This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2011 proceedings.

Re-usable Resources in Wireless Sensor Networks

A linear optimization for a novel application overlay paradigm over multiple networks

Sharief M.A. Oteafy and Hossam S. Hassanein
School of Computing
Queen's University
Kingston, Ontario, Canada
{oteafy | hossam}@cs.queensu.ca

***Abstract*—Today's abundance of sensors and their wireless/wired networks, coupled with a growing plethora of applications, necessitate a dynamic approach to the assignment of tasks to a network. The current practice in WSN design is almost always application specific, due to functional and resource tradeoffs that have justified much of the tailored research done so far. Identifying this as a major bottleneck in WSN advancement, this paper presents a new paradigm which decouples applications from WSN architectures and protocols. This paradigm views the network as an abundance of connected resources (hence functionalities) to match requirements of applications (old and new) based on utilization and feasibility factors. We present an elaborate abstraction of network resources, with detailed description of its governing utility attributes. Then we describe the view of applications as an aggregation of functional requirements based on a given set of resources. The intermediate mapping between applications and resources is then solved by a reduced linear optimization formulation, to realize the system as a whole. The paradigm is further explained via a multiple-application scenario; detailing its representation and operation.**

Keywords – Dynamic WSNs, Resource re-use, Linear optimization, Sensor Networks, Multiple applications, cross-network operation

I. INTRODUCTION

The promise of resourcefulness in Wireless Sensor Networks (WSNs) has been the major seller of this technology in the past decade. A plethora of applications have been investigated based on the premise of resilient architecture and communication paradigms of WSNs. With autonomous nodes that are typically small in size, equipped with computational and communication capabilities, and the flexibility of coordinated and self-healing operation, there was much to expect [1]. Coupled with remote operation and significant research covering its operation in terrains so far deemed inaccessible, the push for adopting WSNs continues to rise; both in diversity and quantity.

Nevertheless, the cost boundaries and margin of feasibility (let alone profitability) for real-life adoption of WSNs has posed much hindrance to the large scale deployments of such networks, despite the foreseen benefits [2]. As such, controlled deployments on medium to small scales, have been adopted to facilitate design, deployment, maintenance and re-construction when needed. The mainstream of protocols and architectures designed for WSNs are hence application-specific; merely attempting to address a set of requirements coupled with a fixed set of goals.

The argument for application specific WSNs is no longer as dominant as it was a decade ago [3], yet it dominantly carries in today's literature [4]. Formerly, considerably constrained sensing nodes had limited capabilities, and the design space was prominently targeting prolonged lifetime and sensing accuracy. This resulted in a significant direction of incremental tweaking and tuning in WSN literature, not stressing much of the abstractness that truly enhances the research scope of WSNs rather than their direct applicability.

Limited resources and cost metrics, as arguments for application-specific architectures, lost much momentum after many disappointing experiences with real life deployments of WSNs [5]. That is, the applications failed, and little has been proposed to leap fundamentally in WSN performance. Moreover, even in specific cases where a simple application should not require a generalized approach; tailored designs suffered the flexibility of scaling both in size and functionality should the need rise. As such, changes in requirements would dictate new deployments; rendering older ones superfluous and the whole system (old + new) shy of cost-effectiveness.

The core problem of design in WSNs is understanding the environment the network will operate in, the available resources (nodes, their costs, components and their accuracies, etc), lifetime expectancy among other requirements, the evolvement in operation and required maintenance. The design process is complicated by coupling between application requirements and interfaces, and the underlying components and topology.

To bridge the gap between applications and architectures, the field of middleware in WSNs has evolved as an interface. Protocols residing in the domain of middleware focus on abstracting the resources available in a node, and porting their functionality to the application layer in the nodes operational stack [9]. Nevertheless, this forms a decoupling strategy to facilitate better exposure of network resources to aid in their utilization at the design phase. As such, this approach lacks malleability for post-deployment adaptation to new requirements or applications.

