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A Survey of Low Duty Cycle MAC Protocols in Wireless Sensor Networks

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1. Introduction

This chapter examines various important low duty cycle MAC protocols and the two most important MAC protocols designed specifically for cooperative Multiple-Input Multiple-Output (MIMO) transmission. In most cases, the low duty cycle MAC protocols trade off latency for energy efficient operation. Also, we can observe later that asynchronous MAC protocols are more scalable than synchronous MAC protocols.

On the one hand, when sensor nodes join or leave a group or a cluster, the MAC needs to re-synchronise the network over and over in such protocols as LEACH and S-MAC. Frequent re-synchronisation can lead to higher energy consumption. The situation becomes more complex when global synchronisation is required instead of local synchronisation. Thus a balance must be made between frequent synchronisation and scalability in synchronous MAC protocol design. On the other hand, in some cases with asynchronous MAC, the higher scalability comes at the cost of higher transmission energy due to the implementation of a long preamble and overhearing in such protocols as RF Wake-up and B-MAC. However, the burden of long preamble transmission is reduced gradually by the introduction of short packet techniques such in SpeckMAC and X-MAC. Moreover, it is important to note that little attention has been paid to increasing the link reliability in SISO systems. The only mechanism used is the ACK packet feedback in protocols such IEEE 802.15.4 MAC and WiseMAC.

The MIMO-LEACH and $CMAC_{ON}$ protocols provide measures to increase link reliability and at the same time reduce transmission power by exploiting spatial diversity gain. On the one hand, the MIMO-LEACH protocol employs a duty cycle mechanism through TDMA time slots assignments which reduces the total energy consumption. Furthermore, multi-hop communication between cluster heads is introduced to replace the direct communication which reduces further the total energy consumption. Also, collisions can be avoided with the distinct time slot assignment to each sensor node. The benefits come at the cost of higher latency (multi-hop communication). In addition, the scalability issue is not addressed at all.

$CMAC_{ON}$ is more scalable and does not require pre-selection of cooperative nodes. $CMAC_{ON}$ does not suffer from tight synchronisation and overhead of cluster formation. Also, collision avoidance is provided through RTS-CTS signalling. Moreover, an ACK

mechanism is used as a double measure of link reliability. However, we note that all the sensor nodes are always on which makes the issues of idle listening and overhearing still need to be addressed. The $CMAC_{ON}$ protocol should deploy a duty cycle mechanism to reduce further the total energy consumption. Also, circuit energy must be included to get a better picture of the overall energy usage in the network.
The comparative study in this chapter provides a basis for further study to design an improved version of the $CMAC_{ON}$ protocol which employs a low duty cycle mechanism in cooperative MIMO communication. The improved MAC will be evaluated with a set of cooperative MIMO systems in terms of energy efficient operation and its trade-off relationship with packet latency.
The rest of the chapter is organized as follows. The concept of a low duty cycle is introduced in Section 2 to provide a basis of energy efficient MAC operation. We examine state-of-the-art duty cycle MAC protocols in Sections 3 and 4. We classify these protocols into synchronous and asynchronous. In Section 5, we explore existing MAC protocols designed specifically for cooperative Multiple-Input Multiple-Output (MIMO) transmissions. Finally the chapter is concluded in Section 6.

2. Low Duty Cycle Concepts

The basic idea of low duty cycle protocols is to reduce the time a node is idle or spends overhearing an unnecessary activity by putting the node in the sleep state. The most ideal condition of low duty cycle protocols is when a node is a sleep most of the time and wakes up only when to transmit or receive packets. In the literature, the concept of a low duty cycle is represented as a periodic wake-up scheme. A node wakes up periodically to transmit or receive packets from other nodes. Usually after a node wakes up, it listens to the channel for any activity before transmitting or receiving packets. If no packet is to be transmitted or received, the node returns to the sleep state. A whole cycle consisting of a sleep period and a listening period is called a sleep/wake-up period and is depicted in Figure 1.
Duty cycle is measured as the ratio of the listening period length to the wake-up period length which gives an indicator of how long a node spends in the listening period. A small duty cycle means that a node is asleep most of the time in order to avoid idle listening and overhearing. However, a balanced duty cycle size must be achieved in order to avoid higher latency and higher transient energy due to start-up costs.
There are various low duty cycle protocols proposed for WSNs which differ in aspects of synchronisation, the number of channels required, transmitter- or receiver-initiated operation etc. (Karl & Willig, 2007). We categorise the low duty cycle protocols into two major classes: namely synchronous and asynchronous schemes. The concept of synchronisation is related with data exchanges in WSNs (Kuorilehto et al., 2007). In asynchronous schemes, there are two basic approaches, namely transmitter-initiated and receiver-initiated. Using a transmitter-initiated approach, a node sends frequent request packets (preamble, control or even data packet themselves) until one of them "hits" the listening period of the destination node. On the other hand, the receiver-initiated approach is applicable when a node sends frequent packets (preamble, control, acknowledgment) to inform the neighbouring nodes about the willingness of the node to receive packets. The

former approach puts the energy cost on the transmitter while the latter moves the cost to the receiver.
Another variation of low duty cycle protocols is a synchronous scheme where all the nodes in a group or cluster have the same wake-up phase. Usually each node sends frequent beacon frames to inform its neighbours about its wake-up cycle schedule and other information such as pending packets to be transmitted, etc. Thus a node schedules its transmission and reception time from the information obtained from the beacon frames. In another approach, a node becomes a group or cluster head and controls the data communications while maintaining the synchronisation between the nodes in the group or cluster. The former approach is more applicable for a distributed or flat topology while the latter is more applicable for a clustered or centralised topology. However, in both approaches, tight time synchronisation requires frequent resynchronisation with neighbouring nodes consuming a significant amount of energy (Karl & Willig, 2007; Kuorilehto et al., 2007).
In the following sections, we examine both synchronous and asynchronous low duty cycle protocols and compare both types of protocols in terms of four major design requirements, namely energy efficiency, latency, scalability and reliability.

