Energy Efficiency in Wireless Sensor Networks: A Utility-Based Architecture[1]

Manoussos Athanassoulis, Ioannis Alagiannis and Stathes Hadjiefthymiades

***Abstract*—Wireless Sensor Networks (WSN) comprise a fast-developing research area with a vast spectrum of applications. A WSN design is influenced by many factors such as transmission errors, network topology and power consumption. Consequently, developing a WSN application introduces several implementation challenges. In this paper, we describe a multi-criteria architecture in order to achieve energy-aware and consistent message forwarding over a WSN. Using the proposed architecture a directed acyclic graph (DAG) is formed throughout the WSN. Such DAG is used for multi-source data aggregation to a single sink. Intermediate nodes evaluate their energy reserve and induced error and decide whether message retransmission is needed. A sink is necessary in order to collect, process and probably forward these data to a more sophisticated system for further processing. The discussed architecture is developed using TinyOS, an operating system designed for WSN nodes, and nesC, an extension of C. Finally evaluation results are presented.**

***Index Terms*—wireless sensor networks, energy efficiency, transmission control mechanism, utility function, message forwarding, extrapolation.**

I. Introduction

The recent advances in highly integrated digital electronics and wireless communication technology have led to the development of low cost, large-scale and low power sensor networks. Such networks are composed by a large number of micro-sensor nodes, which are equipped with communication and minimal computation capabilities. Sensor nodes are able to monitor a wide variety of physical parameters such as temperature, humidity, light, radiation, noise, etc., and report them using ad hoc network protocols and algorithms. The capabilities of sensor networks have significant impact on numerous application areas with varying requirements and characteristics in our life such as military control and communications; environment forecast systems, forest fire detection, medical treatment, as well as, traffic control and security. In the future, sensors collecting data will become really ubiquitous i.e., be found everywhere; in machines, buildings, even on our clothes.

The constraints of sensor nodes render the design and management of a WSN very challenging. Firstly, sensors have limited resources such as battery lifetime (varying from hours to several years depending on the application), computational power, data storage and communication bandwidth. Hence, it is important for a WSN architecture to take into consideration the network topology, power consumption, data rate and fault tolerance in order to avoid significant energy consumption and improve bandwidth utilization [2].

In this paper we propose a multi-criteria message forwarding architecture (MCMFA) [4] and discuss implementation details and evaluation results. The architecture's decision criteria are the current energy reserve, data consistency as well as time constraints. Sensed data are forwarded, using the above criteria, towards the sink node or straight to the sink node depending on their exact network position and using pre-established paths. The above criteria are quantified using a Utility function, described in Section 3, *System Architecture*. The proposed architecture does not apply a retransmission policy upon message loss (intentional or unintentional). Instead, data are approximated using an arithmetic method (e.g., Lagrange, Least Squares) based on recently received measurements. The same arithmetic method is used to approximate data if forwarding does not take place according to the thresholding of the utility function.

The objective of the proposed architecture is to prolong the lifetime of a WSN application. To accomplish this, unnecessary transmissions over the network are reduced and the induced error (due to no-retransmission) is preserved in acceptable levels. The presented architecture can cover a wide variety of application requirements and is further optimized through data aggregation, subject to the peculiarities of the observed physical parameters and WSN spatial distribution.

The rest of the paper is organized as follows. Section 2 refers to existing protocols and algorithms, for energy aware routing. In Section 3 we present our multi-criteria message forwarding architecture and we describe the introduced utility function. Section 4 and 5 are dedicated to the presentation of implementation and evaluation details about development and

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M. Athanassoulis is with the Pervasive Computing Research Group – Dept. of Informatics and Telecommunications, University of Athens, Athens, Greece (e-mail: m.athanassoulis@di.uoa.gr).

I. Alagiannis is with the Pervasive Computing Research Group - Dept. of Informatics and Telecommunications, University of Athens, Athens, Greece (e-mail: i.alagiannis@di.uoa.gr).

