Performance Evaluation Model of Optimization Methods for Wireless Sensor Networks

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Abstract: - Wireless sensor networks are often composed of large number of wireless sensor nodes that are mostly using battery supplies. Nodes are small and equipped with sensors that cooperatively monitor physical world. Communication, sensing and computing have the most influence on performance and power consumption of wireless sensor networks. Various optimization methods are used to decrease power consumption and improve performance of wireless sensor networks. One of the novel methods is cross-layer approach. In this paper, first we present the advantages of cross-layer approach. The articles that are using a cross-layer approach for improving performance and energy preservation in wireless sensor networks are reviewed and state of the art is presented. In their work, scientists propose various optimization methods that are improving performance and decreasing power consumption. One of the fundamental problems is how to systematically make the performance evaluation and get the real contribution of these proposed optimization methods. In this paper, we develop benchmark methodology and performance evaluation model of various optimization methods for wireless sensor networks. Furthermore, we present the benchmark application for collecting and comparing performance measurement results of various optimization methods.

Key-Words: - Benchmark Application, Benchmark Methodology, Cross-Layer, Metrics, Performance Evaluation Model, Wireless Sensor Networks

1 Introduction

Wireless sensor networks are developing rapidly because large number of scientists from fields of electrical engineering, computer science, telecommunications, medicine, biology and other, are researching implementation and optimization of wireless sensor networks. This versatility rises from the fact that wireless sensor networks can be used for various purposes and in different environments because sensor nodes are small, cheap, intelligent and have low power consumption, as shown in [1] and [2]. They are mostly used in areas of environment observation, vehicle traffic monitoring, habitat monitoring, industrial automation and health applications.

Main functions of wireless sensor networks are sensing, computing and communications, similar as presented in [3]. Sensor nodes are small and often spread over huge areas where are no uninterruptible power supplies, so mostly they are using tiny batteries which are very difficult or impossible to replace. Therefore one of most important challenge is development of power efficient wireless sensor networks.

Scientists are using various energy efficient strategies for energy preservation [4]. The classic way it to optimize routing protocols in layered protocol architecture. This could be accomplished by minimizing energy consumption and/or by maximizing network life time. In [5] these classic strategies are put in four categories: energy efficient routing, scheduling the node sleeping rate, topology control by tuning node transmission power and reducing the volume of transferred information. Authors in [5] conclude that the most efficient way would be a combination of all four strategies, which is cross-layer approach.

By comparison with layered protocol architecture based on OSI (Open Systems Interconnection) and TCP (Transmission Control Protocol) models, cross-layer approach allows communication between nonadjacent layers. This ability gives more space for optimization and therefore cross-layer approach improves performance and energy preservation of wireless sensor networks.

Wireless sensor networks consume most energy for communication (transmitting, receiving and idle) and less for sensing and computing. Routing and cross-layer optimization protocols for wireless sensor networks are optimizing only communication but the big challenge is how to optimize data sensing which will decrease computing and the number of communications, as well [4]. Towards the various literatures, cross-layer approach is the best solution for energy-efficient communication in wireless sensor networks but there is no universal systematic methodology for performance evaluation of various optimization methods for wireless sensor networks. There is a need for universal performance evaluation method and standardized performance metrics so various optimization methods could be evaluated and compared.

In this paper, we focus on developing benchmark methodology and performance evaluation model that can be applied on various optimization methods. The main goal is to standardize and unify performance evaluation in order to get the real contribution of new proposed optimization methods. Therefore, we have made benchmark application for collecting and comparing performance measurement results of various optimization methods.

The remaining of this paper is organized as follows. We start out by giving an overview of layered architecture in Section 2 and cross-layer approach in Section 3. State of the art for cross-layer approach is presented in Section 4. In Section 5 we are presenting benchmark methodology and performance evaluation model of various optimization methods for wireless sensor networks. Section 6 concludes the paper.

