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Srikanta Patnaik
Xiaolong Li
Yeon-Mo Yang *Editors*

Recent Development in Wireless Sensor and Ad-hoc Networks

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Yeon-Mo Yang
Editors

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Editors
Srikanta Patnaik
Department of Computer Science and Engineering
SOA University
Bhubaneswar, Odisha
India

Yeon-Mo Yang
School of Electronic Engineering
Kumoh National Institute of Technology
Gumi
Republic of South Korea

Xiaolong Li
Electronics and Computer Engineering Technology
Indiana State University
Indiana, IN
USA

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Preface

A WSN may be described as a network of nodes that cooperatively sense and control the environment enabling interaction between persons or computers and the surrounding environment. Recent developments in networking and material science and nanotechnologies are the driving force for the overall development of large-scale wireless sensor networks (WSNs). In addition, these technologies have merged together to enable a new generation of WSNs that differ significantly from traditional wireless networks, which was implemented 5–10 years ago. Like any other advanced technologies, the origin of WSNs can be traced back to military applications. The first wireless network, which has a close resemblance to a recently used WSN, is the Sound Surveillance System (SOSUS) developed by the United States Military in the 1950s. This network used submerged acoustic sensors hydrophones, distributed in the Atlantic and Pacific oceans. The same sensing technology is still existing today and serving for the peaceful applications. Afterward during 1980s, the United States Defense Advanced Research Projects Agency (DARPA) started the Distributed Sensor Network (DSN) program to formally explore the challenges in implementing distributed/wireless sensor networks. Later on, scientific research communities as well as academia join hands to develop the WSN technology. Subsequently, government and universities began using WSNs for various applications, such as air quality monitoring, forest fire detection, natural disaster prevention, weather stations and structural monitoring, power distribution, waste-water treatment, and specialized factory automation, which were basically heavy industrial applications.

Present day state-of-the-art WSN has less deployment and maintenance costs, more rugged, and last longer, and they are now used for various applications at our homes, work places, bringing new sources of information, control, and convenience to our personal and professional lives. Efficient design and implementation of wireless sensor networks has become a hot area of research, due to the vast potential of sensor networks to enable applications that connect the physical world to the virtual world. This volume covers the recent developments in the area of Wireless Sensor and Ad-hoc Network. Potential applications for such large-scale

WSN exist in a various domains, such as health monitoring, home security and surveillance, and personal environmental monitoring, such as temperature and humidity.

In future, micro-fabrication technology shall bring down the cost of sensor nodes resulting in the pervasive use of wireless sensor networks with a large number of nodes. For the smooth deployment of the future WSN, researchers and designers are now engaged in solving the complex trade-offs among many application variables including deployment costs, hardware and software, system reliability, security, and performance. Wireless embedded system designers must also consider these trade-offs and make alternative decisions, such as transducer and battery technology choices, frequency of wireless operation, output power and networking protocols. The complexity of WSN design not only represents one of the most significant barriers to the widespread adoption of WSNs, but also provides an opportunity for hardware and software technology suppliers to add value. Another trade-off is also use of well established, standardized mix of hardware/software solutions for different WSN applications.

Srikanta Patnaik
Xiaolong Li
Yeon-Mo Yang

Contents

About the Editors

Prof. Srikanta Patnaik is presently serving as a Professor of Computer Science and Engineering, SOA University, Bhubaneswar, India. He holds Doctor of Philosophy in Engineering from Jadavpur University, India. He has published more than 80 research papers and articles in international journals and magazines of repute. He has supervised 10 research scholars for their Ph.D. degrees. He has completed various funded projects as Principal Investigator from various funding agencies of India. Presently, he is serving as an Editor-in-Chief of two international journals namely, *International Journal of Information and Communication Technology* and *International Journal of Computational Vision and Robotics*, published from Inderscience Publishing House, England and also an Editor-in-Chief of Springer Book Series on Modeling and Optimization in Science and Technology (MOST).

