Chapter 2

Review of Related Works

2.1 Introduction

In this chapter, we briefly present the earlier works related to the problems of (i) energy savings and (ii) bandwidth management in wireless communication networks. Most of these research works are concerned with energy efficient communication in wireless sensor networks (WSN) and bandwidth management in cognitive radio networks (CRN).

2.2 Energy-efficient Communication

Various research efforts have been made on reducing energy consumption in wireless communication networks. These include the suitable design of MAC layer, optimizing data transmissions by reducing collisions and retransmissions and through intelligent selection of paths or special architectures for sending data, energy-efficient source coding and digital modulation techniques.
Surveys of routing protocols in ad-hoc and wireless sensor networks are found in [6, 11, 24, 39, 111]. Among the various routing protocols in WSNs, the hierarchical protocols are more energy efficient. The LEACH (Low Energy Adaptive Clustering Hierarchy) protocol introduced by Heinzelman et al. [64] is one of the most popular energy-efficient hierarchical routing protocols for sensor networks. The LEACH algorithm is a cluster-based protocol, which includes distributed cluster formation.

An extension to LEACH, known as LEACH with negotiation, was proposed by Heinzelman et al. in [64]. In this, data transfers are preceded with high-level negotiation using meta-data descriptors. This is to ensure that only data that provide new information are transmitted to the cluster heads (CHs) before being transmitted to the base stations (BSs).

An enhanced descendant of the LEACH protocol, called Power-Efficient Gathering In Sensor Information Systems (PEGASIS), was proposed by Lindsey and Raghavendra [91]. It is a near-optimal chain-based protocol, which forms a chain including all nodes in the network by using a greedy algorithm so that each node can only communicate with its closest neighbor. This algorithm is based on the idea that in order to increase the network lifetime, nodes in the network should communicate with their closest neighbors.

A protocol named Hierarchical PEGASIS was proposed by Savvides et al. [127]. This protocol is an extended version of PEGASIS. Its main purpose was to reduce the delay incurred for packets during transmission to the base station. This hierarchical protocol is found to perform better than PEGASIS.
Heinzelman et al. [63, 83] proposed a family of adaptive protocols called *Sensor Protocols for Information via Negotiation* (SPIN). It disseminates all the information at each node to every node in the network assuming that all nodes in the network are potential base stations (BSs).

Intanagonwiwat et al. [69] proposed a popular data aggregation paradigm for WSNs called *directed diffusion*. Directed diffusion is a data-centric and application-aware paradigm in the sense that all data generated by sensor nodes are named by attribute-value pairs.

Yu et al. [165] proposed the use of geographic information while disseminating queries to appropriate regions since data queries often include geographic attributes. They introduced the protocol, *Geographic and Energy Aware Routing* (GEAR), which uses energy-aware and geographically informed neighbor selection heuristics to route a packet toward the destination region.

Roduplu and Meng [125] proposed a protocol called *Minimum Energy Communication Network* (MECN), that computes an energy-efficient subnetwork for sensor network utilizing low-power GPS. The *small MECN* (SMECN) [88] is an extension to MECN.

Two routing techniques, namely, *Information-Driven Sensor Querying* (IDSQ) and *Constrained Anisotropic Diffusion Routing* (CADR), were proposed by Chu et al. in [36]. CADR aims to be a general form of directed diffusion. *Geographic Adaptive Fidelity* (GAF) [161] is an energy-aware location-based routing algorithm designed primarily for mobile ad hoc networks, but it may be applicable to sensor networks as well.

TEEN (*Threshold-sensitive Energy Efficient Sensor Network*) is another extensively used en-
ergy efficient hierarchical routing protocol proposed by Manjeshwar and Agarwal [96]. *Adap-
tive Periodic TEEN* (APTEEN) is an extension of TEEN also proposed by Manjeshwar and
Agarwal [97]. Kandris et al. suggested an efficient hierarchical routing protocol, named *Scal-
ing Hierarchical Power Efficient Routing*, which aims at energy conservation through the use of
both an efficient routing strategy and a power-aware route selection scheme in wireless sensor
networks [76].