2 Layered Architecture

To understand the cross-layer approach, first we introduce the layered architecture. Traditionally, communication inside wireless sensor network is managed by protocol stack which is organized in a series of different layers. Mostly this model has five layers as described in [6] and represents a hybrid between the OSI seven layer model and the four layer TCP/IP model, as shown in Figure 1.

The protocol stack in wireless sensor networks consists of the physical layer, data link layer, network layer, transport layer and application layer. Physical layer converts a bit streams into signal and it is responsible for frequency generation, signal detection, modulation and data encryption. Data link layer consists of two sublayers as shown in [6]: DLC (Data Link Control) and MAC (Medium Access Control) sublayers. Main objectives for data link layer are: multiplexing of data streams, data frame detection, medium access and error control. Primary function of network layer is routing data from the transport layer and data link layer. It also addresses methods on achieving a reliable and efficient communication between two communicating nodes. Transport layer bridge application and network layer by application multiplexing and demultiplexing, provides data delivery service between the source and the sink with an error control mechanism and regulates the amount of traffic injected to the network. Application layer is the interface for the users who are running their application software. More detailed description can be found in [7].

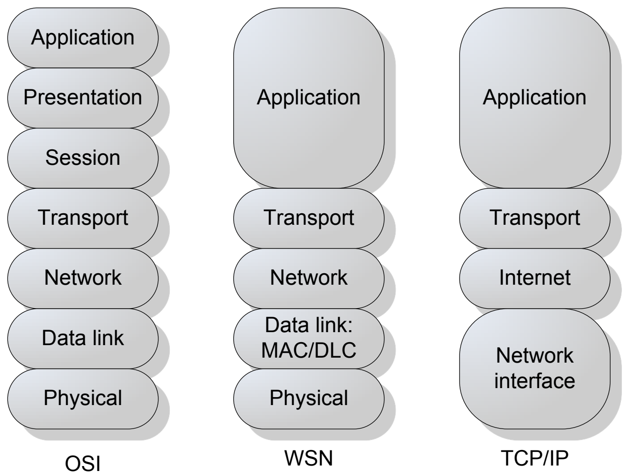

Fig.1 Comparison of similar layer models

Presented layer architecture of wireless sensor network protocol stack can fluctuate from this universal configuration. References [8] and [9] propose their own adapted architectures which have better performance and lower power consumption.

3 Cross-Layer Approach

In presented layered architecture in Section 2, all layers are individual and communication is allowed only between adjacent layers. Each layer has predefined functionality and can use only the services provided by the layer below it. In the cross-layer approach each layer can share information with any other layer.

As described in [10], the motivation for cross-layer approach is based on following:

- Multiple factors determine wireless sensor network system performance. Optimization of

individual layer often leads to inefficient solution;
- Individual and isolated optimization techniques may cause conflicts in optimization goals;
- Each group of applications requires different functionality. Cross-layer can provide application-specific performance;
- Cross-layer approach can hide the differences of various platforms from higher layers [11];
- Cross-layer approach provides nodes with unattended operation which anticipate node autonomy and self-configuration [11].

In many articles, of which state of the art is presented in Section 4, it has been proven that cross-layer approach improves performance by decreasing energy consumption, maximizing network lifetime, maximizing throughput and minimizing delays. As cross-layer approach has many interlayer interactions, big design and optimization space, the algorithms and system design are more complicated and challenging [10].

In [6] and [12], authors classify different kinds of cross-layer approaches from the literature and give the instructions on how these approaches can be implemented in layered architecture. They stated that cross-layer approach can be performed in four ways:

1. Creation of new interfaces between the layers for information sharing at run-time. It can be done into three ways: upward (from lower layer to a higher level), downward (from higher level to a lower layer), back and forth (iterative loop between two layers);
2. Merging of adjacent layers to a new superlayer without creating new interfaces;
3. Design couplings two or more layers at design time without creating new interfaces;
4. Vertical calibration across layers can be done statically by setting parameters at design time or dynamically at runtime.