3. Synchronous Low Duty Cycle MAC Protocols

Synchronised low duty cycle MAC protocols are typically equipped with predetermined periodic wake-up schedules for data exchanges which consist of a sleep period T_{sleep} and an active period, T_{active} repeated at T_{wakeup_period} intervals (Kuorilehto et al., 2007). A typical operation of synchronised low duty cycle MAC protocols is shown in Figure 2 where the synchronisation is achieved by means of frequent beacon frames transmissions. A node broadcasts its beacon frames once it enters the active period in order to share its current schedule and status information with its neighbouring nodes. This way, all the nodes can learn their neighbour's schedules and use this knowledge for data communication.
Consider a case when a node has a data packet to be transmitted. The node wakes up at the time of the active period of the destination node and then transmits its data packet. Clearly, we can observe that the operation of data transmission can be done in such a way due to the advanced timing knowledge of the destination node which was obtained from frequent beacon frames transmissions.
Moreover, synchronisation is typically maintained only within a small group or cluster due to the difficulty of global synchronisation in a large scale WSN deployment and also to ensure high scalability. In the following sub-sections, we examine the most important synchronous low duty cycle MAC protocols proposed in the literature which relate closely with the chapter direction.

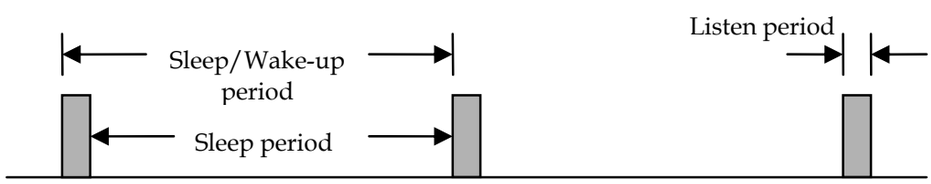


Fig. 1. A periodic wake-up scheme.

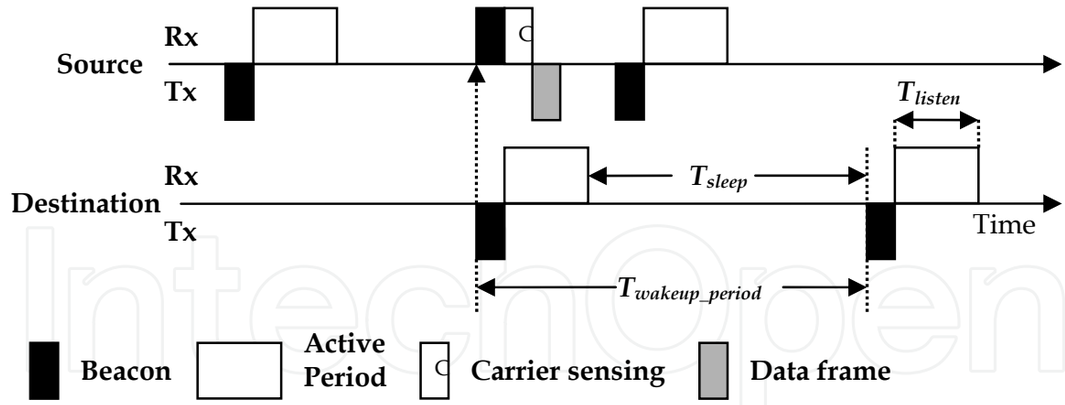


Fig. 2. A synchronous periodic wake-up scheme.

3.1 Power Aware Clustered TDMA (PACT)

Power Aware Clustered Time Division Multiple Access or PACT protocol (Pei & Chien, 2001) was proposed in 2001 for networks with a clustered multi-hop topology. PACT utilises the concept of passive clustering (Gerla et al., 2000) where nodes are allowed to take turns as the communication backbone.

Basically there are three types of nodes in a cluster, namely a cluster head, inter-cluster gateways and ordinary nodes. Gateway nodes are used to exchange traffic between clusters. A simple selection algorithm is used to select the gateway nodes in a cluster which is based on a criterion where a node with the highest number of distinct cluster heads is selected (Kuorilehto et al., 2007). In order to reduce energy consumption within a cluster, the role between cluster heads and gateway nodes is rotated. Furthermore, the duty cycle of each node is adapted to the traffic conditions in the network where the radios are turned off during inactive periods.

3.2 Low-Energy Adaptive Clustering Hierarchy (LEACH)

Low-Energy Adaptive Clustering Hierarchy or LEACH (Heinzelman et al., 2002) is a Time Division Multiple Access (TDMA-based) MAC protocol with clustering features. A network is formed as a star topology in two hierarchical levels as shown in Figure 3. A cluster consists of one cluster head and a number of ordinary nodes. All the ordinary nodes communicate with the cluster head directly. On the other hand, there is a single base station which communicates with all the cluster heads. Direct communication with high transmission power is used in order to ensure the cluster heads can reach the base station.

The LEACH protocol is organised in rounds and each round is subdivided into a setup phase and a steady-state phase. The setup phase begins with the self selection of nodes to become cluster heads. After a node properly sets up as a cluster head, it contends for the channel using a Carrier Sense Multiple Access (CSMA) mechanism and then broadcasts an advertisement packet to its neighbours if the channel is idle. Whenever an ordinary node receives an advertisement packet and in the case of multiple advertisement packets, the node selects a cluster head based on the received signal strength. Next, it contends for the channel using CSMA and sends back an acknowledgment to the selected cluster head in order to join the cluster. Immediately, the cluster head broadcasts a TDMA schedule to its

cluster's members. The cluster is formed completely when all the cluster members are synchronised to the TDMA schedule. The cluster head creates and maintains the TDMA schedule.

The LEACH protocol implements two strategies to ensure energy efficient operation. The first strategy is to shift the total burden of energy consumption of a single cluster head by rotating the assignment of the cluster head to the other members in the cluster. The aim behind this strategy is to distribute evenly the energy usage between the members of the cluster. The second strategy is to switch the ordinary nodes in a cluster into the sleep mode whenever they enter inactive TDMA slots. In this way, we actually create a duty cycle mechanism through the implementation of an active and inactive TDMA time slots schedule. However, high transmission power during direct communication between cluster heads and the base station may dominate the total energy consumption in the network. Furthermore, the fixed clustering structure and the need for global synchronisation make the network not scalable whenever nodes join or leave the network. The condition becomes worse when we consider mobile nodes.

