

Middleware for Wireless Sensor Networks: A Survey

Salem Hadim and Nader Mohamed

*Department of Electrical and Computer Engineering
Stevens Institute of Technology
Hoboken, NJ 07030, USA
{shadim, nmohamed}@stevens.edu*

Abstract

Given the fast growing technological progress in microelectronics and wireless communication devices, in the near future, it is foreseeable that Wireless Sensor Networks (WSN) will offer and make possible a wide range of applications. However real world integration and application development on such networks composed of tiny, low power and limited resources devices are not easy. Therefore, middleware services are a novel approach offering many possibilities and drastically enhancing the application development on WSN. This survey shows the current state of research in this domain. It discusses middleware challenges in such networks and presents some representative middleware specifically designed for WSN. The selection of the studied methods tries to cover as many views of objectives and approaches as possible. We will focus on discovering similarities and differences by making classifications, comparisons and appropriateness studies. At the end we argue that most of the proposed work is at an early stage and there is still a long way to go before a middleware that fully meets the wide variety of WSN requirements is achieved.

1. Introduction

The advent of technology in computing and electronics is pioneering an emerging field of tiny-networked sensors, offering an unprecedented opportunity for a wide array of real time applications. These tiny sensor nodes are low cost, low power and easily deployable. When combined together they offer numerous advantages over traditional networks such as large-scale flexible architecture, high resolution sensed data, and application adaptive mechanisms. Due to their tight integration to the physical world and unique characteristics, sensor networks in general pose considerable impediments and make the development of applications non-trivial. A sensor node should sense, process and communicate the

data to wherever it is used with minimum resource consumption. There must be new programming paradigms and new operating systems that glue every thing together in an efficient manner, supporting concurrency-intensive operations and insuring robustness and modularity. A friendly user programming interface that executes applications and marshals the high level constructs of the programming language to the low level constructs understandable to the operating system should be provided. The middleware should be customizable to different scenarios, applications and environments, also be self-optimizing and self-protecting.

Indeed the need for a middleware layer that fully meets the design and implementation of different challenges of sensor network technologies is a novel approach to resolve many of the open issues and drastically enhance the development of applications on such networks.

Some research effort has been done on surveying WSN. [3] focused more on WSN characteristics and challenges. [10] and [12] investigated potential WSN applications, and [21] presented different routing protocols. However none of the existing work investigated the current state of research on design and development of middleware for WSN. In this paper we explore different relevant middleware projects for WSN, and provide an exhaustive comparative study. The remainder of the paper is structured as follows. Section 2 provides a short overview of sensor networks applications and outlines the most relevant challenges that face a middleware design for wireless sensor networks. In Section 3, which is the focus of our paper, and due to paper length restrictions, extensive description will be reserved for the most representative current research projects and approaches undertaken towards this perspective. In Section 4, a classification and comparison between all the projects is provided. In section 5 we discuss some open research issues, and then we conclude the paper.

2. Middleware For Sensor Networks Challenges

Wireless Sensor Networks are emerging as a suitable new tool for a spectrum of new applications in recent years [12]. They are easily deployable at a large scale, low power, inexpensive and self-organizing. These unique characteristics make them advantageous over traditional networks. Sensor networks applications were originally motivated by military applications such as target detection, surveillance of enemy activities in a battlefield environment and counterterrorism; however, their many advantages over traditional networks resulted in the development of many other potential applications [10] that range from infrastructure security to industrial sensing. Some examples are: environment and habitat monitoring, health applications, home automation, traffic control, etc.