In [11], cross-layer approaches are put into two categories. First is information sharing across layers while maintaining architectural protocol boundaries. Second is design coupling which ignore layer boundaries and integrate functionalities from different layers in order to optimize network performance metrics. Beside these two categories there is a middle ground solution that preserves layering and enhances it with richer interactions among layers to optimize performance.

4 State Of The Art For Cross-Layer Approach

Cross-layer approach has been intensively developed in recent years, because it does not have restrictions as layer approach. Still there is a lot of space for more improvements and this is the main motivation for the scientist to find better, cheaper, safer or more reliable cross-layer solution. In the following, state of the art for the cross-layer approach is presented.

Described cross-layer approach in third section applies to information sharing between different layers of one single station's protocol stack. In [13], authors are going step further. They propose a multi-hop communication model in which information can be exchanged between different layers of multiple stations. In experimental environment, they implemented this additional feature in WiseMAC protocol. WiseMAC protocol belongs to the unscheduled sensor MAC protocols and is very energy-efficient in scenarios with low or variable traffic. Performance results for case when supplying the routing layers with the knowledge of their two-hop neighborhood, shows that average one-way delay was decreased by 30%, without increasing of energy consumption. However, benefits in bigger wireless sensor networks are unknown.

If wireless sensor network consist of a symmetric and asymmetric links between nodes and if transmission protocol uses implicit acknowledges, the message route from source to destination could consist of asymmetric links but this information is hidden from the transport layer and the implicit acknowledgement cannot be sent directly to the source. The solution to this problem is cross-layer retransmission protocol family called IMPACT (IMPlicit Acknowledgement Transmission protocol) [14]. With cross-layer acknowledges and dynamic rerouting it provides bigger success rate which enables energy aware communication that has been proved in two experiments (on simulator and on real sensor nodes).

RMC, an energy-aware cross-layer data-gathering protocol for wireless sensor networks is presented in [15]. Compared to cross-layer scheduling scheme presented in [16], RMC increases the network lifetime. The basic idea is to reduce the overhead caused by managing the transmission schedule by integrating routing, MAC and clustering protocols. Therefore, each node can recompute its schedule and forwarding path without explicit message exchange. However, RMC is location based protocol and simulation is done under strictly determinate conditions which may not be easy to subject in real sensor networks.

In [17], authors presented a cross-layer data reporting scheme that provide an expected information quality at the end system by combining two communication protocols in network and MAC layers: QoS (Quality of Service) -aware data reporting tree construction and QoS-aware node scheduling. Simulation results show that their data reporting scheme is not affected by network density and has good throughput performance. Although this approach is based on single-hop cluster-based topology, authors conclude that it can be used for various topologies.

The extended DSR (Dynamic Source Routing) algorithm is presented in [18]. The extended DSR uses a cross-layer approach to determine whether the packet loss was the result of congestion or node failure. In both cases normal DSR would compute a new route which creates unnecessary energy consumption. Although extended DSR reduce route recomputing by enormous 50%, authors are going further with their future work by including TCP layer interactions.

Authors in [19] developed a cross-layer asynchronous protocol EEFF (Energy Efficient and Fast Forwarding), which improves low power listening approach by coupling MAC protocol with a dynamic routing selection. They evaluate performance by theoretical analysis and testbed experiments. Their experimental results show that in the sparse network average latency for B-EEFF (Basic EEFF) is 24.4% lower than for X-MAC+MiniHop, and in denser network for even 40.9%. In randomly deployed network, average latency is more 36.8% lower in 300 nodes network, and 45.3% lower in the 1000 nodes network. They conclude that EEFF shows great energy performance and improves the latency and it is much more suitable for large scale dense wireless sensor networks. However, their A-EEFF (Advanced EEFF) protocol should be improved to adopt the varying network condition.

In [20] authors did not design a new routing protocol, rather they present a solution that is flexible and easy to implement over several existing routing protocols. They designed a cross-layer multi-objective algorithm that focuses on three main wireless sensor network requirements: network sustainability, reliability and minimum delay. Performance evaluation was performed by computer simulation and real hardware experiments. Results show that their approach improves performance for different application requirements and preserve energy resources trough dynamic parameter tuning.

