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Wireless Sensor Networks: from Application Specific to Modular Design

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1. Introduction

The success of modular design and architecture has been observed in many fields. For examples, in the world of computer systems, the Von Neumann architecture set forth the fundamentals of modern computers. Equally important in computer networks is the Open System Interconnect (OSI) architecture, where the hierarchy of layers abstracts network functionalities and hides implementation complexities. In the multiple layers of OSI, the physical layer defines the actual waveform being transmitted in communication medium and the conversion of digital information bits (modulation/demodulation). The data link layer provides the abstraction of communication channel where packets are transmitted. The networking layer routes data packets across the network, and the transport layer defines an end-to-end tunnel hiding the complexity of communications from high layers. A related success story is the Internet.

Generally speaking, the benefits of modular design and architecture are: 1) it converts complicated system into simplified layers (modules); 2) methods developed for particular layers (modules) would benefit overall system as well; 3) modifications on a single layer (module) would not need a system re-design. Therefore, system modular abstractions have been important for any industrial proliferation, for example in both computer and communication engineering.

The rapid convergence of advances in digital circuitry, wireless transceiver, and micro electro-mechanical systems, has made it possible to integrate sensing, data processing, wireless communication, and power supply into a low-cost inch scale device. Thus, the potential of collaborative, robust, easily deploying, wireless sensor networks with thousands of these inch-scale nodes have been attracting a great deal of attention. For wireless communications and networking, the unique nature of sensor networks, which are application-specific and resource limited, pose unique challenges.

First, the applications of wireless sensor networks need mass collaboration of a large number of sensor nodes. Such applications, e.g., environment monitoring, object/asset surveillance and tracking, utility/energy management, generate very different network

traffic patterns, and require different sets of application Quality of Services (QoS). Before the emerging of wireless sensor networks, the research and development in communications and networking had been usually focused on delivering more packets under bandwidth/power/latency constraints. Introduced by wireless sensor networks, such research and development are, for the first time, completely exposed to and closely correlated with the details of applications.

Second, inch-scale sensor devices are usually subject to tight resource limitations. For example, compared to portable devices such as smart phones and laptops that can have battery recharge frequently, wireless sensor nodes usually do not have such privileges due to cost constraints. Therefore, sensor nodes are usually relying on a small amount of battery energy storage, while at the same time are expected to operate over years. The power constraints also introduce other resource limitations on hardware such as computing, memory, and communication capabilities.

Consequently, the tradeoff between application QoS requirements and the resource limitations of wireless sensor nodes has been unfound in traditional (wireless) communications and networking. Traditional layered architecture of communication protocol stack has also been identified as insufficient in addressing the new challenges, where cross-layer optimizations are needed. More specifically, the research and development in wireless sensor networks have been calling for application specific design, where application details determine the optimization of lower-layer protocol stack. However, the introduction of application specific design has also been causing the loss of architectural modularity in wireless sensor networks.

In the following, we first review the need for application specific design in wireless sensor networks, in Section 2. We then further introduce a non-application-specific architecture, Embedded Wireless Interconnect (EWI), which was generalized from the studies of application specific design, but could also provide a universal platform with modular abstractions. The abstractions of EWI are then described in Section 3. Although a single sensor node is subject to tight resource limitations, a wireless network with thousands of wireless sensor nodes can exploit a wealth of dynamic resources in terms of nodes/radios and spectrum bandwidth. In Section 4, a cognitive-networking method is further introduced to best utilize resources in large-scale wireless systems, being ideally implemented in the abstracted modules of EWI.

From application specific to modular design, we aim to provide: an architecture with a set of Application Programming Interface (API) functions that can decouple application developments from the details of wireless communication/networking; an architecture with a set of modules that can best utilize dynamic resources in large-scale wireless systems. Both have been preliminarily achieved by the work of EWI.

2. Application Specific Design

The need for application specific design and cross-layer optimization can be illustrated by a simple example of wireless sensor networks. As shown in Figure 1, two sensor nodes *A* and *B* are collecting data and sending it to the sink *S* in real-time.