The design and development of a successful middleware layer for WSN is not trivial. It needs to deal with many challenges dictated by WSN characteristics on one hand and the applications on the other hand:

- **Hardware resources:** The advent in microelectronics technology made it possible to design miniaturized devices in the order of cubic centimeters [14]. Limited in energy and individual resources, these tiny devices could be deployed in hundreds or even in thousands in harsh and hostile environments where in some cases no physical contact could be possible for replacement or any maintenance scope; therefore, the wireless media is the only way for remote accessibility. A middleware should provide mechanisms for an efficient use of the processor and memory while enabling lower power communication. A sensor node should accomplish its three basic operations which are: sensing, data processing, and communication [14] without resources exhaustion. As an example of energy aware middleware, most of the device's components including the radio are likely to be turned off most of the time depending on the application.
- **Scalability and network topology:** the topology of the network is subject to frequent changes due to different factors such as malfunctioning, device failure, moving obstacles, mobility, and interferences. If an application gets bigger, the network should be flexible enough to allow the addition of other nodes anywhere any time without affecting network performance. Also, a middleware should support mechanisms for fault tolerance, self-configuration and self-maintenance of collections of sensor nodes.
- **Heterogeneity:** The middleware should provide low level programming models to meet the major challenge of bridging the gap between hardware technology's raw potential and the broad needed activities. It should establish system mechanisms interfacing to the various types of hardware and networks, only supported by basic distributed primitive operating system abstractions.

- **Network organization:** Unlike traditional networks, sensor networks must deal with resources – energy, bandwidth, and processing power that are dynamically changing [12]. Another important issue in sensor networks is to support long running application, efficient design of routing protocols is needed so that the network could run as long as possible [17]. An Ad Hoc network resources discovery should be provided, since knowledge of the network is essential for a network to operate properly. A sensor node needs to know its own location in the network in addition to the whole network topology. In some particular cases self-location by GPS is not possible or feasible, or even expensive. Some important issues on system parameters such as network size and density per square mile affect the tradeoffs between latency, reliability, and energy. A middleware should support the robust operation of sensor networks despite these dynamics by adapting to the changing network environment.
- **Real-world Integration:** most sensor network applications are real-time phenomena, where time and space are of an extreme importance. Hence, middleware should provide real time services to adapt to the changes and provide consistent data.
- **Application knowledge:** another important and unique property of middleware for WSN is dictated by the design principles of application knowledge [12]. However middleware has to include mechanisms for injecting application knowledge in the infrastructure of WSN. This will allow mapping application communication requirements to network parameters that allow fine-tuning of the network monitoring process. Most WSN applications dictate minimum quality of service (QoS) requirements. A Middleware should maintain this QoS over an extended period of time and even adjust itself when the required QoS changes and the state of the application changes. Middleware gets QoS requirements from applications and adapt the network configuration to provide the required QoS.

3. Different Middleware for Sensor Networks

Some design principles and research projects have already been proposed. In this section, which is the focus of our paper, all these different approaches will be presented in details and evaluated to explore the pros and cons.

3.1. Mate [22]: Mate is among the middleware for WSN that uses a virtual machine (VM) approach as an abstraction layer to implement its operation and to tackle the different challenges of WSN described in the earlier section. The project is developed at the University of California at Berkley, and focuses on the need for new programming paradigms to overcome constraints such as

limited bandwidth and the large energy draw from network activity. Mate proposes a spectrum of reprogrammability from simple parameters adjustment to uploading complete program updates using a VM approach. Indeed, the energy cost of sending one single bit of data can consume the energy of executing thousands of instruction to produce the same data. A content specific routing and reprogramming model can be used and supported by the VM.

Mate is a byte code interpreter built on TinyOS[19] operating system designed specifically for sensor networks that run on motes (small devices with a small CPU and limited storage resources) to implement the middleware operations. It uses codes that are broken into capsules of 24 instructions, each of which is a single byte long. This gives the advantage to large programs to be composed to multiple capsules, thus easy to inject into the network. The key components are the VM (Mate), Network, Logger, Hardware, Boot/Scheduler. Using a synchronous model that begins execution in response to an event such as packet transmission or time going off, it avoids message buffering and large storage. The synchronous model makes application level programming much simpler and far less prone to bugs than dealing with asynchronous event notifications. Another key functionality of Mate is infection or network updates done by adding a version number in the capsule, so comparison could be made at the neighbors and the new version is installed. This process cascades with hop-to-hop communication.

