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Review

Multi-channel and cognitive radio approaches for wireless sensor networks

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ABSTRACT

In traditional wireless sensor networks communicating on a single channel data throughput measured at the sink is constrained by the radio capability, interference, and collisions. Enabling a multi-channel transmission is a potential solution to alleviate the above problem and improve the network performance. Many approaches have been proposed to exploit multiple channels on unlicensed frequencies. The advanced development of cognitive radio enables wireless sensor networks to use vacant licensed channels. Cognitive radio wireless sensor networks enable a dynamic channel selection with the restriction of releasing a channel when a primary user is present. When nodes are set on different channels, coordination has to be carefully designed to ensure a successful transmission. This issue is mainly addressed at the MAC and network layers. In this paper, we provide an intensive survey on various aspects of traditional and cognitive multi-channel wireless sensor networks. Different approaches are categorized based on their underlying topology. Major developments are discussed and drawbacks of the existing approaches are identified.

1. Introduction

A Wireless Sensor Network (WSN) consists of a group of sensor nodes linked by a wireless medium which perform distributed sensing tasks [1]. Sensor nodes send their measurements to a sink using direct or multi-hop communication. Convergecast communication is used for data collection by the sink. WSNs constitute the platform of a broad range of applications related to national security, surveillance, military, health care, and environmental monitoring.

Conventional WSNs usually communicate on unlicensed bands, transmit small amounts of data, and have no strict restrictions on latency. Conventional WSNs are mostly suitable for low-duty cycling and monitoring applications. These applications do not have strict requirements on throughput and end-to-end delay. However, emerging WSN applications support more complex operations such as real time surveillance and target tracking and they require timely data delivery and high data rate. Once a certain event is detected, a WSN usually experiences a bursty traffic which results in contentions and collisions that limit the data throughput. The impact of interference in single channel WSNs also limits the network capacity.

By enabling transmissions over multiple channels, interference can be alleviated and collisions can be largely reduced. An efficient use of multiple channels in WSNs enables parallel transmissions over multiple channels, therefore timely communication with high data rate can be achieved. In multi-channel communication nodes may operate on different channels. An important objective is designing efficient schemes for channel assignment to ensure network connectivity and coordination between nodes, besides the performance improvement.

Besides approaches exploiting unlicensed channels, the advances in the technology of cognitive radios makes the utilization of licensed channels possible. Cognitive Radio Sensor Networks (CRSN) which employs cognitive technology into WSNs merged recently. A cognitive radio is capable of spectrum sensing, which enables it to work on both licensed and unlicensed channels. The licensed channels in the lower frequency bands have better propagation characteristics. With the same transmission power, the transmission range is larger on lower frequency. This characteristic makes cognitive radio based approaches promising for energy constrained WSNs. Extra benefit will add to the advantages brought in by the conventional multi-channel approaches.

There are several surveys in literature discussing multi-channel approaches for WSNs. A survey on multichannel assignment protocols in WSNs is presented in [42], which is further extended in [43]. According to [43], there are three types of channel assignment: static channel assignment, dynamic channel assignment,

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and semi-dynamic channel assignment. Some representative approaches from each category are specified. A survey on using multi-channel communication to increase WSN capacity is presented in [44]. The classification is similar to [43] and approaches from different categories are introduced and analyzed. The multi-channel assignment in CRSN is more dynamic and has more restrictions.

Article [45] provides a comprehensive survey on channel assignment in cognitive radio networks. This survey discusses channel assignment approaches for various types of networks including Cognitive Radio Ad-Hoc Networks (CRAHNs), Cognitive Wireless Mesh Networks (CWMNs), Cognitive Radio Cellular Networks (CRCNs), and CRSNs. CRAHNs are infrastructure-free and a CR node is able to communicate with another CR node via ad-hoc connections [63]. CWMNs is a special type of CRAHNs consisting of CR mesh clients and CR mesh routers. CR mesh routers form a connectivity backbone which performs packet forwarding and provides network access to mesh clients [64]. CRCNs are centralized and infrastructure-based networks where a CR base station is responsible for assigning channels and controlling communication among users [45]. A CRSN usually consists of a large number of sensor nodes and one or multiple sinks performing data aggregation using a convergecast communication model. These types of wireless networks have different architectures and communication models, thus algorithms designed for one type of network usually cannot be used directly on another type of network.

In this paper we focus on channel assignment in WSNs and give an in-depth analysis of this particular area. Papers [46] and [47] discuss both single-channel and multi-channel MAC layer protocols. However, channel assignment can be done both at MAC and network layers. We discuss channel assignment approaches at both MAC and network layers. Instead of using the method of channel assignment for classification, we provide a classification in terms of underlying topology in our survey. Furthermore, we discuss both multi-channel approaches using unlicensed bands and cognitive radio approaches which dynamically access licensed bands. These approaches share some common objectives, such as efficient spectrum utilization and reduced interference, while CRSNs have some unique advantages as well as extra challenges which will be discussed later.

In this paper, we introduce traditional multi-channel assignments with cognitive radio based multi-channel approaches. This is not discussed by prior surveys. The reminder of this paper is organized as follows. In Section 2, we first identify challenges in conventional multi-channel assignments, and then we discuss existing approaches based on their underlying topology. In Section 3, we introduce cognitive radio based multi-channel approaches. We present unique challenges using cognitive radio in WSNs and analyze various approaches proposed in literature. We highlight some possible future research directions in Section 4 and we conclude our paper in Section 5.

2. Conventional multi-channel approaches

Conventional multi-channel WSNs approaches are mainly exploiting 16 channels within the 2.4 GHz band, in 5 MHz steps, specified by the IEEE 802.15.4 standard. Current radios used by wireless sensor motes such as CC2420 [2] and DigiXbee [3] use multiple programmable channels. For example, the operating frequency can be programmed with 1 MHz resolution in CC2420.

Table 1 provides an overview of existing sensor nodes with different radios working on different channels. The existing hardware allows exploiting multi-channel communication which alleviates contentions and collision during bursty traffic and reduces interference in WSNs. Next sections discuss multi-channel approaches based on their underlying topology.

The major challenges in conventional multi-channel WSNs are:

- Channel selection: Current radios used by wireless sensor motes can be tuned to operate on different channels. Channel selection plays an important role in multi-channel WSNs. Objectives on channel selection including minimize interference, robust topology and energy efficiency. Two-hop neighbor nodes need to be assigned to different orthogonal channels to eliminate interference. For fixed channel assignment, the channel has to be assigned carefully to prevent network partitioning.
- Channel switching: The energy cost of channel switching and switching delay are not negligible. For example, the CC2420 radio uses around 200 us to perform channel switching [44]. During channel switching, any incoming packet is not received. When designing a multi-channel protocol, channel switching should be taken into account. A desirable multi-channel protocol should minimize channel switching without degrading the network performance.
- Channel coordination: In WSNs, a sensor is usually equipped with a half-duplex transceiver which is capable of switching channels dynamically. However, it can only transmit or listen on one channel at a time. Channel assignment may lead to sender and receiving nodes setting their radios on different channels. The coordination of channel switching is required for successful communication. Channel coordination is also important for resolving the multi-channel hidden terminal problem and deafness problem which are associated with CSMA/CA.
- Broadcast support: Broadcasting requires a successful transmission from one node to all its neighboring nodes. In multi-channel networks, a node may have neighboring nodes listening on different channels. This makes broadcasting more challenging in multi-channel WSNs.
- Scalability: WSNs are usually densely deployed over an area of interest. The size of WSNs varies from a few nodes to thousands of node. The designed protocol should be able to support large and dense networks.
- Energy efficiency: one of the major challenges in deploying WNSs is their dependence on limited battery power. Energy consumption is dominated by the node's radio consumption in typical sensor applications [46]. Main causes of radio's energy consumption include: collisions, overhearing, protocol overhead, and idle listening. An energy-efficient multi-channel protocol for WSNs has to take all the above factors into consideration.

2.1. Tree based multi-channel approaches

A WSN usually consists of a large number of sensor nodes and one or multiple sinks. There are two main types of data collection in WSNs:

- *Periodic* data collection: sensor nodes periodically send their measurements to the sink.
- *Event based* data collection: when a certain event is detected, a set of sensor nodes simultaneously send data to sink.

An important operation in data collection is data aggregation, which can be performed by the nodes in the network before forwarding the data to the next hop. Data collection follows a *convergecast* communication model, where data flow from the nodes to the sink. A natural topology used in convergecast communication is the *tree* topology. The parent of a node in the tree is one of its one hop neighbors located closer to the sink. The parent is usually used as the next hop when forwarding data to the sink.

Different approaches for tree based multi-channel WSNs have been proposed. One of the techniques partitions nodes into different subtrees working on different channels so that the interference

Table 1
Sensor motes working on different frequencies.

SensorMotes	TX range 1/2 wave dipole antenna/ LOS	Frequency band	Data rate (max)	Radio module
Mica2 [4] 868/916 MHz	152 m, outdoor	868/916 MHz	38.4 Kbps	CC1000
Mica2 [4] 433MHz	304 m, outdoor	433 MHz	38.4 Kbps	CC1000
MicaZ [5]	75∼100 m, outdoor	2.4 GHz	250 Kbps	CC2420
Waspmote [6,7] 2.4 GHz	7000 m, outdoor	2.4 GHz	250 Kbps	XBee-PRO-ZB
Waspmote [6,8] 900 MHz	10 km	900 MHz	156 Kbps	XBee-900
Waspmote [6,9] 868 MHz	12 km	868 MHz	24 Kbps	XBee-868

is reduced. If the trees are operating on different channels, then parallel transmissions can be used, resulting in an increase performance. Several tree based approaches are discussed in this section.

(a) HyMAC: HyMAC [10] is a hybrid MAC layer protocol combining both TDMA and FDMA schemes. It aims to achieve an energy-efficient collision-free network by utilizing multiple frequencies. After a tree rooted at sink is constructed using Breadth First Search (BFS), frequency and transmission time slot(s) are assigned for each node in a centralized way by the sink.

The communication period in HyMAC is a fixed length TDMA cycle consisting of a number of frames, where each frame starts with scheduled slots followed by contentions slots. The nodes that have already joined the tree, called scheduled nodes, are sending data in the schedule time slots as assigned by the sink. The newly joined nodes, called unscheduled nodes, randomly choose a time slot in contention slots to send a HELLO message to the sink. At the same time, the scheduled nodes also periodically transmit HELLO messages to the sink. The HELLO message includes the node's neighbor list. The neighbor list of all the nodes is gathered at the sink and used to construct the schedule. The schedule is then sent to each node in a schedule packet. As a result, each node is able to send data to its parent using the assigned slot and frequency.

HyMAC constructs a tree rooted at the sink using BFS. When traversing each node, the interference condition with its one-hop and two-hop neighbors is checked. In this algorithm, two nodes within each other's communication range are considered as conflicting neighbors. If a node N_i is conflicting with its sibling node N_j, then N_i is assigned a different time slot, otherwise N_i is assigned a different frequency.

The HyMAC protocol was implemented on FireFly [34] platform which uses CC2420 IEEE 802.15.4 wireless transceiver. HyMAC is compared with MMSN [19] for potential conflicts. The results show that HyMAC achieves less potential conflicts when node density increases.

HyMAC employs a simple centralized channel assignment method to alleviate interference and conflicts. The sink constructs the schedule and frequency assignments for nodes to achieve a minimum delay schedule. HyMAC is able to provide a bound on the end-to-end delay with relatively high throughput. The disadvantage of this approach is that periodically updating the neighboring information at the sink involves considerable overhead. Also, since a child node may be assigned a different channel than its parent, strict synchronization is required otherwise the deafness problem may occur. Broadcast may be supported in HyMAC if neighboring nodes exchange their channel information, however broadcasting requires channels switching and multiple transmissions on different channels.

(b) TMCP: Another tree based multi-channel protocol (TMCP) is proposed by Wu et al in [11]. TMCP is designed for data collection and uses a greedy channel allocation algorithm. The whole network is partitioned into disjoint subtrees operating on different orthogonal channels rooted at the sink. The number of subtrees is equal to the number of available orthogonal channels.