3.3 Self-Organizing Slot Allocation (SRSA)

The Self-Organising Slot Allocation or SRSA protocol (Wu & Biswas, 2005) was proposed to improve the LEACH MAC protocol in terms of energy efficiency and network scalability. The SRSA protocol is a TDMA-based MAC and has a similar network topology as LEACH. The strategy to increase energy efficiency is by utilising multiple base stations instead of only one base station as in the LEACH architecture. Thus, cluster heads can communicate directly with the nearest base station which reduces transmission energy significantly.

Moreover, in order to increase network scalability, SRSA provides local synchronisation where each cluster maintains its own local TDMA MAC frame. The main idea is to initiate communication with a random initial TDMA allocation and then adaptively change the slot allocation schedule locally based on feedback derived from collisions experienced by the local nodes within a cluster (Kuorilehto et al., 2007). Therefore the scalability that is achieved for large networks depends only on local synchronisation within a cluster. However, frequent local synchronisation may consume a significant amount of energy and may dominate the total energy consumption of the network.

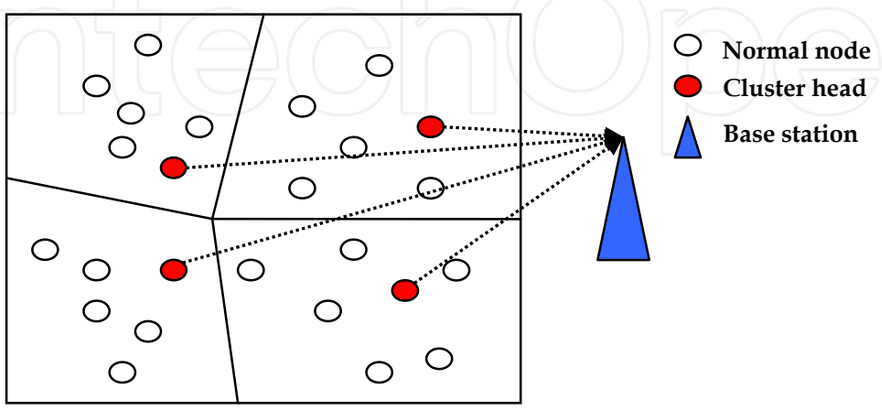


Fig. 3. Clustered LEACH MAC architecture.

3.4 Sensor-MAC (S-MAC)

S-MAC or Sensor MAC (Heidemann et al., 2002) was introduced and uses periodic sleep with virtual cluster features as shown in Figure 4. Basically a network is formed as a flat single-hop topology and S-MAC utilises only one frequency channel for communication.

The active period is fixed at 115 ms and the wake-up period can take up to hundreds of milliseconds. Thus the sleep period is adjustable. Within a cluster, all the nodes are synchronised such that all the nodes can wake up at the same time. The active period is divided into three phases, SYNC, RTS and CTS. Each phase is divided into time slots and each node uses the CSMA mechanism with random back-off to send its SYNC, RTS and CTS packets to its neighbours and the intended receiver. Also, each node shares and learns the sleep schedule with/from its neighbours. After the SYNC phase, any node that wants to transmit a data packet needs to contend for the channel.

A node listens to the channel and receives an RTS or CTS packet and if it is not the target receiver, it extracts and learns the duration of the data transmission from Network Allocation Vector (NAV), and then it enters the sleep mode. Moreover a node can perform both transmission and reception during the RTS and CTS phases.

The duty cycle mechanism in S-MAC leads to higher latency because a transmitter needs to wait for the next cycle to send its data. In order to reduce the latency, an improved S-MAC was introduced (Heidemann et al., 2004) which adopts an adaptive listening mechanism where nodes with NAV information wake up around the time when data transmission is expected to be finished and the nodes wait for a short time listening for any incoming packets. By introducing this method, the latency is cut in half. However, a significant amount of energy is still wasted when the active part remains idle due to no activity or due to overhearing an unnecessary activity in the network.

3.5 Timeout-MAC (T-MAC)

The T-MAC protocol (Dam & Langendoen, 2003) is a variation of SMAC with an adaptive listening mechanism. The main idea is to adjust or shorten the active period according to the traffic conditions in the network. Thus a node does not need to remain idle for the remaining duration of the active period after the SYNC phase, when there is no activity in the network. Basically, the network is formed as a flat single-hop topology and T-MAC utilises only one frequency channel for communication.

After the CTS phase and each received frame, a node waits for a short period of time which defines a timeout window. If no activity is detected, after the timeout the node enters the sleep mode. As observed in (Dam & Langendoen, 2003), T-MAC uses one-fifth of the power consumption of S-MAC. However, this method increases the latency, although the energy is reduced dramatically. Moreover T-MAC is not suitable for high load networks when we consider a lower latency requirement and also a short active period reduces the ability of T-MAC to adapt to changing network conditions.

3.6 Traffic-Adaptive Medium Access (TRAMA)

The Traffic-Adaptive Medium Access or TRAMA protocol (Rajendran et al., 2003) is a TDMA-based MAC with a flat-based network topology. The basic operation of the TRAMA protocol is to create and maintain a TDMA schedule for each node with its neighbouring nodes within the range of two hops from each node. Basically, sensor nodes share a list of

node identifiers from a two-hop neighbourhood and then they exchange their schedules. The strategy to provide energy efficient operation is by implementing a duty cycle mechanism where the node goes to sleep when it enters inactive time slots. The knowledge of active and inactive timeslots is provided during the exchange of the nodes schedules. Moreover, the active timeslots can be adjusted according to traffic patterns in the network thus providing an adaptive duty cycle mechanism. However, the latency gets higher as the load gets higher in the network.

3.7 DMAC

The DMAC protocol (Lu et al., 2004) was proposed with the objective to provide energy efficient operation with low latency requirements. The network for DMAC is structured as a tree-based data gathering architecture where each node is equipped with a different duty cycle schedule according to the level of deepness in the tree structure. Thus nodes at the same depth in the tree have the same duty cycle schedule. Consequently, the nodes at the lowest level have the longest sleep period. Channel access is performed through CSMA and DMAC utilises only one frequency channel for communication. The DMAC protocol is energy efficient for low load; however it suffers higher latency when the load gets higher due to congestion at intermediate nodes.