Dr. Xiaolong Li is working as an Associate Professor, Department of Electronics and Computer Engineering Technology, Indiana State University since 2008. He has done his Ph.D. in Electrical and Computer Engineering in 2006 from University of Cincinnati. He did his M.S. in Electronics and Information Engineering from Huazhong University of Science and Technology, China in 2002 and did his B.A. in Electronics and Information Engineering, from the same University of Science and Technology, China in 1999. His major research includes Wireless and Mobile Networks, Wireless Ad Hoc Networks, Wireless Internet, Modeling and Performance Analysis, QoS in Communication Networks, Wireless Mesh Network, Microcontroller-based Applications, Security in Wireless Networks. He has more than 30 International publications in International Journals and conference proceedings of repute. He has also contributed a Book Chapter entitled "Impact of Mobility on the Performance of Mobile Ad Hoc Networks and Performance Analysis of Mobile and Ad Hoc Networks", published by NOVA Publishers. He has association with the Institute of Electrical and Electronic Engineering (IEEE), American Society of Engineering Education (ASEE), Association of Technology, Management, and Applied Engineering (ATMAE) and Epsilon Pi Tau (EPT).

Prof. Yeon-Mo Yang is a Professor in the Department of Electronic Engineering, Kumoh National Institute of Technology, Gumi, Korea. He received the B. Engg. in the field of Electrical and Electronic Engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea in 1990 and Ph.D. from Gwangju Institute of Science and Technology (GIST), Gwangju, Korea in 2006, in the field of optical networks. From 2005 to 2006, he was a post-doctoral fellow in North Carolina State University (NCSU), Raleigh in Networks Engineering and a short-time visiting scholar at UC Berkeley, Berkeley, CA, in Wireless Sensor Networks. From 2006 to 2008, he was in Daegu-Gyeongbuk Institute of Science and Technology (DGIST) as a senior researcher where he has been a project leader of the developments of wireless sensor networks. His current research interests include wireless sensor networks analysis and implementation both at the physical layer and at the networks layer; dynamic bandwidth allocation schemes in passive optical networks; and realizations of hybrid embedded systems connected to Under Acoustic Sensor Networks, Mechatronics and Information Technology.

Introduction

"Recent Developments in Wireless Sensors and Ad-hoc Networks" is an edited volume in the broad area of WSNs. It covers various chapters like Multi-Channel Wireless Sensor Networks, its Coverage, Connectivity, as well as Deployment. It also covers comparison of performance of various communication protocols and algorithms, such as MANNET, ODMRP, and ADMR Protocols for Ad hoc Multicasting, Location-Based Coordinated Routing Protocol and other Token-based group local mutual exclusion Algorithms.

Chapter 1 entitled "Multi-channel Wireless Sensor Networks" contributed by Amalya Mihnea and Mihaela Cardei, discussed issues and challenges related to multi-channel and multi-radio networks. They have classified the channel assignment schemes into static, semi-dynamic, and dynamic, and also discuss methods proposed in each category. They have presented other related issues such as primary users, network capacity, interference, topology control, and power and traffic aware protocols. They have explained the concept of multi-channel algorithms lucidly for designing additional algorithms for wireless sensor networks.

In Chap. 2 "Coverage, Connectivity and Deployment in Wireless Sensor Networks", Yun Wang et al. have introduced three fundamental problems, i.e., sensing coverage, network connectivity, and sensor placement/deployment in a wireless sensor network (WSN). They have covered the open problems in this area, which includes sensing coverage and connectivity analysis in three-dimensional WSNs, nonuniformly distributed WSNs, and mobile WSNs.

In Chap. 3 "Development of Home Automation System by using ZigbeX and Atmega128 for Wireless Sensor Networks", Nik Khadijah Nik Aznan and Yeon-Mo Yang presented a framework and a test-bed of Home Automation systems by implementing the cost-effective ZigbeX and Atmega128 with TinyOS. They have proposed a house model, which is able to control the lights and curtain depending on the light intensity measured by the photodiode on the ZigbeX.

In Chap. 4 "Efficient Coordination and Routing Protocol for Wireless Sensor and Actor Networks", Biswa Mohan Acharya and S.V. Rao have discussed about the problem of communication and coordination of various sensor nodes and proposed an efficient model based on geometric structure called Voronoi diagram. They have proposed a new protocol, which is based on clustering (virtual grid) and Voronoi region concept and they have given the simulation results which they claim outperforms in terms of throughput, packet delivery ratio, average delay, and normalized routing overhead.

Chapter 5 entitled “Performance Comparison of BEMRP, MZRP, MCEDAR, ODMRP, DCMP and FGMP to Achieve Group Communication in MANET” by M. Rajeswari et al. presents a comparative performance of six multicast protocols for Mobile Ad hoc Networks—BEMRP, MZRP, MCEDAR, ODMRP, DCMP & FGMP focusing on the effects of changes such as the increasing number of receivers or sources and increasing the number of nodes.