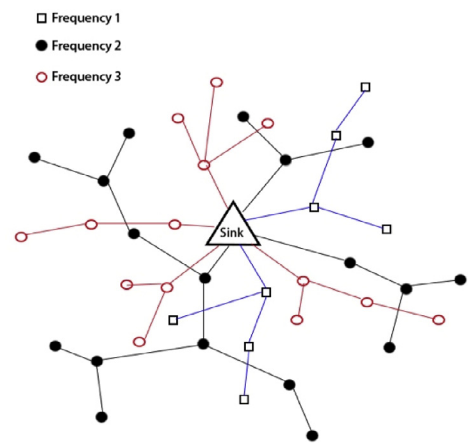


Fig. 1. The conceptual design of TMCP.

The interference in TMCP is determined according to the distance between nodes. The interference set of a node consists of all the neighbors located in its interference disk. The radius of the interference disk is computed according to the protocol model proposed by Gupta and Kumar [18]: $I_v = (1 + \alpha) \times R$, $\alpha > 0$ where I_v is the interference range, R is the node's transmission range, and α is a "bound" parameter. The interference value of a node is the number of nodes in its interference set. The intra-tree interference of a subtree is defined as the maximum interference value of all the non-leaf nodes in the tree. When constructing the tree, the interference set is assumed to be already known.

The tree construction in TMCP is combined with the channel assignment. First, a fat tree rooted at sink is computed using the Breadth-First-Search algorithm. In the fat tree, nodes can have multiple parents operating on different channels and with the same minimum hop count to the sink. Channels are allocated in increasing order of the level, from the top to the bottom of the fat tree. At each level, the node with the fewest number of parents is the first to choose an optimal channel. A node will always join the subtree with the minimum interference as result of its joining. After joining a tree, the node chooses the parent with the least interference value. Using this process, multiple subtrees working on different channels are formed, thus eliminating the inter-tree interference. Fig. 1 shows the conceptual design where multiple trees are rooted at the sink.

The protocol is simulated using GloMoSim and implemented on MicaZ motes. Aggregate throughput, packet delivery ratio, delivery latency, and energy consumption are evaluated. Results show that TMCP achieves higher delivery ratio and throughput compared to MMSN [19].

TMCP assigns different channels to different sub-trees such that the inter-tree interference is eliminated assuming that the assigned channels are orthogonal. TMCP does not require channel switching after channel assignment phase. Intra-tree communication uses CSMA/CA single channel communication thus it inherits the hidden terminal problem and the contention between nodes in the same subtree remains unsolved. Another disadvantage is that TMCP restricts transmission between nodes in different sub-trees thus broadcasting is restricted.

(c) DRCS: Another tree-based topology mechanism is proposed by Pal and Nasipuri in [12]. The Distributed Routing and Channel Selection Scheme (DRCS) aims to improve the network lifetime by reducing the energy consumed from overhearing. Tree construction is combined with routing and channel assignment.

DRCS argues that overhearing consumes the most energy in WSNs and the use of multiple orthogonal channels alleviates the overhearing problem thus prolonging the network life. Battery health metric and path metric are defined for channel assignment and route selection. The health metric H of a node represents the remaining battery which is proportional to the remaining capacity of the battery divided by the estimated current drawn. The path metric is defined as the sum of the expected number of transmission on each link.

In the DRCS scheme each node has a receiver channel and a transmit channel. Nodes work on the receiver channel by default while temporarily switching to the transmit channel for data transmission. Periodic beaconing is used to allow nodes to be aware of their neighboring information. Initially all the nodes operate on the same channel. Each node then chooses the least used channel in its neighborhood as its receiver channel after a random backoff. The selected channel is then broadcasted to the neighbors using a beacon message. After a certain interval, nodes begin their transmit channel selection. A node selects one of its neighbor's receiver channel as its transmit channel based on its health and path metrics. The selected neighbor node becomes its parent for relaying data to the sink.

DRCS is implemented using an experimental testbed consisting of 18 MICAz motes and is simulated using Castalia [35] for a larger network of 150 nodes. The results show that DRCS reduces overhearing without significantly affecting the delivery ratio.

The overhearing problem is alleviated in DRCS by distributing the traffic over multiple orthogonal channels. However, to ensure the connectivity of newly joined nodes, each node has to send a beacon message on each channel in rotation. Broadcast in DRCS can only be done by sending the message multiple times on each neighbor's receiving channel. A drawback of this technique is the constant channel switching for data transmission. Multi-channel hidden terminal and deafness problem exist in this approach. Also, the power consumption for channel switching which is usually not negligible, was not taken into account.

(d) Game theoretic multi-channel: Paper [30] proposes a game theoretic framework for channel selection in multi-channel WSNs. The proposed framework aims to reduce the amount of overhearing by reducing the number of neighbors operating on the same channel based on a tree topology.

The multi-channel allocation game is formulated as a coalition formation game. Neighboring nodes are assigned different receiving channels in the game. Non-leaf sensor nodes are considered a player set and a set of orthogonal channels form coalitions. The payoff that a player receives by joining a coalition is defined as $1/|C_k|$, where $|C_k|$ is the number of neighbors in the same coalition including the player. A balanced coalition structure is achieved when all nodes have a minimum number of neighbors in the coalition where the node belongs. Initially all sensor nodes communicate on the same channel and the communication topology is a tree rooted at the sink. A player will join another coalition if its payoff can be improved. The required knowledge is the number of neighbors assigned to each receiving channel. The coalition game ends when a balanced coalition structure is achieved.

The proposed algorithm is simulated with 100 nodes deployed uniformly in a $70 \times 70\ m$ area. The results show that the lifetime of the network increases when the number of available channels increases. However, some key performance metrics such as packet delivery ratio, throughput, and delay are not evaluated.

The proposed channel assignment method reduces overhearing through the multi-channel allocation game. However, this approach adds a relatively large overhead since each iteration involves a large number of actions and multiple iterations are needed to reach the equilibrium. The authors did not provide a theoretical bound for how many iterations are needed to reach the equilibrium. In this approach, the assigned channel is the node's receiving channel and a child node has to switch to the parent's receiving channel in order to transmit data. This approach does not guarantee that two nodes within each other's interference range are assigned different channels, thus the interference and contention are not fully resolved.

(e) HMC-MAC: HMC-MAC [31] is a multi-channel MAC protocol which reduces the interference and collisions by channel allocation and network segmentation. The network has a Network Coordinator (NC) used for central control and data collection. In HMC-MAC the time is divided into cycles, where each cycle starts with a beacon exchange period, followed by a data transmission period and an inactive period. Each node sends a beacon in a unique time slot during the beacon period, as determined by the NC. A 3-hop neighborhood needs to be discovered during the beacon period. A tree topology is built starting from the root and each branch is indexed. Nodes are organized into groups according to their depth (hops to sink) and the branch index it belongs to. Nodes at even depth and belonging to a branch with odd branch index, as well as nodes at odd depth and belonging to a branch with even branch index form the Group 1. The other nodes form the Group 2. Nodes alternate between transmission and reception mode. When Group 1 is in transmission mode, Group2 is in reception mode, and vice versa. The NC (i.e. the sink) is equipped with multiple interfaces and set in reception mode all the time.

A total of 16 channels are available for channel assignment and each node chooses dynamically its own channel. The node with the smallest network address has the highest priority in choosing a channel. Each node tries to assign a free channel that is being used by its 3-hops neighbors and sends its channel selection through a beacon. If it is not able to find a free channel among the channels that are already used by its 3-hops neighbors, then it tries to find a free channel among its 2-hops neighbors, and then among its 1-hop neighbors. If all channels are used, then the node randomly chooses a channel among those which are least used by its 1-hop neighbors.

The HMC-MAC is evaluated using NS2 simulator. The results show that HMC-MAC achieves larger aggregate throughput compared to an earlier version of HMC-MAC [36] which does not consider a multi-interface sink.

HMC-MAC reduces the interference by assigning different channels to neighboring nodes and by staggering the transmission time. However, since each sensor node has only one radio interface, channel switching is needed to communicate with a parent node operating on a different channel. This coordination process is not specified. Network wide synchronization is required for the alternation between transmission and reception phases. With limited number of available channels, neighboring nodes may still be assigned the same channel. HMC-MAC cannot totally eliminate interference. CSMA/CA is used by nodes transmitting on the same channel, thus it inherits the hidden terminal problem and contention between nodes in the same sub-tree remains unsolved. In addition, the proposed centralized approach does not scale well because the beacon transmission is scheduled by the NC.

(f) RMCA-FR: Routing-based Multi-Channel Allocation with Fault Recovery (RMCA-FR) is proposed in [48]. We focus on the channel allocation mechanism. Based on the routing tree, RMCA-FR defines a Logical Node (LN) as the set of nodes that have the same parent. An interference link exists between two LNs if any node in one LN is within the interference range of any node in another LN or its parent node. An interference graph is defined where vertices are LNs and an edge exists if there is an interference link between two LNs.

The network is divided into layers, where each layer consists of LNs with the same hop-count to the sink. Graph coloring is used to assign channels to each layer with the aim of minimizing the interference between nodes belonging to the same layer. The algorithm begins by coloring the LN with the highest degree, then all logical nodes not interfering with the first node are colored with the same color. If no more colors are available, each node is colored with the color of the node having the smallest number of conflicts.

RMCA-FR is simulated with Omnet++ and compared with an earlier work [49]. Work [49] addresses the channel allocation in a centralized way following a similar idea. The results show that RMCA-FR generates less collisions and requires less radio switching in a single path.

RMCA-FR is a distributed solution based on routing trees for the multi-channel allocation. It aims to minimize the interference by assigning different channels to interfering logical nodes. However, due to a limited number of channels, this solution cannot avoid all interferences. RMCA-FR may assign parent and children to different channels. Lack of a proper coordination between parent and child nodes to synchronize them on the same channel when transmitting leads to network partition. Broadcast is limited in this approach as well.

(g) MinMax: MinMax [55] is a link-based channel-assignment protocol which aims to minimize the maximum interference experienced by any transmission link. MinMax approach first builds a tree based on the conflict graph G_L consisting of all the nodes in the network, except the sink, as vertices and an edge between every interfering sender pair. Initially, all nodes assign a random channel then broadcast their IDs and the selected channel to the neighbors in G_L. Each node calculates its conflict based on the channel assignments received from neighbors in G_L, then broadcasts this information.

After a node receives conflict values from its neighbors in G_L, it excludes the channels used by neighbors with higher conflict value, and assigns a channel that can reduce its own conflict. This procedure repeats as long as a node can decrease its conflict value by assigning an available channel. MinMax minimizes the maximum conflict in the network by avoiding to assign channels with higher conflict among neighbors. Switching to such a higher conflict channel may further increase the conflict value of that neighbor which may lead to a higher maximum conflict in the network.

The proposed protocol is evaluated through simulations based on data traces collected from a WSN testbed with 74 TelosB motes. The simulation results are compared with GBCA [56]. MinMax achieves less conflict and interference as well as less delay. The biggest drawback of this approach is energy efficiency. The channel assignment process runs in rounds and it can take up to *EI* rounds to converge, where *EI* is the number of interfering links in the network. *EI* can be very large in densely deployed WSNs. Synchronization between sender and receiver is also required for this approach. A packet may be lost if the receiver is tuned to another channel. The link-based channel assignment also involves frequent channel switching as a parent node may need to switch to different channels to receive packets from children.

(h) WAVE: The routing tree-based protocol WAVE is proposed in [37]. WAVE first builds a conflict graph. A node *n*'s conflict graph includes the node itself, its parent, its children, all nodes that are 1-hop away from its parent, and all nodes whose parent is 1-hop away from *n*. WAVE assumes that each node knows the number of packets it has to transmit, including packets generated by itself and from its children, before the channel and time slot assignment. Only one packet can be sent in a time slot.

One cycle of data gathering phase contains W successive waves (i.e. joint channel and time slot schedule), where W is the maximum number of packets a node has to transmit. All nodes assign their time slot and channel in decreasing order of the number of packets they have to send. In the first wave, the node with the largest number of packets to send has priority. Each node tries to assign the earliest time slot on any available channel as long as there is no conflict. The wave pattern is reproduced in an optimized way (i.e. only the slots needed by at least one node are reproduced in the next wave) for W times, until all packets in the current data gathering cycle reach the sink.

WAVE is evaluated and compared using GNU Octave with earlier works [38] and [39]. Results show that WAVE requires less time slots, thus less delivery delay. The authors did not evaluate the packet delivery ratio and throughput which are important metrics for WSN performance evaluation.