S. Hadjiefthymiades is with the Pervasive Computing Research Group - Dept. of Informatics and Telecommunications, University of Athens, Athens, Greece (e-mail: shadj@di.uoa.gr).

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energy awareness issues. Finally, our conclusions and our ideas for future work are summarized in Section 6.

II. Prior and related work

In the recent years, numerous articles have been published describing new algorithms, routing protocols and architectures aiming at WSN lifetime maximization, through energy awareness.

Already proposed routing techniques ([1], [3]) for WSNs aiming at energy conservation, employ routing tactics such as data aggregation, in-network processing, clustering, different node role assignment and data-centric methods. There are several ways of categorizing these protocols and algorithms. For example, they can be discriminated depending on the network structure to Flat Networks Routing (Data-centric routing [1]), Hierarchical Networks Routing and Location-based Routing [3]. Intanagonwiwat et al. [9] proposed *Directed Diffusion* a data-centric (i.e. all communication is for named-data) and application-aware paradigm aiming at avoiding unnecessary operations of network layer routing in order to save energy by selecting empirically good paths and by caching and processing data within the network. Yao and Gehrke [17] proposed another data-centric protocol, namely, *COUGAR*, for an architecture which treats the network as a huge distributed database system. *Energy Aware Routing*, a protocol proposed by Shah and Rabaey [13], although similar to Directed Diffusion, it differs in the sense that it uses occasionally sub-optimal paths to obtain energy benefits. This protocol can achieve longer network lifetime as energy is dissipated more equally among all nodes. *TEEN and APTEEN*, two hierarchical routing protocols are proposed by Manjeshwar and Agarwal [12]. TEEN (Threshold-sensitive Energy Efficient sensor Network protocol) and APTEEN (Adaptive Periodic Threshold-sensitive Energy Efficient sensor Network protocol) are suitable for time-critical applications. In both protocols the key factor is the measured attribute’s value. The additional feature of APTEEN is the capability of changing the periodicity and the parameters of TEEN according to user and application needs. The concept of generic, utility-based decision making in WSN is described in [5], where Byers and Nasser try to quantify the cost of each action performed by a sensor, by adopting heuristic assessments. Apart from routing protocols, PowerTOSSIM [14], a WSN simulation tool has been developed. PowerTOSSIM provides an accurate, per-node estimate of power consumption. PowerTOSSIM is an extension of TOSSIM ([10]-[11], [15]), the event-driven simulation for TinyOS [16] applications.

III. System architecture

The considered system architecture relies on three types/roles of sensor nodes:

- Sensing nodes (or sources) that sense certain physical parameters and transmit the relevant information towards other nodes in the infrastructure.
- Communication (or relay) nodes that, wirelessly, receive readings from sensing nodes (or other communication nodes) and relay them upstream towards the final recipient of such information. Communication nodes come into play whenever direct network connectivity is not feasible (due to limited resources such as power in the radio interface) and bridge the, otherwise inaccessible, nodes.
- Sink nodes that are the final recipients of the sensed information. Sink nodes are typically connected to conventional computing equipment for complex processing of the accumulated readings. Alternatively, sink nodes may be attached to another, more elaborate network topology (e.g., a WLAN or a fixed network) for further forwarding.

The aforementioned nodes form a directed acyclic graph, a rooted tree structure. The root of the tree is the sink node (exactly one node), all other nodes may assume the role of sensing nodes (at least one node is required), or communication nodes.

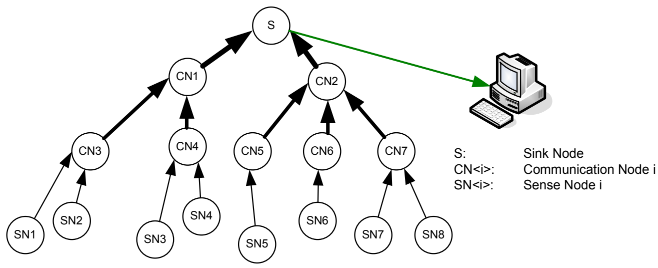

Fig. 1. WSN topology.