Chapter 6 entitled “Token based Group Local Mutual Exclusion Algorithm in MANETs” by Ashish Khanna et al. proposed a generalization of the group mutual exclusion problem based on the concept of neighborhood, which is named as group local mutual exclusion (GLME). They have also proposed a token-based solution of the group local mutual exclusion. The authors have claimed that their proposed method is the first token-based algorithm to solve group local mutual exclusion problem in MANETs.

In Chap. 7 “A Dual-band Z-shape Stepped Dielectric Resonator Antenna for Millimeter-wave Applications”, Ashok Babu Chatla et al. have presented a dual-band z-shape stepped dielectric resonator antenna (DRA) for millimeter wave applications. The authors claimed that their design can be used for inter-satellite service applications, which operate at 65–66 GHz.

In Chap. 8 “OCDMA: Study and Future Aspects”, Shilpa Jindal and Neena Gupta, discussed the future trend of OCDMA technique that highlighted on the newly developed three dimensional codes based on optical orthogonal codes and codes from algebra theory and their performance is evaluated on two models Model A and Model B.

In Chap. 9 “Focused Crawling: An Approach for URL Queue Optimization Using Link Score” by Sunita Rawat has presented a case of scaling challenges for traditional crawlers and search engines due to the expansion of the worldwide web and also proposed a method of efficient and focused crawling to enhance the quality of web navigation.

In Chap. 10 “An Optimized Structure Filtered-x Least Mean Square Algorithm for Acoustic Noise Suppression in Wireless Networks”, Asutosh Kar and Mahesh Chandra have proposed an improved pseudo-fractional tap-length selection algorithm in context with the FX-LMS algorithm to find out the optimum structure of the acoustic noise canceller, which best balances the complexity and steady state performance.

Last but not least, in Chap. 11 entitled “An Exhaustive Comparison of ODMRP and ADMR Protocols for Ad hoc Multicasting” myself along with my colleague Ajit Nayak have presented a comparative study of two well-known protocols for wireless multicasting. One of the considered protocols is *On Demand Multicast Routing Protocol* (ODMRP) and the other one is *Adaptive Demand driven Multicast Routing Protocol* (ADMR). ODMRP is a mesh based protocol, whereas ADMR uses a tree-based technology for routing.

Chapter 1
Multi-channel Wireless Sensor Networks

Amalya Mihnea and Mihaela Cardei

Abstract In this chapter, we discuss some issues and challenges related to multi-channel and multi-radio networks. We classify channel assignment (CA) schemes into static, semi-dynamic, and dynamic and discuss methods proposed in each category. Other aspects presented are related to primary users (PUs), network capacity, interference, topology control, and power- and traffic-aware protocols. For a better understanding, some basic concepts related to wireless communication are explained. An understanding of multi-channel algorithms in general could help in designing additional algorithms for wireless sensor networks (WSNs).

Keywords Multi-channel · Multi-radio · Wireless sensor networks · Channel assignment · Primary user · Interference · Energy efficiency

1.1 Introduction

Wireless sensor networks (WSNs) constitute the foundation of a broad range of applications related to national security, surveillance, military, health care, and environmental monitoring.

Many results and channel assignment (CA) schemes proposed for wireless ad hoc networks and mesh networks cannot be directly applied to sensor networks, which have different characteristics such as smaller packet size, less powerful radios, or fewer radios. There are also differences related to energy source, power, computational capacity, and memory. The main type of communication used by

A. Mihnea (✉) · M. Cardei
Department of Computer and Electrical Engineering and Computer Science, Florida Atlantic University, Boca Raton, FL 33431, USA
e-mail: amihnea@fau.edu

M. Cardei
e-mail: mcardei@fau.edu

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WSNs for data gathering is *converge cast* where data travel from many nodes (e.g., sensor nodes) to a single node called sink or base station (BS).

With a single-radio and a single-channel, WSNs cannot provide reliable and timely communication in case of high data rate requirements because of radio collisions and limited bandwidth. Therefore, designing multi-channel-based communication protocols is essential for improving the network throughput and providing quality communication services.

Multi-channel protocols consist of two major components: CA and medium access control (MAC). In some protocols, these two are combined: Channels are selected at every access to the medium. A good CA is one that reduces interference among concurrent transmissions, maximizes the capacity of the network, mitigates packet congestion within a single channel and in the case of primary users, and preserves robustness to the presence of a primary user (PU).

