A Research Based Review of Wireless Sensor Networks

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Abstract — Tracking back its origin is the early nineties; the subject of wireless sensor networks (WSNs) has seen a remarkable growth and interest in both academia and industry. WSNs are already being used to monitor large geographic areas for modeling and forecasting, environmental pollution and flooding, controlling usage of water, fertilizers, and pesticides to improve crop health and quantity. WSNs, can be considered as a special breed of wireless ad-hoc networks with reduced or no mobility. These networks combine wireless communication and minimal on-board computation facilities with sensing and monitoring of physical and environmental phenomena. Much work has been reported on different aspects of WSNs; however, much of this work focuses on a specific area. In this context, this article contributes a general survey on WSNs. We believe this work will assist researchers to develop sound introductory background knowledge and understanding of WSNs.
Keywords: Wireless Sensor Networks; WSNs; Sensors; Fault Management

Introduction

The phenomenal advances in technologies, such as Micro-electromechanical Systems (MEMS), Very Large Scale Integration (VLSI), and Wireless Communication contributed to the widespread use of distributed sensor systems. Further, the miniaturization of computing and sensing technologies, and their integration enables the development of tiny, low-power, and low-cost sensors, actuators and controller. Embedded computing systems continue to find applications in an increasing number of areas. For example, as these systems are highly demanded in the military domain for defence and aerospace system, there is also an increasing focus on these systems in the civil domain to monitor and protect critical infrastructure (such as bridges and tunnels), the national power grid, and pipeline infrastructure. Such wireless networks of distributed sensor nodes are commonly known as Wireless Sensor Networks (WSNs). WSNs take network formation concepts from mobile ad-hoc network. Mobile ad-hoc network is the collection of mobile nodes establishing network without requiring any supporting infrastructure [A+02c, A+08].

In WSNs, small sizes, low-cost wireless devices have embedded onboard radio transceiver, micro-controller, memory, power supply and the actual sensors. All these components together in a single device form a so-called wireless S*ensor node* or simply a *Sensor*. Sensor links the physical world with the digital world by capturing, interacting and revealing real-world phenomenon and converting these into a form that can be stored, processed, analyzed and further acted upon. Integrated into various devices, machines, and environments, sensor devices provide tremendous societal benefits. For example, they can help to monitor and avoid catastrophic infrastructure failures, conserve precious natural resources, increase productivity, enhance national security, and enable new applications such as smart homes and smart cities technologies.

A typical WSN is composed of a large number of sensor nodes and a *Sink* or *Base-station*. Sink can be a computer, laptop or a sensor node. It is a powerful data processing and storage centre and serves as an access point for human interfaces (e.g. link through the Internet to Satellite). Sensor nodes are usually scattered in a sensor field, and each sensor has a capability to collect data and route back to the Sink and then forward it to the remote user on request. The position of a sensor node does not need to be engineered or pre-determined, which allows random deployment in inaccessible or hostile terrains such as disaster-relief operations [A+02a]. Figure 1, it shows a typical functional architecture of a WSN.