Evaluation: Mate aims to provide a better interaction and adaptation to the ever changing nature of sensor networks. It demonstrates the use of active messages to update the network protocols and parameters by injecting new capsules. Mate is small and expressive, has concise programs which are resilient to failure. It makes the network dynamic, flexible and easy reconfigurable. Mate gives a user-land supplemented by the VM and Provides efficient network and sensor access. However, In terms of energy, Mate is only suitable for a sleepy application, for complex applications, it is wasteful because of the interpretation overhead. Also in its current state, Mate is only an architecture and byte codes; a higher-level language and programming models for application development are needed.

3.2. Magnet [5]: This effort is being carried out at Cornell University. It is in the middleware category that uses a Virtual Machine. MagnetOS is a power-aware, adaptive operating system specially designed for sensor networks and ad hoc networks. It constitutes of a layer defined as Single System Image that provides homogeneity for the heterogeneous of the distributed components of ad hoc networks. The abstraction provided is that the whole network is a single unified java virtual machine composed of dynamic and static components.

The static component is responsible for rewriting regular java applications in byte code in the form of objects or modules, which explains the object-oriented nature of MagnetOS. Then it injects them into the network with special instruction to keep the semantics. At this point a dynamic runtime component on each node monitors the objects creation, invocation and migration providing different services for the application.

For performance purposes, MagnetOS runtime provides flexibility for programmers to explicitly adjust object placement and migration. This allows reducing network communication by moving objects closer to their source. MagnetOS provide a robust power aware algorithms using object migration of the same application to nodes that are topologically closer together. This mechanism reduces application energy consumption and increases longevity.

Evaluation: With its Single System Image MagnetOS overcomes the heterogeneity of distributes ad hoc sensor networks. It offers application adaptation and network scalability, which makes a general-purpose system. However, it uses java virtual machine that introduces an overhead in its instructions. More effort should be put to come up with a VM more suitable for WSN applications.

3.3. EnviroTrack (Data centric) [1]: Another work worth mentioning is EnviroTrack, which is well suited for embedded tracking application. It adopts a *data centric* programming paradigm called attributed-based naming through “context labels”, where the routing and addressing are based on the content of the requested data rather than the identity of the target sensor node. As most projects, it is also built on top of TinyOS using compiled NesC [35] programs. Its contribution stems from its convenient robust interface to the application developer geared towards tracking the physical environment. The attributed based naming is applied by associating user-defined entities (context label) to real physical targets. With this network abstraction layer the programmer declares the environmental characteristics which define the context label of the object to be tracked. Based on this, all sensor nodes that sense the same declared characteristics (object) are aggregated to track that physical target such as a car or a fire. With powerful network management mechanisms such as lightweight group management and group leader election, it supports the dynamic behavior of the tracked targets such as mobility. Thus the presence of any moving target is detected and reported, very useful for environmental watch applications and military applications

Evaluation: The proposed work is a well distributed programming support for environmental tracking. However its performance is based only on very small-scale implantation and it is at its early stage of

development. More work need to be done in terms of self-organization and autonomic system approach.

3.4. Impala [25]: Stems its insight from the observation that sensor networks are long running and autonomous. It was specially designed as part of ZebraNet project (A wildlife watch project). It proposes an asynchronous event based middleware layer that uses program modules (mobile agents) compiled into binary instructions. It ensures application adaptation and can automatically discern needed parameters settings or software usages. New protocols can be plugged in at anytime and switches between protocols can be performed at will. The middleware itself is separated in two layers:

- The upper layer that contains all the application and protocols for ZebraNet project. These applications use various strategies to achieve a common task of gathering environment information and routing it to a base station.
- The lower layer contains three middleware agents: the application adapter, the application updater, and the event filter.