Through a sequence of nodes a data flow (DF) associating a certain leaf node with the root node is being served. For example, a data flow is SN4 → CN4 → CN1 → S. Every communication node reserves memory and communication resources for each DF, while sense nodes reserve resources only for their own DF. The architecture can be generalized in order to support a forest-like topology with multiple sinks. It is essential to maintain the concept of the DFs, that is, each node forwards all of its messages to the selected sink following an already established path. The core of the proposed architecture is an embedded control mechanism (called Transmission Control Mechanism, TCM) which optimizes the energy consumption within the WSN. Every sensing and communication node uses TCM in order to determine the utility of each upstream transmission. The TCM takes certain criteria into account and may decide not to propagate the considered message upstream. The peer TCM (i.e., the TCM found in the next node upstream) should be able to conceive this situation and react accordingly. Below, we describe briefly the criteria considered by the TCM for assessing the utility of message transmission, as well as the main components of the mechanism.

The considered mechanism implements Heart-Beat (HB) messages in order to determine whether a node is alive. These messages contain also sensor readings and they are transmitted unconditionally from every sensing node. Communication nodes forward HB messages unconditionally. Each TCM implements an extrapolation scheme on the received sensor readings. The monitored physical parameter is assumed to vary smoothly over time (e.g., as a polynomial function of time). Whenever a new measurement is presented to the TCM, the latter entity determines whether the peer TCM (in the upstream path) can reproduce the new value without, explicitly, receiving it. To achieve this objective, an a-priori agreed extrapolation scheme[2] (common throughout the WSN) is engaged. The local TCM calculates an extrapolated value (EV) for the sensed physical variable using previous measurements. The EV is compared against the actual, new measurement and the relevant error is calculated. The estimated error level will contribute to the determination of the message transmission utility. If the message is not transmitted upstream, then the peer TCM will perform the same extrapolation calculation and consider the (locally estimated) EV as the new received measurement. The receiving end performs this calculation when a timeout event occurs. Each TCM has a timer, which is restarted upon reception of a message or a timeout event. A timeout period is application specific. The mandatory forwarding of HB messages avoids an unconstrained error increase spatially and temporally. This scheme is applied for all the DFs handled by the considered node.

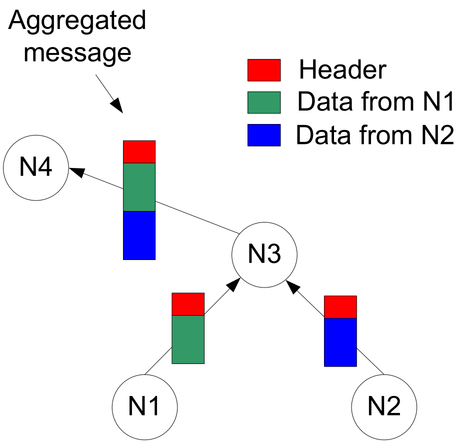

Fig. 2. Message Aggregation.

Furthermore, data aggregation is performed when a communication node is required to propagate values from more than one DF. The new message consists of the values that TCM designated as necessary transmissions. Using this aggregation mechanism, the data received and/or extrapolated from a node N, form a single message which is forwarded upstream, towards the sink. For example, as shown in Figure 2, messages from nodes N1 and N2, which are forwarded through N3, are aggregated forming a single message delivered to N4.

[2] An appropriate extrapolation scheme is chosen according to the nature of the sensed data.

A. Discussion on the Utility function design

In this section we describe the scheme that TCM adopts for the assessment of the utility of a message transmission upstream.

