Crowded Spectrum in Wireless Sensor Networks

Gang Zhou, John A. Stankovic and Sang H. Son
Department of Computer Science, University of Virginia, Charlottesville 22903
{gzhou,stankovic,son}@cs.virginia.edu

Abstract— **With the exciting progress of wireless sensor network (WSN) research, we envision that in 5-10 years, the world will be full of low power wireless sensor devices. Due to the independent design and development, together with the unexpected dynamics during deployment of co-existing networks and devices, the limited frequency spectrum will be extremely crowded. Plus, existing electric appliances like microwaves make the congestion even worse. This paper proposes to develop new suites of WSN protocols along three complementary dimensions: (1) to achieve high communication throughput within a single WSN, (2) to achieve multi-frequency functionality among overlapping but cooperative WSNs and (3) to resolve the crowded spectrum issue caused by any reason, such as random transmitting devices, other nearby sensor networks, or even co-existing electric appliances.**

I. INTRODUCTION

Wireless sensor network (WSN) is an exciting new technology with application to environmental monitoring, agriculture, medical care, smart buildings, factory monitoring and automation, and numerous military applications. A WSN can also be considered as the underlying infrastructure that will be an integral part of future ubiquitous and embedded computing applications. We project that in 5-10 years, (i) many individual WSNs will be very sophisticated and operating at high levels of utilization, and (ii) there will exist many thousands, if not millions, of sensor networks. When this latter situation materializes, WSNs will overlap and co-exist. One significant problem is that the majority of WSN research work today is focused on single frequency systems. To deal with high performance WSNs and with the projected situation of large numbers of deployed sensor networks will require multi-frequency systems. In this paper, we present new suites of protocols for multi-frequency WSNs along three complementary dimensions. They are: (1) to achieve high performance for both broadcast and unicast communications within a single WSN, (2) to support overlapping, but cooperative WSNs, and (3) to handle noise and the crowded spectrum caused by any reason, such as random transmitting devices, other nearby sensor networks, or even co-existing electric appliances.

By incorporating the collection of new solutions, we envision excellent throughput performance for sophisticated, high workload WSNs. The WSNs will also be robust to noise, the crowded spectrum and even to certain degrees of jamming attacks. We also anticipate a new ability to deploy multiple overlapping and cooperative WSNs in different time frames. These cooperative WSN systems will be able to seamlessly interact to improve overall performance of many applications. For example, in assisted living facilities the first deployed WSN system may be a specialized WSN to monitor patients's indoors activities and improve their lifestyle and health. Later, another specialized WSN (perhaps built and sold by a different company) may be deployed to better monitor both indoors and outdoors environmental conditions such as temperature, air quality and hazards such as fire. It may be impractical to shut down the previous system and create a single new system, or to reload the older system with new software that results in a single new integrated system. Having these multiple WSNs co-exist and interact seamlessly is likely to be a necessary feature in the future and can result in major additional benefits to patients. Similar application examples can be described for embedded systems in environmental and military domains.

The rest of the paper is organized as follows: Section II presents a solution to achieve high communication performance within a single WSN. Section III explains multi-frequency support for overlapping but cooperative WSNs. Section IV analyzes how to handle the crowded spectrum issue caused by any reason, including co-existing sensor network devices as well as electric appliances. Finally, conclusions are given in Section V.

II. ACHIEVING HIGH THROUGHPUT

Media access control (MAC) is an essential part of the communication stack, and a number of MAC protocols [1] [2] [3] [4] [5] [6] have been proposed in WSN context, to achieve high throughput. While these designs demonstrate good performance in single-channel scenarios, parallel transmission within a vicinity through multiple channels is not considered, to further improve the throughput. Since the current sensor devices provide very limited single-channel bandwidth, 19.2Kbps in MICA2 [7] and 250Kbps in MICAz [8] and Telos [9], it is imperative to design multi-channel MACs that can achieve a higher throughput through parallel communications. Plus, the CC2420 radio [10] used in MICAz and Telos motes already provides multiple physical channels, paving the way for multi-channel sensor network MAC designs.