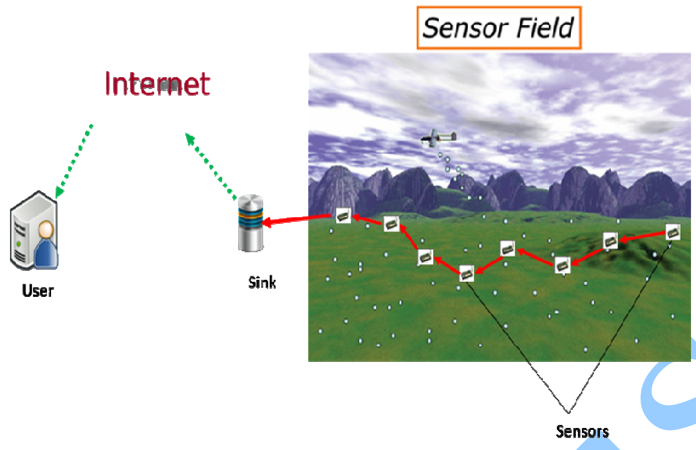


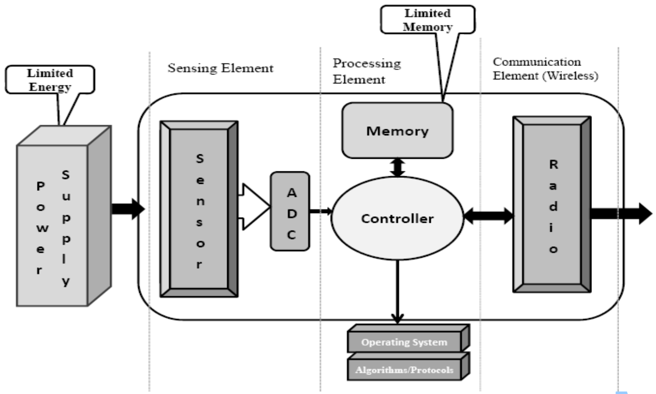
Figure 1. Typical functional architecture of a WSN

WSNs have different communication patterns for different applications according to their requirements. The most common patterns include:

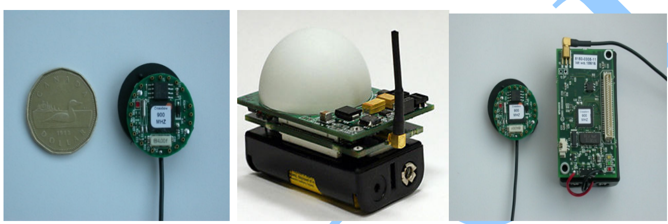
- Sensor node to sink communication, e.g., sensor readings and specific alerts.
- Sink to sensor node communication, e.g., data requests and control information.
- Sink to all sensor nodes, e.g., routing beacons, queries or re-configuration of the network.
- Communication among a group of sensor nodes, e.g. a node to all its neighbours.

Sensor Node - Sensor nodes are capable of interacting with their environment through various sensors[1]; aggregate and process information locally, and communicate this information wirelessly with their neighbor sensor nodes. Therefore, a wireless sensor node has not only a sensing component, but also have on-board processing, communication, and storage capabilities with limited power supply. A basic sensor node comprises of five main components, see Figure. 2 (a), [Kri05, KW05]: Micro-Controller or Processing Unit, Memory Unit, Sensors Unit, Radio Transceiver and Power Supply Unit. All these sub units may need to be fit in match box size module. The required size may be smaller than a cubic centimeter, see Figure. 2 (b), a Mica2dot sensor node is small as the size of a coin.

[1] Sensors here referrers to the physical hardware interface of a sensor node. It should not be confused with the sensor node device.



(a)



(b)

Figure 2. (a) A sensor node hardware architecture and (b) Mica2 and Mia2dot motes supplied by Crossbow Technologies Inc.

These tiny sensor nodes must consume extremely low power, operate in high volumetric densities, and have low production cost, be dispensable and autonomous, operate unattended, and be adaptive to the environment. Apart from the above mentioned basic components, a sensor node can have additional components, depending on the nature of application. Additional components can be a location finder or Geo-positioning system, power generator and an actuator or mobilizer. A wide variety of platforms had been developed in recent years, including Mica2, MicaZ, Iris, Cricket, Telos, SunSPOT, and IMote 2, just to name a few [AV10].

Much work has been reported on different aspects of WSNs [AY05, A+02b, Y+08]; however, much of this work focuses on a specific area. In this context, this article contributes a general survey on WSNs. We believe this work will assist researchers to develop sound introductory background knowledge and understanding of WSNs. The rest of the paper is organized as follows. In Section I, we describe some various sensor network scenarios. In section II, we discuss applications of WSNs. In Section III, we describe the unique characteristics of WSNs and mention some of the most important design challenges in WSNs. Section IV, present the paper contribution and finally the conclusion and future work in last section.