Our contribution in this domain is twofold. The first presents a dynamic abstraction of network utility, in terms of the resources it encompasses, to facilitate run-time functional allocation to cater for multiple applications. Thus, presenting a framework for overlaying (assignment of) multiple applications over the same WSN after deployment. The second fold of contribution approaches this assignment problem as an

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2011 proceedings.

optimization one, presenting a (relaxed-to) linear formulation that is both tractable and readily solvable by the inherently resource-constrained WSN.

This paper presents the seed of this work in the following structure. Section II presents the motivation for this work, detailing the relevant background in middleware research and respective post-deployment maintenance protocols. The resource and application overlaying model is presented in Section III, abstracting the network into resources and mapping functional requirements of the applications to it. This mapping problem is analyzed and presented as an optimization problem, which is presented with its formulation in Section IV. This framework is evaluated in Section V, and its efficiency (cost) and resilience are demonstrated. The paper concludes with final remarks and future directions in Section VI.

II. Motivation and Background

Today's world is already covered by many WSNs. The spectrum of domains in which sensors are incorporated is vast. Current efforts of analyzing post-deployment faults, in addition to mainstream research on improving performance, will render even more WSNs feasible and deployable in the near future. As such, it is inevitable that we will witness a significant number of sensing systems, deployed in isolation, utilized for different applications yet sharing a similar resource pool.

We note this as alarming resource underutilization, unnecessitated redundancy, and degrading interference. That is, catering for the same task by different networks, within the same region, is unreasonable redundancy. Our argument articulates on leveraging network performance by utilizing resources already deployed in a region, instead of re-introducing similar ones to cater for a given application.

A. Why application overlay

It is quite notable now that significant improvements in WSN performance cannot be achieved solely by incremental achievements in hardware nor protocols governing their operation. A clear saturation is being drawn in routing, MAC and load balancing protocols. Though much has been proposed in new domains, such as energy harvesting to sustain prolonged information (e.g. with more efficient photovoltaic cell – such as organic cells), there's a significant cap on feasibility due to costs. These include designing and implementing new WSNs for new applications, and the costs of deployment and maintenance. These issues incur even more costs when the network has to scale to larger deployment/coverage regions [8].

With these hindrances, it is inevitable to consider resource re-use for multiple applications. This should not be capped at running different versions of software on the same platform, to introduce a modified operational scheme; as this still views the WSN as a single application network. The true leap lies in visualizing the network as a pool of resources that different applications could exploit; in parallel or in succession. For example, a camera might only be used by one application at a given time to direct it towards an application-specific target. Yet, a luminosity sensor might be probed by more than one application concurrently. The first could use it to dictate light dimming in urban lighting, an other application utilizes it to decide on dependency on solar power, and the third could utilize it for setting ISO parameters on surveillance cameras. Compare the foreseen redundancy in a simple resource such as this, if all these applications deployed their own WSNs.

B. Middleware in WSNs

One of the earlier efforts tapping into inefficient coupling of hardware and applications was approached by research in middleware for WSNs [7]. The basic idea was introducing an interface between the application layer and the underlying operating system functionalities. This allows for an abstraction that eases the programmers task in utilizing a node's capabilities. Current efforts in this track incorporate many methods of remote dynamic re-programming of sensor nodes to adapt to new operations. This includes fixing problems in older versions of code, and the adaptation of possibly more than one application [9].

C. Post-deployment maintenance schemes in WSNs

An other track of research is focused on identifying efficient means of distributing newer versions of the firmware governing node operation [7]. Many hindrances in communication overhead and time latency are being addressed to improve WSN operation while undergoing frequent firmware updates. It is imperative to note the gains in being able to revamp a nodes protocol and introduce a new one for new applications, yet the cap on resource utilization and inter-network operation remains a major hindrance to their improvement. Other efforts have discussed going in-field to address maintenance issues in nodes, and re-programming them manually [2]. Yet, major shortcomings are faced especially in large scale deployments or hazardous terrains.