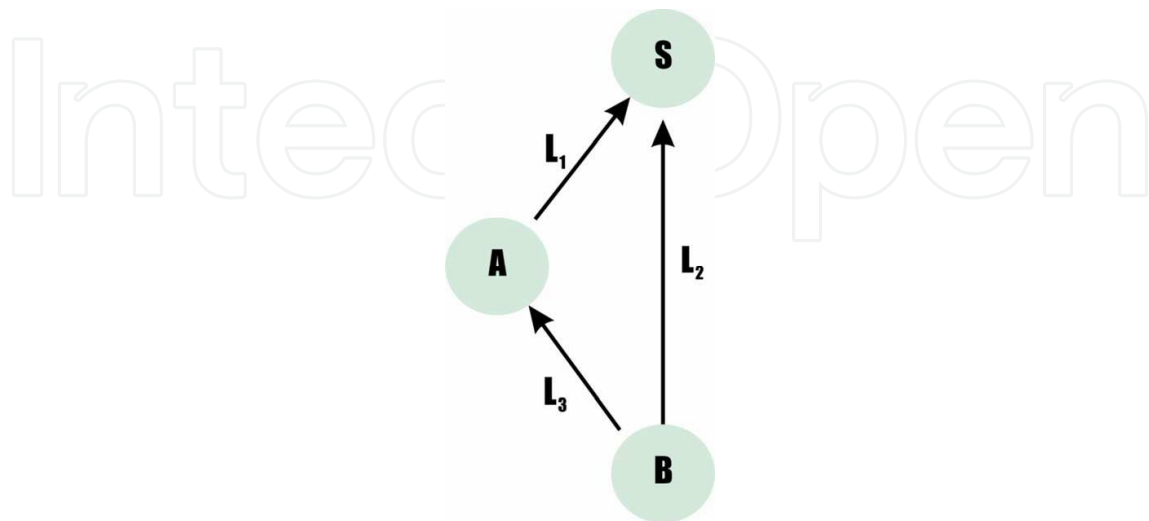


Fig. 1. A Simplified Illustrative Example

There can be three links in this simplified network: L_1 between nodes *A* and *S*; L_2 between nodes *B* and *S*; L_3 between nodes *B* and *A*. Given a constant data transmission rate, it is further assumed that the sum of packet power consumption on L_1 and L_3 is less than the packet power consumption on L_2 . Here, “packet power consumption” denotes the power consumption of transmitting/receiving one data packet on the corresponding wireless linkage.

Let’s first assume that the design objective is to minimize the sum of energy consumption on nodes *A* and *B*. A simple think shows that application requirements decide the network topology. For example, if data packets arrive only sporadically, link L_2 can be removed, since node *B* should always take the multi-hop transmission, and have node *A* forward the packet, so as to minimize the total energy consumption. However, if data packets arrive continuously in time on both nodes *A* and *B*, e.g., multimedia streaming, the “multihop” topology will require a higher transmission data-rate on link L_1 . Since link power consumption could increase exponentially with the data-rate under Gaussian assumption, according to Shannon, C. E., 1948, it may turn out that a “star network” is more preferable, where link L_3 can be removed. However, if some processing capability, such as data fusion, is available on sensor nodes, node *A* might then compress two packets originated from the two sensor nodes, *A* and *B*, into one single packet. Since the high data-rate problem no longer exists, the “multihop” topology can be more favorable again.

If the network lifetime ends when either one of the two sensors runs out of energy, designers should balance the energy consumption between the two sensor nodes. This lifetime would be reduced by the “multi-hop” topology, since node *A* becomes a “hot spot”, and would die much faster than node *B*. As one possible solution, node *B* might

probabilistically decide between the switching between the multi-hop and the direct transmissions. The optimal value of this probability is decided by the source data-rate on both nodes *A* and *B*.

Furthermore, due to the broadcast nature of wireless medium, when node *B* transmits on link *L2*, node *A* is also able to decode the packet. If the transmission fails and is rescheduled, many possibilities of cooperative transmission exist even among two sensor nodes. Under our simplified channel model, node *A* may re-transmit the lost packet, on link *L1*, in order to save energy.