1.2 Challenges and Classifications of Multi-channel Protocols

MAC methods are designed for coordinating communication: sharing the wireless medium and alleviating conflicts. They are contention-based such as carrier-sense multiple access (CSMA) or schedule-based such as time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access (CDMA). Some other approaches use power control and directional antennas to further reduce interference [1].

CA schemes can be static, semi-dynamic, or dynamic. The static ones assign channels for permanent use, at deployment time or during runtime. Even if the assignments can be renewed, radios do not change their frequencies during communication. Semi-dynamic schemes assign constant channels to radios, but these can change during runtime while in the dynamic approaches, there is no initial assignment of channels to radios and the channels can change between successive data transmissions.

Some dynamic schemes use a dedicated control channel which can only be used for exchanging control messages (negotiations of the channels for data transmission) while data are exchanged using data channels. These approaches do not need time synchronization and are easier to implement.

Another classification can be related to implementation/execution. If the CA is done by a central scheduler, then the implementation is centralized. Otherwise, if nodes negotiate and more nodes are involved in assigning channels, then the implementation is distributed. The communication between devices involved in the distributed protocols is done by exchanging messages. Centralized approaches have limitations such as lack of a global common control channel to support centralized control and poor scalability due to the difficulty of capturing consistent global information in a dynamic environment [2].

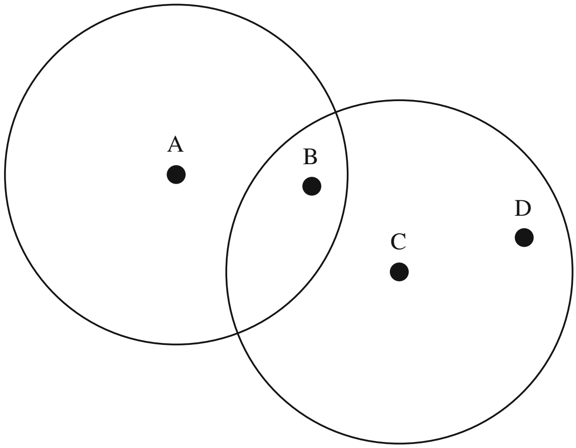

Fig. 1.1 The multi-channel hidden terminal problem

If switching channels is allowed, some problems that reduce network performance are as follows: multi-channel hidden terminal problem, deafness problem, and broadcast support [3].

The multi-channel hidden terminal problem (Fig. 1.1) can occur in carrier-sense multiple access with collision avoidance (CSMA/CA)-based protocols when the control packets (RTS/CTS) sent on a specific channel are not received by the nodes communicating on other channels. For example, suppose that we have four nodes A, B, C, and D that use a common control channel, let us say channel 1. Assume that A and B have successfully established a communication on channel 2. Assume that the node C was busy receiving on another channel when B sent the CTS to A, and thus, C is not aware of A communicating with B on channel 2. If subsequently C initiates a communication with D on channel 2, this will cause collisions at the node B. The cause of this problem is that nodes may listen to different channels when other nodes exchange RTS/CTS control messages on the common control channel [4].

In order to communicate, a sender and a receiver have to be on the same channel; otherwise, the deafness problem occurs in multi-channel communication. Suppose that a transmitter sends a control packet to initiate communication and that the receiver is tuned to another channel. If the sender does not get any response after sending multiple requests, then it may conclude that the receiver is not reachable anymore [3].

Broadcast support refers to the difficulty of supporting successful broadcasts when the nodes change their channels frequently. Usually, protocols use a broadcast channel to support broadcasts. If nodes operate on multiple channels, channel switching introduces delays and computational overhead.

Some additional problems that are mentioned in the literature are idle listening, when nobody is sending, and overhearing of messages, when a node receives messages that are destined to other nodes. It is known that the energy spent for receiving a message can even be a bit higher than the energy spent for transmitting a message [1]. All these problems are connected to power consumption, and they could shorten the lifetime of the network. They have to be taken into account when designing power-aware algorithms. Later, we will present some power- and traffic-aware protocols.

In [3] CA methods are classified using criteria such as assignment method, control channel, implementation/execution, synchronization, medium access, broadcast support, channel model, interference model, and objective. We elaborate on the classification into fixed (static), semi-dynamic, and dynamic methods, and we give a few examples for each category. The algorithms are assumed to be single radio unless otherwise specified.

1.2.1 Fixed Channel Assignment

An idea related to this category is to take advantage of *clustering* the nodes such that all the nodes in a cluster use a unique frequency that is different than the frequencies of other clusters. The goal is to avoid or to minimize interference.