III. Application overlay model

Supporting multiple applications on a single WSN has been marginalized in research due to the foreseen overhead in design complexity and network performance; prominently the effect on energy-efficient operation. The "no-free-lunch" argument long hindered a truly dynamic approach to handling varying function requirements as the network evolves.

This paper presents a model for establishing this overlaying approach, under the same umbrella of tradeoffs henceforth deeming it impossible. This paradigm is built on three core principles. (1) Resources should be utilized in isolation of their governing nodes, such that low-duty cycles, stringent spatial confinement and enforced locks on resources should not hinder their utilization. (2) The network should be able to adapt to new functional requirements if the required resources are available. (3) Network utility should be determined based on the applications it could support while retaining its globally set lifetime and QoS constraints.

To these three problems, we present an elaborate model for abstracting resources in a typical homogenous WSN scenario; being the general case. The flow of operation from application requirements to actual mapping on available resources will be detailed in this section. Figure 1 presents an overview of how the system maps functional requirements of multiple applications to the underlying WSN, in contrast to current paradigms; handling applications in singularity and overlayed.

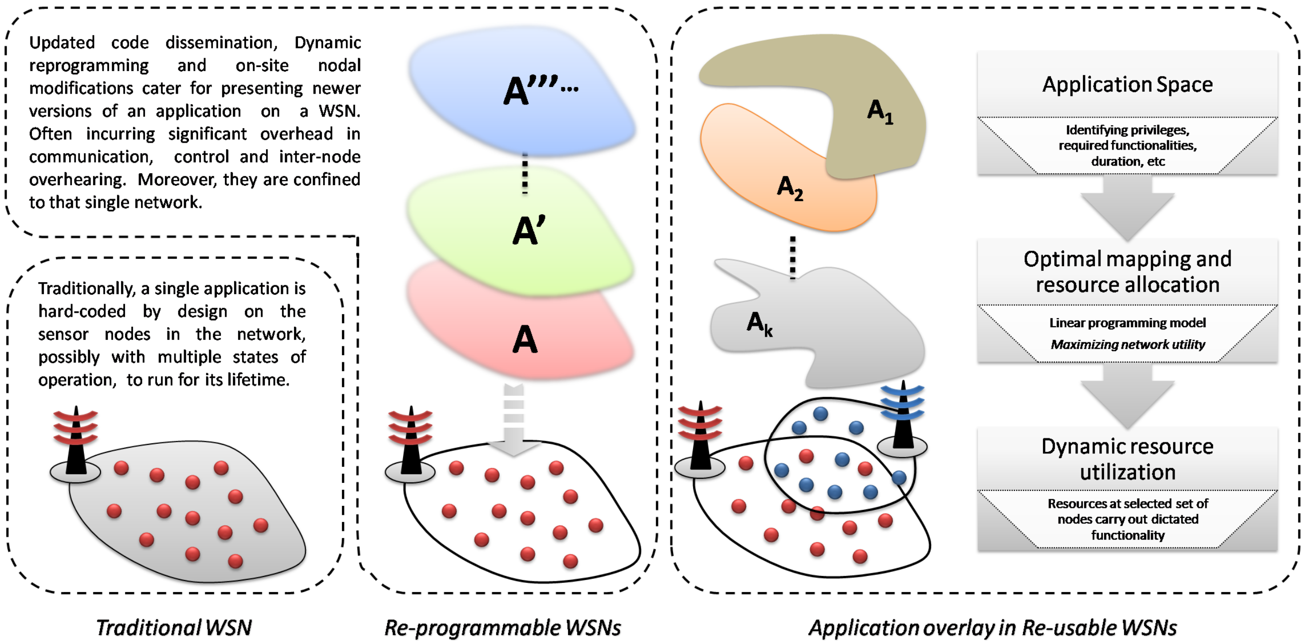

Figure 1 – From a network perspective, this diagram depicts the different approaches to implementing applications over the architecture, and its evolvement over introducing new applications and modifying existing ones. Our Re-usable WSNs are presented in contrast to former paradigms.