WAVE is a multi-channel approach using TDMA. Not all interfering links have been removed by channel allocation. Collision free transmission is achieved by assigning interfering nodes to different time slots. However assigning different time slots may result in a longer schedule, thus an increased delay. WAVE is efficient if all nodes, except the sink, generate packets in each cycle. However, a non-leaf node without a packet still occupies time slots, waiting packets from its children.

Among the tree based approaches discussed above, HyMAC, MinMax and WAVE are schedule-based MAC protocols which address multi-channel communication. In schedule-based protocols, collision free access to the medium is guaranteed if each node sending packets is assigned an exclusive time slot in its 2-hop neighborhood. HyMAC and MinMax assign channels and time slots for a newly joined node while WAVE assumes a fixed topology with nodes aware of the number of packets they have to send. DRCS [30] and HMC-MAC are contention based multi-channel MAC protocols. These contention based protocols suffer from the problems associated with CSMA such as the deafness problem and the hidden terminal problem. RMCA-FR [48] addresses the channel allocation problem at the network layer. TMCP address the channel assignment problem by constructing sub-trees communicating on different channels. Any single-channel MAC and routing protocols can be applied to a single sub-tree.

2.2. Cluster based multi-channel approaches

In cluster based approaches the network is divided into clusters, where each cluster is usually equipped with a cluster head. Cluster heads are sometimes resource rich devices that have extra energy or multiple radios. A cluster head can be responsible for channel assignment of all nodes within the cluster such that to minimize the interference within the cluster. One approach assigns nodes within the same cluster to transmit on the same channel and the cluster head is responsible to forward the data between different clusters. Some mechanisms do not use cluster heads. In such cases channel switching is needed for communication between nodes in different clusters. This section presents different cluster-based approaches proposed recently in the research literature.

(a) Dynamic multi-channel MAC: A dynamic multi-channel MAC protocol based on clustering is proposed by Le et al in [13]. Nodes are categorized into different clusters based on their transmitting channel. Nodes transmitting on the same channel are within the same cluster. Initially, all the nodes are working on the same channel called the *home channel* which means that the whole network is within the same cluster in the beginning. When a channel gets overloaded, nodes switch the channel and the network gradually partitions into several clusters.

The *crowdness* of a spectrum is measured by the parameter α, and each node periodically broadcasts a tuple $\langle s, f \rangle$. A node i receives tuples from its neighbor set j and computes $\alpha_i = \frac{\Sigma_j s_j}{\Sigma_j (s_j + f_j)}$, where s_j is the neighbor j's total number of successful acquirement of the current channel and f_j is the total number of unsuccessful acquirement. When α_i is below a threshold, it indicates that the channel is too crowded and the node i considers switching the channel.

Each node also computes a sink factor which measures its received messages versus the transmitted messages. A node receiving heavy traffic behaves more like a sink and has a higher probability to switch channels (i.e. initiate the cluster split). The neighbors who have heavy traffic destined to that node will switch to the same channel. This approach creates well-isolated clusters and inter-cluster communication involves channel switching.

Each node keeps neighboring table storing its neighbors' IDs and operating channels. When a node joins the network it broadcasts a HELLO message on the home channel to inform neighbors of its presence. When a node has to send a message to a neighbor but does not know its operating channel, then it sends a WHERE IS message (including the sender's ID and the channel) on each available channel in a round robin manner until an acknowledgment is received. The neighboring table is updated for the sender and for all the nodes receiving the message. If the destination channel is known, then the node just switches to that channel in order to transmit the message. After the acknowledgment is received, the node switches back to its original channel. Before a node switches to a new channel, it uses a message of type BYE to inform its neighbors. Each node i periodically sends a CHANNEL UPDATE message containing the pair $\langle t_i, s_i \rangle$ which is used to estimate the channel crowdness as discussed earlier. Simulations and experiments using a MicaZ testbed show that throughput and delivery ratio are increased compared to single channel MAC protocols.

[13] is a simple and light-weight MAC protocol which does not require synchronization. Channel switching is performed dynamically according to the channel crowdness, thus network congestion is avoided in an efficient way. However this approach has a considerable overhead due to the periodical broadcast of nodes' status. The impact is more drastic in large-scale networks where energy efficiency is degraded. This protocol also suffers from the deafness problem. This happens when a node switches to a new channel and the BYE message is not successfully received by all neighbors. Some nodes might be in transmit mode when the leaving node sends the BYE message.

(b) Implicit prioritized-access: An implicit prioritized-access protocol based on a structure similar to a cellular network is proposed by Caccamo et al in [14]. The network is partitioned into hexagonal cells using seven different channels. Adjacent cells are assigned to different channel frequencies in order to avoid interferences. Intra-cell messages are exchanged between nodes inside each cell and inter-cell messages are exchanged among neighboring cells. In order to exchange messages with neighboring cells, each cell is equipped with a router node located in the center of the cell. A router node has two transceivers. It transmits inter-cell messages using the channel of the cell where it belongs to and it receives inter-cell messages on the channel of the cell from where the message is received. Non-router nodes are equipped with a single transceiver. They transmit intra-cell messages to the router who is then responsible to forward the message throughout the network. To avoid conflicts, the intra-cell communication is scheduled using the Earliest Deadline First (EDF) mechanism [15].

The nodes within the same cell have an identical schedule table. The schedule table contains nodes' priorities to transmit messages according to their deadlines and each node's reserved frames for transmitting. Based on the table, a node can select the right frame to transmit just by counting the frames. An inter-cell frame is reserved every T_{block} frames for inter-cell communication. A router node can only communicate with its six adjacent cells' router nodes and they are assigned statically to inter-cell frames following a periodic fashion.

The authors simulated the proposed protocol in NS2. The average delivery delay and throughput are evaluated. Simulation results show that the proposed protocol achieves better throughput and less delay compared to IEEE 802.11 CSMA/CA access protocol.

A frame sharing technique is also proposed for a more efficient use of the frames. Collision free communication within the same cell is achieved by assigning different transmission slots to nodes in the same cell. The interference between adjacent cells is eliminated by assigning them different channels. Since each cell is adjacent to six different cells, seven orthogonal channels are needed to fully eliminate interference. In this protocol each node schedules all messages in the network, thus the complexity grows linearly with the number of messages. Another drawback of this technique is the requirement of a rather strict deployment of router nodes in the center of the cell. In addition, the assumption that router nodes have two transceivers may constitute a disadvantage for a large number of cells. The energy consumption is not considered in this approach.

(c) MCMAC: MCMAC [16] is another TDMA based multi-channel protocol based on the cluster topology. The network is grouped into many overlapping clusters and each cluster has a cluster head (CH). Each node is only required to be equipped with a single half-duplex transceiver, while the CHs are assumed to transmit with more power so that they can communicate with each other. In this approach CHs are not responsible for aggregating messages from all the member nodes. A CH works as a coordinator who is responsible for the channel assignment of all the nodes in the cluster.

In MCMAC the time is divided into cycles, where each cycle has four stages: synchronous beacon, transmission request, channel schedule, and data convey. With N available channels, one is used as the control channel and the remaining are used as data communication channels. Initially, all the nodes listen on the control channel.

In the first stage, each CH sends out a synchronous beacon so that all the member nodes in the cluster synchronize. In the transmission request stage, the time is divided into a number of slots equal to the number of member nodes in the cluster. The CH distributes a fix time slot to every member. When a node has data to send, it first sends a request containing the destination information to the CH. This request is sent in the node's appointed slot, during the transmission request stage.

In the schedule stage, each CH performs the channel assignment for the source and destination nodes based on the received requests. Different channels are assigned to different communication pairs. After a node receives a channel assignment information packet, it switches to the data transmission channel. The communication structure of a frame is illustrated in the Fig. 2. Neighboring clusters negotiate their sleep time. They enter the active period alternatively so that the inter-cluster interference is eliminated. They also negotiate a Contact-Time when CHs can communicate with each other.

MCMAC protocol is simulated using OMNET++. Simulation results show that energy consumption per byte decreases when the number of available channels increases. MCMAC achieves better energy efficiency than MMSN [19]. This protocol is mainly designed to save energy and to alleviate interference and collisions. Data throughput and delivery delay are not taken into account. Collision free communication is achieved by slot schedule. The request and schedule stages increase communication latency and precise time synchronization at nodes is required.

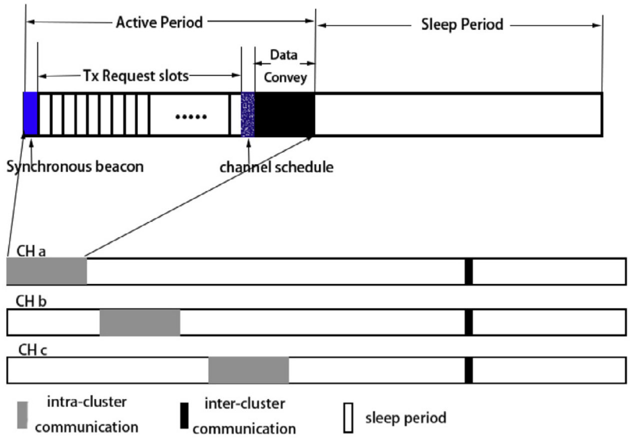


Fig. 2. MCMAC frame structure.

MCMAC works well for duty-cycle sensor networks that only transmit small amounts of data. However, it is not well suited for real-time applications. In addition, these two stages increase the overhead and consume more energy. CHs are transmitting messages with a stronger power, thus they may deplete their energy resources at a faster rate compared to other nodes. Broadcast is not supported in MCMAC.

(d) Application based channel assignment: Article [17] is proposing an application based clustering mechanism for topology control and channel assignment. Nodes with similar type of sensed data (e.g. temperature) are assigned the same channel, thus forming a data plane (e.g. a cluster). It is assumed that geographical proximity implies high data correlation. CHs in each data plane and the sink communicate though the common control channel, while sensor nodes forward their data to their CHs through the assigned intra-cluster channel.

Nodes are usually densely deployed in WSNs. In many monitoring applications (e.g. forest fire monitoring applications), nodes deployed within a certain proximity are sensing the same data. If all the nodes simultaneously transmit data to the sink, they will generate many collisions and many messages will be lost. In addition most of the data transmitted are redundant. Ideally, only one node in the event area is sending data to the sink. Based on this observation the nodes with similar sensed data are grouped into a cluster. Each cluster is assigned a different communication channel. When a node has data to send and senses that the communication channel is busy, it assumes that another node has already forwarded the data to the sink and it drops the data.

Channel assignment can be programed to minimize inter-cluster interference. For example, if we want the WSN to sense temperatures 10° apart, we can use 12 channels as follows. One channel is used for inter-cluster communication between cluster heads and the rest of the channels are assigned separately for temperatures below 10 °F, 10 °F ∼20 °F, 20 °F ∼30 °F, and so on. A node automatically tunes its radio to the specific channel based on its sensed temperature value.

The proposed mechanism is simulated using GloMoSim. Results show that the proposed multi-channel mechanism transmits less packets than the single channel approach, thus it consumes less energy. This clustering mechanism uses a simple channel assignment scheme and is easy to implement. It also reduces the energy consumption since only few nodes within a cluster are involved in data transmission. However, the proposed mechanism reduces energy consumption by sacrificing sampling accuracy. Dropping packets when channel is sensed to be busy may lead to information being lost. This approach is also application dependent. Clustering based on sensed data makes this scheme unsuitable for certain applications.

Among the cluster based protocols discussed above, approaches [13] and [17] are contention-based MAC protocols. Both approaches assign different channels to different clusters. [13] assigns channels based on the crowdness of a channel, while [17] assigns channel based on the sensed data. The protocol proposed by [17] is also restricted by the application.

The implicit prioritized-access protocol [14] and MCMAC [16] are schedule-based multi-channel protocols. MCMAC eliminates collisions and overhearing by scheduling a time slot and channel for a specific pair of sender and receiver. The implicit prioritized-access protocol schedules just the sender. It eliminates collisions, but overhearing still remains an issue since all receiving nodes are still required to listen.

In cluster based approaches the channel assignment and transmission schedule are usually computed by the CH using a local centralized scheme. The main drawback of the cluster based approaches is the large overhead experienced by the CH.