When switching from WSN to general wireless ad hoc networks, multi-channel MAC designs are not new and have been well studied. However, due to the reasons discussed below, these protocols are not appropriate for resource-restrained sensor network applications. The first reason comes from different hardware assumptions. A typical sensor device is usually equipped with a single radio transceiver, which can not conduct simultaneous transmission and reception, but can work on different channels at different times. On the contrary, many MAC protocols in general wireless ad hoc networks assume more powerful radio hardware. For instance, protocols

[11] [12] are designed for frequency hopping spread spectrum wireless cards, and protocol [13] assumes the busy-tone ability for the hardware. Also, some protocols [14] [15] [16] [17] require the hardware to be capable of carrier sensing on multiple channels simultaneously. Second, WSNs have very limited communication bandwidth and the MAC layer packet size is very small, 30∼50 bytes, compared to the 512+ bytes used in general wireless ad hoc networks. Due to such small data packet sizes, the RTS/CTS control packets in IEEE 802.11 [18] no longer constitute a small overhead that can be ignored. So protocols [19] [20] [21] that use RTS/CTS for frequency negotiation, and protocols [22] [23] that are based on IEEE 802.11 are not suitable for WSN applications, even though they perform well in general wireless ad hoc networks.

To further understand the cost that RTS/CTS control packets incur in general wireless ad hoc networks versus WSNs, we choose MMAC [19] as a case study. MMAC is a typical multi-channel MAC protocol proposed for general wireless ad hoc networks. In MMAC, periodically transmitted beacons divide time into beacon intervals, each of which starts with a small ATIM window. During the ATIM window, nodes that have packets for transmission negotiate frequencies with destination nodes, using a default frequency. After the ATIM window, nodes switch to the negotiated frequencies and use IEEE 802.11 for data communication, i.e., exchanging RTS/CTS before sending out DATA packets. We implement MMAC in GlomoSim [24] with the same experiment set up as in [19].

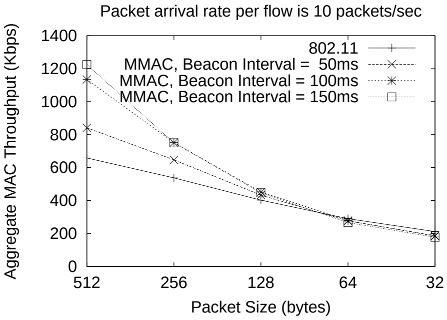

Fig. 1. Effect of Packet Size on MMAC

As demonstrated in the result (Figure 1), when the packet size is large, the MMAC protocol with 3 frequencies and a beacon interval of 100ms (the default configuration suggested in [19]) impressively achieves almost twice the throughput of IEEE 802.11. This result is consistent with that presented in [19]. However, when the packet size decreases, both MMAC and IEEE 802.11 obtain diminished performance. The reason is that the overhead of RTS/CTS control becomes more prominent when the data packet size is smaller. When the packet size is as small as 32 bytes, IEEE 802.11 has even a slightly higher throughput than MMAC. Also, Figure 1 demonstrates that while using a shorter beacon interval (50ms) helps to some extent, MMAC with 3 frequencies still can not even outperform IEEE 802.11 with a single frequency, when the packet size is as small as 64 or 32 bytes. While more detailed analysis can be found in [25], the main observation we make here is that while MMAC is a good multi-frequency MAC protocol for general wireless ad hoc networks where data packets are usually large, it is not suitable for WSNs where data packets are much smaller.

Since multi-channel MAC designs for general wireless ad hoc networks are not adequate for WSNs, the key question is: what are the essential design considerations for multi-channel MACs in WSNs to achieve higher throughput? In what follows, we analyze two core aspects: frequency assignment and media access design.