A. Network design considerations

Homogenous WSNs are quite dominant in research as they promote many positive design parameters. They allow for efficient load balancing, coordinated off-loading between nodes, reduction in production and deployment costs, and reduced complexity in coverage and connectivity maintenance. All these parameters promote an efficient base for dynamic operation with scalability to varying nodal densities.

As such, we adopt a homogenous architecture, and model the resources distributed uniformly over all the sensing nodes. Accordingly, resources need not be realized in terms of which node they are attached to, but rather where they deliver their functionality. With such an architecture, connectivity and coverage issues are beyond the scope of this work. Their establishment is a trivial problem of adequate deployment density and uniform distribution over the sensed region; already heavily investigated in the literature.

It is important to note here the view of a WSN as an aggregation of its resources. Hence, functionality is determined by the attributes if these resources, and their accessibility over time. We assume a network where a given set of resources **R** is available, and a set of applications **A** are catered for. The set **A** changes over time, and at each change the network is probed to re-assess the efficient mapping of **A** over **R**.

B. Resource abstraction

Resources, as the founding base of this approach, need a concrete representation reflecting their usage feasibility whenever probed. That is, successful mapping of functionality to resources, hence catering for multiple applications, requires a thorough manifestation of all its attributes.

We identify six major attributes for each resource, over the homogenous network, to present a rigorous manifestation of the domain of applications it could support. The first describes the *functional capability* of this resource. For example, if this resource is an RF unit, it could Tx, Rx and listen to the channel. The second pertains to *power consumption* patterns, prominently in mW, to calculate how much energy a certain task would consume by that resource (draining its battery if dedicated, or that of the node holding the resource).

The third and fourth attributes, namely *location* and *duty cycling*, pertain to the availability of such a resource. The former gives us locations at which this resource is available (in the region of deployment) and the latter projects the temporal aspect of its availability; that is, when would this resource be up for use.

Region of fidelity, an abstraction of coverage, encompasses the broader definition of what it is to accurately report information about a certain region in the vicinity of the sensor. For a temperature sensor for example, this could span many meters. On the other hand, an ultrasound sensor set to detect thickness may only span a few centimeters. The interested reader may refer to [9] for a detailed view of coverage issues. As far as this model is concerned, fidelity region has to do with the shape of the sensing region (especially irregular ones often referred to as amoeba coverage), and physical attributes of the environment and sensed phenomena/object that would dictate varying levels of accuracy (as a threshold) and fidelity in reporting.

Finally, the sixth attribute covers *levels of operation*. For a given resource, it is imperative to decide upon distinguishable operational levels (also referred to as states) that dictate functional capacity as well as power dissipation models.

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2011 proceedings.

C. Applications as a function of resources

On a higher level of abstraction we formalize an application as the aggregated coordination of resource utilization to achieve a pre-determined sensing task (or more). For example, forestry monitoring applications might probe a deployed WSN for temperature/humidity readings, detecting movements and taking images when extremities are noted in any of the scalar phenomena it senses. Simply, this is the aggregation of data collected from these scalar resources (sensors) and the communication (transceivers) and control logic of determining when images need to be taken (processors and memory) and relaying all of this to a collection point with enough resources (memory, processing, etc) to analyze the information and relay it. Thus, we introduce a definition for applications as follows.

Definition 1: *An application is a best-effort scheme for mapping functional requirement* **F** *to a set of resources* **R** *within connected WSNs, with tradeoff considerations for efficiency and QoS measures given cost constraints.*

D. Mapping Applications to network functionality

In most cases, identifying resources available in a network is quite trivial. Nevertheless, determining all of the attributes of these resources, their temporal properties and current resilience to faults is non-trivial. It is trivial to design an architecture wherein resources would declare their availability periodically, and provide information about their attributes when probed. Yet, an inherently complex problem is determining when and where failures have impacted nodal performance, hence the attached resources are severed from the network backbone.