The above simplified example can already demonstrated numerous ways of cross-layer optimization in accordance with application requirements. Application specific design have been found necessary in wireless sensor networks for dealing with sensor-device resource limitations. Similar to what we have identified in the above simplified example, research literatures have already identified two basic approaches to the cross-layer optimization for wireless sensor networks.

Top down approach: it is to apply the application details to deciding network topology and packet routing. More specifically, data/message exchanges in sensor networks are event-centric, location-centric, and data-centric. A number of research works have been concentrated on adapting the ad-hoc routing and network management paradigm to accommodate the new application-specific features. For example, [Intanagonwiwat, C. et al., 2002] developed a data-centric routing paradigm for wireless sensor networks: Directed Diffusion; [Madden, S. et al., 2005] developed the TinyDB system which uses semantic routing and aggregation trees to set up database applications in wireless sensor networks; similarly [Abdelzaher, T. et al., 2004] developed EnviroTrack as an application-specific network design for environmental tracking sensor networks.

Bottom up approach: it is to utilize the broadcasting nature of wireless medium to improve the quality and efficiency of wireless communications. For example, physical layer inter-node cooperation is usually neglected in traditional wireless (ad-hoc) networks, but can offer a large performance margin in terms of reliability and energy efficiency. Both features are of key importance in sensor-network applications. [Scaglione, A. et al., 2003] designed Opportunistic Large Array to utilize physical-layer cooperative transmission; [Barriac, G. et al., 2004] studied a scheme of distributed beamforming where wireless sensor nodes can act as elements of virtual antenna array; [Song, L. et al., 2006] was using cooperative transmission to achieve better communication reliability in wireless sensor networks.

However, both approaches need the cross-layer optimization of communication protocol stack, therefore have caused an issue at the same time: the lost of modularity. It could be concluded that traditional network architecture (primarily based on OSI) is not appropriate for meeting the challenges of wireless sensor networks, and a new modular network architecture needs to be identified from application specific designs.

3. Modular Abstraction and Architecture

Embedded Wireless Interconnect is one of the first modular architecture for wireless sensor networks. The key architectural differentiation is based on the abstract wireless linkage, where wireless links are now redefined as arbitrary mutual cooperation among a set of neighboring (proximity) wireless nodes. In comparison, traditional wireless networking relies on point-to-point “virtual-wired links” with a predetermined pair of wireless nodes and allotted spectrum. The architectural diagram of EWI is illustrated in Figure 2.

The concept of EWI was firstly proposed in some application specific studies of wireless sensor networks, including [Song, L. et al., 2007a, 2007b]. A protocol for target tracking in wireless sensor networks has been the first example to demonstrate the EWI architecture in [Song, L. et al., 2007a].