Vidyapriya et al. also proposed energy aware routing for wireless sensor networks [152].

Hey suggested power-aware smart routing for wireless sensor networks [66].

Vergados et al. studied various route selection strategies to prolong the life of WSNs and pro-
posed energy efficient route selection for wireless sensor networks [150]. In [151] they sug-
gested enhanced route selection for energy efficiency in wireless sensor networks.

Trigoni et al. proposed wave scheduling technique for energy efficient data dissemination for
sensor networks [148].

Energy efficiency to maximize the network lifetime is the primary objective of any medium
access control (MAC) protocol in wireless sensor networks. The main reasons for energy wastes
in WSNs are collision, overhearing, control packet overhead, idle listening and overremitting.

A good MAC protocol is designed to remove these sources of energy waste. Demirkol et al.
discussed about various MAC protocols in use for wireless sensor networks [39].

Sensor-MAC (S-MAC) proposed by Ye et al. [164] consists in locally managed synchronization
and periodic sleep-listen schedules based on these synchronizations.
El Hoiydi proposed the *Spatial TDMA and CSMA with preamble sampling* protocol [67].

*Traffic-Adaptive MAC* (TRAMA) was proposed by Rajendran et al. [124].

Lin et al. proposed *Dynamic Sensor MAC* (DSMAC) [90].

Li et al. discussed about energy and latency control in low duty cycle MAC protocols [89].

Wang et al. proposed energy efficient collision-aware (EECA) node-disjoint multi-path routing for WSNs based on optimization of data transmissions by reducing collisions [154]. EECA utilizes the broadcast nature of wireless communication in order to avoid collisions between two discovered routes without extra overhead. It also restricts flooding and adjusts transmit power with node position information. This results in improved energy efficiency and good performance of communication.

For reducing energy consumption K. Sinha et al. proposed a fast deterministic and gossiping algorithm [137] in mobile ad-hoc networks.

Cagalj et al. [29] focussed on the minimum energy broadcast problem and proposed an energy efficient broadcasting in all wireless networks.

Chen et al. [33] investigated energy-efficient aggregator deployment in wireless sensor networks and suggested an *Energy-efficient Protocol for Aggregator Selection* (EPAS) for wireless sensor networks.

Enz et al. proposed “WiseNET” as an energy efficient solution for ultra low-power wireless sensor network [42]
Yang et al. proposed a wake-up scheme for sensor networks in order to achieve balance between energy saving and end-to-end delay [163].

Wu et al. suggested an energy efficient wake-up scheduling for data collection and aggregation in wireless sensor networks [159].

Sleep scheduling is used in TDMA based protocols for energy efficient communication in wireless sensor networks. Pantazis et al. suggested ways to achieve energy efficiency in wireless sensor networks using sleep mode TDMA scheduling [118]. Ma et al. proposed energy efficient TDMA sleep scheduling in wireless sensor networks [94]. Gobriel and others used TDMA scheduling with adaptive slot stealing and parallelism in TDMA-ASAP sensor networks [58].

Wang and Manner [154] investigated the use of data compression techniques to reduce the energy consumption in mobile networks. From their investigations it was found that content-aware compression can substantially reduce the energy required for wireless data communication.

2.2.1 Energy Savings with Physical Layer centric approach

In 2005, a novel communication technique that enables energy-efficient communication in wireless sensor networks was presented by Zhu and Sivakumar [170]. The strategy was called Communication through Silence (CtS). Most forms of communication in wireless sensor networks are typically assumed to use a common strategy for communication that we refer to as Energy based Transmissions (EbT) [34, 170]. This new communication strategy, Communication through Silence, is based on conveying information using silent periods as opposed to energy
based transmissions. Though the CtS Strategy can deliver considerable amounts of energy improvement, it suffers from the disadvantage of being exponential in communication time.