Let U_k denote the utility of the sensor node k with respect to the transmission of a new (not HB) message upstream. U_k is a function of time, the current node energy reserve and the received measurement for a certain DF. U_k is calculated as follows:

$$U_k = w_1 \cdot U^k_{energy} + w_2 \cdot U^k_{error} + (1 - \sum_{i=1,2} w_i) \cdot U^k_{time}, \quad \sum_{i=1,2} w_i \le 1$$

$$U_k = 1, \quad \textit{for all HB messages}$$

The weights w_i are application specific. The three utility components, for a given sensor node k, are calculated as follows:

$$U^k_{energy} = 1 - e^{\left[-10\frac{E}{E_{\max}}\right]}$$

$$U^k_{error} = \begin{cases} \dfrac{err^2}{(err_{threshold})^2} & err \le err_{threshold} \\ U_k = 1 & err \ge err_{threshold} \end{cases}$$

$$U^k_{time} = \begin{cases} 2 \cdot \dfrac{\Delta t}{\Delta T} & 0 \le \Delta t \le \dfrac{\Delta T}{2} \\ -2 \cdot \dfrac{\Delta t}{\Delta T} + 2 & \dfrac{\Delta T}{2} \le \Delta t \le \Delta T \end{cases}$$

where E denotes the current energy reserve of the considered node, E_{max} is the maximum energy quantity that can be accumulated in the node, *err* denotes the error induced in the measurement sequence by the extrapolation scheme that is globally adopted throughout the WSN topology, $err_{threshold}$ is the maximum tolerable deviation that can be induced in the collected readings, ΔT is the HB interval and Δt is the time that elapsed from the previous HB message transmission. The time component is mainly used in order to reduce the possibility of transmitting a message right after or right before the transmission of HB message.

The three utility components provide a full synopsis of the current status of the WSN, i.e., the energy component reflects the energy status of the node, the error component reflects the variance within a DF, and the time component reflects the clocking status of the entire topology.

Whenever the utility for a given sensor node k drops below an application specific threshold g, the sensor node halts upstream message re-transmission. Hence, the control condition for intelligent, energy aware message forwarding is:

$$U_k \ge g > 0$$

Threshold parameter g represents the trade-off between the two conflicting goals: energy conservation and quality of the gathered data. Taking into consideration the value of g, each node k achieves a balance between the energy cost of a message's forwarding and the utility of this transmission with respect to its usefulness to the specific application.

B. Node Finite State Machine

An important aspect of the proposed architecture is the step-based network synchronization. Each node follows a predefined duty cycle. During each duty cycle, a node changes states according to the operation being performed. This scheme ensures that each node will be synchronized with its neighbors. Synchronization is crucial in order to achieve reliable message forwarding, as well as, energy conservation. Having knowledge of its neighbors' duty cycle, a node's state can be changed to sleep mode in order to reduce energy consumption. During sleep mode, the node stops any computation and communication with its neighbors.

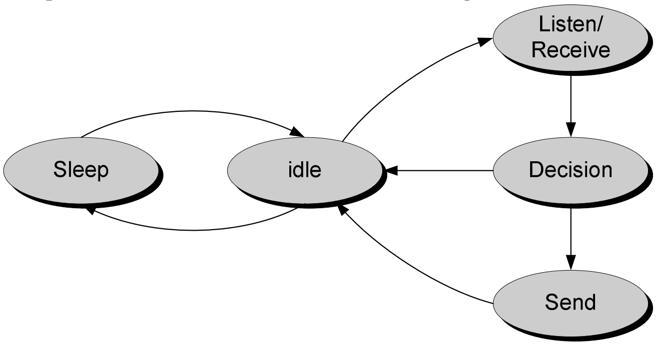

Fig. 3. Node's duty cycle.

As shown in the Finite State Machine presented, a communication node firstly listens for incoming messages. After the reception of a message (or after a timeout), the node computes the utility of the transmission of the values received (or extrapolated). Based on this computation, TCM decides whether an upstream message is going to be forwarded. During the remaining period of the duty cycle, the node stands by (in sleep mode). It is estimated that a node remains in sleep mode for over 75% of its lifetime.

IV. Performance Assessment

In this section we present the simulation of the proposed architecture, which was carried out using an event-driven WSN simulator. We describe in detail the simulation and evaluation parameters along with our basic design choices. This section also summarizes the simulation results, compares the performance of the proposed architecture against two basic forwarding schemes and discusses our main conclusions.