2.3. Node based multi-channel approaches

In node based multi-channel approaches, no underlying topology is specified. A node may switch channels dynamically, based on the current network condition. The channel assignment can be done locally using nodes' neighborhood information. By assigning different channels among neighboring nodes, the interference can be minimized. Frequent channel switching usually occurs in node based approaches. Several node based approaches are discussed next.

(a) MMSN: MMSN [19] is one of the first multi-channel MAC protocols designed for WSNs. No specific topology is required for this approach. It aims to assign different frequencies among 2-hop neighbors for interference free data reception.

In this approach four frequency assignment schemes are proposed: exclusive frequency assignment, even-selection, eavesdropping, and implicit-consensus. In the exclusive frequency assignment nodes exchange their IDs among 2-hop neighbors through beacon messages. Frequency decisions are made in a distributed manner in increasing order of their IDs. The node with the smallest ID chooses the lowest frequency among the available ones and then beacons the choice to its 2-hop neighbors. Other nodes wait for the decisions of all the neighbors with smaller IDs and then choose the smallest frequency among those not chosen by its 2-hop neighbors. If there are not enough frequencies, then the even-selection scheme is used. When a node finds out that all the available frequencies have been chosen by neighbors, then it randomly chooses one of the least selected frequencies.

The eavesdropping scheme can be used to reduce the overhead since it does not require neighborhood information. In the eavesdropping scheme, each node selects a random backoff interval and eavesdrops its 1-hop neighbors' frequency decisions during this period. Nodes randomly choose one of the least used frequencies and broadcast their decision after a random backoff interval. The last channel assignment scheme is implicit-consensus, where all nodes share the same pseudo-random number generator. In the implicit-consensus scheme, the 2-hop neighbors' IDs are also collected. Each node calculates a random number for itself and a random number for all its 2-hop neighbors. A node chooses the current frequency only if its current random number is higher than those of its 2-hop neighbors.

Media access takes place after the frequency assignment, when each node is assigned a data reception frequency. The broadcast frequency f_0 is used by all the nodes. The receive frequency of a node is called f_{self} and the intended destination's receiving frequency is called f_{dest}. A node is snooping on these frequencies. A

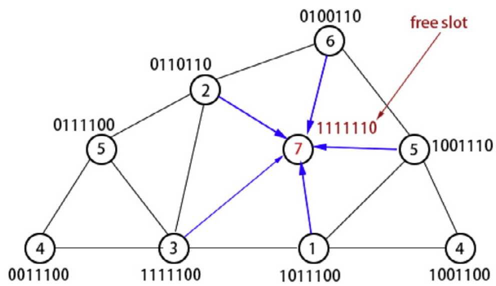


Fig. 3. MC-LMAC timeslot selection.

time slot is divided into a broadcast contention period T_{bc} and a transmission period T_{tran}. When a node has a unicast packet to send, it first listens to the broadcast channel f_0. If it senses any signal during $T_{bc,}$ then the node sets the rest of the time slot receiving the broadcast packet. Otherwise, the node takes a random backoff. During the backoff period, the node snoops f_{self} and f_{dest} alternately. If the f_{self} is sensed busy, then it gets ready for receiving possible incoming packets on its receiving channel. If the f_{dest} is sensed busy, then it assumes that there is another node transmitting to the destination and choses not to transmit in this time slot in order to avoid collision. If neither f_{self} nor f_{dest} are busy, the node proceeds with the transmission of the unicast packet.

MMSN is implemented using GloMoSim and its performance is compared with single channel CSMA. MMSN achieves better throughput when the number of available channels increases, and better delivery ratio.

MMSN's four frequency assignment schemes allow users to choose frequencies depending on the WSN attributes. Due to the limited number of available channels, MMSN cannot eliminate the interference between interfering nodes. Back-off based CSMA is used when a node intends to transmit on the destination channel frequency. MMSN supports broadcast and it allocates a broadcast period in each time slot. Synchronization is required. A node alternatively snooping on different channels may lose packets. A node will miss incoming packets when listening on another channel. The frequent channel switching required by this approach makes this protocol less energy efficient.

(b) MC-LMAC: MC-LMAC [20] is another distributed node-based multi-channel MAC protocol based on the single channel MAC protocol LMAC [21]. In this approach, all nodes are initially communicating on the same predefined base channel. A node only switches channels when the current channel is overcrowded.

Initially, when all the nodes communicate on the base channel, each node selects its transmitting time slot based on the 2-hop neighbor information similar to LMAC. Each node stores the slot selection of its 2-hop neighborhood in a vector whose length is equal to the number of timeslots in a frame. Each node transmits the time slot selected and its 1-hop neighbors' slot selection through a control message.

On receiving a packet, a node executes the logic OR operation to update the information about the occupied slots of its neighborhood and its vector. If the node has not yet selected a transmitting slot, then it selects one from the free slots. The time slot selection scheme is shown in Fig. 3, where the node 7 is seeking a time slot. When node 7 receives information from its neighbors, the logic OR operation is executed and it takes the free slot 7 as its transmitting time slot. If a node seeking a time slot finds all of them occupied, then the node becomes slotless. Such a node will try to switch channels for data transmission.

In MC-LMAC, the slots occupied by the 2-hop away neighbors can be reused on a different channel. A node broadcasts the slots occupied by its 2-hop away neighbors as free slots to the neighbors. A slotless node monitors the advertised free slots and selects one node to negotiate a slot and a frequency pair. After this, both nodes are switching to the negotiation channel in the specified time slot.

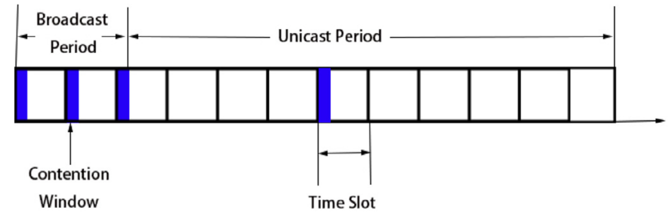


Fig. 4. Y-MAC frame structure.

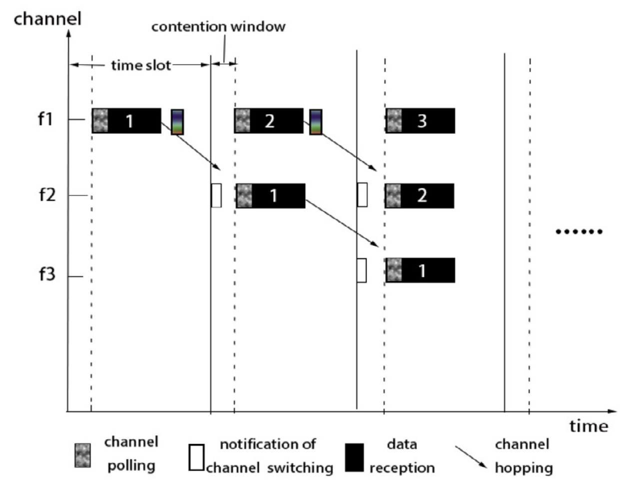


Fig. 5. Y-MAC channel hopping mechanism.

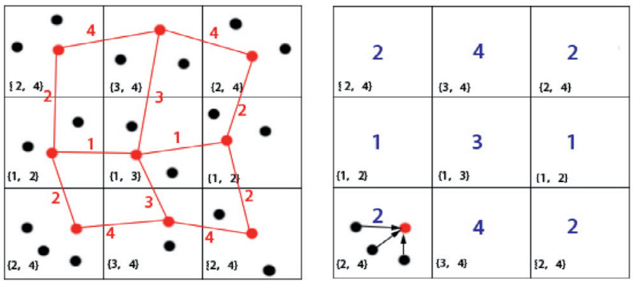
MC-LMAC is simulated using OMNeT++. The results show that MC-LMAC is more energy efficiency than single channel LMAC. However, energy efficiency is measured in terms of collisions which is not sufficient.

MC-LMAC is a schedule-based MAC protocol, which supports broadcast. Synchronization is required. MC-LMAC enables more transmissions in the same time slot by assigning slot-less nodes to different channels. Thus it allows more nodes to communication during the same time slot compared to LMAC. The disadvantage of this protocol is the overhead of control messages. Large overhead occurs in the exchange of messages used to discover channels used in different TMDA slots by the nodes in the 2-hop neighborhood.

(c) Y-MAC: An approach similar to MMSN is Y-MAC proposed in [22]. Unlike MMSN, which divides a time slot into two periods, Y-MAC divides a frame into a broadcast period and a unicast period, each consisting of a different number of time slots. The frame architecture is illustrated in Fig. 4. Among all the available channels, one is defined as the base channel. Originally, all the nodes communicate on the base channel.

The time slot assignment is similar to LMAC [21], where each node chooses its receiving time slot by OR-ing the slot allocation vectors of its 2-hop neighbors. The broadcast messages are exchanged in the broadcast period. At the beginning of each broadcast period all the nodes tune to the base channel. A channel hopping mechanism is employed for the unicast messages. When a node receives a unicast message on the base channel, it hops to the next channel to receive the following message. Any node that has the pending message to the receiver hops to the same channel.

The channel change information is transmitted by the receiver to all the neighbor nodes using a small independent packet. The channel hopping mechanism is illustrated in Fig. 5. The next



a. Inter-cell Communication b. Intra-cell Communication

Fig. 6. Grid-based channel assignment.

channel is calculated by the hopping sequence algorithm, which must guarantee that among the 1-hop neighbors there is only one node on any particular channel.

Y-MAC is implemented with real sensors. Authors compared Y-MAC with LPL [40] and Crankshaft [41] in terms of delivery rate, reception rate, and duty cycles. The results show that Y-MAC achieves better reception rate under high traffic conditions. Also the delivery latency of Y-MAC remains relatively steady when the traffic load increases.

For unicast communication, when multiple nodes have packets for the same destination, they need to compete in the contention window. The winner and receiver will hop on the same channel sequence for data communication. In this way, Y-MAC reduces latency by distributing bursty messages across multiple channels. Y-MAC requires time synchronization. However, the channel hopping mechanism involves frequent channel switching. The channel switching information sent out by receiver nodes to inform neighbors every time they hop on a new channel increases the overhead.

(d) MCAS-MAC: A multichannel asynchronous scheduled MAC protocol (MCAS-MAC) is proposed in [50]. MCAS-MAC extends the asynchronous scheduled MAC protocol (AS-MAC) [51] to support multi-channel communication. MCAS-MAC is a duty cycling based protocol where nodes periodically turn on their radio for short periods of time for transmitting or receiving packets.

Each node in the network periodically sends out Hello messages including the communication channel (home channel), the wake up interval, and the hello interval. When a node first joins the network, it gathers information about all its neighbors by listening to Hello messages on all available orthogonal channels. The least used channel of all the neighbors is chosen as the home channel. The new node decides its wake up interval so that its waking up period is unique among all neighbors. When a node has to send a packet to a neighbor, it calculates the receiver's next waking up time and switches to the receiver's home channel to send the packet.

MCAS-MAC is implemented in TinyOS for Mica2 platform to evaluate its performance in terms of energy efficiency, delay, and packet delivery ratio. MCAS-MAC is compared with other single channel based protocols such as AS-MAC. MCAS-MAC achieves a better delivery ratio in high density networks. However, MCAS-MAC does not outperform AS-MAC in terms of energy efficiency and delivery ratio.

MCAS-MAC alleviates interference and collisions by assigning neighboring nodes to either different wake up times or different receiving channels. A sender needs to wait for the wakeup period of the receiver to send buffered packets. It mainly suits duty cycling-based WSNs which do not have strict restrictions on delivery delay. When multiple senders intend to transmit to the same receiver at the same time, the media access method is contention based, thus it inherits the drawbacks of contention based MAC protocols such as deafness and hidden terminal problems. Broadcast is limited in this approach.

Among the node based multi-channel approaches discussed above, MMSN and Y-MAC use a combination of schedule based and contention based access protocol. The difference is that MMSN divides each time slot into broadcast and unicast periods, and it follows a contention based media access in each period. Y-MAC divides a frame into broadcast and unicast slots and each slot starts with a contention period. The winner of the contention period transmits all its packets in the following time slots. MCAS-MAC is a contention based MAC protocol. MCAS-MAC involves longer delays since it assigns different wake up periods for neighboring nodes. Thus a sender has to wait for the receiver to wake up in order to perform data transmission. MC-LMAC is a schedule based MAC protocol which allows multiple nodes to transmit in the same time slot at the cost of an increased overhead.