3.8 IEEE 802.15.4 MAC

The Institute of Electrical and Electronics Engineers (IEEE) released the 802.15.4 MAC standard (IEEE Standard, 2006) for wireless personal area networks (WPANs) equipped with a duty cycle mechanism where the size of active and inactive parts can be adjustable during the PAN formation. The IEEE 802.15.4 MAC combines both the schedule-based and contention-based protocols and supports two network topologies, star and peer-to-peer as shown in Figure 5.

Basically, there are two special types of peer-to-peer topology (Kohvakka et al., 2006). The first type is known as a cluster-tree network which has been used extensively in ZigBee (Zigbee Alliance, 2004). The other type is known as a mesh network which has been used extensively in IEEE 802.15 WPAN Task Group 5 (TG5) (IEEE Standard, 2008).

The standard defines two types of nodes namely the Full Function Device (FFD) and Reduced Function Device (RFD). The FFD node can operate with three different roles as a PAN coordinator, a coordinator and a device while RFD can operate only as a device. The devices must be associated with a coordinator in all network conditions. The multiple coordinators can either operate in a peer-to-peer topology or star topology with a coordinator becoming the PAN coordinator.

The star topology is more suitable for delay critical applications and small network coverage while the peer-to-peer topology is more applicable for large networks with multi-hop requirements at the cost of higher network latency. Furthermore, the standard defines two modes on how data exchanges should be done, namely, the beacon mode and the non-beacon mode. The beacon mode provides networks with synchronisation measures while the non-beacon mode provides the asynchronous features to networks.

The beacon mode of IEEE 802.15.4 MAC defines a superframe structure to organise the channel access and data exchanges. The superframe structure is shown in Figure 6 with two main periods; the active period and inactive period. The active period is divided into 16

time slots. Typically the beacon frame is transmitted in the first time slot and it is followed by two other parts, Contention Access Period (CAP) and Contention-Free Period (CFP) which utilise the remaining time slots. The CFP part is also known as Guaranteed Time Slots (GTS) and can utilise up to 7 time slots.

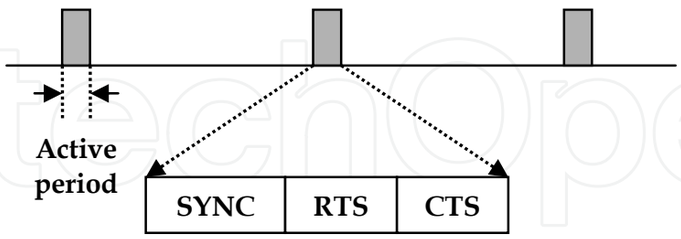


Fig. 4. S-MAC synchronous periodic wake-up scheme.

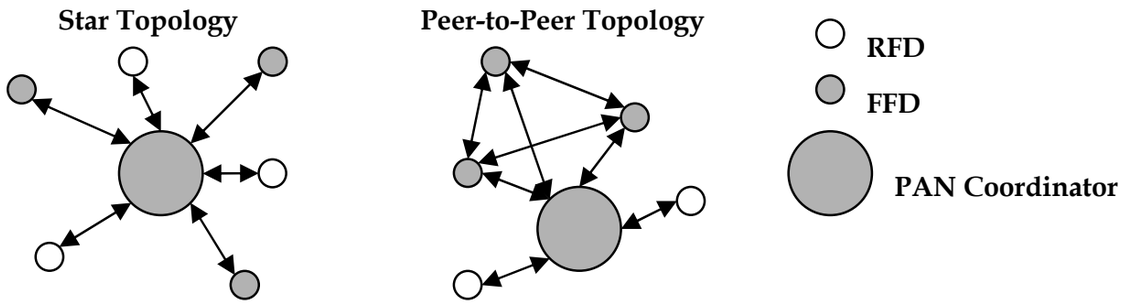


Fig. 5. Topology configurations supported by IEEE 802.15.4 standard.

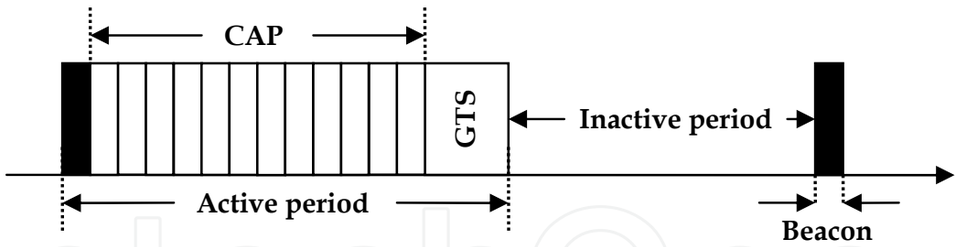


Fig. 6. Superframe structure in beaconed mode IEEE 802.15.4 MAC.

The length of the active and inactive periods as well as the length of a single time slot are configurable and traffic dependant. Data transmissions can occur either in CAP or GTS. In CAP, data communication is achieved by using slotted CSMA-CA while in GTS nodes are allocated fixed time slots for data communication.

The strategy to achieve energy efficient operations in IEEE 802.15.4 MAC is by putting the nodes to sleep during the inactive period and when there is neither data to be transmitted nor any data to be fetched from the coordinator. However, the burden of energy cost is put on the coordinator where the coordinator has to be active during the entire active period.

3.9 Zebra MAC (Z-MAC)

The Z-MAC (Rhee et al., 2005) protocol combines CSMA and TDMA advantages. The network is formed as a flat multi-hop topology. Nodes must be fixed in their locations. The setup phase is the most crucial part with neighbour discovery, local frame exchange of neighbours' lists and slots assignment. All the nodes are synchronised with a global time synchronisation feature. Each node is assigned a slot but it is not fixed. Any node can contend for the channel within any slot for data transmission but the assigned node will get the highest priority.

In a high contention situation, the slots assignment is enforced to reduce collisions. Any data transmission is preceded with a long preamble to increase the probability of hitting the receiver's active period. Z-MAC experiences high latency together with high transmission power for long preamble transmission. Also, all the nodes need to be fixed which limits the network scalability. If new nodes join the network, the setup phase needs to be repeated over and over.