A. Evaluation Model

In this section, we discuss the underlying operating system, the adopted simulation platform and provide some details for the energy state model of a WSN node. TinyOS, an event-driven operating system specifically designed for sensor networks, has been used to develop several parts of the proposed multi-criteria message forwarding scheme. TinyOS has become a popular environment for experimenting with and developing sensor network applications. A TinyOS program is a graph of components (independent entities). It is a component-based runtime environment which has been developed using the nesC language. NesC ([6]-[7], [18]) is an extension of C that provides support for the TinyOS component and concurrency model and all the low-level features necessary for accessing hardware.

TinyOS supports a simulation environment, called TOSSIM (TinyOS SIMulator), which has been used to test some parts of the proposed architecture. TOSSIM is a discrete event simulator which executes components/applications intended for the WSN node but on PC hardware.

B. Simulation

To specify our simulation methodology we have to describe the WSN topology, the node energy model and the basic parameters of the architecture.

1) Simulation Setup

We carried out several experiments using WSN topologies having several source nodes but a single sink node. Every source node initiates a data-flow towards the sink which is routed through the communication nodes. During the WSN initialization phase each node dynamically acquires an identifier (ID), knows its role (communication node/source node) and neighbors (children, parent). Each message comprises a 56-bit-header and a variable sized body, depending on the forwarding decisions. Based on the role assigned to each node, only the needed modules are enabled, following a duty cycle. The duty-cycle aids in synchronizing communication and organizes the sequence of scheduled events, in order to increase energy efficiency. The simulation results are based on 15-node and 31-node DAG network topologies (full binary trees).

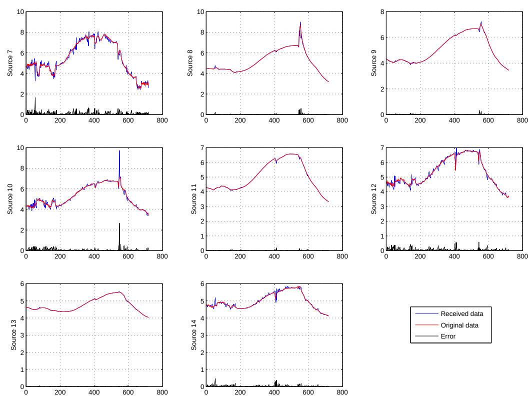

Fig. 4. Data and approximations (DFs from numbered sensing nodes – evaluated at the sink)

Moreover, we implemented several extrapolation schemes (i.e., Lagrange polynomials, least squares) and selected the appropriate scheme according to the sensed data. The following results are based on outdoor temperature data sensor readings[3]. The extrapolation scheme for this type of data was a linear polynomial, which demonstrated satisfactory accuracy. The HB messages were sent periodically (i.e., 2 messages

[3] http://www.stormwatch.com/index.asp

every 9 readings). Each experiment consisted of O(10^3) sensor readings and transmissions.

The evaluation of the utility for each transmission depends on certain parameters. Specifically, the weights w_1, w_2 and w_3, as well as the thresholds g, $err_{threshold}$ should be provided, based on the application. In our simulations, the chosen values were: $w_1 = w_2 = 0.35$ and $w_3 = 0.3$. The threshold g is set to 0.85 and $err_{threshold}$ is set to 0.1, allowing the induced error to get as high as 10% of the actual, sensed value.