3. Cognitive radio multi-channel approaches

The multi-channel approaches discussed previously aim to achieve higher throughput, alleviate interferences, and avoid collisions. They mainly operate on the unlicensed channels, usually on the 2.4 GHz ISM band, such as the 802.15.4 networks for example. IEEE802.15.4 standard defines 16 channels on the 2.4 GHz ISM band with 2 MHz bandwidth and 5 MHz inter-channel spacing. Among them, only four are not overlapping with the IEEE802.11 channels. It has been showed in [23] that the interference with IEEE802.11 is not negligible. Any 802.15.4 sensor network is actually critically affected by the coexistence. Recent advancements in Cognitive Radio (CR) technology allow opportunistic spectrum access of the licensed spectrum. CRs have been incorporated into the WSNs as well.

A cognitive radio is capable of spectrum sensing, which enables it to work on both licensed and unlicensed channels. In CRNs, a wireless user who is assigned with certain channels is called a Primary Users (PUs), for example a TV transmission tower. The other wireless devices which access the spectrum opportunistically as long as they do not interfere with the PUs are called Secondary Users (SUs). This means that when a PU starts transmitting on the channel used by a SU, the SU is able to detect it and stop or switch its transmission to another channel.

Cognitive Radio Sensor Networks (CRSN) enable more applications than conventional WSNs and have the potential to better solve the interference and collision issues in WSNs. CRSNs benefits many recently wireless sensor applications [24]. A WSN usually experiences a bursty traffic once a certain event is detected; contentions and collisions cause transmission delay. The dynamic spectrum access to licensed channels in CRSN better solves this problem compared to conventional multi-channel approaches due to the limited number of orthogonal channels in the unlicensed band. This makes CRSN suitable for military applications such as surveillance, which requires timely delivery.

Even more, licensed channels provide better propagation characteristics and larger bandwidth. This is especially relevant for multimedia WSNs which may need to transmit multimedia data such as image and audio files which demand high bandwidth. Traditional WSNs are not able to support QoS for such applications. CRSNs can provide better indoor sensing because of the crowded spectrum in 2.4 GHz ISM band. Indoor sensing applications usually coexist with IEEE802.11 applications such as WiFi. In the traditional WSNs the coexistence causes interference with each other.

CRSN has many benefits and distinguishes as a research direction worth investigating. It brings many challenges from the physical to the application layer. We focus our discussion on the channel assignment/spectrum allocation and topology control.

Channel assignment in CRSN is essentially multi-channel assignment in a more dynamic environment. It inherits the challenges from the conventional multi-channel approaches identified in Section 2. The extra challenges that are unique to CRSNs are identified as follows:

- Spectrum sensing: A PU may not occupy its spectrum continuously. The unused portion of the spectrum is called a spectrum hole. A cognitive radio is capable of scanning the wireless spectrum at any time and detecting spectrum holes. Channel assignment is based on the available channels sensed during the channel sensing period. Spectrum sensing is usually abstracted from the MAC layer. Longer sensing periods lead to high energy consumption while insufficient sensing may degrade the network performance. Finding an optimal sensing time is an important research direction in CRSN.
- Spectrum handoff: CRSNs are more dynamic than conventional multi-channel WSNs. A certain channel which is sensed available may be assigned to a SU at a specific time. However, once a PU is detected, the SU must vacate the channel and switch to an idle channel for transmission. This process is referred to as the spectrum handoff.

3.1. Single node channel assignment approaches

One of the challenges of using CRSN is designing energy-efficient approaches. Energy-efficiency is an important design criteria in WSNs. Cognitive radios with spectrum sensing ability consumes more energy. When incorporating cognitive radio technology into WSNs, energy efficiency has to be considered. Channel assignment is usually based on the availability of sensed channels, which vary between nodes, thus making it more challenging than conventional multi-channel approaches. A few works addressing channel assignment of a single node or a pair of nodes have been proposed.

(a) Residual energy aware channel assignment: [25] proposes a cluster-based residual energy aware channel assignment scheme for multi-channel CRSN. Residual energy for each node is estimated by an *R-coefficient*. Channel assignment is based on the R-coefficient and it aims to balance the residual energy of each sensor.

In this approach, the whole network is composed of different clusters where each cluster has a cluster head (CH). A common control channel is defined for nodes within the same cluster. Nodes exchange information on the common control channel and the CH is responsible for assigning data transmission channels for the nodes in its cluster. A frame is divided into $k+1$ time slots, where the first slot is reserved for channel assignment and the remaining k slots are used for data transmission. Since this work addresses the issue of channel assignment within a cluster, we still consider it as an approach for single node channel assignment.

In this work the PU behavior for each channel is modeled as a two-state Markov model. The channel activity level is modeled using P_j^{idle} – the probability that the channel j is idle and $P_j^{success}$ – the probability that the channel j is idle for the next L slots given that it is idle initially (L is the number of time slots needed to transmit a packet). The *R-coefficient* R_{ij} predicts the residual energy after the node transmits a packet on a particular channel. The coefficient is calculated as $R_{ij} = R_i^c - \bar{E}_{ij}$ where R_i^c is the current residual energy of the node i and $\bar{E}_{ij}$ is the expected energy consumption of the node i transmitting on the channel j. $\bar{E}_{ij}$ is calculated as follows:

$$\bar{E}_{ij} = \sum_{l=1}^{L} E_i\ (l)P_j^l + E_i(L)P_j^{success}$$

$E_i(L)$ is the energy consumption for the successful transmission of a packet on the channel j, $E_i(l)$ is the energy consumption of a successful transmission for l ($l < L$) slots, and P_j^l is the probability that channel j has a PU activity on l^{th} slot.

Two channel assignment strategies are proposed: greedy channel assignment and optimization-based channel assignment. The greedy algorithm assigns channels in iterations. The *R-coefficient* of each unassigned node on each available channel is calculated in each iteration. The node and channel pair with maximum *R-coefficient* is selected in each iteration and marked as assigned. A channel can only be assigned to one node within the same cluster. The algorithm terminates when all nodes are assigned with available channels or all available channel are used. The optimization-based channel assignment aims to maximize the cluster wide residual energy. Suppose there are N sensors and M available channels in a cluster. The objective is to maximize $\sum_{i=1}^{N}\sum_{j=1}^{M} R_{ij}x_{ij}$, where x_{ij} is 1 if sensor i is assigned to the channel j and 0 otherwise. Also in this case if $N > M$ then $N-M$ nodes will not be able to transmit in this frame.

The greedy channel assignment, the optimization-based channel assignment, and the random paring mechanism are evaluated via simulations. The optimization-based channel assignment mechanism has a longer network lifetime compared to the two other schemes. In addition, the optimization-based channel assignment mechanism is also compared with OSA-MAC [52]. Results show that optimization-based channel assignment mechanism consumes less energy per slot over frames. Other important metrics such as packet deliver ratio and delay are not evaluated.

The residual energy aware channel assignment is a locally centralized approach. CHs assign channels to each pair of nodes in the cluster and aim to achieve residual energy balance. The proposed channel assignment does not consider the interference between neighboring clusters. Two neighboring nodes belonging to different clusters may be assigned the same channel, resulting in interference. The spectrum handoff is not addressed in this approach. In this scheme a frame consists of one channel assignment slot and a number of data transmission slots. However, scheduling for data transmission is not specified. A proper scheduling of transmissions between the CH and CMs is needed in order to address the multi-channel hidden terminal and deafness problems. Broadcast is not supported by the proposed scheme.

(b) Energy aware channel selection: Another single node channel assignment approach is proposed in [26]. It incorporates CR technology into WSNs and proposes an energy aware channel selection scheme. This work focuses on the channel decision between a pair of nodes in order to minimize the energy consumption. Initially nodes communicate on a common control channel. When a node S_1 has to send packets to S_2, S_1 first transmits the number of packets to S_2. S_2 estimates the energy cost of each available channel, selects an optimal one, and informs S_1 of the selected channel. After that both nodes tune their radios to the selected channel for data transmission.

Channel occupancy is modeled using a simple semi-Markov model which is similar to the work in [25] where a channel can be either in the state *idle* or *busy* so that the average channel occupancy can be calculated. The purpose is to determine whether to stop the sensing procedure and to choose one of the channels from the already sensed channel set S_k, or to continue sensing other channels until it finds a better one.

Suppose that k channels are already sensed and stored in the set S_k. The total energy cost for stopping sensing and choosing the best channel so far is

$$E_{Tr}(S_K, u) = k \cdot E_s + N \cdot C(u)$$

where $C(u)$ is the energy cost for successfully transmitting a packet over the channel with the minimum estimated channel load (i.e. the average channel occupancy) in the set S_k. N is the number of packets needed to send, and E_s is the energy required to sense one channel. E_{Tr} is updated accordingly if more channels are sensed. If a new channel j is sensed, then the sensed channel set is updated to $S_k \cup \{j\}$ and $C(u)$ is updated if the channel j has the minimum channel load.

There are two scenarios for channel selection. In the first scenario channel load of each available channel is known to all sensor nodes. In such a case a node can take a decision that results in the minimum total energy consumption. Since this is often not the case in reality, we focus on the second scenario where nodes do not have any prior information on channels condition. A satisfying energy threshold is $E_T = e_T \cdot N$, where e_T is the satisfying energy threshold for transmitting one packet. $E_{Min} = e_{Min} \cdot N$, where e_{Min} is the energy required to transmit a packet over an interference free channel. When $E_{Tr}(S_K, u) < E_T$ then it means that a satisfactory channel has been found and the node will transmit on the best channel sensed so far. If $k \cdot E_s + E_{Min} > E_T$, then no satisfying channel can be found any more. If neither of the conditions is met, then the node keeps sensing a new channel.

The two schemes are evaluated using simulations and compared with a sensing scheme that senses all available channels. The proposed sensing schemes show good energy improvements compared to the sense-all scheme.

The proposed energy-aware channel selection scheme focuses on a sensing strategy that allows nodes to decide whether to stop sensing or to sense additional channels. Energy efficiency is improved by reducing the sensing time. However, it does not specify the channel selection criteria or the spectrum handoff mechanism. The proposed scheme addresses the channel assignment problem with the sole objective of minimizing energy consumption. The multi-channel problems such as multi-channel hidden terminal problem, deafness problem, and broadcast support depend on the underlying MAC protocol which is not specified.

(c) KoN-MAC: A MAC protocol (KoN-MAC) for CRSN is proposed in [53]. Nodes are clustered using a simple clustering algorithm from [32]. For intra-cluster communication, cluster members (CM) only communicate with the cluster head (CH) and inter-cluster communication is made through gateways. The proposed protocol contains the following phases: channel sense and selection phase (CSSP), channel schedule phase (CSP), data transmission phase (DTP), and the sleep phase (SP). Channel weight is defined to measure the channel condition. Channel weight increases when a channel is sensed idle in CSSP or when a successful data transmission is made over that channel in DTP. Channel weight decreases when a channel is sensed busy in CSSP or when collisions occur in DTP.

In the CSP, CH allocates channels and time slots for CMs such that to guarantee collisions free intra-cluster data transmissions. Since in the cluster-based structure two-hop neighbors are either within the same cluster or in adjacent clusters, adjacent clusters try to assign different channels to mitigate the multi-channel hidden terminal problem according to the channel weights.

KoN-MAC is evaluated by simulations using NS-2. Its performance is compared with traditional multi-channel MAC protocol CR-COM which is transformed from [54] by adding an additional channel sensing process. Simulation results show that KoN-MAC achieves better throughput, less delay, and lower packet loss.

KoN-MAC proposes a cluster based MAC protocol to reduce collisions and the hidden terminal problem for CRSN. The communication between gateways, i.e. inter-cluster communication, is not addressed. Since two gateway nodes belong to different clusters, they are most likely assigned different channels, and therefore a coordination mechanism is need for a successful communication.

(d) CogLEACH: CogLEACH [57] is a probabilistic clustering algorithm which uses the number of sensed idle channels as a metric in choosing CHs. A node with more sensed idle channels has a higher probability to become a CH. The cluster formation starts by CHs broadcasting their sensed idle channel list. If a node has one or more common channels with a CH, then it replies with a tentative join request message containing its idle channels and ID. CHs decide a final communication channel based on the received channel lists from non-CH nodes. The channel sensed available by most nodes is chosen as the communication channel. Cluster communication is performed on the common control channel.