Frequency Assignment: Since RTS/CTS frequency negotiation constitutes too high an overhead for bandwidth limited and small packet size sensor networks, frequency assignment stands out to be a more promising design choice. During frequency assignment, neighboring nodes are allocated different frequencies for unicast packet reception, for supporting of parallel communication to achieve high throughput. A naive frequency assignment design is to let each node overhear its neighbors' frequency choices, and then choose one of the least used frequencies for its own data reception. A more sophisticated design needs to consider the hidden terminal problems [18], as well as the in-situ reality that the radio interference range may be greater than the communication range [26]. In [25], we present a collection of frequency assignment schemes that demonstrate different merits in different application scenarios, together with corresponding performance comparison.

Media Access Design: When nodes within a vicinity are assigned different frequencies for unciast packet reception, the question of broadcast support is raised. A simple choice is to interpret a broadcast transmission as multiple unicast transmissions. Since WSNs usually maintain high node densities to trade for enhanced system lifetimes, parsing a broadcast as multiple unicasts actually involves a very high communication overhead and makes it a poor choice. A better design we suggest is to assign a default broadcast channel for all nodes to receive broadcast packets, while at the same time maintain different channels for unicast packet reception.

There are two general schemes to integrate broadcast and unicast communications, in such a multi-channel, but single-transceiver context. First, periodic beacons can divide time into fixed-length beacon intervals. During each interval, each node can choose to send/receive a broadcast/unicast packet. By assigning different priorities for broadcast and unicast communications, together with carefully designed carrier sense and backoff schemes, communication correctness can be guaranteed, and also the throughput can be maximized. Interesting readers can refer to [25] for details.

Second, without the presence of time synchronization, a toggle snooping technique can be used instead to provide efficient broadcast support from the root. The basic idea is to let a receiver carrier sense on the broadcast and unicast channels, in an alternating fashion. Whenever it overhears a signal, it stops toggling between the broadcast and unicast channels, and stays on the current channel to receive the data packet. This can either be a broadcast or unicast packet. Also, the transmitter needs to prepare a longer preamble than normal, which can cover the time period when the receiver stays on the other channel for carrier sensing. Due to the space limits, the specific design details are not presented here.

III. CROSS-NETWORK COOPERATION

In the near future, we envision that multiple WSNs will be deployed together within the same physical location, serving different purposes. In this case, detecting co-existing networks and conducting possible MAC layer cooperation among them become very critical for reducing cross-network interference and improving aggregated throughput. In this multi-network context, the ultimate design goal is to assign different frequencies to different nodes at different times, achieving the maximum parallel transmission, at any time and for any location. Three major properties should be provided by this design:

Space-Dimension Flexibility: In a single-network case, we use a "node density" concept, and its value varies from location to location. In the multi-channel scenario, we introduce another concept "network density", which is defined as the number of networks within a communication range. Its value also varies from location to location. The frequency assignment should be differentiated according to different network densities and node densities.

Time-Dimension Flexibility: The application traffic pattern varies from time to time, in both single-network and multi-network contexts. The environmental noise also varies from time to time. Plus, new networks are introduced and old networks fade out dynamically. All these dynamics raise the need for dynamic frequency adjustment.

QoS Control: QoS control is desired when the available physical bandwidth is not able to fully support all traffic from all co-existing networks, for all locations and for all times. So, a λ parameter is offered for users to set different priority values for different networks. At any location at any time, each network is assigned the bandwidth, according to the ratio its λ value over the sum of all λ values whose networks co-exist within that specific location. The ratio depends on the number of competing networks, varying from location to location and from time to time.

To achieve the forgoing three properties, there is a need for both static frequency assignment and dynamic frequency adjustment.

A. Static Frequency Assignment

Let net_i, $1 \leq i \leq M$, represent the M co-existing networks in the environment, and let fre_i, $1 \leq i \leq N$, denote the N non-overlapping physical frequencies. Each network net_i is assigned a comparative priority λ_i. Within any location and at any time, each network net_j competes with locally co-existing networks, and is supposed to use γ_j percent of available frequency spectrum:

$$\gamma_j = \frac{\lambda_j}{\sum_1^K \lambda i} \tag{1}$$

where K is the number of available nevlworks within that location at that time, and $1 \leq K \leq M$.