1. Sensor Networks Scenarios

The arrangement of sensor nodes and sinks in the network and their interaction patterns show different sensor network scenarios [CA06]. The choice of a particular sensor network scenario is contingent upon the type of application. Some of the most relevant sensor network's scenarios are:

- **Homogeneous and Heterogeneous Sensor Networks -** In homogeneous sensor networks, all sensor nodes are identical in terms of battery energy and hardware capabilities and complicity. While in heterogeneous sensor network two or more different types of sensor nodes have different battery energy, communication range and functionality. Heterogeneous sensor networks have proven to be more successful in real deployments because of their potential to increase network lifetime and reliability without significantly increasing the cost [GP09].
- **Static and Mobile Sensor Networks -** As the name depicts, there is no motion among communication sensors and source in a static sensor network. In contrast, in mobile sensor networks, either the sensor nodes or the phenomenon under observation are mobile [CC07]. Mobility in sensor networks has many requirements and related challenges in terms of energy consumption and network-reconfiguration.
- **Event-Based and Query Based Sensor Networks -** In even-based or source-driven WSNs, sensors initiate data transmission for observed events to interested users or sink, including possibly reporting sensor readings periodically [I+11]. However, in query-based sensor networks, the sensors remain silent until they receive a query from the interested entities only [Dre07].
- **Flat and Hierarchical Sensor Networks -** The architecture of traditional WSNs generally adapts a flat structure, where a large number of homogenous sensor nodes are deployed in the mentoring area, and the data is routed sensor by sensor to the sink see Figure 3 (a). However, hierarchical WSN is usually composed of some kind of heterogeneous devices, which mainly act as sinks that are responsible for gathering and forwarding data from underlying sensor nodes see Figure 3 (b). Some of them are energy-rich or rechargeable; some have a better capability of communication than that of sensor nodes, and some even are able to

move randomly [XP10]. A common example of a well-known hierarchical clustering algorithm is LEACH [H+00].

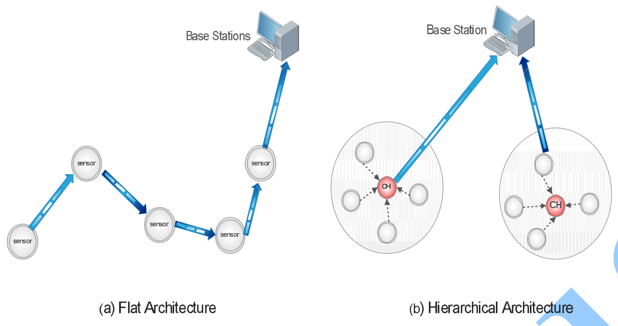


Figure 3. (a) Flat architecture and (b) Hierarchical architecture

2. Applications of Wireless Sensor Networks

Initially, WSNs have been conceived and developed for military applications in mind, specifically battlefield surveillance and tracking of enemy activities. However, in the past few years many WSNs applications, including both civil and military have been developed and deployed. In fact, its civil applications considerably outnumber the military ones, and presently WSNs have been used in many practical applications. According to IDTechEx research in the new report, "Wireless Sensor Networks 2011-2021", WSN will grow rapidly from $0.45 billion in 2011 to $2 billion in 2021. The report further says that WSNs will eventually enable the automatic monitoring of forest fires, avalanches, hurricanes, failure of country-wide utility equipment, traffic, hospitals and much more over wide areas, something previously impossible [Das11]. Applications of wireless sensor's networks are very much same as mobile sensor's network. A mobile ad-hoc sensor network follows a broader sequence of operational scenarios, thus demanding a less complex setup procedure [A+10].

In the literature, civil and military applications are mainly classified into to two broad categories: Monitoring and Tracking [A+02b, Y+08, H+08, S+07a]. Civil monitoring applications include environmental monitoring (indoor/outdoor), health monitoring, power monitoring, industrial processes monitoring. Civil tracking applications include tracking human (e.g. tracking and monitoring doctors and patient inside a hospital), animals tracking, objects and vehicles theft control tracking system, etc.