Another idea is to use *component-based channel assignment* [5], which assigns the same channel to all nodes belonging to a component formed by nodes belonging to mutually intersecting flows. Two flows are said to be intersecting, if there is a common node in the set of active nodes for each flow, which serves both flows. If flow f_1 intersects with flow f_2 and flow f_2 intersects with flow f_3, then all nodes on the paths traversed by these three flows are assigned the same channel.

Different connected components can potentially operate on different channels. A connected component in a flow graph is defined as the largest subgraph, such that there exists a path from any node in the subgraph to all other nodes in the subgraph. The authors of [5] show through theoretical and quantitative analysis that this simple strategy can improve the network performance. They also propose centralized and distributed routing layer algorithms that implement this strategy effectively.

The main advantage of fixed CA is its simplicity since nodes maintain their assignments. But there are also disadvantages, such as not being adaptive to changes in the network topology due to traffic changes or unstable links, and no possibility of communication between two nodes that have different channels. These issues, which could lead to poor performance and network partitions, could be solved by renewing channel assignments from time to time.

The multi-hop scenario used in WSNs assumes that data travel from source nodes through intermediate nodes toward one or several BSs. Therefore, the routing topology is a tree or a forest.

In [6], a tree-based multi-channel protocol (TMCP) for data collection applications in WSNs is proposed. The authors assume that there is a single BS equipped with multiple radio transceivers, each of which works on different channels. The network is partitioned into multiple vertex-disjoint subtrees all rooted at the BS. Each tree is allocated a different channel, and a data flow is forwarded only along its corresponding subtree. TMCP is distributed and it works with a small number of channels, without any time synchronization requirement.

TMCP has three components: channel detection (CD), channel assignment (CA), and data communication (DC). Given k orthogonal channels, the CA module partitions the whole network into k subtrees, and one unique channel is assigned to each subtree. There is no inter-tree interference so the goal of partitioning is to divide the network into subtrees with low intra-tree interference. The DC component manages the data collection through each subtree.

TMCP uses the *protocol model* (a graph-based interference model) to estimate interference: Two nodes interfere with each other if the distance between them is smaller than a threshold value. The size of a node's interference set is used in subsequent subtree partition. However, the distance-based interference model does not hold in practice as shown by recent empirical studies.

In [7], TMCP has been extended to employ interchannel received signal strength (RSS) models for interference assessment in channel allocation. A novel algorithm is proposed, which can significantly reduce the overhead of multi-channel interference measurement by exploiting the spectral power density (SPD) of the transmitter.

In [2], three algorithms are presented: node-based, link-based, and node-link-based. The best of them, the node-link-based distributed algorithm, partitions the network into "stars," which resemble 2-level trees, and uses maximal matching between channels and adjacent links by the Hungarian algorithm. Channels are assigned to links that minimize channel-conflict probability by computing channel weights based on the conflict probability of every available channel on each link.

In dense networks, this algorithm could be used for the backbone consisting of cluster heads with longer transmission range while the communication within clusters could be done using CSMA. Cluster heads could solve inter-cluster interference by assigning inner-cluster communicating channels.

In [8], network robustness and channel interference are jointly considered when developing centralized and distributed algorithms. Backup channels are used to avoid network partition, but the requirement to adjust channels for previously assigned links might be unsuitable for WSNs, which have limited resources. The proposed solutions outperform existing interference-aware approaches when primary users appear and achieve similar performance at other times. The algorithms from these last two papers are not specifically designed for WSNs.

1.2.2 Semi-dynamic Channel Assignment

Methods in this category, which appear to be the most popular ones, assign fixed channels either to senders or receivers, but the assignments can change during communication. Graph coloring algorithms are useful in such approaches.

Network partitioning could be eliminated using a coordinated channel switching between senders and receivers, which need to be on the same channel at the same time in order to communicate.

In [9], a distributed game-based channel assignment algorithm (GBCA) is proposed to solve the problem of multi-channel assignment in WSNs. Unlike previous static assignment protocols, this algorithm takes into account both the network topology information and the transmission routing information. Simulations show that GBCA achieves better network performance than MMSN in terms of delivery ratio, throughput, packet transfer delay, and energy consumption.