4. Asynchronous Low Duty Cycle MAC Protocols

Unlike the synchronous case, asynchronous low duty cycle MAC protocols do not provide prior knowledge about the global or local timing information and schedules to the nodes in a network to assist with data communications. Thus the nodes do not need to remember the schedules of its neighbours which significantly reduce the usage of memory and energy cost due to schedule sharing between the nodes.

Asynchronous low duty cycle MAC provides a frequent channel sampling mechanism for detecting possible starting transmissions in the network. In the literature, the frequent channel sampling at the receiver is also known as a low power listening (LPL) mechanism. The concept of preamble packet transmission is used in order to hit the intended destination node. When the destination receives the preamble packet, it waits for the data to be transmitted. The transmission of a preamble packet is one of the examples of transmitter-initiated approach in asynchronous WSNs. However, the long preamble packet size contributes to higher transmission energy in the network. Other approaches such as receiver-initiated and redundant transmission of preamble packets are explored to reduce the burden on the transmitter. Furthermore, the very frequent channel sampling also can contribute to higher start-up costs where proper measures must be taken to ensure the optimal wake-up period is implemented.

In the following sub-sections, we examine the most important asynchronous low duty cycle MAC protocols proposed in the literature which relate closely with the chapter direction.

4.1 RF Wake-up Protocol

One of the earliest proposed preamble sampling protocols is the RF wake-up scheme (Hill & Culler, 2002). This protocol samples the channel every 4 seconds to check the channel activity. If it detects any activity, it waits for a short period of time for any incoming packets. At the sender side, the data is preceded with a long preamble with CSMA being performed. The size of the preamble packet must be at least the same as the wake-up period size in order to have a chance of hitting the receiver. This type of configuration has achieved a very low duty cycle, below 1% in a dense WSN with 800 nodes (Hill & Culler, 2002). However, this protocol is not suitable for latency-critical networks because of the overhead of long

preamble packet transmission. Clearly, we can observe that latency is traded off with energy efficiency. Also transmission power gets higher when the size of the preamble packet gets longer, thus putting a constraint on the maximum length of the sleep period. Furthermore, the unintended nodes in the vicinity of the sender stay on for the remaining duration of the preamble packet transmission, resulting in the overhearing problem.

4.2 ALOHA with Preamble Sampling

Instead of using CSMA, ALOHA is used with preamble sampling in (El-Hoiydi, 2002a). An ACK packet is transmitted immediately after the data is received correctly. The protocol inherits the advantage of the RF wake-up protocol to reduce the idle listening cost and at the same time provides higher reliability. However, the protocol is not suitable for high contention networks and inherits the latency and overhearing problems from the RF wake-up protocol. Later the same authors improved the protocol by replacing the ALOHA scheme with CSMA and maintaining the ACK mechanism (El-Hoiydi, 2002b). The collision probability is reduced with higher reliability but still the latency and overhearing problems occur.

4.3 Wireless Sensor MAC (WiseMAC)

The Wireless Sensor MAC or WiseMAC protocol (El-Hoiydi et al., 2004) was proposed to reduce the burden of long preamble packet transmission at the sender side and to tackle the high collision probability in previous protocols. WiseMAC defines two types of nodes, the access point and the ordinary sensor nodes. All the ordinary sensor nodes must communicate only with the access point which basically forms a network with a star topology. WiseMAC utilises the same channel access method as the previous protocol where the ALOHA protocol is used before a preamble packet is transmitted. Unlike the previous protocol, only the access point can initiate data transmission which means that collisions can be avoided. Moreover, the access point learns the wake-up schedule of each sensor node where by knowing the schedule, the access point can make the preamble transmission time shorter. This knowledge is obtained from the ACK packet sent back by the sensor nodes after the data packet is received correctly. WiseMAC provides more energy efficient operation than the previous protocols but at the cost of low scalability due to the fixed star topology operation.

4.4 Asynchronous IEEE 802.15.4 MAC

In non-beacon mode, the IEEE 802.15.4 MAC standard defines a wake-up period or a sleep cycle for devices only and the coordinators are always on. Also no GTS mechanism is used which means that the asynchronous IEEE 802.15.4 MAC is a pure contention-based protocol. Data transmission is performed using an un-slotted CSMA-CA mechanism with a single CCA operation. No preamble sampling mechanism is deployed. Data is acknowledged immediately after the successful data reception to ensure reliability. The energy efficient operation is guaranteed for devices through a sleep cycle mechanism. As a comparison, most of the performance evaluation work on the IEEE 802.15.4 standard has suggested that the beacon MAC is more energy efficient than the non-beacon MAC (Kohvakka et al., 2006).

4.5 Berkeley MAC (B-MAC)

(Polastre et al., 2004) introduced B-MAC or Berkeley MAC. The protocol is a variant of CSMA with a preamble sampling mechanism. The preamble sampling is improved with a selective sampling method where only energy above the noise floor is considered as useful. This selective measure makes sure that the receiver is not wasting its energy just for an insignificant channel activity. The channel sampling interval is made adjustable at the receiver side when a significant activity is detected. If the channel is sensed busy and the energy is above the noise floor, the receiver turns on until the data packet is received or timeout occurs.

At the transmitter, CSMA is implemented before data and long preamble packets are transmitted. In order to ensure high reliability, an ACK mechanism can be used with the basic B-MAC operation. Furthermore, RTS-CTS can be implemented in high load networks to reduce the collision problem.

Figure 7 illustrates the basic operation of the B-MAC protocol. B-MAC defines the whole wake-up period of the LPL structure as a check interval, T_i. The check interval consists of two parts, the listen interval and the sleep interval. (Polastre et al., 2004) provides a framework for analysing the operations of B-MAC in a WSN. An analytical model for monitoring applications was developed where the B-MAC's parameters were calculated to optimise the application's overall power consumption. The impact of various application variables such as the check interval, duty cycle and sample rate were considered. Moreover, the authors considered a specific periodic monitoring application for a case of single cell analysis where the sensor data is streamed to a base station.

Although B-MAC is considered for a periodic monitoring application, the authors claim that the protocol is flexible to be realised efficiently with various kinds of applications. Furthermore, a Chipcon CC1000 transceiver was used as the hardware reference due to its low complexity when compared to other transceiver models, such as CC2420 and its primitive operations are given in (Polastre et al., 2004).