The event filter controls different operations and initiates chains of processing: timer event, packet event, send done event, data event, and device event. Armed with Application Finite State Machine (AFSM), the adapter agent handles application adaptation depending on different scenarios such as energy-efficiency and other attributes determined by the applications. The Updater agent is in charge of achieving effective software updates with resource constraints by taking into account the tradeoffs such as: high node mobility, constrained bandwidth, wide range of updates, propagation protocol, and code memory management.

Impala adopts a module-based system with a version number, and each application as a whole has a version number. Before exchanging software updates, nodes first exchange an index of application modules then only request the changed modules for transmission which saves network bandwidth. Before being injected into the network, a program module is compiled into binary instructions. A module will not be linked to the main program for installation until the whole update is received.

Evaluation: Impala provides application adaptation at runtime by its good architecture model, and ensures security against unfortunate programming errors. It is novel with its autonomic approach. Impala is self-organizing and uses AFSM mechanisms to choose and switch between adequate protocols. It uses updates using modules that are small and introduces little transmission overhead. However, Impala doesn't support heterogeneity in terms of hardware platform since it is being destined to run only on HP/Compac iPAQ Pocket PC handheld running Linux, therefore its applications are limited.

3.5. Milan [18]: The “master piece” in MILAN, Middleware Linking Applications and Networks, is its focus on high level concerns by providing a high level interface mainly characterized by applications actively having an effect on the entire network. It is being developed at the University of Rochester. MILAN allows (i) sensor network applications to specify their QoS needs and (ii) to adjust the network characteristics to increase application lifetime while still meeting those needs. To accomplish that it receives information from: (i) The individual applications, about their QoS requirements over time and a way to meet these QoS requirement using different combinations of sensors. (ii) The overall system and the user, about the relative importance of the different applications. (iii) The network, about available sensors and resources such as energy and channel bandwidth.

With specialized graphs incorporating state based changes in application needs, MILAN can determine the adequate combination F_A , applications feasible set, of sensors satisfying the application's QoS requirements. Then with Its architecture that extends into the network protocols stack and an abstraction layer that allows network specific plug-ins to convert commands to protocol-specific commands, MILAN can configure and manages the network. Depending on F_A , it is for the network plug-ins to determine which sets of nodes (sensors) F_N that best meet the requirement and other information such as what role each node must play. It combines the two constraints to get an overall set of feasible combination: $F = F_A \cap F$

Evaluation: Milan by its application driven network management is certainly very well suited for application adaptation and tackles very well the challenges of QoS requirements. However its architecture lacks innovation in new programming models suitable for WSN and that offers support applications and hardware heterogeneity.

3.6. Cougar [11]: A research group at Cornell University Introduced a new dimension in middleware research by adopting a database approach where sensor data are considered like a “virtual” relational database and WSN management operations are implemented in forms of queries using an SQL like language. Cougar defines a sensor data base system composed of sensor database and sensor queries. The sensor database in its turn contains stored data and sensor data. The stored data are represented as relations and they include the set of sensors that participate in the sensor database together with characteristics of the sensors or the physical environment. The sensor data are generated by signal processing functions and represented as time series to facilitate the formulation of sensor queries. Cougar then, uses Abstract Data Types (ADT) with virtual relations to model the signal processing functions represented as sequences based on the fact that ADT are supported by object-

relational databases. All sensors of the same type in the physical worlds are represented by an ADT. With algebra operators the sensor queries are formulated in form of SQL language with little modification. The long running queries are supported by using incremental results to maintain a persistent view of such queries.

Evaluation: The cougar database approach is very suitable for large sensor collections, and offers a simple implementation for different network operations. However, it uses valuable resources to transfer large amount of raw data from devices to the database server and there is a potential risk for communication links failure in case of a large scale sensor network. Another impediment is that sensor data are measurement and not facts, and often sensor measurement corresponds to continuous distributions. Also the dynamic nature of large-scale sensor networks poses a problem for the centralized optimizer that Cougar uses to maintain a global knowledge of the network.