Mapping the network view of what it could offer, and the requirements side of the application, given the governing cost/QoS measures, inherently belong to the "no free lunch" optimization problems. Many heuristics have approached this, especially in a tailored-application specific approach, to alleviate problems with intractability of efficient allocation of resources to requirements. This has not been hitherto a major problem to tackle as WSNs were built to their tasks, hence it was merely a one-to-one mapping as needed. Yet, our approach dictates a new challenge in facilitating this allocation, and doing so efficiently to leverage its feasibility.

Given a set of applications **A**, we represent the functional requirements of each application $\boldsymbol{a_i} \in \boldsymbol{A}$ as a set $\boldsymbol{f_i}$. Thus, catering for all applications, we generate the set $\boldsymbol{F} = \cup_i \boldsymbol{f_i}$ to represent the detailed functions required under the same attribute representation of resources. With all resources in the network, across multiple WSNs, finitely accounted for in the set **R**, our network would require optimal mapping of: $\boldsymbol{F} \rightarrow \boldsymbol{R}$

Thus, given **A, F** and **R**, we aim to efficiently maximize *network utility*. As such, it is inherently an optimization problem with two sets of constraints. The first encompasses network level constraints such as lifetime, cap on available resources, privileged operations, load balancing scheme and threshold of loads on certain (mostly pivotal) nodes/resources in the network. The second set of constraints are application dependent. They could change over application life time and as new applications are introduced (and others terminated). These mostly pertain to functional aspects, the degree of service required and resources needed at each service level.

IV. Optimization Model

The goal of this model is to solve the problem of mapping multiple applications on a given group of WSNs. While different approaches for solving this mapping could be proposed, we present a linear optimization formulation.

A. Assumptions

Each application would be introduced via only one network, we assume it to be the central network. WLOG, having all nodes running the same scheme of resource abstraction and functional mapping, it does not matter to which network a used resource belongs to. Since this model is built upon the wirelessly communicating nodes and resources, this abstraction of single-entry to network does not undermine the global goal; especially as the network enforces local lifetime constraints on the solution space.

We assume the networks to be used are already deployed and connected. The connectivity requirement is sufficed by a sink that is reachable by all nodes (a graph which maintains paths from all sources to a single destination). All nodes are assumed to have a measurable reservoir of energy, in J, which the attached resources could use and report. Generally, each node should be able to identify its resources, and represent them according to the attributes highlighted in sub-section III.B. This inherently includes their locations and functionalities. In typical scenarios, the latter requirement is trivial when the network is homogenous.

Finally, resource's region of fidelity is assumed to be known by the application. Since varying resources could have different representations of coverage, we adopt a point-based coverage. Accordingly, each application will dictate a finite set of points which should fall within the regions of at least 1 node/point, to satisfy application coverage criteria.

B. Linear optimization model

Since the goal is maximizing Network Utility (NU) over the number of applications imposed on the network. The objective function and its constraints are defined as follows:

Maximize Network Utility (NU), defined as:

$$NU = \sum_{i=1}^{k} a_i \, s_i$$

where $\boldsymbol{a_i} \in \boldsymbol{A}$, the set of applications to run over the network, s.t. $\boldsymbol{a_i}$ and $\boldsymbol{s_i}$ represent application $\boldsymbol{i}$ and its serviceability, respectively, and $\boldsymbol{k}$ is the number of applications, subject to:

(1) Ensuring each point of service request for application $\boldsymbol{i}$ is covered by at least 1 node:

$$\sum_{v \in fid(P_{i,cp})} R_{v,r,i} \geq 1$$

where $P_{i,cp}$ is a point $\boldsymbol{cp}$ in the plane of application $\boldsymbol{i}$ that requires coverage, and R is the set of resources available for all the nodes in the network, defined as:

$$R_{n,r,i} = \begin{cases} 1 & \text{if resource } r \text{ of node } n \text{ is used for application } i \\ 0 & \text{otherwise} \end{cases}$$

and $\boldsymbol{fid}(P_{i,cp})$ is the set of all nodes that contain $\boldsymbol{P_{i,cp}}$ in their region of fidelity.