With the assumption that all nodes share spectrum similarity, a node is able to identify itself as a CH in a decentralized manner, otherwise, CogLEACH has to be performed in a centralized manner. In CogLEACH, intra-cluster communication uses a collision free TDMA schedule calculated by the CH. CogLEACH is compared with the single channel protocol LEACH [58] through simulations. The results show that CogLEACH achieves better throughput and longer lifetime.

In CogLEACH, member nodes transmit data to CHs on the assigned time slots and channels, thus CogLEACH is considered to be a single node channel assignment approach. Once the communication channel is determined, the media access follows a single channel schedule, thus collision-free communication can be achieved. In CogLEACH, CMs only transmit to the corresponding CH, therefore broadcast is not supported since CMs are set on different channels. This schedule-based protocol is not affected by the hidden terminal and deafness problems associated with carrier sensing. The inter-cluster communication is not addressed in this approach. This is more challenging since inter-cluster communication requires channel coordination between CHs as well as a schedule which efficiently addresses both inter- and intra-cluster communication.

Among the node based channel assignment approaches discussed above, [25] and [26] address the channel assignment problem alone. They both aim to achieve energy efficiency. [25] selects channels to balance the residual energy of sensors, while [26] focuses on designing a stopping rule of the sensing process such that to minimize the energy spent on spectrum sensing. KoN-MAC and CogLEACH are joint channel assignment and medium access control protocols. They both address medium access in order to achieve collision-free transmissions. However, KoN-MAC is mainly designed for duty-cycled WSNs with sleeping phases. WSN applications supported do not usually have strict restrictions on delivery delay, thus cognitive radio wireless networks do not necessarily outperforms conventional WSNs.

3.2. Network wide channel assignment approaches

In CRSN, SUs are required to vacate the spectrum when a PU starts transmission on the same channel. When a PU transmission affects a certain area of a WSN, nodes originally transmitting on that channel either switches to another available channel or suspend transmission. This causes disconnection and network partition. Robust topology maintains connectivity in the presence of PU. This is an important property in CRSNs. Few works have been proposed to address topology control in WSNs.

(a) Grid-CA: A gird based channel assignment Grid-CA for CRSN is proposed in [27]. The channel assignment aims to provide a robust topology control and the network wide connectivity is ensured with the presence of a primary user. The network is divided into girds with cell size equal to $r/\sqrt{5}$ where r is the communication range of the senor nodes. In this way any two sensors in neighboring cells are one-hop neighbors. Each cell locally elects a representative based on the residual energy. Nodes in a cell forward data to the representative who routes data between cells. Nodes are equipped with Q radios and there are C channels available. The paper discusses in detail the case Q = 2 and C = 4.

The network is modeled as an undirected graph with the set of vertices being the set of sensors and an edge exists between two nodes if they are within each other's communication range. The graph is denoted by $G_A(V, E_A)$, where

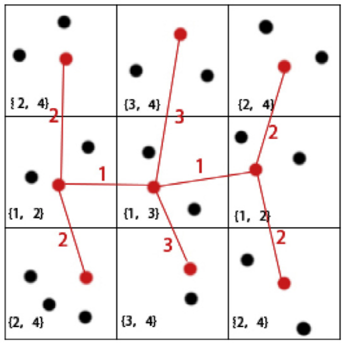
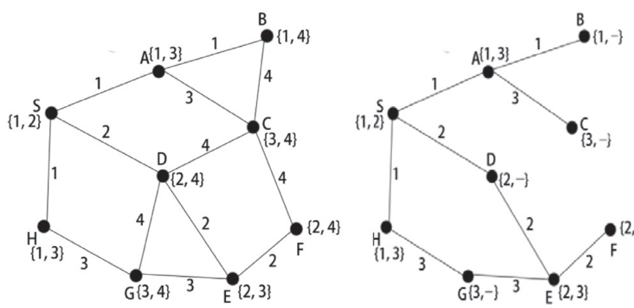


Fig. 7. Channel assignment when channel 4 is occupied by a PU.



a. Example of Channel Assignment   b. Resulting Topology when d by a PU

Fig. 8. Channel assignment example.

$E_A = \{(u, v, c) : (u, v) \in E \text{ and } c \in A(u) \cap^{A}(v)\}$ and $A(u)$ is the set of channels assigned to a node u. The channel assignment A is performed such that G_A remains connected if any channel c is reclaimed by a PU. A secondary objective is to reduce network interference. At the beginning of channel assignment, each sensor computes the grid $cell_{i,\,j}$ it belongs to based on its location. Assume that the available channels are {1, 2, 3, 4}. The static channel assignment is illustrated in Fig. 7. Fig. 7a illustrates the channel used for inter-cell communication. For example, all nodes in $cell_{2,\,2}$ are assigning their radios to the channels {1, 3}. The representative in $cell_{2,\,2}$ uses the channel 1 to communicate with the representatives in left and right adjacent cells and uses the channel 3 to communicate with the representatives in adjacent cells above and below. Also the channel 1 is used for intra-cell communication. Fig. 7b shows the channel assignment for intra-cell communication. Adjacent cells are using different channels for intra-cell communication so that the interference is minimized. Fig. 8 shows that the network is connected when one of the channels, channel 4, is reclaimed by a PU.

The performance of the Grid-CA is evaluated through simulations using NS-3. Packet delivery ratio, end to end delay, and throughput are evaluated based on different PU interference ranges. It is showed that Grid-CA outperforms the case when nodes have single-radio single-channel.

(b) Distributed-CA: The grid-based mechanism proposed in [27] provides a robust topology control with low overhead. Another distributed channel assignment scheme (Distributed-CA) is proposed in [28]. The network model and assumptions are the same as in [27]. The mechanism has two phases. In phase 1, neighbor nodes' ID and hop count to the sink are obtained by each node. The channel assignment is performed in phase 2 based on the information obtained in phase1.

In phase 1, each node broadcasts a *HELLO* message containing its *ID*. These messages are transmitted on a common channel. Nodes receive the *HELLO* message from the sink resend another *HELLO* message including its neighbor table, so that the sink has its 2-hop neighbor information. After this, the sink broadcast a *Hops* message containing a parameter *hops* - the number of hops from the sink. When a node receives the *Hops* message for the first time, it increments the value of *hops* by 1 and rebroadcasts it. When a node receives another *Hops* message and the value of *hops* is less than its current value, it updates *hops* and retransmits the *Hops* message. Otherwise, the *Hops* message is dropped. At the end of phase 1, each node obtains its hop count to the sink.

The channel assignment mechanism starts from the sink. First the sink assigns channels to cycles of length 4, computed using depth-first search, starting from the sink, such that all the available channels are used and interference is minimized. For each cycle connected to the sink, the sink assigns the channel so that each pair of neighboring nodes communicates on a different channel and all four channels are used. An example is shown in Fig. 8a where the sink computes the channel assignment for 2 cycles: (S, A, C, D), (S, D, G, H). The list of channel assignment is then broadcasted to its 2-hop neighborhood via a *SinkLNChannelSet* message. Nodes receiving the message set their channels accordingly and broadcast a *ChannelSet* message containing their channels to their 1-hop neighbors.

The unassigned nodes set a timer that is proportional to the hop count to the sink. When the time expires, it examines all the *ChannelSet* messages received and assigns its radios to the two least used channels among the channels received from the *ChannelSet* messages. The assignment is then broadcasted to its 1-hop neighbors. For example the node B knows the channels assigned by A and C and selects the two least used channels {1, 4}. Fig. 8b shows the robustness of the topology. When channel 4 is no longer available due to a PU, the networks is still connected.

Distributed-CA algorithm is evaluated through simulations using NS-3 and packet delivery ratio, end to end delay, and throughput are measured. The performance of Distributed-CA is compared with Grid-CA. Results show that the Distributed-CA has higher throughput and delivery ratio than the Grid-CA mechanism.

The approaches proposed in [27,28] assign channel with small overhead which is suitable for WSNs. Once the channels are assigned, the communication between neighboring nodes is actually single channel communication. Broadcast is supported by sending packets on all radios. Main drawbacks are in the assumption that sensor devices are equipped with multiple radios and knowing the channels prior to executing the channel assignment mechanism. Also, a change in the set of available channels requires an additional broadcast by the sink with the new channel set in [27] and a new execution of the channel assignment algorithm in [28].

(c) CNOR: Some of the CRSN approaches are combining the routing algorithm with channel assignment mechanism. An opportunistic routing algorithm (CNOR) is proposed in [29]. There are four types of packets: Request To Send (RTS), Clear To Send (CTS), DATA, and ACK. When a node t has a packet to transmit, it first senses the medium for available channels. If there is an available channel, then the node broadcasts a RTS over that channel. When the neighbor node n receives the RTS packet, it replies with a CTS after a time $T_{Backoff}$. The time $T_{Backoff}$ is inverse proportional to $D_{t,\,d} - D_{n,\,d}$, where $D_{t,\,d}$ is the distance from the node t to destination d and $D_{n,\,d}$ is the distance from the node n to destination d. In this way neighbor nodes closer to the destination have a smaller backoff time. Node t transmits the data packet to the first neighbor node replying CTS and waits for a time T_{ACK} to receive an ACK message. If no ACK is received, the node t retransmits the data packet. When a node sends out a RTS and no CTS is received after a time T_{RTS}, the node rebroadcasts the RTS.

CNOR is evaluated through simulations using OMNeT++. Simulation results show that CNOR outperforms traditional routing and opportunistic routing in terms of energy consumption, throughput, and average end-to-end delay.

In this approach the routing path changes dynamically according to network conditions and data packets follow different paths toward the destination. However, network connectivity is not guaranteed. When a node does not receive CTS after sending a RTS, it is possible that no neighbor node is operating on that channel. One intuitive way to improve communication is to retransmit RTS on a different channel and wait for CTS. This will increase the overall overhead. It is not specified in the paper which MAC protocol is used. It is clear that a CSMA-based protocol should be used rather than a schedule-based protocol. The multi-channel hidden terminal and deafness problems are not addressed. Broadcast can be implemented by sending the packet to all nodes, following the same strategy used for unicast, however there is no guarantee of delivery success.

(d) SEA-OR: Another opportunistic channel assignment SEA-OR is proposed in [59]. Channel allocation is done at the routing layer in an opportunistic manner and it aims to enhance network lifetime and delivery ratio. When a node has to transmit a packet, it broadcasts a RTS packet on a sensed available channel. Nodes receiving the RTS reply with CTS after a backoff time. The backoff time is calculated such that a node with more residual energy and less distance to the sink replies first. The sender forwards the packet to the node that replied first.

The performance of SEA-OR is evaluated through simulations and compared with traditional geographic routing. Results show that SEA-OR achieves longer network life time and better delivery ratio. SEA-OR has similar drawback as CNOR. SEA-OR is guaranteed to work only if the radio can operate on different channels simultaneously which is usually not the case. If a transmitting node broadcasts RTS on its sensed available channel and no neighbor node is operating on that channel, then the transmitting node is not able to forward the packet.

(e) PUawareRMA: PUawareRMA [33] proposes a distributed algorithm used by sensor nodes to reconfigure their radios according to some predefined radio-modes, such that the resulting topology is connected to the sink and is robust to the presence of a PU. PUawareRMA constructs multiple overlapping topologies accounting for the fact that different radio-modes are characterized by different transmission ranges and different data rates. Each sensor node is assigned a primary radio-mode (*prm*) and a backup radio mode (*brm*). The sink switches to the *brm* when a PU is present on the *prm*.

The sink is equipped with multiple radios and each sensor node is equipped with a single radio. Initially all nodes communicate on the radio-mode with the smallest transmission range. The sink assigns radio-modes to its 1-hop neighbor sensors with the objective of balancing the number of nodes using each radio-mode as well as minimizing the interference, by assigning neighboring nodes to different frequencies. All other nodes assign their radio-modes in increasing order of their distance to the sink. A node selects its *prm* from the *prm* advertised by neighbors that are closer to the sink, and with a higher probability will select a *prm* with higher data rate. The “switch distance” of a node is defined as the number of ancestors that have to switch from *prm* to *brm* in order to avoid network partition. A node chooses its *brm* such that to minimize its switch distance. If a node u has a neighbor v with $u.prm \neq v.prm$, then u assigns its *brm* to *v.prm*.

