table 1: Common Simulation Parameters

Paremeter	Value
Area Size	100 x 100 m^2
Node Density	0.006 to 0.042 $nodes/m^2$
Data Rate	20 kbps
Packet Size	1024 Bits
Trans. Range (min,max)	22 m , 102 m
Trans. Power (min,max)	2 mW , 22 mW
Sensing Radius	10 m
Initial Energy per Node	1 J
Packet Generation Rate	1 Packet / 15 Min (per node)

The experiment design is comprised of a setup in which performance of a sensor network is studied as the node density is varied. Detailed packet level simulations are carried out with OPNET [13] in which multihop communication among nodes including the initial self organization period has been considered in the energy consumption relations. Common simulation parameters are presented in Table 1.

A total of 200 simulation runs carried out in which each routing algorithm is tested under 10 different random sensor networks for each of the 10 different node density values. Results presented depict the averaged values.



(a) (b)

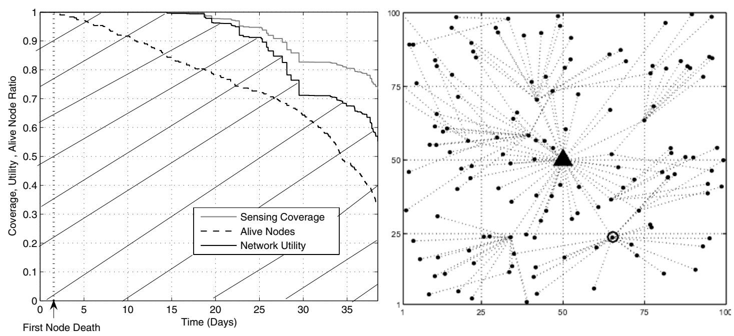
Figure 4: Performance evaluation in terms of WCOT and FND. (a) MER Case (b) BPR Case

A Node Deployment Density and Network Lifetime

How WCOT and FND quantify the effect of the increased deployment density for the routing algorithms involved is explored in Fig. 4. As seen in the figure, FND not only underestimates the operational lifetime of the network, but also gives the misleading impression that denser deployment results in shorter lifetime values. Error in lifetime quantification is more pronounced for the BPR case, since BPR is a dynamic routing algorithm that use energy more efficiently, hence has an elongated utility degradation period.

To further understand this phenomenon, Fig. 5(a) shows where the *first node death time* corresponds to on the overall lifetime cycle of the network. FND, as a milestone, does not represent a network-wide characteristic that can serve as a lifetime metric since the utility of the whole network does not necessarily gets affected on the initial sensor death. The same argument can be extended to other lifetime metrics that focus on a single point for the determination of the non-functionality threshold, such as the time for 50% of the initial nodes die. The problem with such metrics is based on the fact that the functionality of the network is dependent on more complicated variables, such as node redundancy and other application dependent factors. WCOT, on the other hand, incorporate these factors via a utility function and record the degrading utility by performing a discrete integration over the utility vs. time graph which corresponds to the shaded area in Fig. 5. Since utility values are in [0,1] interval, integration does not affect the unit of the lifetime.

Focusing on Fig. 5(b) enables us to realize how local the information obtained from the *first node death time* is. On the figure, the circled sensor node is the first node to die since it has the highest energy-wise load. In MER, FND always corresponds to the lifetime of such a heavily loaded node, instead of the lifetime of the whole network.

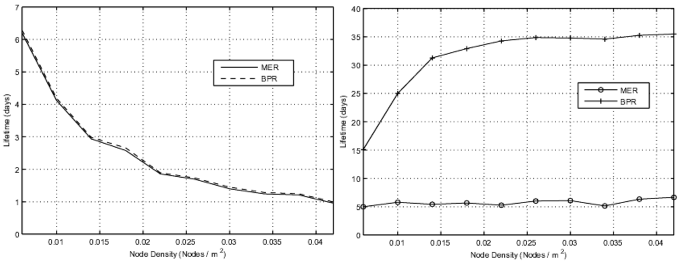


(a) (b)