(2) Ensuring all points of each application $\boldsymbol{a_i}$ are covered:

$$\forall\, \boldsymbol{a_i} \in \boldsymbol{A} \qquad \sum_{n \in N} R_{n,r,i} \geq m_i$$

where $m_i \in M$ representing the set of minimum resources needed to sustain application $\boldsymbol{i}$ and N is the total number of nodes (with resources) in the network.

(3) Ensuring the load of all applications will not exceed available energy reservoirs at nodes:

$$\forall\, \boldsymbol{n} \in \boldsymbol{N} \qquad \sum_{i=1}^{\boldsymbol{k}} \left(\boldsymbol{d_i} \sum_{\mu=1}^{\sigma_n} \left(\boldsymbol{c_{i,\mu}} \times \boldsymbol{R_{n,\mu,i}} \right) \right) \geq e_n$$

where $\boldsymbol{d_i} \in \boldsymbol{D}$ represents the duration for which application $\boldsymbol{i}$ would run for over the network. $\boldsymbol{\sigma_n}$ is the number of resources each node $\boldsymbol{n}$ holds. $\boldsymbol{c_{i,\mu}}$ denotes the incurred power consumption if resource μ is used for application $\boldsymbol{i}$. Finally $\boldsymbol{e_n} \in \boldsymbol{E}$ is an indicator of the remaining energy (in J) in node $\boldsymbol{n}$.

(4) The following scalars are to meet the domains identified by: $\mu, r, n, k, i \in \mathbb{N}^*$, $\sigma_n \in \mathbb{N}^0, R \in \{0,1\}, v \in N$

Finally, serviceability of application I, denoted by $\boldsymbol{s_i}$ is calculated as:

$$s_i = \frac{\sum_{P_{i,\tau}} R_{n,\tau,i}}{m_i}$$

Which would represent NU in terms of proportional service offered to each application.

V. A USE CASE

To demonstrate how our paradigm of resource re-use over multiple applications works, we detail in this section a simple example incorporating two applications A and B. The former requires still images and the latter requires temp monitoring.

The problem is depicted in Figure 3. Each application requires three points to be covered marked by cameras for A, and thermometers for B. We have two networks, the one on the left, marked in red (3 nodes), and the bottom right marked in blue (2 nodes). E = {100, 80, 40} for the red network and E = {80, 50} for blue. The fidelity regions of nodes in both networks are marked by the outer circle marking its coverage borders. Assume D = 100 hours for each, and power consumption is equal across resources. Coverage points (cp) are enumerated in a top- bottom, left- right order.

For A and B we note: $\boldsymbol{fid}(P_{A,1}) = \{red_1\}$, $\boldsymbol{fid}(P_{A,2}) = \{blue_1\}$, $\boldsymbol{fid}(P_{A,3}) = \{blue_2, red_3\}$, $\boldsymbol{fid}(P_{B,1}) = \{blue_1, red_2\}$, $\boldsymbol{fid}(P_{A,2}) = \{red_2, red_3\}$, $\boldsymbol{fid}(P_{A,3}) = \emptyset$.

Thus, running our optimization scheme, based on the energy values given and the duration noted, we note the following assignments:

$$for\ blue \rightarrow R_{n,i} = \begin{bmatrix} 0 & 1 \\ 0 & 1 \end{bmatrix} \qquad for\ red \rightarrow R_{n,i} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \\ 1 & 0 \end{bmatrix}$$

Yielding $NU = \frac{2}{3} A + B$, and the outlying point by application A (bottom left) un-serviced with balanced network load.