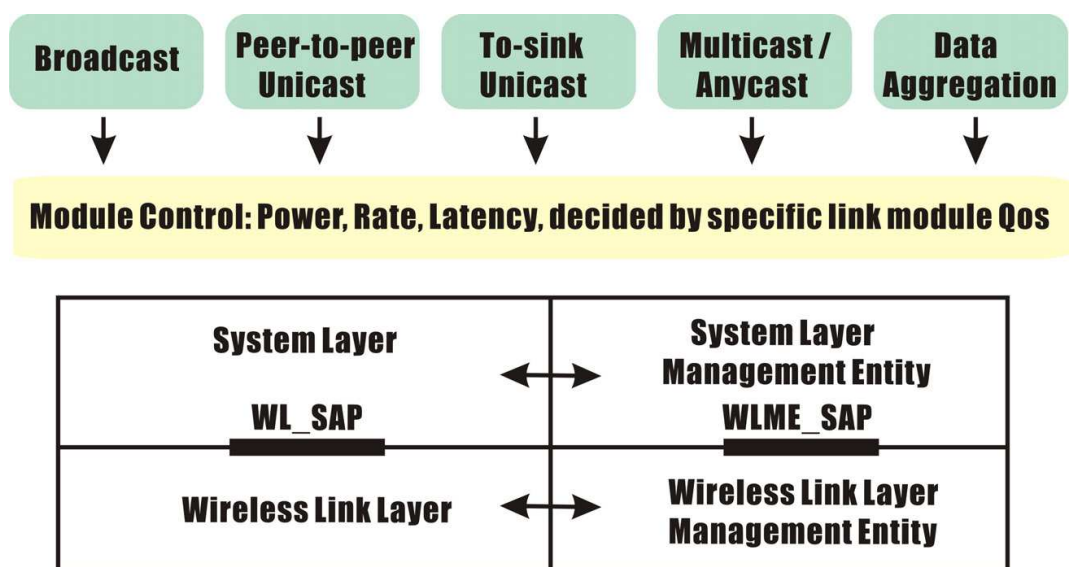


Fig. 2. EWI Architecture

Three principles about the EWI architecture have been generalized from application specific studies:

1. *Functional linkage abstraction:* By the functional abstractions, wireless linkage is redefined as arbitrary functional abstraction of proximity node cooperation. Therefore, “wireless link modules” are the building blocks for individual wireless nodes, so as to establish different types of abstract wireless links. For example, categories of wireless links (modules) can include: broadcast, unicast, multicast and data aggregation, etc. At the architecture level, this results in two hierarchical layers: the upper system layer and the lower wireless link layer. The wireless link layer offers a library of wireless link modules to the system layer; the system layer organizes the provided wireless link modules and API to achieve effective application implementation.

2. *Opportunistic wireless links*: In the formation of abstract wireless links, both the occupied spectrum and participating wireless nodes are opportunistically decided by their instantaneous availability. This largely differentiates from traditional wireless networking where both types of resources (spectrum and radio) are predetermined for point-to-point wireless links. The resulting system performance shall improve with larger network scale, since higher network density provides more redundancy for the opportunistic utilization. This also introduces the concept of large-scale cognitive networking that will be further described in Section 4.

3. *Global QoS decoupling*: Global QoS requirements at both application and network levels are statistically decoupled into local wireless link QoS, which are local requirements of proximity node cooperation. By decoupling global network QoS such as throughput, end-to-end delay and delay jitter, the wireless link module design such as unicast or multicast can achieve global end-to-end performance requirements. Similarly by decoupling global application QoS, the system layer can better organize the wireless link modules that are provided by the wireless link layer. Since wireless networking complexities are well encapsulated in the wireless link modules, the implementation complexity at individual wireless nodes shall be independent of network scale/size.

Like the merits of any modular architecture, the defined wireless link modules can provide system designers with reusable open network abstractions, where the modules can be individually updated or added in the wireless link layer. Five different wireless link modules are illustrated in Figure 2, which are broadcast, peer-to-peer unicast, multicast, to-sink unicast and data aggregation, respectively. Other types of wireless link modules can be added, subject to other system design consideration. The broadcast module simply broadcasts data to neighboring nodes; the peer-to-peer unicast module [Song, L. et al., 2008] can reliably send data from source to destination over long distance (multiple wireless hops); the multicast module sends data to multiple destinations; the to-sink unicast module [Song, L. et al., 2007b] can utilize higher power of data collectors (sinks) to achieve better data collecting; and the data-aggregation module [Song, L. et al., 2007a] can opportunistically collect and aggregate data from neighboring wireless sensor nodes.

EWI is an organizing-style architecture, where the system layer can manage and organize the wireless link modules. Peer wireless link modules can exchange module management information by putting it in the packet headers to system-layer information units. As illustrated in Figure 2, the interface between the system layer and the wireless link layer is defined by two service access points (SAP): the wireless link SAP (WL SAP) and wireless link management SAP (WLME SAP) that are utilized for the data plane and the management plane respectively. Each SAP is composed of a set of API functions [Song, L. et al., 2009] to control the state of the wireless link layer and link QoS.