The energy model of a sensor node consists of five major consumers: transmitting energy E_{tx}, receiving energy E_{rx}, listening energy E_{listen}, sampling sensor data energy E_{sensor}, and energy of sleeping E_{sleep}. All the modelled energy components are defined in units of millijoules per second, or milliwatts. The total energy, E is given as:

$$E = E_{tx} + E_{rx} + E_{listen} + E_{sensor} + E_{sleep} \tag{1}$$

The energy of sampling sensor data is included in the model which is based on an application deployed by (Mainwaring et al., 2002). The related parameters are given in (Polastre et al., 2004). Each node takes 1100ms (T_{sensor}) to start its sensor, sample and collect data. If the data is sampled every T_s minutes, the sample rate can be given as:

$$r_s = \frac{1}{(T_s \times 60)} \tag{2}$$

The sample rate is chosen based on the application requirements and network conditions. The energy associated with sample data, E_{sensor} is given as:

$$\begin{aligned} T_d &= T_{sensor} \times r_s \\ E_{sensor} &= T_d \cdot c_{sensor} V \end{aligned} \tag{3}$$

where T_d is the frequency of sample data, c_{sensor} is the current consumption during the sample data and V is the supplied voltage.

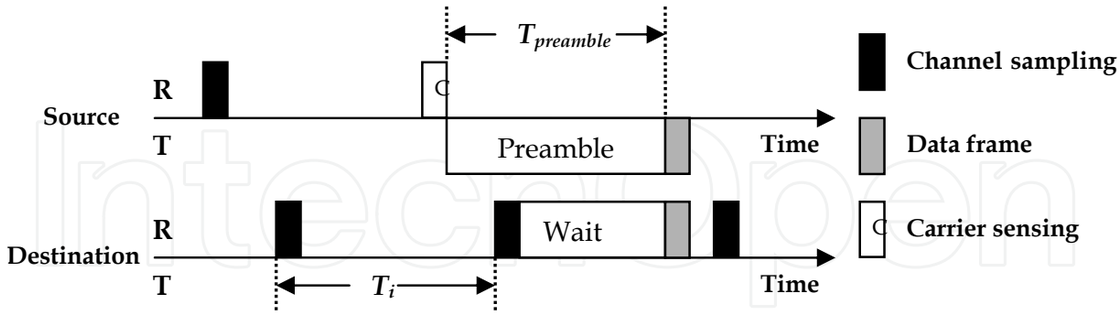


Fig. 7. Basic operation of unsynchronised Berkeley MAC.

The energy consumed during transmissions is simply the length of the preamble packet, $N_{preamble}$ and data packet, N_{data} times the rate the data packets are generated by the application and it is given as:

$$T_{tx} = r_s \times \left(N_{preamble} + N_{data}\right) \cdot T_{txb}$$
$$E_{tx} = T_{tx} \cdot c_{txb} V \tag{4}$$

where T_{tx} is the frequency of packet transmission, c_{txb} is the current consumption when transmitting 1 byte and T_{txb} is the time taken to transmit 1 byte. The receiving energy of a node is modelled as reception of packets from its n neighbours regardless of the packets' destinations. Thus the energy consumed during reception is given as:

$$T_{rx} \le n \cdot r_s \times \left(N_{preamble} + N_{data}\right) \cdot T_{rxb}$$
$$E_{rx} = T_{rx} \cdot c_{rxb} V \tag{5}$$

where T_{rx} is the frequency of packet transmission, c_{rxb} is the current consumption when receiving 1 byte and T_{rxb} is the time taken to receive 1 byte. In order to make sure that the intended receiver receives the transmitted packet, a measure of reliability is implemented with the length of the preamble packet set to be equal or higher than the length of the check interval. Thus we have the constraint:

$$N_{preamble} \ge \left\lceil \frac{T_i}{T_{rxb}} \right\rceil \tag{6}$$

The power consumption of a single LPL CC100 radio sample was measured by the authors and the value is given as E_{sample} = 17.3 μJ. Thus the total energy spent listening to the channel can be defined as the energy of a single channel sample times the channel sample frequency:

$$E_{listen} \le E_{sample} \times \frac{1}{T_i} \tag{7}$$

and the frequency of listening to the channel and the transient time are given as:

$$T_{listen} = \left(T_{rinit} + T_{ron} + T_{rx/tx} + T_{sr}\right) \times \frac{1}{T_i} \tag{8}$$

$$T_{transient} = T_{rinit} + T_{ron} + T_{rx/tx} \tag{9}$$

where T_{rinit} is the time taken to initialise the radio, T_{ron} is the time taken to turn on the radio and its oscillator, $T_{rx/tx}$ is the time taken to switch the radio to the receive mode and T_{sr} is the time taken to sample the channel. The sleep time is defined as the time remaining each second that is not consumed by other operations. Thus the total energy consumed during the sleep time is given as:

$$\begin{aligned} T_{sleep} &= 1 - T_{rx} - T_{tx} - T_d - T_{listen} \\ E_{sleep} &= T_{sleep} \cdot c_{sleep} V \end{aligned} \tag{10}$$

where c_{sleep} is the current consumption when a node is sleep B-MAC provides flexibility to the higher layer by allowing the important parameters to be adjusted, such as the sample rate and the check interval, based on the changing network conditions. However, some trade-off relationships must be considered before any changes take place. For example, increasing the sample rate actually increases the amount of traffic in the network. As a result, each node overhears more packets which leads to the overhearing problem. Moreover, lowering the check interval size can reduce the size of the preamble packet. On the one hand, the burden of long preamble packet transmission can be reduced. On the other hand, the radio is sampled more often which contributes to the increase of transient energy during the start-up period. Clearly, the trade-off relationship must be considered carefully before any changes to the parameters can be made.

4.6 Speck MAC (SpeckMAC)

SpeckMAC (Wong & Arvind, 2006) was introduced as a variation of the B-MAC protocol with the ideas of redundant transmission of short packets and an embedded destination address. The first idea is targeted to reduce the transmission energy and the second idea provides a measure of reducing the significant overhearing problem in heavy traffic conditions. Figure 8 illustrates the basic operation of the SpeckMAC protocol.