After the radio-mode assignment, all nodes switch to their *prm* to transmit data. If a PU claims a channel, then all nodes with the *prm* on the same channel will switch to *brm* while the topology is still connected.

PUawareRMA algorithm is evaluated through simulations using NS-3. The performance metrics considered are packet delivery ratio, end to end delay, and throughput. PUawareRMA is compared with RMA [60], a channel assignment algorithm which does not address the PU interference. PUawareRMA achieves better delivery ratio and throughput in the presence of a PU. PUawareRMA provides a low overhead robust topology for CRSN and any routing protocol can be applied in the data gathering phase. The channel switching is also minimized. Since the protocol partitions the network into sub-trees transmitting on different channels using the convergecast communication model, packets are only forwarded to the parent node within the same sub-tree. Communication between neighboring nodes in the same sub-tree is actually single channel communication. Broadcasting in this approach can only be initiated by the sink node. The major drawback of this approach is that the case when multiple channels are reclaimed by PUs is not addressed in this paper.

(f) CRSN hybrid MAC: [61] proposes a hybrid MAC protocol for CRSN based on a two-level cluster architecture. The network is organized into clusters and each cluster is equipped with a cognitive radio based cluster head (CR-CH). Non-CH nodes send data to the corresponding CHs using CSMA/CA over a single ISM channel. Each CH transmits data to the sink directly.

When a CR-CH has packets to send, it first sends a RTS message to the sink requesting a data channel on the control channel. If all channels are sensed busy, then the sink replies with a negative CTS. In this case the CR-CH runs a backoff mechanism and tries again later. Otherwise, the sink assigns a data channel to the CR-CH in the CTS packet. Data transmission is performed on the agreed data channel.

The proposed protocol is implemented on a real sensor testbed. The intra-cluster communication uses a ZigBee transceiver operating on 2.4 GHz ISM band. CR-CHs and the sink are equipped with two MRF49XA RF modules transmitting over 434 MHz and 868 MHz, and one ZigBee module transmitting over the 2.4 GHz band. Packet success and loss rate are evaluated over a relative small network consisting of three clusters.

The proposed protocol assumes the sink and CR-CHs are equipped with multiple radios and one of them constantly listens on the control channel. By doing this, multi-channel hidden terminal and deafness problems can be resolved since a node is able to overhear RTS and CTS messages on the control channel, even when it performs data transmission on another channel. The proposed work assumes CHs are able to transmit packets to the sink directly, which is not practical for large WSNs. Increasing the transmission power of CHs may be a solution to this problem, however, CHs will drain their battery fast, leading to network partitioning.

Among the network wide channel assignment approaches discussed above, Grid-CA, Distributed-CA and PUawareRMA address the channel assignment problem with the objective of ensuring connectivity in the presence of a PU. The medium access and routing mechanisms are not affected. CNOR and SEA-OR are opportunistic approaches that combine channel assignment and routing. The opportunistic approaches are more dynamic and do not require a control channel. CNOR selects a forwarding node closer to the sink, while SEA-OR selects a forwarding node with higher residual energy. However, CNOR and SEA-OR do not guarantee packet delivery even assuming no packet loss at lower layers.

4. Future research challenges

This section highlights some challenges and future research directions.

- Common control channel:
  Except opportunistic approaches which do not guarantee data delivery, most of the channel assignment approaches for CRSN depend on the use of a common control channel. Information exchange and channel negotiation are performed on a common

control channel that is assumed to be available throughout network. However, a dedicated control channel has several drawbacks. First of all, a control channel would get saturated as the number of users increases [62]. Contentions and collisions over the control channel remain unsolved. Second, using a common control channel makes the network vulnerable to attacks. Since all control messages are exchanged over the control channel, a jamming on the control channel leads to network failure. Third, WSNs are usually deployed over large areas and nodes may experience different PU activities. It is not feasible to find a globally available channel unless using a channel from the ISM band. There are only a few works in literature addressing the development of CRSN protocols without using a dedicated common control channel. This topic remains a challenging task for future research.

- Deciding between conventional and cognitive radio based multi-channel approaches:
  Multi-channel approaches using ISM unlicensed bands and mechanisms for cognitive radios using licensed bands are often addressed separately. CRSNs have many advantages as discussed in Section 3. However, cognitive radio hardware is more expensive than traditional transceivers. CRSN also brings challenges such as spectrum sensing and spectrum handoff. It should be noted that CRSNs are suitable for high throughput and delay-sensitive applications. It is not justified for example using cognitive radio networks for duty-cycled sensor networks intended for applications transmitting limited amount of data with no strict restrictions on the delay. The trade-offs have to be carefully analyzed before deciding whether to use cognitive radio based sensor networks.
- Cross layer design:
  Channel assignment is critical to the design of MAC and routing protocols. Very few works are considering all aspects. Especially in CRSNs, many proposed approaches only focus on one aspect of the performance. Cross layer designs that jointly optimize channel assignment, medium access, and routing are worth investigating.
- Energy efficiency:
  Energy efficiency is critical in WSNs since sensors are battery powered with limited energy. There is no comparison between single channel WSNs, multi-channel conventional WSNs and cognitive radio WSNs regarding to energy efficiency. Current research works lack realistic models to estimate power consumption.
- Multiple applications running simultaneously and QoS support:
  QoS is the ability to provide different priority to different applications or data flows, and guarantee a certain level of performance to a data flow. QoS should guarantee a certain bit rate, delay, jitter, and bit error rate. WSNs are mainly used for low-duty cycle and monitoring applications. Recently, multi-channel and cognitive radio approaches enable various QoS demanding applications such as real-time surveillance and target tracking. It is possible to support different applications running simultaneously within the same network. Different applications may require different QoS. In multi-channel approaches, channel usage should be monitored and channels with sufficient capacity should be selected for QoS demanding applications.
- Implementation on real platforms:
  There are a number of conventional multi-channel approaches evaluated on real platforms. However, most of the cognitive radio approaches are evaluated only with simulations. Nowadays, with the occurrence of affordable SDR development platforms, evaluating cognitive radio approaches on real platform is realistic. Many CRSN approaches assume an ON/OFF random process to model PU behavior in simulations. In reality, PU behav-

Table 2
Summary of multi-channel approaches for WSNs.

Protocol	Frequency band	Topology	Channel allocation	Protocol layer	Broadcast support	Implementation	Objective	Evaluation
HyMAC [10]	Unlicensed	Tree-based	Semi-dynamic	MAC	Only with multiple tx	Centralized	Collision-free network	Testbed
TMCP [11]	Unlicensed	Tree-based	Fixed	Network	Within same subtree	Distributed	Enhance data collection rate	Simulation/Testbed
DRCS [12]	Unlicensed	Tree-based	Dynamic	Network	Only with multiple tx	Distributed	Reduce overhearing	Testbed
[30]	Unlicensed	Tree-based	Fixed	N/A	No	Distributed	Reduce overhearing	Simulation
HMC-MAC [31]	Unlicensed	Tree-based	Dynamic	MAC	No	Distributed	Reduce overhearing, collision	Simulation
RMCA-FR [48]	Unlicensed	Tree-based	Semi-Dynamic	Network	No	Distributed	Reduce interference	Simulation
WAVE [37]	Unlicensed	Tree-based	Fixed	Network	No	Centralized	Collision-free network	Simulation
MinMax [55]	Unlicensed	Tree-based	Dynamic	MAC	No	Distributed	Reduce interference	Simulation
[13]	Unlicensed	Cluster-based	Dynamic	MAC	Only within same cluster	Distributed	Improve throughput	Simulation/Testbed
[14]	Unlicensed	Cluster-based	Fixed	MAC	No	Centralized	Reduce interference	Simulation
MCMAC [16]	Unlicensed	Cluster-based	Semi-dynamic	MAC	No	Centralized	Reduce interference	Simulation
[17]	Unlicensed	Cluster-based	Fixed	N/A	Only within same cluster	Distributed	Reduce energy consumption	Simulation
MMSN [19]	Unlicensed	Node-based	Semi-dynamic	MAC	Yes	Distributed	Increase parallel transmission	Simulation
MC-LMAC [20]	Unlicensed	Node-based	Semi-dynamic	MAC	Yes	Distributed	Reduce interference	Simulation
Y-MAC [22]	Unlicensed	Node-based	Dynamic	MAC	Yes	Distributed	Alleviate collisions	Testbed
MCAS-MAC [50]	Unlicensed	Node-based	Dynamic	MAC	No	Distributed	Alleviate collisions/interference	Testbed
[25]	Unlicensed/Licensed	Node-based	Dynamic	MAC	No	Centralized	Energy efficient	Simulation
[26]	Unlicensed/Licensed	Node-based	Dynamic	N/A	N/A	Distributed	Energy efficient	Simulation
KoN-MAC [53]	Unlicensed/Licensed	Cluster-based	Dynamic	MAC	No	Centralized	Alleviate collisions	Simulation
CogLEACH [57]	Unlicensed/Licensed	Cluster-based	Dynamic	MAC	No	Distributed/Centralized	Collision-free network	Simulation
Grid-CA [27]	Unlicensed/Licensed	Grid-based	Fixed	N/A	Yes	Distributed	Robust topology control	Simulation
Distributed-CA [28]	Unlicensed/Licensed	Tree-based	Fixed	N/A	Yes	Distributed	Robust topology control	Simulation
CNOR [29]	Unlicensed/Licensed	Node-based	Dynamic	Network	No	Distributed	Efficient communication	Simulation
SEA-OR [59]	Unlicensed/Licensed	Node-based	Dynamic	Network	No	Distributed	Efficient communication	Simulation
[61]	Unlicensed/Licensed	Cluster-based	Dynamic	MAC	Yes	Distributed	Efficient communication	Testbed
PUawareRMA [33]	Unlicensed/Licensed	Tree-based	Fixed	N/A	Within same subtree	Distributed	Robust topology control	Simulation

ior changes dynamically and it depends on the location, thus evaluation on real platforms is of great importance for CRSNs

5. Conclusions

Utilizing multiple channels in WSNs can alleviate interferences and reduce collisions, thus enhancing the network capacity. Existing approaches incorporate channel assignment to MAC protocols, routing protocols, or address it as a separate topology control problem. In this paper, we categorized and described WSN multi-channel approaches proposed recently in the research literature. We further extended our discussion to the CRSN which is a newly emerging research area. CRSN is a multi-channel WSN utilizing licensed frequencies. The opportunistic access to licensed frequencies enabled by cognitive radio technology brings appealing benefits to WSNs as well as new design challenges due to the unique characteristics of cognitive radios. The approaches discussed in this paper are summarized in Table 2.