3.7. SINA [27]: More elaborated data base approach is proposed in SINA, System Information Networking Architecture, developed at the University of Delaware. For the purpose of achieving adaptive sensor network organization SINA models the network as massively distributed objects. Its kernel provides efficient mechanisms enabling scalability, and energy efficiency. Its architecture backbone is based on a spreadsheet database for querying and monitoring. A logical datasheet composed of cells, where each cell represents an attribute of a sensor node (e.g. in the form of a single value such as power level and location or multiple values such as temperature changes history). Each cell is namely unique and the whole datasheet is maintained by each sensor node. The sensor network as a whole is viewed as a collection of datasheets. The spreadsheet approach is the abstraction that allows information management to meet application changes and needs. SINA then incorporates two robust mechanisms: hierarchical clustering allowing scalability and an attribute – based naming scheme based on an associative broadcast to manage the spreadsheets. The cells are initiated in a node by a request from other nodes (e.g. user or cluster head). The requests are made in a form of SQL like statement. The cells are maintained and updated by four possible approaches namely, on demand content retrieval, content coaching, periodic content update and triggered content update.

Evaluation: SINA offers an advantage over Cougar by incorporating low-level mechanisms such as hierarchical clustering of sensors for efficient data aggregation. However as cougar it does not address the distributed systems heterogeneity.

3.8. DsWare [31]: Data service Middleware is another database like abstraction approach that is tailored to sensor networks based on event detection. It provides

more flexibility by supporting group – based decision, reliable data-centric storage, and implementing a mix of approaches to improve real-time execution performance, reliability of aggregated results and reduce network communication (overhead). DsWare provides application with services supported by its architecture modules such as data storage, data caching, group management, event detection, data subscription, and scheduling. Like Cougar [11] DsWare uses SQL like language for the registration and cancellation of events.

Evaluation: DsWare supplies applications with a very rich and convenient interface so that applications do not have to implement their own application data-service. It allows sensor data to be represented using interfaces as conventional databases. It handles the dynamic nature of sensor network data and provides more reliability since services could be provided by a group of geographically close sensor nodes; hence it can easily tackle failures as long as enough sensors remain in the area to provide valid measurements. In the other hand DsWare, in its present form does not provide solutions for heterogeneity and mobility.

3.9. Others: At the end, it is important to mention that there has been other research effort in middleware for sensor networks. However, most of them fall in one of the approaches studied earlier at some extent and use similar mechanisms. One example is AutoSec[33] Automatic Service Composition; it is an application driven middleware framework whose focus is on provision of support for dynamic service brokering for a better use of resources within a distributed system. Distributed application have QoS requirement that can be translated into the underlying system-level resources. AutoSec has an architecture that goes deep in the network and performs resource management and organization within a sensor network by providing the required QoS for applications on per-sensor basis. This is done by choosing a combination of information collection and resource provisioning policies from a given set based on user needs and system needs. Agilla [34] is another example that is based on Mate and extends it by providing mechanisms for better injection of a mobile code into the sensor network to deploy user applications, where the mobile agents can intelligently move or clone themselves into desired locations based on network changes. This turns to be more suitable than the flooding mechanisms used in Mate for the same purpose. Garnet [28] is a middleware framework focusing on managing data streams as an abstraction within a sensor network. That is, it offers a collection of system services such as receivers, filtering and dispatching services, resource manager and orphanage.

Table1. Approaches of Sensor Networks Middleware.