Flooding techniques are used in transmitting information from one node to all other nodes in network. After nodes receive the packets they retransmit it to all neighbor nodes which exist within their transmission range. FARNS (Flooding Algorithm with Retransmission Node Selection), described in [21] is cross-layer based flooding algorithm that reduces unnecessary retransmission by using identifier information and distance information of neighbor nodes from MAC and physical layer. Simulation results show that FARNS outperforms other flooding schemes in terms of broadcast forwarding radio, broadcast delivery ratio and the number of redundancy packets and overhead. However, these results are obtained in predefined network environment therefore addition benchmarks should be done for different environments.

5 Benchmark Methodology

Wireless sensor network is an active part of often big computer system. On the other hand, each sensor node is one small computer system that consists of several subsystems: power supply, sensing, computing (processing) and communication subsystem. Therefore wireless sensor network can be presented as collection of small computer systems.

As mentioned in [22], various factors of wireless sensor network have influence on performance and power consumption. These factors include computation at the nodes, network bandwidth, environmental problems and queuing at the sensor in the routing path. Each node consumes energy for sensing, data computing, communication and coordination. It is considered that data transmission consumes most energy of wireless sensors but data sensing and computing also consume a large amount of energy, sometimes more than data transmission [4]. Also energy-efficient data acquisition techniques decrease number of communications and reduce data sensing. Beside energy efficiency, energy balancing is main issue for energy preservation and prolonging network lifetime [23].

Whereas exist numerous various methods for energy consumption optimization and performance improvement of wireless sensor networks, following question is raised: What optimization approach is the best? In articles where new optimization methods are proposed, like [13], [14], [15], [17], [18], [19], [20] and [21], authors choose themselves performance evaluation methods. Mostly they compare their proposed optimizations with older one, and then evaluate results of comparison. However, the real contributions of new methods are unknown. As far as we know, there is no universal systematic methodology for performance evaluation of various optimization methods for wireless sensor networks.

In literature, individual performance evaluations are presented. Authors arbitrarily choose benchmark methods and metrics. In [24] authors create a WiSeNBench (Wireless Sensor Network Benchmark) benchmark suite from various sensor network applications to explore how they affect underlying architecture. They considered following metrics: code size, memory accesses, loads in memory accesses, frequent instructions and frequent pairs of instruction. In [25], authors selected benchmarks that represents usual tasks in wireless sensor network applications and perform experimental analysis of wireless sensor nodes current consumption. Performance evaluation of energy efficient ad hoc routing protocols is presented in [26]. For assessment, they use energy-related performance metrics such as average delivery ratio, average end-to-end delay, average overhead, average energy consumption and standard deviation of remaining energy among all the nodes. Similar performance metrics, as in [26], authors are using in [27] and [28]. In [27] authors perform a performance evaluation of IEEE 802.15.4 ad hoc wireless sensor networks. In [28] authors compare performance of the four mobile ad hoc network routing protocols.

5.1 Performance Evaluation Model

Universal benchmark suite for performance measuring of various wireless sensor network optimization methods would make possible to have universal and systematic methodology for collecting, comparing and evaluating optimization methods for wireless sensor networks. Universal benchmark suite should operate across all simulation platforms (e. g. as a framework) and it should be applicable on all types of wireless sensor networks.

All metrics that have influence on performance and energy consumption of wireless sensor networks should be evaluated. Performance metrics must be measurable, independent and comparable between various optimization methods. As wireless sensor networks are energy constrained, the main goal for the most optimization methods is to optimize energy consumption. Proposed energy-related performance metrics that should be evaluated in universal benchmark suite are similar as in [26], [27] and [28]:

1. Energy consumption: could have few submetrics as total energy consumption (in some time interval), average energy consumption per received packet or per node;
2. Network lifetime: time until first node failure;
3. Average delivery ratio: number of total packets successfully received/number of total packets sent;
4. Average packet delay: average time taken by the packets to reach its destination;
5. Average overhead: average energy consumed for overhearing;
6. Total data aggregation: amount of information sensed/amount of the power consumed by all nodes;
7. Standard deviation: deviation of the remaining energy among all nodes.