An alternative strategy, called Variable-Base Tacit Communication (VarBaTac) was proposed by Chen, Wang and Zhang [34] that uses variable radix-based information coding along with CtS for communication. It is, however, observed that for an $n$-bit binary string the duration of transmission is, in general, much longer than $n$. Also, both CtS and VarBaTac do not address the issue of finding the amount of energy saved for noisy channels.

Various investigations have been carried out to realize energy efficient communication in wireless sensor networks by applying energy saving measures on all possible fronts. These measures include appropriate MAC protocols and source coding techniques to enhance the occurrence of silent intervals during radio transmission and energy-efficient modulation techniques. To realize these, Polastre et al. suggested Telos to enable ultra low-power radio research [121].

In [136, 140] a communication technique for WSNs, called RBNSiZeComm has been proposed involving the conversion of the data to be transmitted to its equivalent redundant binary number (RBN) representation with the strategy of using silence for communicating the digit zero. It was shown that by using the redundant binary number system (RBNS) that utilizes the digits from the set $\{-1, 0, 1\}$ to represent a number with radix 2, one can significantly reduce the number of non-zero digits that need to be transmitted. They have utilized this property of RBNS to recode a message string so as to reduce the number of 1’s in the string while transmitting the message. The original binary message can be obtained at the receiver end by reconverting the received message from RBNS to binary. The basic ideas of the recoding scheme, transmission
protocol and receiver side decoding process have been described by Sinha in [141]. The above scheme can achieve substantial energy savings in the transmitter. However, no energy saving is generated at the receiver by RBNSiZeComm.

The Run-Zero Encoding (RZE) scheme proposed by Sinha and Sinha [142] is another energy efficient communication protocol that uses recoding of data to RBNS and exploits the statistics on the distribution of runs of 1’s (and 0’s) in binary strings similar to the RBNSiZeComm protocol proposed by Sinha [136, 140]. The RZE scheme [142] can save energy both in the transmitter and the receiver.

Sinha et al. proposed an energy-efficient communication scheme called CNS (Compression with Null Symbol) which combines the power of data compression and communication through silent symbol [139]. This scheme uses a radix-4 based encoding of binary data. The CNS encoding process reduces the number of symbols to be transmitted by a factor of 2 and hence the communication duration. However the cost/complexity of the transmitter and the receiver using CNS scheme is on the much higher side.

### 2.3 Multimedia Wireless Communication and Cognitive Radio Networks

Some results are available in [85, 105, 130] regarding multimedia communication through Cognitive Radio Networks (CRNs). Mitola III first introduced the concept of *flexible mobile multimedia communications* [105] in a CRN. Wireless multimedia applications require significant
bandwidth. Some of this requirement will be provided by third-generation (3G) services. Even if substantial investment is made in 3G infrastructure, the radio spectrum allocated to 3G will be limited. Cognitive radio may be used to overcome this scarcity of bandwidth particularly for multimedia communications. It offers a mechanism for the flexible pooling of radio spectrum using a new class of protocols called formal radio etiquettes. Radio etiquette is the set of RF bands, air interfaces, protocols, spatial and temporal patterns, and high level rules of interaction that moderate the use of the radio spectrum. With this approach it would be possible to expand the bandwidth available for conventional uses (e.g. police, fire and rescue) and extend the spatial coverage of 3G in a novel way. [105] characterizes the potential contributions of cognitive radio to spectrum pooling and outlines an initial framework for formal radio etiquette protocols.

Kushwaha et. al. used fountain coding for packet generation and conversion [85] to send data with high reliability and tolerable delay. With the explosive growth of wireless multimedia applications over the wireless internet in recent years, the demand for radio spectral resources has increased significantly. In order to meet the quality of service, delay and large bandwidth requirements, various techniques such as source and channel coding, distributed streaming, multicast etc. have been considered. Kushwaha et al. [85] proposed a technique for distributed multimedia transmission over the secondary user network. It makes use of opportunistic spectrum access with the help of cognitive radios. Digital fountain codes are used to distribute the multimedia content over unused spectrum and also to compensate for the loss incurred due to primary user interference.