WSNs can be an integral part of military command, control, communications, computing, intelligence, surveillance, reconnaissance and targeting C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance) systems [Y+08]. Military applications of WSNs are monitoring and tracking the enemy movement, monitoring friendly forces, equipment and ammunition, battlefield surveillance and security detection, and chemical attack detection. For example, figure. 4, shows a WSN deployed in a factory to monitor chemical spells, contamination and fire in the area and sends this information to the control centre using the Internet or satellite to take action.

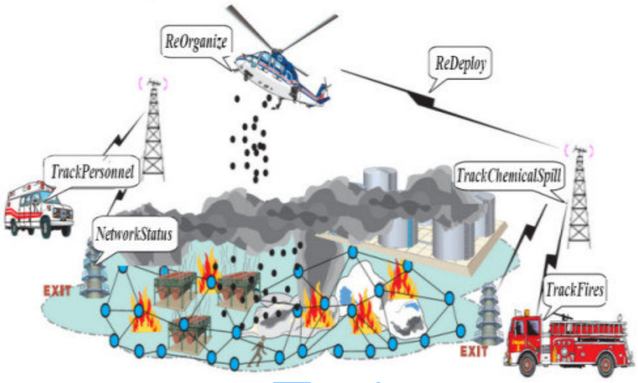


Figure 4. An example of a WSN deployed in an atomic reactor for monitoring

Below we describe some of the existing and popular real-word WSNs projects for different applications, including both Civil and Military one.

- **PinPtr** – PinPtr (Figure 5. [S+04]) is a counter-sniper system developed to detect and locate shooters. Sensors are densely deployed to detect and measure the time of arrival of muzzle blasts and shock waves from a shot. Sensors route their measurements to a base station (e.g., a laptop or PDA) to compute the shooter's location. Sensors in the PinPtr system are second-generation Mica2 motes connected to a multi-purpose acoustic sensor board.

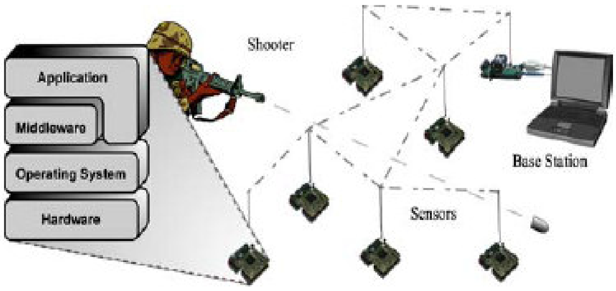


Figure 5. PintPtr counter-sniper system

- **FireWxNet** - It is a multi-tiered wireless system for monitoring weather conditions in rugged wild land fire environments. FireWxNet (Figure 5) enables the fire fighter community to measure and view fire and weather conditions over a wide range of locations and elevations within forest fire [H+06].

Recently, the use of WSNs has highly increased in Critical Infrastructure Monitoring and in the area of Emergency Response Applications [N+11] specially in metropolitan areas. In Metropolitan areas, effective monitoring is a very challenging task. Environmental pollution – whether in the form of gases such as CO2 and NO2 or dust – is a big health threat in urban areas, which cause many diseases. In addition, structural monitoring of many largest structures, including buildings, bridges, roads that are located in the city need constant monitoring and is critical for public safety. Libelium, a leading technology firm in WSNs, recently announces the completion of its Smart Cities platform. A new sensor board that can measure noise, pollution, dust quantities, structural health and garbage levels.

3. Characteristics of wireless sensor networks

Due to the intrinsic resource constrained nature of WSNs and its application scope; there are many characteristics of WSNs, which make it unique. In general, characteristics of wireless sensor's network relate it with mobile ad-hoc network. Mobile ad-hoc network is defined with characteristics such as purpose-specific, autonomous and dynamic. This section discusses some of these unique characteristics which include [KW05, AV10, S+07b]:

Application Specific – WSNs are highly application specific. Different applications have different requirements. E.g. a sensor network with very different network densities - from very sparse to very dense deployment -

will require different communication protocols. Therefore, there is no "one-size-fits-all" solution for all these potentially very different possibilities.