TABLE 1
ENERGY COSTS

Node Operation Mode	Energy Cost
Instruction Execution	4 nJ/instruction
Idle	9.6 mJ/s
Stand-by	0.33 mJ/s
Transmitting	720 nJ/bit
Receiving	110 nJ/bit

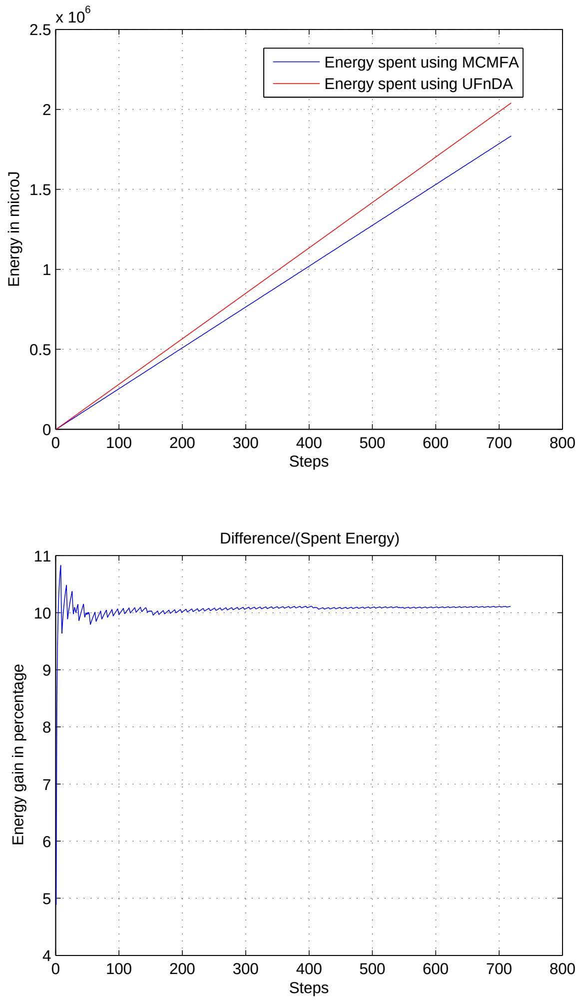

Fig. 5a and 5b. Comparison between UFnDA and MCMFA

Another very important design parameter is the node energy model. We adopted the Mica2 energy consumption model. Specifically, the execution of a single CPU instruction requires 4 nJ, the CPU while staying in idle mode consumes 9.6 mJ/s and in stand-by mode consumes 0.33 mJ/s. We also take into account the transition energy cost between different states. Finally, the energy cost of transmitting and receiving messages is measured per bit. Specifically, the transmission of a message costs 720 nJ/bit and the reception of a message 110 nJ/bit. These estimates are mean values of the lower and upper bound of transmission and reception costs. The above values are summarized in Table 1.

Our architecture is compared against two forwarding schemes. The first one assumes unconditional message forwarding upstream without performing data aggregation (labeled UFnDA). This scheme adopts the network synchronization following a similar duty cycle mechanism and is the worst-case scenario (with respect to energy efficiency in our simulations. The second scheme, (labeled UFDA) implements unconditional message forwarding upstream with data aggregation (concatenation of readings), following the same duty-cycle as the proposed architecture. This scheme provides better results than the first one, but worst from the proposed scheme, since all readings are actually transmitted towards the sink node.