The MMSN protocol [10] is the first multi-frequency MAC protocol designed specifically for WSNs, and it consists of two aspects: frequency assignment and media access. Frequency assignment allows users to choose one of four available frequency assignment strategies to evenly assign different channels among two-hop neighbors. In media access design, potential conflicts are solved by accessing the shared physical frequencies in a distributed way. Both GBCA and MMSN are distributed approaches.

1.2.3 Dynamic Channel Assignment

In these approaches, mostly distributed, a channel selection takes place before every data transmission. The channel selection can be measurement-based or status-based. The first category is related to communicating parties measuring signal-to-interference noise ratio (SINR) and the second one to the status of the channels: idle (available) or busy.

When the traffic is light, many multi-channel MAC protocols for WSNs are less energy-efficient than single-channel MAC protocols. In contrast to these, Y-MAC [11] is energy-efficient and maintains high performance under high traffic conditions. It is also the first protocol that uses dynamic channel assignment in WSNs.

In this TDMA-based multi-channel MAC protocol, a send time slot is used for data transmission and a receive time slot for data reception. An exclusive send time slot in two-hop neighborhood guarantees collision-free access to the medium, which reduces the energy wasted by contention and collisions. However, energy is wasted due to overhearing and idle listening, since all nodes have to wake at every time slot to avoid missing incoming messages. Initially, a base channel is used to exchange messages. Sensor nodes hop to the next radio channel if they have additional pending messages for the receiver (bursty traffic). Y-MAC improves the performance of the network (increased throughput, reduced message delivery latency) under high traffic conditions and uses multiple channels with low energy consumption. Other dynamic protocols such as MAC and MuChMAC are presented in [3].

1.3 Primary Users (PUs)

Due to the recent growth of wireless applications, the communication on the unlicensed spectrum (e.g., ISM) has become congested, while the utilization of the licensed spectrum varies between 15 and 85 % temporally and geographically [12]. Cognitive radio networks (CRNs) constitute a promising solution used to address the issue of inefficient spectrum usage.

A cognitive radio, also called a software defined radio because its communication functions are implemented on software instead of hardware, is a radio that can sense its environment, track changes, and react based upon its findings by efficiently avoiding interference.

Cognitive radios are designed to operate on a wide spectrum range and can switch to a different frequency band with limited delay. This technology allows PUs to share the spectrum with secondary users (SUs), where SUs communicate through un-assigned spectrum bands without disrupting the regular usage of the PUs. CRNs allow SUs to take advantage of unoccupied spectrum in an opportunistic manner using dynamic spectrum access strategies.

To avoid interference with a PU, a SU must vacate the spectrum when the channel is being used by a PU. This affects ongoing communication of the SUs. The challenge occurs due to the difficulty to predict when a PU will appear in a given spectrum. To use other channels, SUs have to spend a considerable amount of time for spectrum sensing and channel switching [13]. In addition, a change in a SU channel may trigger other nodes to change their channels in a ripple effect in order to maintain the desirable topology.

In the presence of PUs, the robustness constraint requires that if a channel is reclaimed by a PU, then the resulting SU topology still preserves the connectivity between any two nodes. The PUs can affect part of the network or the entire network (e.g., transmission of the TV tower). If two sensors u and v communicate on a channel that is reclaimed by a PU, then the packet is re-routed from u to v through another channel of u and possibly another radio of v. Thus, packet dropping and significant delays can be avoided.

1.4 Capacity, Interference, and Topology Control in Wireless Sensor Networks

A special type of WSNs are wireless multimedia sensor networks (WMSNs), which enable advanced surveillance, traffic monitoring, and healthcare systems, and require larger bandwidth. A challenge of WMSNs is an increased bandwidth demand in the presence of higher levels of interference. Using multiple channels for parallel transmissions could improve network capacity.

The most common communication types in WSNs are broadcast and data collection. The main goal of broadcasting is to send a message to all the nodes in the network, and the goal of data collection is to send data messages from source nodes to the sink(s). Broadcast could be used as an initial step in data collection to determine shortest paths between nodes and the sink(s). Communication in WSNs has to take several factors into account, such as link length, number of hops to the BS, and node degree [14].

For a given network topology, different routing trees or CA mechanisms have impact on the maximum achievable network throughput. With multiple channels, there is a need for channel coordination: The sender and the receiver have to transmit and to listen on the same channel at the same time.

In the *receiver-based channel allocation*, a fixed channel is assigned to each sensor node and that channel is used to receive messages. A neighbor that wants to send a message to this node should use the receiver's channel to send. In this allocation, the nodes that do not receive any message are not assigned any channel.