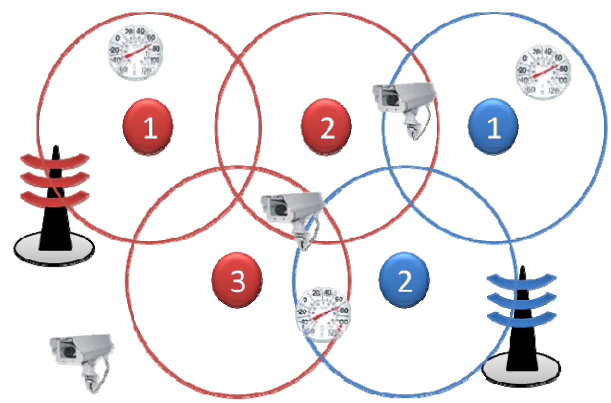

Figure 2 –Mapping applications to resources from the use case

VI. CONCLUSIONS

Current practices for designing Wireless Sensor Networks (WSN) persistently yield application specific networks; thus far driven by a basic tradeoff between functionality and resource availability - one that has received great research attention over the years. This paper parts from this traditional model and offers a new WSN approach that decouples application considerations from network architecture and protocol. We presented this paradigm on three levels. The first abstracts resource across existing networks to enable identification & feasible utility. The second represents applications as a group of functional requirements to be met by a given finite number of resources. Finally we present an optimized mapping model to attach applications to the available resources. The model promises a great potential for realizing large-scale WSN unity.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, E. Cayirci, Wireless sensor networks: a survey, Comp. Net., Vol 38, Iss 4, 2002, pp 393-422.

[2] G. Barrenetxea, F. Ingelrest, G. Schaefer and M. Vetterli, The hitchhiker's guide to successful wireless sensor network deployments. In Proceedings of the 6th ACM conference on Embedded network sensor systems (SenSys '08). ACM, New York, NY, USA, 43-56.

[3] A. Salhieh, J. Weinmann, M. Kochhal, L. Schwiebert, Power Efficient Topologies for Wireless Sensor Networks, icpp, pp.0156, International Conference on Parallel Processing (ICPP '01), 2001

[4] G. Anastasi, M. Conti, M. Francesco, A. Passarella, Energy conservation in wireless sensor networks: A survey, Ad Hoc Networks, Volume 7, Issue 3, May 2009, Pages 537-568

[5] R. Kuntz, A. Gallais and T Noel, Medium access control facing the reality of WSN deployments. SIGCOMM Comput. Commun. Rev., Vol 39, Iss. 3 (June 2009), pp. 22-27.

[6] T. Heimfarth, E. Pignaton de Freitas, F. Wagner, & T. Larsson, Middleware Support for Wireless Sensor Networks: A Survey. Handbook on Developments and Trends in Wireless Sensor Networks: From Principle to Practice. (2010). pp. 235-261

[7] W. Li, Y. Zhang, J. Yang, and J. Zheng., Towards update-conscious compilation for energy-efficient code dissemination in WSNs. ACM Trans. Archit. Code Optim. 6, 4, Article 14 (October 2009), 33 pages.

[8] D. Puccinelli and M. Haenggi, Reliable data delivery in large-scale low-power sensor networks. ACM Transactions on Sensor Networks (TOSN) Vol 6, Iss. 4, Article 28 (July 2010), pp. 1-41.

[9] M. Wang, J. Cao, J. Li, S. Dasi, Middleware for wireless sensor networks: A survey. Journal of Computer Science and Technology Vol. 23, Iss. 3, 2008, pp. 305 -326

[10] C. Huang and Y. Tseng, The coverage problem in a wireless sensor network. Mobile Nets & App Journal, Vol.10, Iss.4 (2005), pp. 519-528