When a new network is deployed in a space, where existing networks are running, each node in the existing networks is called to temporarily switch through the following two cooperation steps to get its frequency reassigned, and then switch back to its normal operation.

Differentiated QoS Computation: Each node first conducts neighbor discovery. Different networks are identified with different group IDs, shortened as "gID", which is a standard field for all TinyOS [7] messages. During neighbor discovery, each node beacons the following information: ID, gID and λ. With this information, each node computes its local QoS control parameter γ, according to Formula 1.

Chained Frequency Decision: With neighbor information collected, each node makes two decisions: 1) What portion of frequency range to choose from and 2) What frequency to use. The chained decisions proceed in the increasing order of gID. When two nodes tie with gID, the node with the smaller node ID wins. During the whole process, each node (node α) keeps the following rules in mind:

1) Node α checks all neighbors from which it has not heard frequency decisions. If gID_α is the smallest one among the neighborhood, and also no neighbor has the same gID and a smaller node ID, node α starts its frequency decision. Otherwise, it waits for its neighbors' decisions.
2) During node α's frequency decision, it first decides the portion of frequency range to choose from. The range starts where the most recently overheard neighbor stops, and the length of the range is $\gamma_\alpha \times N$.
3) When the frequency range is decided such as [$Sfre_\alpha$, $Efre_\alpha$], node α checks the overheard frequencies that have been chosen by neighbors from the same network (they carry the same gID). Node α randomly chooses one of the least loaded frequencies among the range [$Sfre_\alpha$, $Efre_\alpha$].

B. Dynamic Frequency Adjustment

Since traffic patterns vary with time, the spectrum usage must be monitored during runtime. When the spectrum usage is found heavily imbalanced, dynamic frequency adjustment is triggered, reassigning nodes from crowded frequencies to lightly loaded frequencies. If $fre(\alpha)$ denotes node α's frequency and $Tra(\alpha)$ represents α's traffic load, the traffic load for a frequency ($FTra_i$) and the traffic load for a network ($NTra_j$) can be calculated as follows:

$$FTra_i = \sum_{fre(\alpha)=fre_i} Tra(\alpha),\ NTra_i = \sum_{\alpha \in net_i} Tra(\alpha) \tag{2}$$

Also, the spectrum imbalance level can be computed as:

$$ImbLevl = \frac{max\{FTra_i\}}{min\{FTra_i\}} \tag{3}$$

When a node (node α) detects that the imbalance level $ImbLevl$ is greater than a threshold $ImbLevl_{Thr}$, it triggers the dynamic frequency adjustment, which repeats the following process until the imbalance level is below the threshold: notifying a node from the busiest channel to switch to the least busy channel. The busiest channel is identified as the channel that has the maximum $FTra_i$, and is denoted as fre_{busy}. Among node α's neighbors that use frequency fre_{busy}, there may be multiple candidates from multiple networks. Among these candidates, nodes from a comparatively more *aggressive* network should be considered first, which is identified as having a comparatively larger $\frac{NTra_i}{\lambda_i}$ value. If again, multiple candidates exist within this network, the node with the highest $Tra(\alpha)$ value stands out. Having located this neighbor, node α informs it to switch to the currently least loaded frequency, the one that carries the smallest $FTra_i$ value.

Hot Potatoes: During dynamic frequency adjustment, each node individually decides whether the local spectrum usage is balanced. In some extreme cases, there may be a node that has extraordinarily heavy bandwidth requirements compared to others. No matter what frequency this node uses, that frequency becomes overloaded. Instead of pushing these "hot potatoes" around, individual nodes can detect them locally, and keep the imbalance brought by them within the local region.