In the *link-based channel allocation*, every link or edge is assigned a channel and every transmission along that link uses that channel. A difference between this and the receiver-based channel allocation is that here, for the same receiver, various senders can use different channels, resulting in less interference.

In data gathering WSNs where source and sink nodes are all equipped with half duplex transceivers, the maximum throughput per node is *W*/*n*, where *n* is the number of source nodes and *W* is the transmission capacity. According to [1], the maximum throughput can be reached only if the sink is 100 % busy receiving packets and if the schedules of all nodes are aligned for interference-free communication for the given network topology.

In [15], it was proved that minimizing the schedule length for an arbitrary network in the presence of multiple frequencies is NP-hard. Also, finding the minimum number of frequencies that are necessary to remove all the interfering links in an arbitrary network is NP-hard.

The authors use an *aggregated convergecast model* [16] where each node has the ability to aggregate all the packets from its children as well as its own data into a single packet before transmitting it to its parent. The routing structure used in data collection is a tree rooted at the sink, and the frequency assignment strategy is receiver-based.

Each node has a single, half duplex transceiver, so it can either transmit or receive a single packet at any given time slot. The radio cannot receive multiple packets simultaneously so assigning different frequencies to the transmitters that are children of the same parent does not help in reducing the schedule length. A contention-free multiple access protocol such as TDMA is used, and each node generates only one packet at the beginning of every frame.

A graph-based interference model is used, where the interference range of a node equals its transmission range. Two types of interference for concurrent transmissions on two edges are considered: *primary interference*, if the two edges are adjacent, and *secondary interference*, if the receivers of both edges are on the same frequency and at least one of the receivers is within the communication range of the other transmitter.

The authors give an upper bound on the maximum number of frequencies required to remove all the secondary interfering links and also propose a polynomial time algorithm that minimizes the schedule length under this scenario. A secondary interfering link is removed if the two receivers of an edge pair are assigned different frequencies. Because half duplex radios are used, the primary interference cannot be removed using multiple frequencies.

A closely related work [16] describes a realistic simulation-based study on a tree-based data collection utilizing transmission power control, multiple frequencies, and efficient routing topologies. It was shown that the data collection rate becomes limited by the maximum degree of the tree once all the interfering links are removed by assigning multiple frequencies. This rate can be further increased on degree-constrained trees.

In [17], a multi-path scheduling algorithm for the snapshot data collection in single-radio multi-channel WSNs is proposed. A tighter lower bound for its achievable network capacity is given compared to the results in [18]. Also, a novel continuous data collection method for dual-radio multi-channel WSNs is shown to speed up the data collection process and improve the network capacity. Most of the previous works related to network capacity consider just single-radio single-channel WSNs. The protocol used in [18] is the *protocol interference model,* but the results can be extended to WSNs under the *physical interference model* [19].

The protocol interference model assumes that all nodes have the same interference range R. If a node X_i sends data to a node X_j over a channel, the transmission is successful if the destination node is far enough from the source of any other simultaneous transmission on the same channel or $\left|X_k - X_j\right| \geq (1 + \Delta)\left|X_i - X_j\right|$, where $\Delta > 0$, for any node X_k transmitting over that channel. This model can take advantage of the graph-coloring-based scheduling algorithms.

The physical interference model (SINR model) is considered better because it can capture the interference from multiple simultaneous senders. If $\{X_k;\ k \in T\}$ is the subset of nodes transmitting simultaneously at some point in time over a certain channel and P_k is the power level chosen by the node X_k for $k \in T$, then the transmission from a node X_i, $i \in T$, is successfully received by a node X_j if

$$\frac{\frac{P_i}{\left|X_i - X_j\right|^\alpha}}{N + \sum_{k \in T, k \neq i} \frac{P_k}{\left|X_k - X_j\right|^\alpha}} \geq \beta$$

where β is the minimum SINR for successful receptions, α represents the exponent for signal loss due to distance, and N is the level of the ambient noise [3].

In [20], the authors analyze the capacity limits of multi-hop paths in a WSN with multiple channels. Also, a control channel-based MAC protocol is implemented and analyzed using IEEE 802.15.4-based networks with 16 orthogonal channels. This protocol is based on the split-phase approach described later, which does not require any time synchronization and is simple to implement, but could suffer from saturation of the control channel.