Basically there are 2 variants: SpeckMAC-Back-off (SpeckMAC-B) and SpeckMAC-Data (SpeckMAC-D). The first variant, SpeckMAC-B, sends a short wake-up frame preceded by carrier sensing with embedded target destination address and data transmission timing information. Any receiver that wakes up performs selective sampling and after that checks the address field of the received wake-up frame. If the address does not match, it goes to sleep immediately. In the case of matching, it sets its timer to wake up later in order to receive the data packet before going to sleep. The sender transmits the short wake-up frame till the moment the data packet is transmitted.

The problem with this scheme is that the sender wastes its transmission power by still sending the wake-up frames although the receiver has already received this frame. Although the burden at the transmitter is reduced and overhearing at the receiver is eliminated, SpeckMAC-B still inherits the excess latency problem. SpeckMAC-D, on the

other hand, sends the data packet many times which is preceded by carrier sensing until one of the data packet hits the receiver. The method of retransmission of data packets reduces the energy at the receiver but still suffers from excess latency.

A comprehensive comparison study has been done (Wong & Arvind, 2007) between the SpeckMAC variants which is based on different traffic types in terms of energy efficient operation. The results demonstrated that SpeckMAC-D is more energy efficient than SpeckMAC-B when broadcast packets are transmitted. SpeckMAC-B, on the other hand, is more energy efficient when unicast packets are transmitted.

Later, the SpeckMAC Hybrid or SpeckMAC-H protocol (Wong & Arvind, 2007) was proposed combining the advantages of each of the SpeackMAC variants. SpeckMAC-H adopts an adaptive approach where the sender selects which SpeckMAC variant to be used depending on the current traffic type. In this way, the energy consumption can be reduced significantly but the excess latency problem is still not addressed.

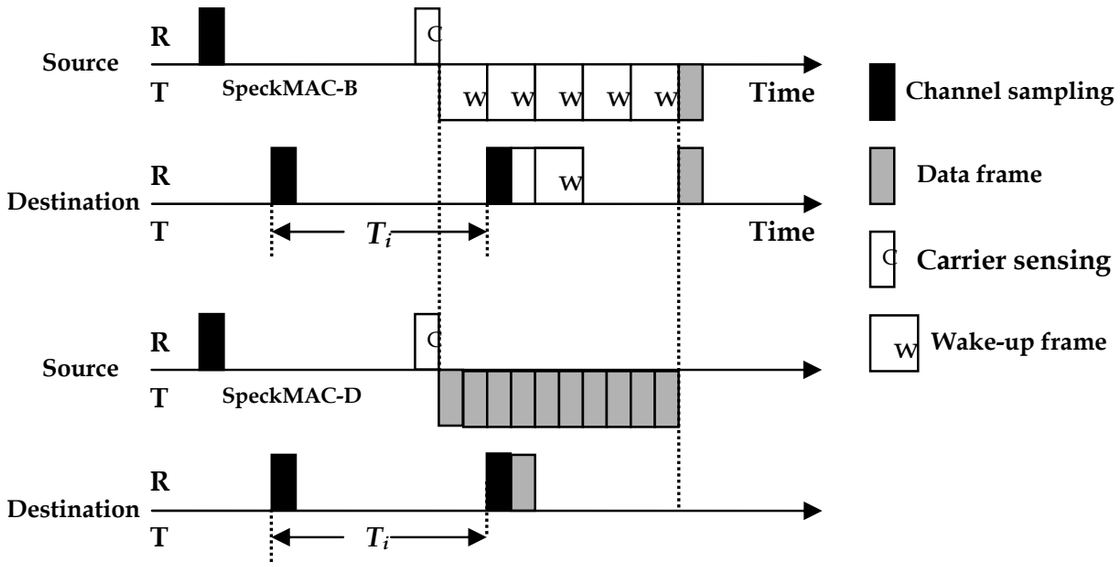


Fig. 8. Basic operation of unsynchronised SpeckMAC.

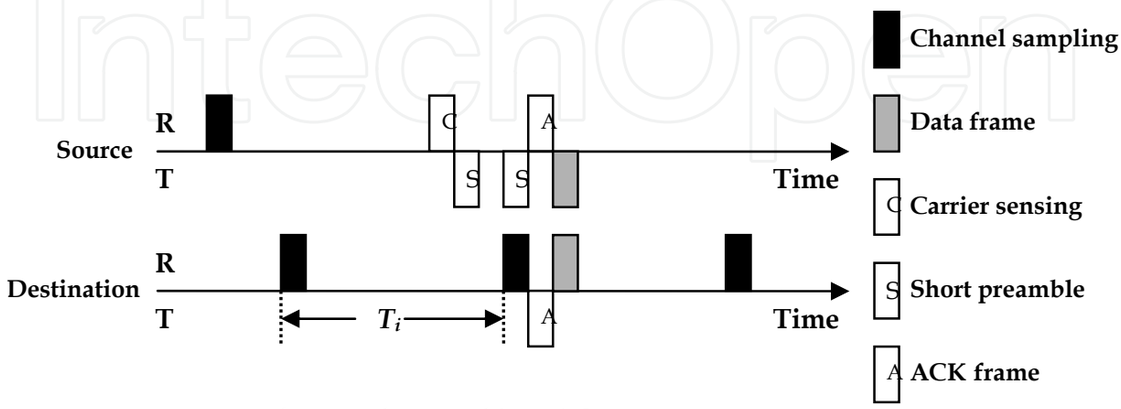


Fig. 9. Basic operation of unsynchronised X-MAC.

4.7 X-MAC

Further work by the X-MAC (Buettner et al., 2006) protocol proposed the use of a series of short preamble packets with the destination address embedded in the packet. Figure 9 illustrates the basic operation of the X-MAC protocol.

The idea of the ACK packet is used here but not after the data packet reception but, instead after the first preamble packet that hits the target receiver's active period. By doing that, the preamble packets transmission can be stopped and the data packet can be transmitted immediately. Also, the size of the preamble packet now can be made very short with redundant transmission of the same packet until the sender gets the ACK packet. Like in the previous protocol, CSMA is performed before the preamble packet is transmitted. After the data packet is received, the receiver waits for a short period to give a chance to any nodes that want to send packets.