Figure 5: (a) Evolution of the network parameters (300 Nodes, BPR case) (b) Static routing paths of MER. Circled node denotes the first node to die

B Comparative Evaluation of BPR and MER

Similar results are obtained when WCOT and FND are used for the comparative evaluation of the routing algorithms at hand. Fig. 6(a) depicts that FND is actually incapable of differentiating the lifetime performances of the routing algorithms for the density range studied. A more realistic picture is presented in Fig. 6(b), in which BPR performance first increases rapidly then saturates due to the inscalability of the algorithm itself. MER, on the other hand, generates smaller lifetime values and show only slight increase which is due to the fact that static routing paths render descendant nodes unreachable in the case of eventual sensor deaths.



(a) (b)

Figure 6: Performance comparison of the routing algorithms MER and BPR (a) Lifetime metric is FND (b) Lifetime metric is WCOT

VI Conclusion

In this work, we proposed a novel lifetime metric called WCOT for the performance evaluation of WSNs. WCOT is a utility based metric in which not only the time but changing utility of the network is taken into account. By doing so, a finer resolution and a more representative metric are obtained. Also more importantly, by employing a utility function, WCOT can precisely measure the lifetime for any well defined WSN application. WCOT is compared with a commonly known lifetime metric, *time till the first node death*. It is observed that WCOT makes a significant difference for the performance evaluation of the proposed mechanisms for WSNs. This paper considers the sensing coverage as an indication of the instantaneous utility of the network. As a future work, we are planning to introduce other types of utility functions to embrace different applications in the WSN spectrum. Possible utility indicators to consider are: reliability, breach probability and reporting delay.

References

[1] J.-H. Chang and L. Tassiulas, "Maximum lifetime routing in wireless sensor networks." *IEEE/ACM Trans. Netw.*, vol. 12, no. 4, pp. 609–619, 2004.

[2] ——, "Energy conserving routing in wireless ad-hoc networks." in *INFOCOM*, 2000, pp. 22–31.

[3] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks." in *HICSS*, 2000.

[4] M. Yu, A. Malvankar, and S. Y. Foo, "An energy-efficient path availability routing algorithm for mobile ad hoc sensor networks," in *IEEE International Conference on Communications*, 2006.

[5] R. Shah and J. Rabaey, "Energy aware routing for low energy ad hoc sensor networks," in *Wireless Communications and Networking Conference, 2002. WCNC2002. 2002 IEEE*, vol. 1, March 2002, pp. 350 – 355.

[6] M. Youssef, M. Younis, and K. Arisha, "A constrained shortest-path energy-aware routing algorithm for wireless sensor networks," in *Wireless Communications and Networking Conference*, vol. 2, 2002, pp. 794–799.

[7] L. van Hoesel, T. Nieberg, J. Wu, and P. Havinga, "Prolonging the lifetime of wireless sensor networks by cross-layer interaction," *Wireless Communications, IEEE*, vol. 11, no. 6, pp. 78–86, December 2004.

[8] M. Bhardwaj, A. Chandrakasan, and T. Garnett, "Upper bounds on the lifetime of sensor networks," in *IEEE International Conference on Communications*, 2001, pp. 785–790.

[9] H. Zhang and J. C. Hou, "Maintaining sensing coverage and connectivity in large sensor networks," *Wireless Ad Hoc and Sensor Networks: An International Journal*, vol. 1, no. 1-2, pp. 89–123, January 2005.

[10] A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, and J. Anderson., "Wireless sensor networks for habitat monitoring," in *ACM International Workshop on Wireless Sensor Networks and Applications (WSNA)*, 2002.

[11] F. Chiti, M. Ciabatti, G. Collodi, D. D. Palma, R. Fantacci, and A. Manes, "Design and application of enhanced communication protocols for wireless sensor networks operating in environmental monitoring," in *IEEE ICC*, 2006.

[12] A. Manjeshwar and D. P. Agrawal, "Teen: Arouting protocol for enhanced efficiency in wireless sensor networks." in *IPDPS*, 2001.

[13] "Opnet technologies inc. www.opnet.com."