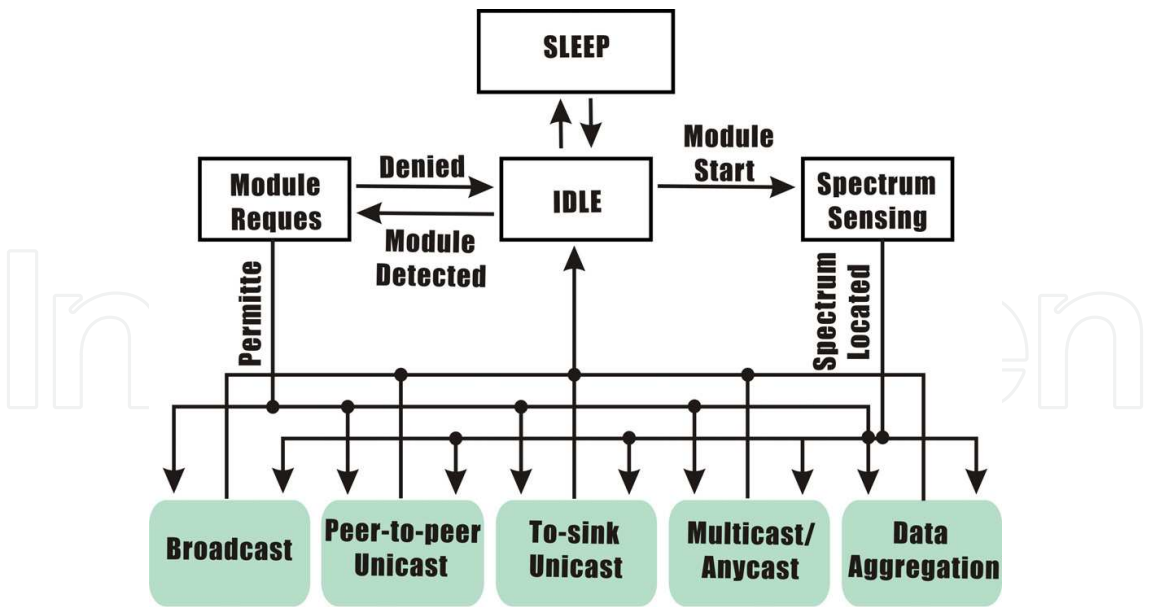


Fig. 3. State Diagram of the Wireless Link Layer

A state diagram of the wireless link layer can be illustrated in Figure 3. The wireless link layer remains in the IDLE state, when no wireless link module is invoked. A pair of primitives (API functions) can be utilized for the switching between the IDLE state and the SLEEP state (power-saving mode). In the IDLE state, the wireless link layer keeps monitoring if there are new abstract wireless links being initiated. Once an initiation from any neighboring nodes is detected, the wireless link layer transfers from the IDLE state to the Module Request state. This provides the system layer with the control of wireless link activities, so that the wireless link layer would either transfer back to the IDLE state or join in the new abstract wireless link, as decided by the system response. On the other hand, once receiving a command to initiate an abstract wireless link, the wireless link layer transfers from the IDLE state to the Spectrum Sensing state; a wireless link module would be then started after available spectrum resource being opportunistically located.



Fig. 4. Commercial Hardware/SDK based on EWI

An implementation of the EWI architecture for wireless sensor networks, including hardware platform and SDK (Software Development Kits), is now commercially offered by OMESH Networks Inc. (Toronto, Canada URL: www.omeshnet.com). The system has been used in commercial applications including wireless location and monitoring/controlling sensor networks in agriculture, mining, electricity, environmental monitoring, and industrial controlling. It has also been used for sensor network test-bed in academic research including a number of projects in the University of Toronto.

4. Cognitive Networking Method

As described previously, both the operating spectrum and participating nodes are opportunistically decided for an abstract wireless link under the EWI architecture. This introduces the concept of large-scale cognitive networking [Song, L. et al., 2009] which can best utilize network resources in large-scale wireless systems, such as the applications of wireless sensor networks. The networking concept is one-step further of cognitive radio [Zhao, Q. et al., 2007], and creates dynamic and real-time network with unlimited scalability.