IV. THE CROWDED SPECTRUM

With the explosive application of 802.11b, 802.15.1 and 802.15.4, we vision that the human world will be full of electronic devices and most of them work on the same or overlapping frequency spectrum. The original 802.11 standard released in 1997 operates within the 2.4 GHz ISM band and divides it into 78 channels (1 MHz distance). The 802.11b also uses the 2.4 GHz ISM band and divides it into 14 channels (5 MHz distance). IEEE 802.15.1 divides the 2.4 GHz ISM band into 79 1-MHz channels and IEEE 802.15.4 divides it into 16 5-MHz channels. When these electronic devices, such as wireless keyboards, wireless PDAs, wireless cell phone headsets and wireless sensor networks, are bought home and used in the same building, it is obvious that the 2.4 GHz ISM band will be congested and overloaded.

What is worse, the widely used electric appliances like microwaves, can also generate very strong interference. To obtain a better understanding of the crowded spectrum, in the presence of electronic devices as well as electric appliances, we measured the 2.4GHz ISM band spectrum usage with a HP 8593E Spectrum Analyzer. A Sharp Carousel microwave is used as a representative electric appliance, which is typical in a home care sensor network application. Also, a Logitech cordless 2.4GHz PowerPoint presenter is used as a representative electronic device, which is typical for an office environment. Figure 2 plots the result.

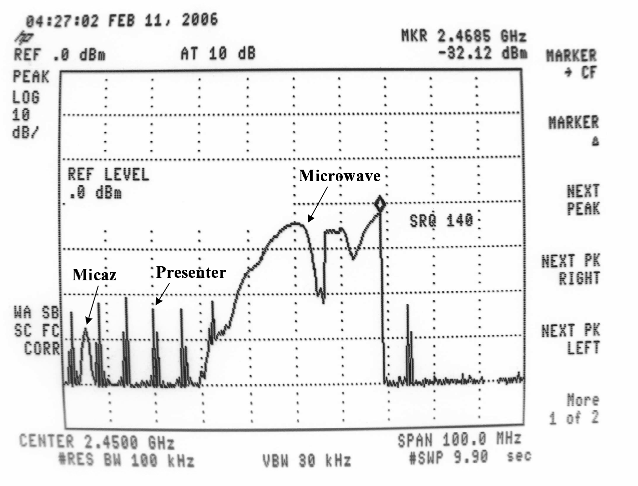

Fig. 2. Interference from Both Electronic Devices and Electric Appliances

As shown in Figure 2, the small sinusoidal curve within 2.4GHz and 2.41GHz (adjacent to bottom left), indicates the power level of the sensor network signals we deployed within the measured environment. The large mountain like curve, which lies between 2.43GHz and 2.47GHz (in the middle), reflects the microwave's interference. According to the IEEE 802.15.4 specification [27], the 2450 MHz PHY range starts from 2.4GHz and ends at 2.4835 GHz, i. e., the first 8 columns in the figure. It is obvious that the interference from an existing microwave covers almost half of the 2450 MHz PHY spectrum. Plus, within the other half of the frequency range, the interference from the Logitech presenter shows up frequently, which are the evenly distributed pulse signals (about -52dBm). The main observation we make here is that the spectrum crisis is a coming challenge we have to face.

One solution for this crowded spectrum is to introduce more unlicensed frequency band, which the Federal Communications Commission is in charge of in the United States, and hence is beyond our scope and ability. A second solution is to use spread spectrum techniques. For example, MICAz devices adopt direct sequence spread spectrum (DSSS), in which the data signal gets multiplied twice by the PN sequence, while the interference signal gets multiplied only once [10]. To assess DSSS's strength in real situations, we measured the packet reception ratio, when a pair of MICAz motes are deployed close to the Sharp microwave used in Figure 2. The MICAz motes are configured to operate on frequency 2.45GHz, which is surely covered by the microwave's interference. The obtained result shows that the packet reception ratio varies from 46% to 81% when the microwave is on, but keeps a straight 100% when the microwave is off. This experimental observation informs us that DSSS addresses the crowded spectrum issue in some degree, but is still far from enough.