References

[1] K. Sohrabi, J. Gao, V. Ailawadhi, G.J. Pottie, Protocols for self-organization of a wireless sensor network, in: IEEE Personal Communications, 2000, pp. 16–27.
[2] “CC2420 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver”, CC2420 data sheet, http://www.ti.com/lit/ds/symlink/cc2420.pdf, last accessed Aug. 2015.
[3] DigiInternationalInc, “XBee multipoint RF modules, embedded RF module family for OEMs” XBee Multipoint RF Modules Data Sheet, http://www.digi.com/pdf/ds_xbeemultipointmodules.pdf, last accessed Aug. 2015.
[4] Crossbow Technology, “MICA2, wireless measurement system”, Mica2 Datasheet, http://www.eol.ucar.edu/isf/facilities/isa/internal/CrossBow/DataSheets/mica2.pdf, last accessed Aug. 2015.
[5] MEMSIC Inc, MICAz, wireless measurement system, Micaz Datasheetlast http://www.memsic.com/userfiles/files/Datasheets/WSN/micaz_datasheet-t.pdf, last accessed Aug. 2015.
[6] Libelium Comunicaciones Distribuidas, Waspmote Technical Report, http://www.libelium.com/downloads/documentation/waspmote_technical_guide.pdf, last accessed Aug. 2015.
[7] Digi International Inc, “XBee® &XBee-Pro® ZB ZigBee, embedded RF module family for OEMs” XBee® &XBee-Pro® ZB data sheet, http://www.adafruit.com/datasheets/ds_xbeezbmodules.pdf, last access Aug. 2015.
[8] Digi International Inc, “XBee-PRO 900 point-to-multipoint embedded RF modules for OEMs”, XBee-PRO 900 Data Sheet, https://www.sparkfun.com/datasheets/Wireless/Zigbee/XBee-900-Datasheet.pdf, last accessed Aug. 2015.
[9] Digi International Inc, “XBee-PRO 868 long-range embedded RF modules for OEMs”, XBee-PRO 868 Data Sheet, http://www.digi.com/pdf/ds_xbeepro868.pdf, last access Aug. 2015.
[10] M. Salajegheh, H. Soroush, A. Kalis, HYMAC: hybrid TDMA/FDMA medium access control protocol for wireless sensor networks, in: IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications, Sep. 2007, pp. 1–5.
[11] Y. Wu, J.A. Stankovic, T. He, S. Lin, Realistic and efficient multi-channel communications in wireless sensor networks, in: The 27th Conference on Computer Communications, Apr. 2008, pp. 1867–1875.
[12] A. Pal, A. Nasipuri, DRCS: a distributed routing and channel selection scheme for multi-channel wireless sensor networks, in: 9th IEEE International Workshop on Pervasive Computing and Communications, Mar. 2013, pp. 602–608.
[13] H.K. Le, D. Henriksson, T. Abdelzaher, A practical multi-channel media access control protocol for wireless sensor networks, in: International Conference on Information Processing in Sensor Networks, Apr. 2008, pp. 70–81.
[14] M. Caccamo, L.Y. Zhang, L. Sha, G. Buttazzo, An implicit prioritized access protocol for wireless sensor networks, in: Proceedings of the 23rd IEEE Real-Time Systems Symposium, 2002, pp. 39–48.
[15] C.L. Liu, J.W. Layland, Scheduling algorithms for multiprogramming in hard real time environment, J. ACM (1973) 40–61.
[16] X. Chen, P. Han, Q. He, S. Tu, Z. Chen, A multi-channel MAC protocol for wireless sensor networks, The Sixth IEEE International Conference on Computer and Information Technology, Sep. 2006 224-224.
[17] A. Gupta, C. Gui, P. Mohapatra, Exploiting multi-channel clustering for power efficiency in sensor networks, in: First International Conference on Communication System Software and Middleware, 2006, pp. 1–10.
[18] P. Gupta, P.R. Kumar, The capacity of wireless networks, in: IEEE Transactions on Information Theory, Mar. 2000, pp. 388–404.
[19] G. Zhou, C. Huang, T. He, J.A. Stankovic, T.F. Abdelzaher, MMSN: multi-frequency media access control for wireless sensor networks, in: 25th IEEE International Conference on Computer Communication, Apr. 2006, pp. 1–13.
[20] O.D. Incel, S. Dulman, P. Jansen, Multi-channel support for dense wireless sensor networking, in: Smart Sensing and Context, Lecture Notes in Computer Science, 2006, pp. 1–14.
[21] L. Hoesel, P. Havinga, A lightweight medium access protocol (LMAC) for wireless sensor networks, in: Proceedings of the 3rdInternational Symposium on Information Processing in Sensor Networks (IPSN), 2004, pp. 55–60.
[22] Y. Kim, H. Shin, H. Cha, Y-MAC: an energy-efficient multi-channel MAC protocol for dense wireless sensor networks, in: International Conference on Information Processing in Sensor Networks, Apr. 2008, pp. 53–63.
[23] S. Pollin, M. Ergen, M. Timmers, A. Dejonghe, L. Perre, F. Catthoor, I. Moerman, A. Bahai, Distributed cognitive coexistence of 802.15.4 with 802.11, in: 1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications, Jun. 2006, pp. 1–5.
[24] O.B. Akan, O. Karli, O. Ergul, Cognitive radio sensor networks, IEEE Netw. (2009) 34–40.
[25] X. Li, D. Wang, J. McNair, J. Chen, Residual energy aware channel assignment in cognitive radio sensor networks, in: Wireless Communications and Networking Conference (WCNC), Mar. 2011, pp. 398–403.
[26] L. Stabellini, Energy-aware channel selection for cognitive wireless sensor networks, in: 7th International Symposium on Wireless Communication Systems (ISWCS), Sep. 2010, pp. 892–896.
[27] M. Cardei, A. Mihnea, Channel assignment in cognitive wireless sensor networks, in: 2014 International Conference on Computing, Networking and Communications (ICNC), Feb. 2014, pp. 588–593.
[28] M. Cardei, A. Mihnea, Distributed protocol for channel assignment in cognitive wireless sensor networks, in: IEEE 32nd International Performance Computing and Communications Conference (IPCCC), Dec. 2013, pp. 1–9.
[29] P. Spachos, P. Chatzimisios, D. Hatzinakos, Cognitive networking with opportunistic routing in wireless sensor networks, in: 2013 IEEE International Conference on Communications (ICC), Jun. 2013, pp. 2433–2437.
[30] S. Roy, N. Darak, A. Nasipuri, A game theoretic approach for channel selection in multi-channel wireless sensor networks, in: 11th Annual High-capacity Optical Networks and Emerging/Enabling Technologies (HONET), Dec. 2014, pp. 145–149.
[31] R. Diab, G. Chalhoub, M. Misson, Enhanced multi-channel MAC protocol for multi-hop wireless sensor networks, in: 2014 IFIP, Wireless Days (WD), Nov. 2014, pp. 1–6.
[32] C.R. Lin, M. Gerla, A distributed architecture for multimedia in dynamic wireless networks, in: IEEE Global Telecommunications Conference (GLOBECOM), Nov. 1995, pp. 1468–1472.
[33] Y. Wu, M. Cardei, Robust topology using reconfigurable radios in wireless sensor networks, in: 10th International Conference on Mobile Ad-hoc and Sensor Networks (MSN), Dec. 2014, pp. 38–45.
[34] A. Rowe, R. Mangharam, R. Rajkumar, FireFly: a time synchronized real–time sensor networking platform, Wireless Ad Hoc Networking: Personal-Area, Local-Area, and the Sensory-Area Networks, CRC Press Book Chapter, Nov. 2006.
[35] Castalia: A Simulator for WSN, https://castalia.forge.nicta.com.au/index.php/en/.
[36] R. Diab, G. Chalhoub, M. Misson, Channel allocation evaluation for a multi--channel MAC protocol, IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Sep. 2013.
[37] R. Soua, P. Minet, E. Livolant, A distributed joint channel and slot assignment for convergecast in wireless sensor networks, in: 2014 6th International Conference on New Technologies, Mobility and Security (NTMS), Apr. 2014, pp. 1–5.
[38] R. Soua, E. Livolant, P. Minet, Adaptive strategy for an optimized collision-free slot assignment in multichannel wireless sensor networks, Journal of Sensor and Actuator Networks, Special Issue on Advances in Sensor Network Operating Systems, Jul. 2013.
[39] R. Soua, P. Minet, E. Livolant, MODESA: an optimized multichannel slot assignment for raw data convergecast in wireless sensor networks, Performance Computing and Communications Conference (IPCCC), Dec. 2012.
[40] J. Hill, D. Culler, Mica: a wireless platform for deeply embedded networks, IEEE Micro. (2002).
[41] G. Halkes, K. Langendoen, Crankshaft: an energy- efficient MAC-protocol for dense wireless sensor network, EWSN07 (2007).
[42] R. Soua, P. Minet, A survey on multichannel assignment protocols in wireless sensor networks, Wireless Days (WD), 2011 IFIP (Oct. 2011) 1–3.
[43] R. Soua, P. Minet, Multichannel assignment protocols in wireless sensor networks: a comprehensive survey, Perv. Mob. Comput. 16 (Part A) (Jan. 2015) 2–21.
[44] O.D. Incel, A survey on multi-channel communication in wireless sensor networks, Elsevier Comput. Netw. 55 (13) (Sep. 2011) 3081–3099.
[45] E. Ahmed, A. Gani, S. Abolfazli, L.J. Yao, S.U. Khan, Channel assignment algorithms in cognitive radio networks: taxonomy, open issues, and challenges, IEEE Commun. Surv. Tut. (Oct. 2014) 1–38.
[46] A. Bachir, M. Dohler, T. Watteyne, K.K. Leung, MAC essentials for wireless sensor networks, IEEE Commun. Surv. Tut. (2010) 222–248.
[47] P. Huang, L. Xiao, S. Soltani, M.W. Mutka, N. Xi, The evolution of MAC protocols in wireless sensor networks: a survey, IEEE Commun. Surv. Tut. (2013) 101–120.
[48] S. Chouikhi, I.E.L. Korbi, Y. Ghamri-Doudane, L.A. Saidane, Routing-based multi-channel allocation with fault recovery for wireless sensor networks, in: 2015 IEEE International Conference on Communications (ICC), Jun. 2015, pp. 6424–6430.
[49] S. Chouikhi, I.E.L. Korbi, Y. Ghamri-Doudane, L.A. Saidane, Fault tolerant multi-channel allocation scheme for wireless sensor networks, in: in proceedings WCNC’14, 2014, pp. 2438–2443.
[50] J.B. Lim, B. Jang, M.L. Sichitiu, MCAS-MAC: A multichannel asynchronous scheduled MAC protocol for wireless sensor networks, Comput. Commun. (Feb. 2015) 98–107.

[51] J.B. Lim, B. Jang, M.L. Sichitiu, AS-MAC: An asynchronous scheduled mac protocol for wireless sensor networks, 5th IEEE International Conference on Mobile Ad Hoc and Sensor Systems, Oct. 2008.
[52] L. Le, E. Hossain, OSA-MAC: a mac protocol for opportunistic spectrum access in cognitive radio networks, in: Wireless Communications and Networking Conference, Mar. 2008, pp. 1426–1430.
[53] Y. Xu, C. Wu, C. He, L. Jiang, A cluster-based energy efficient MAC protocol for multi-hop cognitive radio sensor networks, in: Global Communications Conference (GLOBECOM), Dec. 2012, pp. 537–542.
[54] C. Li, P. Wang, H.H. Chen, M. Guizani, A cluster based on- demand multi-channel mac protocol for wireless multimedia sensor networks, in: IEEE International Conference on Communications (ICC), 2008, pp. 2371–2376.
[55] A. Saifullah, Y. Xu, C. Lu, Y. Chen, Distributed channel allocation protocols for wireless sensor networks, in: IEEE Transactions on Parallel and Distributed Systems, Sep. 2014, pp. 2264–2274.
[56] Q. Yu, J. Chen, Y. Fan, X. Shen, Y. Sun, Multi-channel assignment in wireless sensor networks: a game theoretic approach, in: Proc. IEEE INFOCOM, Mar. 2010, pp. 1–9.
[57] R.M. Eletreby, H.M. Elsayed, M.M. Khairy, CogLEACH: a spectrum aware clustering protocol for cognitive radio sensor networks, in: 9th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), Jun. 2014, pp. 179–184.
[58] W. Heinzelman, A. Chandrakasan, H. Balakrishnan, An application-specific protocol architecture for wireless microsensor networks, in: IEEE Transactions on Wireless Communications, 2002, pp. 660–670.
[59] P. Spachos, D. Hatzinakos, Poster-SEA-OR: spectrum and energy aware opportunistic routing for self-powered wireless sensor networks, in: Proceedings of the 20th annual international conference on Mobile computing and networking, 2014, pp. 429–432.
[60] M. Cardei, Y. Wu, Using reconfigurable radios to increase throughput in wireless sensor networks, in: 10th International Conference on Mobile Ad-hoc and Sensor Networks (MSN), Dec. 2014, pp. 112–119.
[61] H.B. Salameh, M.F. Dhainat, A. Al-Hajji, R. Aqeli, M. Fathi, A two-level cluster-based cognitive radio sensor network: system architecture, hardware design, and distributed protocols, in: 2015 IEEE International Conference on Cloud Engineering (IC2E), Mar. 2015, pp. 287–292.
[62] J. So, N. Vaidya, Multi-channel MAC for ad hoc networks: handling multi-channel hidden terminals using a single transceiver, in: Proc. ACM MobiHoc, 2004.
[63] I.F. Akyildiz, W.Y. Lee, K.R. Chowdhury, CRAHNs: cognitive radio ad hoc networks, Ad Hoc Netw. 7 (5) (Jul. 2009) 810–836.
[64] K.R. Chowdhury, I.F. Akyildiz, Cognitive wireless mesh networks with dynamic spectrum access, IEEE J. Selected Areas Commun. 26 (1) (Jan. 2008) 168–181.