Previous MAC protocols such as McMAC, CMAC, and MAC are not considered efficient. The channel coordination mechanisms are divided into four categories: (1) dedicated control channel, (2) common hopping, (3) split phase, and (4) McMAC. The differences of these mechanisms are related to the number of radios they use: a single radio or two radios.

The dedicated control channel mechanism is used with multiple radios. There is a specified control channel used for one radio to transmit information related to channel selection. After a channel is selected, data are transferred through that channel between the sender and the receiver.

The common hopping mechanism is used with a single radio. There is a common pattern of shifting channels followed by all nodes. An RTS/CTS handshake takes place using the current common channel when two nodes want to communicate. During this handshake, the given sender–receiver pair stops hopping and stays tuned to this common channel. After data transfer is done, the two nodes resume the same hopping sequence.

The split-phase approach is used with a single radio and has two phases: control and data. The control phase includes agreements that are made between sender(s) and receiver(s) regarding the channel on which data have to be transferred. In the data phase, the data are transmitted using the chosen channel.

The fourth category includes the McMAC [21] protocol, which uses random hopping of channels for each node. When a node A has to transfer data to a node B, if data to be transferred are large, then A follows B's hopping pattern. After data transfer, A resumes its own hopping sequence.

In addition to MAC protocols, other methods to alleviate interference are as follows: transmission power control (transmitting signals with sufficient power instead of maximum power) and use of directional antennas instead of omnidirectional antennas.

Topology control is a very important technique in WSNs which deals with sensor nodes' power control and network structure. Some of the design goals of topology control are as follows: minimum energy consumption, low interference, small node degree, connectivity, and planarity.

Some topology control algorithms that have been proposed in the last few years are inappropriate because they do not address both communication types in WSNs: message dissemination and data collection. Very often, the robustness of the topology is neglected. The node failure is handled by most of the algorithms by simply resetting the whole network, which has a high cost in terms of energy consumption. Other algorithms try to establish several disjoint routes between sensor nodes and the BS or between sensor nodes in order to improve the network robustness, which is not an easy task.

The simplest topology control strategy is called unit disk graph (UDG), in which all sensor nodes communicate with each other using their maximum power so that all possible communication links are preserved. Other approaches try to eliminate all or some of the redundant links, keeping some links to improve the network's tolerance to node failure and network capacity, or try to improve the robustness of the network by a specially designed edge weight function, which contains link length and number of hops to the BS.

Other topology control algorithms partition the network into several disjoint parts or clusters, each of which has one selected cluster head and several cluster members. The cluster head is responsible for inter-cluster communication, and all cluster members only communicate with their own cluster head in a TDMA manner. Each cluster head is elected periodically in order to balance energy consumption.

In [14], the authors propose a novel tree-based topology control algorithm which contains a fast dissemination tree (FDT) for message broadcast and a balanced data collection tree (BDCT) for data collection. This algorithm has better performance than the existing ones and helps balance energy consumption between nodes.

FDT uses the maximum power and chooses the nearest neighbor for transmission. Node *i* chooses as its parent the nearest node *j* which has the smallest number of hops to the BS, so that the message can be received and relayed as quickly as possible. The BS is placed in the center of the network, and each node has information about its neighbors, such as ID, number of hops to the BS, energy left, and location, which are used in the construction of the BDCT.

The objective of the BDCT is to achieve a balance among different design goals: link length, number of hops to the BS, remaining energy, and robustness. The selection of a parent node is based on the link weight whose settings give priority to a node with more residual energy. This helps balance the energy consumption throughout the whole network, which in turn prolongs the lifetime of the network.

Robustness is related to the number of critical nodes. Node *i* is said to be a critical node if, once *i* fails, the network is no longer connected. A tree-based topology has a severe drawback: once a parent node fails, all its children lose connection with the BS. A solution to this case is topology reconstruction, but this approach is expensive in terms of energy and time. Another solution is to establish multiple paths between a node and the BS, but computing multiple paths increases the computational complexity. A better solution proposed in [14] is to choose a network topology that resembles a spider web which has to be reinitialized just in the case of multiple node failures.

1.5 Power- and Traffic-Aware Protocols

Many WSNs applications need data to be transmitted in a timely manner, such as WSN-based disaster warning systems or a warning surveillance system that has to notify authorities when intruders are detected. It is known that wireless links are lossy and retransmissions increase the end-to-end delay. A solution to improve link quality is to increase transmission power, but this may increase interferences and channel contention, which leads to a decreased network capacity. An alternative solution is to use multi-channel protocols to increase network capacity and to reduce interference and delays.