We also conducted another experiment by configuring the MICAz motes to work on frequency 2.42GHz, where the PowerPoint presenter generates a strong signal as plotted in Figure 2. Our measured result shows that the presence of the PowerPoint presenter almost has no impact on the packet reception of the MICAz motes. This is because that the interference from the presenter is not strong enough, and that DSSS multiplies the useful signal twice, but the noise signal only once using the PN sequence. To get a broader and deeper analysis, we need to conduct more systematic and refined experiments in the future.

Another solution on the research side is try to make the best use of the existing unlicensed spectrum by taking advantage of frequency diversity. Unfortunately, the state-of-the-art sensor network research has not paid attention to the future spectrum crisis. No existing PHY or MAC design has seriously taken this into consideration, and to the best of our knowledge, we have not seen any proposed protocol that targets the spectrum management for these co-existing electronic devices and electric appliances. In addition, these devices and appliances may not be capable of communicating with each other, which is essentially different from the cooperating networks analyzed in Section III, where cross-network communication exists. This research vacuum motivates us to design a self-adaptive spectrum management service, named SAS.

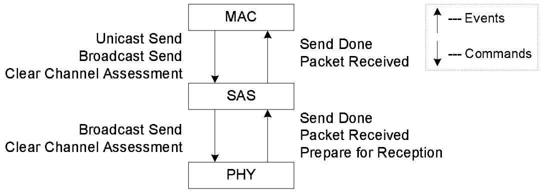

Fig. 3. SAS Middleware Architecture

To provide a general frequency diversity service, SAS extracts out the “Toggle Transmission and Toggle Snooping” techniques, from our previous multi-frequency MAC [25] designed for WSNs. This general service works transparently between the MAC and PHY layers, as shown in Figure 3. The SAS design and implementation explore the answers to the following research questions:

- How to parse and serve requests from the single-channel minded MAC layer, within the multi-channel context in SAS? For example, how to parse the MAC layer’s carrier sense requests in the multi-channel implementation? In addition, what is the performance enhancement the SAS middleware brings to the upper layer CSMAs and TDMAs? What is the cost it pays?
- Besides the interfaces for general services, SAS can also provide extra functions for upper layer protocols that seek special treatment. These extra functions are added, for the purpose of supporting cross-layer designs, which are widely adopted in WSNs to squeeze out even higher efficiency from the resource-restrained devices. With extra functions from SAS, what design changes can the upper layer protocols make to get better performance? For instance, is the exponential backoff still the best way for CSMA, when SAS releases the frequency switch details? If not, what is the best backoff scheme?

V. CONCLUSIONS

By observing the current WSN research and applications, together with preliminary experimental measurements, this paper presents a vision of a crowded wireless sensor network environment in the near future. This paper presents the coming spectrum crisis, and also puts forth initial efforts to resolve this crisis through three complementary dimensions.