Project Name	Main Features	Heterogeneity	Scalability	Mobility	Easy for use	Power aware	General purpose
Virtual Machine based approach							
Mate [22]	Uses TinyOS, Synchronous, Byte code interpreter, Mobile active capsules.	Yes	Yes	Yes	No	Yes	Yes
Magnet [5]	Java virtual machine, Single System Image., Objects migration	Yes	Yes	Yes	No	Yes	Yes
Database based approach							
Cougar [11]	Virtual relational database, Abstract Data Types, SQL Like Language	No	No	No	Yes	Some	Some
SINA [27]	Spreadsheet database, Hierarchical clustering, Base naming scheme, SQL like statement	No	Some	No	Yes	Yes	Some
DsWare [31]	Data service, Event detection, SQL like statement, Real time aspects	No	Some	No	Yes	Yes	Some
Modular programming approach							
Impala [25]	Mobile agents, Asynchronous, AFSM, Autonomic approach	No	Yes	Yes	Some	Yes	No
Application driven approach							
Milan [18]	High level concerns, QoS requirement, Network protocol stack	No	Some	No	Yes	Yes	Some
Data centric approach							
Envirotrack [1]	NesC prog, TinyOS, Mobile code, Context label.	Yes	Yes	Yes	No	Yes	No

4. Comparison and Classification

In the previous section we surveyed different existing middleware approaches, based on the programming models used. To the best of our knowledge we can classify them into four main categories: virtual machine, modular programming, database based, and application driven. We will evaluate these approaches based on their performance in respect to the challenges and constraints presented in section 2 such as heterogeneity, scalability, expressiveness and general purpose.

The virtual machine approach provides an efficient programming paradigm that allows the development of any distributed algorithms and hides the heterogeneity of the run time environments and the hardware resources. It provides efficient mechanisms to support sensor networks dynamisms and allows highly scalable applications. However, sometimes its interfaces lack expressiveness as in Mate [22], and its instructions introduce a considerable overhead.

The database approach's treats the whole sensor network as a large "virtual" data base. Interactions with the sensors are done in form of system queries using SQL like language. It is easy to use and suitable for some applications. On the other hand it suffers from supporting real time applications that need the detection of spatio-temporal relationships between events. Also, it maintains a fixed global network structure which is not suitable for scalability nor for highly dynamic applications.

The modular programming paradigm as in impala provides efficient mechanisms for networks updates to support dynamic applications. Its autonomic behavior

increases its fault tolerance and self-organization of the network. However, the nature of its code instruction does not allow hardware heterogeneity which makes it unsuitable for devices with limited resources.

The application driven approach in Milan [18] introduces a new dimension in middleware design since applications will dictate network management operations, which makes it advantageous in terms of QoS for some applications. On the other hand heterogeneity poses a serious problem, since Milan did not provide a low level-programming paradigm to overcome systems and hardware heterogeneity.

The data centric approach stems from the observation that in most sensor network applications, the focus is more on the *nature* of sensor readings rather than their address in the network. Hence, nodes are addressed based on the data produced, for example: detect a target having a shape of "tank" which is used in military applications.

Table.1 classifies and summarizes the different approaches and evaluates exhaustively each approach.

5. Open Research Issues

Most of the projects are at an early stage focusing on developing algorithms and components of middleware for WSN. The design of a middleware layer for sensor networks fully meeting the challenges highlighted in an earlier section is now open. One primordial issue is to satisfy application QoS requirements while providing a high level abstraction dealing with the heterogeneity of sensor nodes. Another crucial challenge is to come up with easy to use and expressive programming interfaces while meeting different sensor network application challenges such as limited hardware resources and QoS requirements. Middleware using autonomic computing and policy-based management could provide more robustness, reliability and self-management. At this point it is not obvious yet whether network management and programming abstractions will stem from the existing known paradigms as the work surveyed in this paper, or possibly fully new abstractions and approaches will emerge specifically to meet WSN goals.

6. Conclusion

Throughout this survey, we discussed the main challenges that face the design and the development of middleware for WSN. We investigated most of the relevant existing projects carried out towards this perspective. We provided a state of the art comparison and classification by concentrating on similarities and differences between the approaches. Middleware approaches for WSN are mainly classified into four categories: virtual machine, database based, modular programming, and application driven. Further, and based on the results of our comparison, we discussed and proposed potential enhancements and new research possibilities in the field. Finally we argue that there is still a long way to go for a "perfect" middleware for WSN to really exist.

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