Sensor Limitations – In many sensor networks, sensor nodes have limited power (probably a few hundred mAh), limited computing capability, small memory (probably a few hundred Kbytes of RAM), low data transmission (up to 20Kbps) and limited computing range (10-50 meters). Due to these limitations, the impact of energy considerations on the entire system architecture of WSNs is much deeper. Specific protocols and algorithms have to be designed to take into account these limitations. To compensate for these resource limitations, energy-efficient operations is a key technique.

Dense Deployment – Potentially, WSNs scale to a much larger number (thousands or perhaps hundreds of thousands of sensor nodes) of sensor nodes to study a phenomenon, depending on the nature of the application. From a network point of view, in a large-scale WSN, sensor nodes will require to act as relay nodes to avoid using a long-distance antenna which as high-power consumption. Therefore, multi-hop communication is a particular feature of WSN to conserve energy consumption.

Hostile Deployment Environment – WSNs may be deployed in an inaccessible and hostile environment (e.g. volcano monitoring, battlefield surveillance, bottom of an ocean, etc.) where there is less or no human intervention. Typically, sensor nodes operate unattended in remote geographic areas for a long period of time [A+02a, C+04]. This characteristic makes WSNs unique from other traditional wireless networks.

Self-Configuration – Because of their scale and nature of their applications, WSNs are inherently unattended distributed system. WSN configures most of its operational parameters autonomously, independent of external configuration. In most of the applications, from the very start, nodes configure their own topology; localize, synchronize, and calibrate themselves to coordinate inter-node communication; and determine other important operating parameters. Furthermore, WSNs have self-configuration and self-organizing capabilities to manage the network resources and re-configure the network dynamically in the presence of mobility and faults.

The unique nature of WSNs and its characteristics pose a number of related challenges and issues that should be addressed to improve performance, lifetime, QoS, and reliability of WSNs. In the next section, we will briefly discuss some of the challenges in WSNs.

4. Challenges in Wireless sensor networks

Due to the resource limitations, WSNs are subject to a variety of design challenges, leading to the development of protocols and algorithms specific to WSNs. For instance, one of the main design goals of WSNs is to prolong the lifetime of the network and prevent connectivity degradation by employing aggressive energy conservation and fault management techniques. Therefore, existing routing protocols and architectures designed for traditional wireless network cannot be used directly in WSNs [CA06]. Such requirements are, to some extent, similar to those in mobile ad-hoc networks. Some of the known protocols of mobile ad-hoc networks are mobile ad-hoc on-demand data delivery protocol (MAODDP) [A+02c, A+08]; Destination sequence distance vector routing (DSDV) and dynamic source routing (DSR). This section describes some of the key challenges that need to be taken into account when designing protocols and architecture for WSNs [A+02b, Y+08].

Limited Energy Reserves and Energy-Efficiency - In many WSN scenarios, sensor nodes have limited energy reserves (mostly operated by AA batteries), and recharging or replacing these energy sources in the sensor network field is usually not practical. Therefore, to conserve energy and provide energy-efficient operations becomes one of the principal challenging techniques for WSN. Energy-efficiency plays a vital role to prolong the lifetime of a WSN.

Mobility and Network Dynamic Topology - Due to the mobility of nodes, the topology of the sensor network frequently changes, thereby; it is necessary to update the routing information of a sensor node, which consumes a significant amount of energy and reduces the overall system lifetime. Furthermore, network topology also changes due to the factors such as device failure, malfunctioning, and interference, which brings more complicated challenges (related to security, scalability, routing, network management and so on) [L+07]. The network management system and communications protocols should support network's robust operations despite these dynamics by adapting to the changing network environment.

Scalability - Scalability can be defined as: if the network size grows, the system should be flexible enough to allow this growth anywhere and anytime without affecting network performance. For many envisioned applications the number of sensor nodes deployed in the sensing area may be in order of hundreds, thousands or more. Protocols need to be inherently distributed, involving localized communication, and sensor network must utilize hierarchical architectures in order to provide such as scalability.

Wireless Networking - The reliance on wireless communication technology poses a number of challenges to the design and deployment of WSNs. Increasing distance between a sensor node and a base station rapidly increases the required transmission power. Therefore, it is more energy-efficient to split a large distance into several shorter distances, leading to the challenge of supporting multi-hop communication and routing.