Additional performance metrics for evaluating wireless sensor network protocols are:

1. Throughput: number of total packets successfully received in observed time interval;
2. Average packet journey length: number of visit nodes on packet journey;
3. Response time: time needed for node to respond;
4. Sampling frequency: number of samples taken by each sensor in observed time interval.

Performance metrics used in our benchmark application are shown in Table 1. Total energy consumption E_T is defined as sum of all nodes energy consumptions in observed time interval. Network lifetime T is defined as time until first node failure but in shortest simulations it is mostly same as simulation time. Average delivery ratio is defined as number of total packets successfully received $pack_R$ per number of total packets sent $pack_S$, as shown in (1):

$$\%R_d = \frac{pack_R}{pack_S} \times 100 \qquad (1)$$

Average packet delay T_D is time metric expressed as total time needed for all packets

Table 1 Performance metrics of wireless sensor networks

Metric	Explanation	Unit	Relevance
E_T	Energy consumption (total)	mJoule	Less is better
T	Network lifetime	hour	Longer is better
R_d	Average delivery ratio	%	More is better
T_D	Average packet delay	second	Less is better
E_O	Average overhead	mJoule	Less is better
D_a	Total data aggregation	kbit/mWatt	More is better
σ	Standard deviation of the remaining energy among all nodes	mJoule	Less is better
v	Throughput	kbit/second	More is better
N_{np}	Average packet journey length	nodes/packet	Shorter is better
T_R	Average response time	second	Shorter is better
f_S	Sampling frequency	Hz	More is better

delivery per number of successfully delivered packets. Average overhead E_O can be calculated as sum of all overhearing energy per number of nodes. Total data aggregation D_a is defined as total amount of information sensed S_T per amount of the power consumed by all nodes P_T, as shown in (2):

$$D_a = \frac{S_T}{P_T}$$
$$S_T = \sum_{i=1}^{N_{nodes}} S_i \qquad (2)$$
$$P_T = \sum_{i=1}^{N_{nodes}} P_i$$

Smaller standard deviation σ means that the remaining energy of all nodes E_i is similar, and can prolong the whole network lifetime. It is expressed by:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(E_i - \bar{E})^2}$$
$$\bar{E} = \frac{E_1 + E_2 + ... + E_N}{N} \qquad (3)$$

The primary goal of some measurements is to determine which optimization method is “faster”. Therefore, we use the speed performance metric called throughput, defined in (4). Throughput v is calculated as number of total packets successfully received $N(pack_R)$ per observed time interval t. In order to simplify comparison, observed time interval is one second.

$$v = \frac{N(pack_R)}{t}$$
$$t = 1s \qquad (4)$$

Average packet journey length N_{np} is defined as count of all visit nodes for every successfully delivered packet per number of packets. The shorter packet journey length leads to less energy consumption [29]. Average response time T_R is important for event driven sensor networks. It is defined as sum of all response times per number of nodes. Sampling frequency is expressed as number of samples taken by each sensor $N_{samples}$ in one second, as shown in (5):

$$f_S = \frac{N_{samples}}{t}$$
$$t = 1s \qquad (5)$$

Sampling frequency depends on the purpose of the wireless sensor network. Some purposes like measuring atmospheric and body temperature or barometric pressure do not require high sampling frequencies as they are not changing often. Other purposes, like blood pressure or heart activity requires very high sampling frequency as their values are changing frequently.