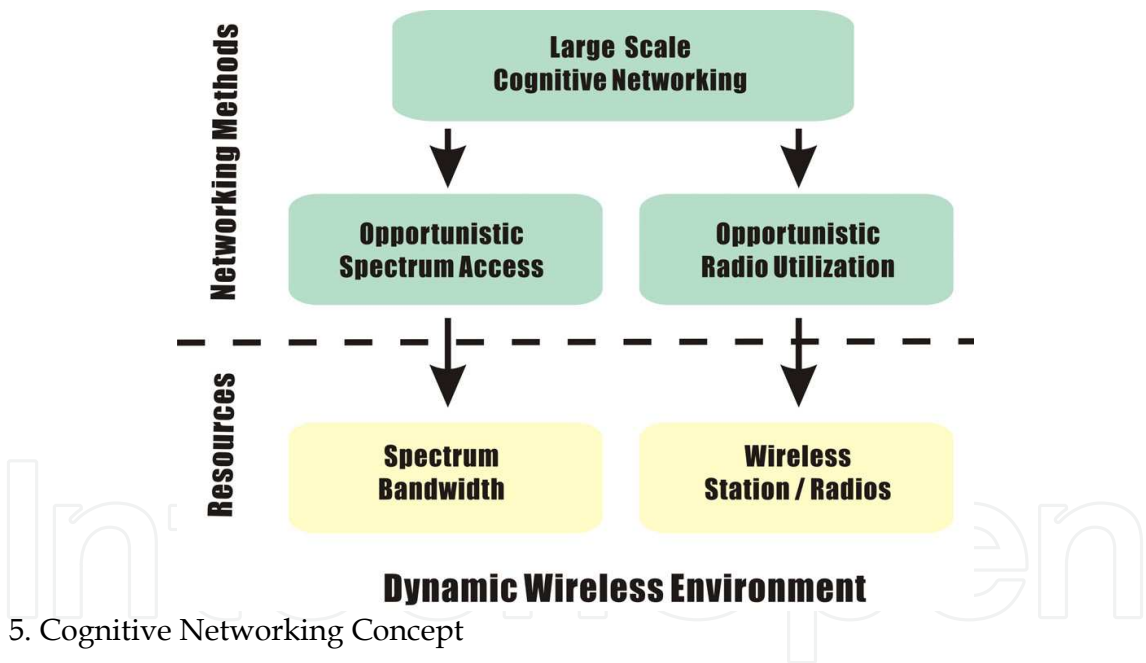


Fig. 5. Cognitive Networking Concept

In principle, large-scale cognitive networking is highly differentiated from traditional wireless networking, by its opportunistic network resource utilization of both spectrum bandwidth and wireless node/radio availability. On the contrary, traditional wireless networking assumes that those resources can be predetermined.

The cognitive-networking method creates a dynamic (fluid) wireless network without predetermined topology and spectrum allocation. For example, in multi-hop wireless communications, every packet takes opportunistically available paths in the wireless

network, and with opportunistically available spectrum on every hop. The network-resource utilization can thereby reach its instantaneous maximum, disregarding volatile changes and the demand placed on the network. In large-scale wireless networks such as wireless sensor networks, the problem of volatile spectrum availability is typical in unlicensed bands where interference prevails. Similarly, the problem of random radio availability is also often encountered due to the dynamic traffic load and other factors such as radio failure. In dynamic wireless environment, traditional wireless networking seldom functions properly, given its assumption of predetermined “virtual-wired” links and network topology for (ad-hoc) network routing protocols. As a result, almost every today’s real-world wireless network is based on single-hop wireless (e.g., cellular networks, WLAN – wireless local area networks) rather than a true multi-hop mesh.

A set of key comparative advantages of the cognitive-networking method is further explained as follows:

Dynamic network planning and deployment model:

No deterministic network topology has to be maintained, because the wireless node/radio resource is opportunistically utilized. The wireless sensor nodes, when implemented with the cognitive-networking method, become “drop-and-play” in the network deployment. Inserting more radios/nodes can improve the radio resource to be opportunistically exploited, and therefore increase the network capacity. Likewise removing any individual radio/node does not create bottlenecks in the network. This fluid “drop-and-play” nature offers the potential of vast cost-saving in network planning and deployments. The setup of wireless radio/node does not need expensive planning and calibration, as multi-tier new deployments (for example introduced by operators) guarantee improved network capacity. High mobility of the nodes/radios can be supported.