Shing et al. proposed the idea of dynamic channel selection for video streaming over a CRN
based on some priority-based scheduling of video signals. Because of the dynamic nature of cognitive radio networks, multiuser video streaming requires efficient dynamic channel selection schemes to exploit available spectrum resources. Thus, a wireless user needs to effectively model the dynamic wireless environment and estimate the delay of video packet transmission when selecting a specific frequency channel. In this paper [130], the authors applied the priority virtual queue model for these wireless users to adapt their channel selection and maximize video qualities.

Techniques for detection of unused spectrum and sharing the spectrum without harmful interference with other users with the help of a common control channel (CCC) have been presented by Krishnamurthy et al. [82] and Masri et al. [99]. The CCC is used for supporting the transmission coordination and spectrum related information exchange between the cognitive radio users. CCC also facilitates neighbor discovery, helps in spectrum sensing coordination, and control signaling and exchange of local measurements between the CR users. In a cognitive radio network, MAC-layer configuration involves determining a common set of channels to facilitate communication among participating nodes. Further, the availability of multiple channels and frequent channel switches add to the complexity of route selection. In [82], a distributed algorithm for gathering global network topology information for a CR network was proposed. Zhao et al. [168] pointed out several drawbacks if a dedicated common control channel was used. A dedicated common control channel is wasteful of channel resources. Also, So et al. [145] showed that as the number of users increases, a control channel would get saturated as in a multihop network. Bian et al. [23] stated that an adversary could cripple the dedicated
control channel by intentionally flooding the control channel. To overcome this denial of service (DoS) attack [23] it was suggested in [168] to choose one of the free channels as the control channel. As the primary user of the chosen channel returns, a new control channel is selected. This, however, would create a Network Setup Problem as nothing was mentioned in [168] about how the first node contacts the Cognitive Base Station (CBS) and how it would be informed about the chosen control channel for the first time.

In order to address and solve this Network Setup Problem, Kondareddy et al. [81] suggested the probabilistic and deterministic ways to start the initial communication and setup a cognitive radio network without using a common control channel in both centralized and multihop networks. Xin and Cao [160] also considered spectrum sensing without using a CCC.

Allocation of channels from the available white spaces or holes in the spectrum avoiding interference with other neighboring users have been studied by a number of authors. Allocation schemes can be fixed, dynamic or hybrid. In fixed channel allocation (FCA) schemes [1], a set of channels is permanently allocated to each cell in the network. Due to short term fluctuations in the traffic, FCA schemes are often not able to maintain high quality of service and capacity attainable with dynamic traffic demands. One approach to address this problem is to borrow free channels from neighboring cells. In dynamic channel allocation (DCA) schemes, all channels are kept in a central pool and are assigned dynamically to new calls as they arrive in the system. DCA schemes can be centralized or distributed. The centralized DCA scheme [1, 166] involves a single controller selecting a channel for each cell. On the other hand, the distributed DCA scheme [1, 166] involves a number of controllers scattered across the network. In hy-
brid channel allocation (HCA) schemes [1], the available channels are divided into fixed and dynamic sets. The fixed set contains a number of nominal channels that are assigned to cells as in the FCA schemes, and the dynamic set is shared by all users in the system to increase flexibility.

Yuan et al. [167] presented a cognitive radio system termed as *Kognitive Networks over White Spaces* (KNOWS) which enabled opportunistic access and sharing of the white spaces by adaptively allocating the spectrum among contending users. In KNOWS, the authors proposed a system consisting of a new hardware platform and a spectrum-aware Medium Access Control (MAC) protocol. KNOWS cooperatively detects incumbent operators and efficiently shares the vacant spectrum among unlicensed users.