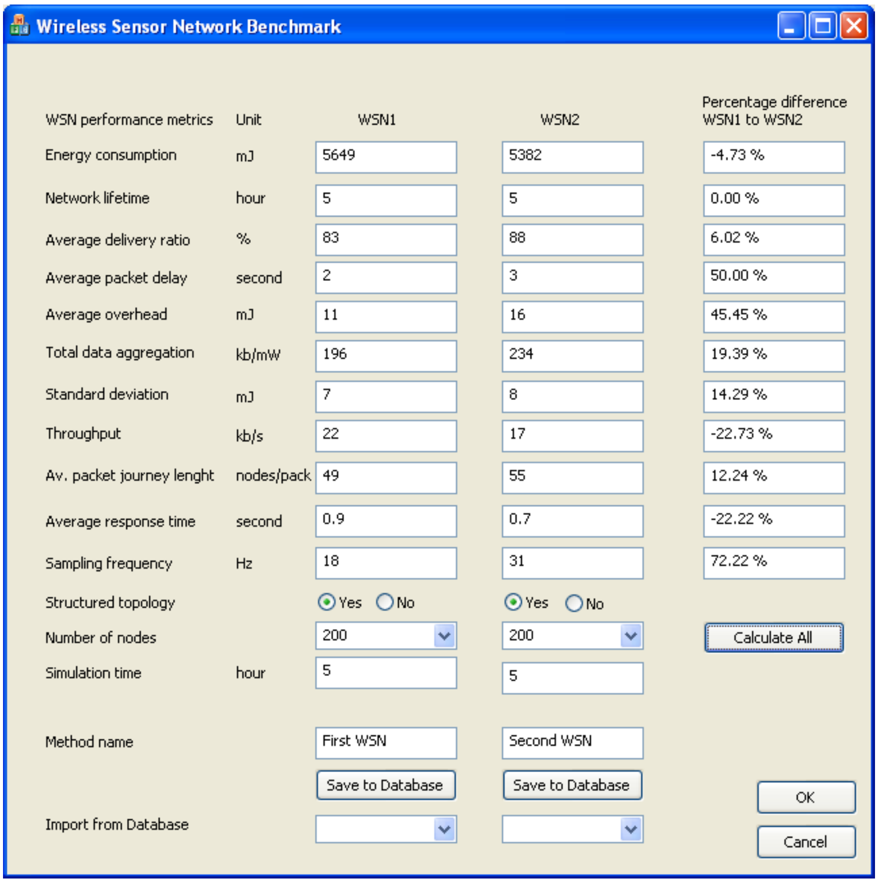

Fig.2 Benchmark application window

5.1.1 Experimental setup

As some methods are optimized to work on pre-planned structured topology and other for the unstructured (ad hoc) networks, universal benchmark suite should consider these two categories separately, however experimental setup must be identical for all optimization methods that are compared to each other. Performance measurements are divided according to predefined number of nodes (e. g. 5, 10, 20, …, 1000). These results of performance measurements on different number of nodes could show if optimization methods are affected by scalability. Also, simulation times must have unified values. Option for various traffic loads would be useful to show method efficiency. Benchmarking must be done under the same conditions for all optimization methods that are included in comparison in order to have valid performance evaluation.

The target of benchmarking is to present wireless sensor network optimization method behavior with numeric values which can be compared and evaluated. From the performance metrics results, optimization methods could be easier classified and therefore their purpose can be specified.

5.2 Benchmark Application

The primary goal of our benchmark application is to determine which wireless sensor networks performance optimization method is better, that is which has better performance measurements results. Therefore, performance comparison of two different methods is done with percentage error formula which calculates percentage difference between performance measurement results of two different optimization methods, as shown in (6):

$$\%Difference = \frac{WSN2 - WSN1}{WSN1} \times 100 \qquad (6)$$

As scientists often want to compare their results of a given measurement to some known results, performance measurement results of known (previous) optimization method (WSN1) are used as the referent values and performance measurement results of new optimization method (WSN2) are compared regarding to known.