Better network resource utilization:

The network resource in large-scale wireless networks includes: the amount of spectrum bandwidth and the number of wireless nodes/radios. Theoretical network capacity is decided by the network resources, and the multiplication of these two factors. Traditional wireless networking depends on a deterministic network topology. It is therefore difficult to efficiently utilize the network resources, subject to a dynamic wireless networking environment where both spectrum bandwidth and radio availability cannot be predetermined. The cognitive networking method offers a means of better network-resource utilization, approaching the information-theoretical limit on wireless-network capacity.

Supporting guaranteed real-time services:

Due to the opportunistic network-resource utilization, reliable wireless communications with specified dataflow throughput, end-to-end delay, and delay variance can be supported over multiple wireless hops. Therefore, real-time services,

including multimedia streaming, can be supported by the cognitive-networking method. In order to better understand this, note that the opportunistic exploitation of local random-networking environment can result in overall-reliable end-to-end communications. Dataflow throughput is independent of the number of wireless hops; end-to-end delay and delay variance only increase linearly with the number of wireless hops; and delay variance can also diminish to zero with higher network density. Therefore, network operators only need to assure that sufficient network resources are deployed to support their applications, so as to provide guaranteed services of real-time communications, where the resources, e.g., gateway capacity and nodes/radios, can be deployed with low cost.

Robust to wireless interferences:

Due to the opportunistic network-resource utilization of spectrum bandwidth, the network is very robust to interferences which can be substantial in unlicensed spectrum bands (e.g., ISM bands). For example, viable operation within unlicensed bands can bring large free bandwidth to wireless sensor networks, which results in large network capacity with virtually zero cost.

Compatibility with current industrial standards:

The cognitive-networking method can be compatible with all established wireless radio standards, so that the implementation can be independent of physical radios. Therefore, the radio modules (with cognitive-networking capabilities) can use off-the-shelf RF chips which offer relatively low cost. The implementation can also be seamlessly integrated with all network-layer protocols, including for example Internet Protocols.

Supporting scalable radio complexity (low power):

The complexity of individual radio modules (with cognitive-networking capabilities) is low and independent of network scale/size. The low radio complexity results in lower power consumption, lower cost, and longer battery life. When needed, it also makes it possible to power the wireless node by cost-effective solar panel, which will further reduce installation cost by removing any cable attachment.

Better economics and business case (low cost):

As explained above, the cognitive-networking method can offer excellent economics in large-scale wireless systems including wireless sensor networks, by which 1) the costs of deploying network resources could be vastly reduced by the utilization of unlicensed spectrum bands and drop-and-play (mobile) wireless nodes; 2) much higher efficiency in network-resource utilization results in excellent performance with all the available resources being used to their instantaneous maximum.

5. Conclusion

In this chapter, we have not only reviewed the need for application-specific network design in the current research of wireless sensor networks, but also have pointed out the need for appropriate modular abstractions or network architecture. System modular abstractions are important for any industrial proliferation of computer and communication systems, where any modification and improvement of one layer or module would not need a system re-design.

We then introduced one of the first modular architecture for wireless sensor networks, Embedded Wireless Interconnect. The abstractions of EWI take a layered architecture, and hide networking complexities from application design in large-scale wireless systems, by the redefinition of wireless linkage. Modular abstractions are given on wireless links, and a set of API functions can be provided for the system to organize and manage the wireless link modules. Major resources in large-scale wireless networks, including both spectrum bandwidth and wireless nodes (radios) are opportunistically utilized in the construction of abstract wireless links, according to the cognitive-networking method. Therefore, the modular architecture of EWI creates low-complexity wireless sensor networks that can efficiently deal with dynamic changes typically in large-scale wireless environment, and ensure reliable application-level QoS at the same time, addressing the major challenges in wireless sensor networks.

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Wireless sensor networks are deployed in a rapidly increasing number of arenas, with uses ranging from healthcare monitoring to industrial and environmental safety, as well as new ubiquitous computing devices that are becoming ever more pervasive in our interconnected society. This book presents a range of exciting developments in software communication technologies including some novel applications, such as in high altitude systems, ground heat exchangers and body sensor networks. Authors from leading institutions on four continents present their latest findings in the spirit of exchanging information and stimulating discussion in the WSN community worldwide.

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