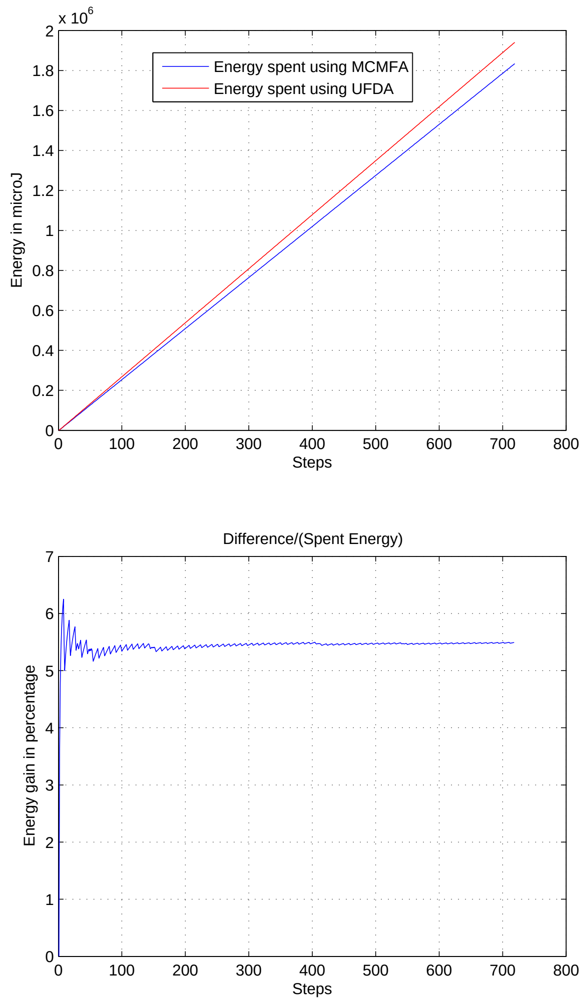

Fig. 6a and 6b. Comparison between UFDA and MCMFA

V. SIMULATION RESULTS

In the following paragraphs, we present in detail the simulation results of a typical node in the WSN topology. The considered node is a communication node which forwards readings and performs aggregation when necessary. The precise workload for this example is 715 readings.

The node under consideration, using the proposed scheme, received 335 messages (47640 bits) and forwarded 175 messages (37400 bits), out of a maximum of 715 messages. The same node, using UFnDA received 2860 (715 messages for each sense node attached to the subtree beneath the specific receiving node) messages (297440 bits) and forwarded all these messages upstream. In the UFDA mode, the same node received 1430 (715 for each communication node directly connected to the specific node) messages (217360 bits) and transmitted 715 messages (177320 bits). Figures 5 and 6 show the energy spent throughout the simulation period and the energy gain of the proposed solution with respect to the UFnDA and UFDA schemes.

Figure 5 plots the comparison between the energy spent using MCMFA and UFnDA along with the corresponding energy gain. We can observe that the relative energy gain is approximately 10%. Such savings could significantly elongate the WSN lifetime. The same comparison between MCMFA and UFDA is performed in Figure 6. The gain is lower, as expected, in particular about 5.5%. Numerous simulations using different parameter values, shows that effective energy conservation strongly depends on the succession of sensor states and WSN synchronization. Another very important issue when designing such a scheme is the fact that each node continuously consumes energy even in idle or in stand-by mode. As a result switching-off the radio component and limiting the listening period prolongs the lifetime of the WSN. Based on the simulation results (against UFnDA and UFDA) the conditional forwarding of MCMFA eliminates unnecessary transmissions, thus reducing the transmitted messages for about 60% - 70%. The proposed scheme, by combining conditional transmission, data aggregation and network synchronization succeeds significant energy savings. As stated earlier the gain climbs up to 10%, which is lower than the percentage of the messages which were not transmitted. This can be explained by the fact that the CPU of a mote consumes energy in the idle and standby modes.

VI. CONCLUSIONS - FUTURE WORK

In this paper we have presented a multi-criteria message forwarding architecture for WSN. The goal of the proposed architecture is to reduce energy consumption by avoiding unnecessary message transmissions. Energy awareness in WSNs is an emerging research area and the protocols presented in the relevant literature are focused on determining low-cost paths within the existing network. On the other hand, we try to avoid in-network transmissions if the induced error is acceptable. A combination of both techniques would lead to better results ensuring the prolongation of the lifetime of the WSN. Two protocols that could be combined with the proposed architecture are Energy Aware Routing and TEEN.

We believe that it is very important to evaluate the responsiveness of our architecture to increased node mobility. Node mobility is a prerequisite for some WSN applications, thus, resulting to even more demanding energy awareness and routing protocols. Moreover, we plan to implement intelligent data aggregation schemes to be embedded in the communication nodes. Such schemes may significantly reduce the upstream communication requirements by merging DF at a certain level within the WSN hierarchy. The applicability of the aggregation model is closely related to the nature of the monitored physical variables, the spatial WSN node distribution and temporal correlation of upstream messages. Finally, we intend to compare the presented scheme with already implemented protocols (i.e. Directed Diffusion).

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