Lightweight Software Design - The small form factor and resource restrictions on sensor node hardware impact the software design at various levels of application development. For example, the sensor node Operating System (OS) must have small memory footprints and must be efficient in their resource management tasks. Therefore, the software architectures and solutions (operating systems, network protocols, middleware) designed must be lightweight and must operate efficiently on very resource-constrained sensor node hardware [KW05, AY05].

Unattended Nodes and Self-Organization - Many sensor networks' applications are deployed in hostile and inaccessible environments, usually operate unattended. Therefore, sensor network must be self-managing in the way that they configure themselves, operate and collaborate with other nodes and adopt to failures, changes in the environment, and changes in the environmental stimuli without human intervention [DP10, Dre07, H+05]. Self-management can take place in a variety of forms. Self-organization is the term frequently used to describe a network's ability to adapt configuration parameters based on system and environmental state. Sensor nodes should be self-organizing as the ad-hoc deployment of these unattended nodes requires the system to form a covered and connected network. The node organization techniques should also take the resource limitations of sensor nodes into account while forming the network.

Fault Tolerance and Fault Management - Due to their low-cost, tiny sensor nodes are normally deployed in a remote hostile territory, where they suffer numerous attacks. The node can get crashed by external factors such as heavy rain fall, or it can fail due to battery exhaustion. Therefore, fault tolerance becomes vitally important for WSNs, where they must be able to respond to the faults and failures and must ensure the smooth operations of the system. A set of functions or applications designed specifically for this purpose is called a *fault-management platform*. By employing belligerent fault management operations, the network lifetime and reliability can significantly be improved. Sympathy, MANNA, WinMS, and WSNMP are some of the most notable work focuses on fault management in WSNs [K+09, K+10]. The main drawbacks of the current fault tolerance mechanisms are that they consume large computational resources and energy. The implementation of low cost and high reliable fault tolerance mechanisms is a major challenge in WSNs.

Other Challenges: Other challenges mentioned in the literature are: production cost [L+07, HM06], programmability and maintainability [KW05], security, synchronization and localization [KW05, A+02c], Quality of Service (QoS) [HM06], and heterogeneity of devices, just to name few.

5. Contributions

WSNs are being deployed in different places and have been assisting us for over a decade. Such networks have been proving their importance in meeting challenging of today's world. In essence, a growing interest in them requires addressing challenges evolve around WSNs. Much effort is under going to resolve some of the existing issue. However, most of the existing literature on WSNs focuses on a specific area, and less attention has been paid on topics, which can aid researchers at early stages to develop their background understanding and knowledge. The contribution of this paper is to fill the gap of survey studies within this area by compiling and presenting related information. In this context, essential topics are being presented in a manner, which can give a researcher an insight view of WSNs. A review presented in this paper could yield a direct impact on a researcher selection of area of further study. In addition, certain aspects which are not otherwise well presented in the reported literature have been included. That's to detail operational requirements; characteristics, applications and challenges of WSNs.

Conclusions and future work

We have presented a research based review of WSNs with a view of filling gap of such studies. WSNs have been successful in providing surveillance and data collection services for situations where it is not possible or difficult otherwise. Research interest in such network has been growing both in industry and academia. In this academic article besides an in-depth detail of WSNs working, specific focused has been given to explain some associated essential topics. Unlike traditional wireless networks, where the main focus is on maximizing channel throughput or minimizing node deployment, the major design goals of WSNs is to extend system lifetime, improve network performance and enhance system robustness. In the light of a comprehensive literature survey [K+09, A+08, A+10], energy-efficient operations and fault management has been identified as the core design issues of WSNs. By employing belligerent energy-efficient and fault management operations, the network lifetime and reliability can significantly be improved.

We believe this work will assist researchers to develop sound introductory background knowledge and understanding of WSNs.In future, we will be conducting further research by paying attention to the selected fundamental concepts of such networks. We are committed to share our finding with the on-going research in this area.

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