REFERENCES

[1] J. Polastre, J. Hill, and D. Culler, “Versatile Low Power Median Access for Wireless Sensor Networks,” in *ACM SenSys*, 2004.
[2] I. Rhee, A. C. Warrier, M. Aia, J. Min, and P. Patel, “Z-MAC: A hybrid MAC for wireless sensor networks,” in *ACM SenSys*, 2005.
[3] W. Ye, J. Heidemann, and D. Estrin, “An Energy-Efficient MAC Protocol for Wireless Sensor Networks,” in *IEEE INFOCOM*, 2002.
[4] V. Rajendran, K. Obraczka, and J.J. Garcia-Luna-Aceves, “Energy-Efficient, Collision-Free Medium Access Control for Wireless Sensor Networks,” in *ACM SenSys*, 2003.
[5] T. Dam and k. Langendoen, “An Adaptive Energy-Sufficient MAC Protocol for Wireless Sensor Networks,” in *ACM SenSys*, 2003.
[6] A. Woo and D. Culler, “A Transmission Control Scheme for Media Access in Sensor Networks,” in *ACM MobiCom*, 2001.
[7] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler, and K. Pister, “System Architecture Directions for Networked Sensors,” in *ASPLOS-IX*, 2000.
[8] “XBOW MICA2 Mote Specifications,” http://www.xbow.com.
[9] J. Polastre, R. Szewczyk, and D. Culler, “Telos: Enabling Ultra-Low Power Wireless Research,” in *ACM/IEEE IPSN/SPOTS*, 2005.
[10] “CC2420 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver,” http://www.chipcon.com.
[11] Z. Tang and J.J. Garcia-Luna-Aceves, “Hop-Reservation Multiple Access (HRMA) for Ad-Hoc Networks,” in *IEEE INFOCOM*, 1999.
[12] A. Tyamaloukas and J. J. Garcia-Luna-Aceves, “Channel-Hopping Multiple Access,” in *IEEE ICC*, 2000.
[13] J. Deng and Z. Haas, “Dual Busy Tone Multiple Access (DBTMA): A New Medium Access Control for Packet Radio Networks,” in *IEEE ICUPC*, 1998.
[14] A. Nasipuri, J. Zhuang, and S. R. Das, “A Multichannel CSMA MAC Protocol for Multihop Wireless Networks,” in *IEEE WCNC*, 1999.
[15] S.-L. Wu, C.-Y. Liu, Y.-C. Tseng, and J.-P. Shen, “A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Networks,” in *I-SPAN*, 2000.
[16] A. Nasipuri and S. R. Das, “Multichannel CSMA with Signal Power-based Channel Selection for Multihop Wireless Networks,” in *IEEE Vehicular Technology Conference*, 2000.
[17] M. Caccaco, L. Y. Zhang, L. Sha, and G. Buttazzo, “An Implicit Prioritized Access Protocol for Wireless Sensor Networks,” in *IEEE RTSS*, 2002.
[18] “IEEE 802.11, Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification,” 1999, ANSI/IEEE Std. 802.11.
[19] J. So and N. Vaidya, “Multi-Channel MAC for Ad-Hoc Networks: Handling Multi-Channel Hidden Terminal Using A Single Transceiver,” in *ACM MobiHoc*, 2004.
[20] N. Jain and S. R. Das, “A Multichannel CSMA MAC Protocol with Receiver-Based Channel Selection for Multihop Wireless Networks,” in *IEEE IC3N*, 2001.
[21] A. Tzamaloukas and J.J. Garcia-Luna-Aceves, “A Receiver-Initiated Collision-Avoidance Protocol for Multi-Channel Networks,” in *IEEE INFOCOM*, 2001.
[22] P. Bahl, R. Chancre, and J. Dungeon, “SSCH: Slotted Seeded Channel Hopping for Capacity Improvement in IEEE 802.11 Ad-Hoc Wireless Networks,” in *ACM MobiCom*, 2004.
[23] A. Raniwala and T. Chiueh, “Architecture and Algorithm for an IEEE 802.11-Based Multi-Channel Wireless Mesh Network,” in *IEEE INFOCOM*, 2005.
[24] X. Zeng, R. Bagrodia, and M. Gerla, “GloMoSim: A Library for Parallel Simulation of Large-Scale Wireless Networks,” in *IEEE PADS*, 1998.
[25] G. Zhou, C. Huang, T. Yan, J. A. Stankovic, and T. F. Abdelzaher, “MMSN: Multi-Frequency Media Access Control for Wireless Sensor Networks,” in *IEEE INFOCOM*, 2006.
[26] G. Zhou, T. He, J. A. Stankovic, and T. F. Abdelzaher, “Radio Interference Detection in Wireless Sensor Networks,” in *IEEE INFOCOM*, 2005.
[27] “IEEE 802.15.4, Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs),” 2003, IEEE Std. 802.15.4.