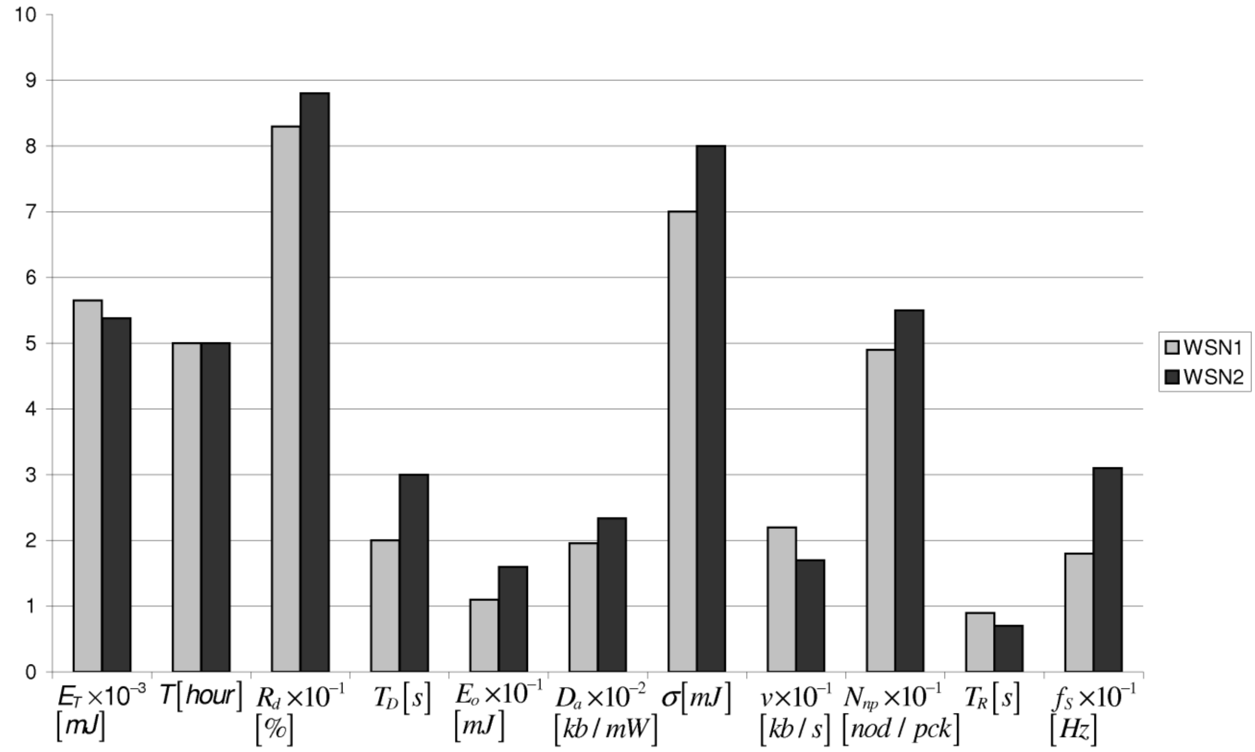

Fig.3 Performance measurement results of two different optimization methods

In order to obtain accuracy and precision of performance measurement results all measurements must be repeated ten times in same experimental condition. Final result of each measurement must be calculated as arithmetic mean of these ten repetitions.

We made the benchmark application shown in Figure 2, that collects performance measurement results and provide a comparison of two different optimization methods for wireless sensor networks. Furthermore, all results are stored in a database and can be accessed in any time. Main purpose of this application is to become a universal method for performance evaluation and comparison of various optimization methods.

Performance metrics used in our benchmark application are explained in Section 5.1 and shown in Table 1. Beside performance metrics, characteristics like topology, number of nodes and simulation time must be same for both optimization methods. Furthermore, previous performance measurement results can be imported to application. We simulated two different optimization methods and performance measurement results are shown in Figure 3.

6 Conclusion

In this paper, first we analyze the advantages of cross-layer approach in optimizing wireless sensor network performance and than present state of the art. Since wireless sensor networks consume most energy for communication, sensing and computing, various optimization methods are used to improve performance, conserve energy and extend network lifetime. In order to get the real contribution of various optimization methods we propose the benchmark methodology and performance evaluation model. The contribution of this model lies in standardizing and unifying performance evaluation of various optimization methods. Performance evaluation model is implemented in benchmark application that can be used for collecting and comparing performance measurement results of various optimization methods for wireless sensor networks.

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