The X-MAC protocol provides more energy efficient and lower latency operation by reducing the transmission energy and transmission period burdens, idle listening at the intended receiver and overhearing by the neighbouring nodes. One concern is that the gaps between the series of preamble packets transmission can be mistakenly understood by the other contending nodes as an idle channel and they would start to transmit their own preamble packets which can lead to collision. One solution is to ensure that the length of the gaps must be upper bounded by the length of the listening interval.

5. MAC Protocol for Cooperative MIMO Transmission

As already discussed, all the duty cycle MAC protocols were designed mainly to reduce the total energy consumption by reducing idle listening, overhearing and both transmission and reception energy consumption over a single link. We can observe that most of the protocols traded off latency for energy efficient operation. Also, some of them, such as the IEEE 802.15.4 MAC and the variants of the ALOHA with preamble sampling MAC protocols including CSMA and WiseMAC, provide certain measures to increase the reliability of WSNs with the feedback of the ACK packet. Furthermore, we observed that the asynchronous duty cycle MAC provides higher scalability than the synchronous duty cycle MAC.

To the best of our knowledge, little attention has been paid in the previous duty cycle MAC protocols to consider the impact of deep fading on the total energy consumption. As already discussed in the previous chapters, deep fading contributes to packet errors (if a portion of the packet is affected) or to packet loss (if the whole packet is totally lost). The consequences are severe with a higher retransmission rate and thus higher transmission and reception energy consumption. By utilising the collaborative nature of sensor nodes, the cooperative MIMO scheme provides a higher reliability link than the single link which significantly reduces the retransmission rate. Moreover, the cooperative MIMO scheme exploits the spatial diversity gain and reduces the transmission energy as the number of the transmitting nodes, M, gets higher.

5.1 MIMO-LEACH MAC

Perhaps among the first duty cycle MAC protocols introduced to accommodate cooperative MIMO transmission is the MIMO-LEACH protocol (Yuan et al., 2006) which is an improved version of the original LEACH MAC protocol (Heinzelmann et al., 2002). The cluster-based

MIMO-LEACH protocol is designed with multi-hop routing and incorporates a Space-Time Block Coding (STBC) scheme for inter-cluster communication. Figure 10 shows the architecture of the multi-hop MIMO-LEACH scheme.

In each cluster, a star topology is maintained with the cluster head managing the TDMA schedules for data transmissions. The selection of cooperative nodes is done by the cluster head within each cluster during the cluster formation phase. The selection is based on three major parameters: the remaining energy in the sensor nodes at the moment of measurement, the distance between the sensor nodes to the targeted cluster head and the distance between the sensor nodes and the current cluster head. The selection criterion is defined as the ratio of the remaining energy of a sensor node over the sum of communication energies for both distances. Thus a node with higher remaining energy and lower communication energy for both distances has a higher probability to be selected as one of the cooperative nodes.

When a cluster head has data packet to be transmitted, it broadcasts the data packet to the selected cooperative nodes. Then the cooperative nodes encode the data packet according to STBC and transmit the transmission sequence to the intended cluster head towards the sink. Clearly, in this way, the cost of high transmission power from a cluster head to the base station in original LEACH MAC can be reduced by using the multi-hop and cooperative MIMO transmission strategy. However, the excess latency and scalability issues are not addressed.

5.2 The Always On Cooperative MAC ($CMAC_{ON}$)

In 2007, a MAC with an always on transceiver or $CMAC_{ON}$ protocol was designed to accommodate cooperative MIMO transmission (Yang et al., 2007). Basically, the MAC is a variant of CSMA protocols with RTS-CTS signalling features. The RTS-CTS control packets are used as a measure to avoid collision due to hidden- and exposed-nodes during the cooperative transmission. Also an ACK packet is sent when the data packet is received correctly in order to guarantee reliable communication.

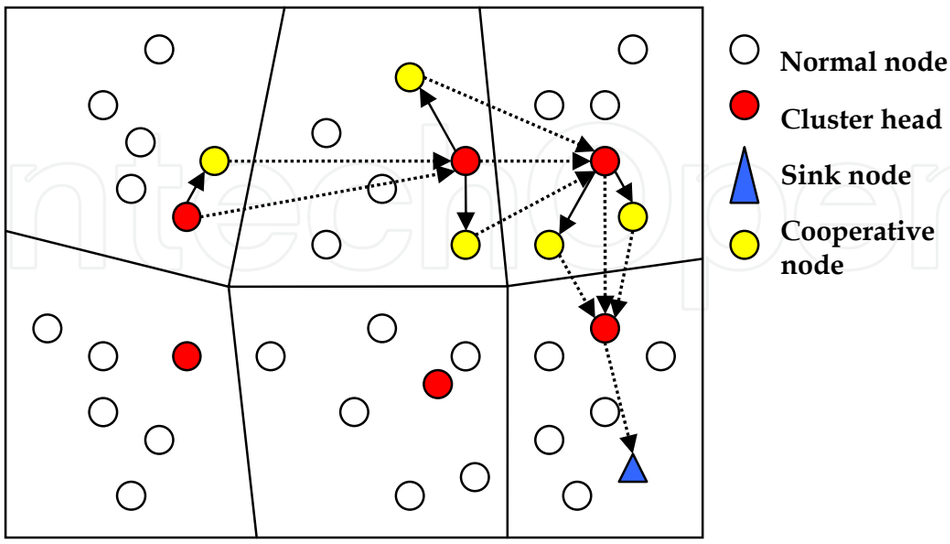


Fig. 10. Multi-hop clustered MIMO-LEACH MAC architecture.

Unlike MIMO-LEACH, the $CMAC_{ON}$ protocol does not provide pre-selection of cooperative nodes prior to data transmission. When a node has a data packet to be transmitted, the node starts to transmit an RTS packet to hit the intended destination. Once received the RTS packet, the destination broadcasts a packet with lower power to recruit its neighbours in order to cooperatively receive the data packet. The destination informs its neighbours about the estimated arrival time of the data packet. Following the broadcast packet, a CTS packet is sent to the source node. When the source node receives the CTS packet, it broadcasts the original data packet to its neighbours with lower power.

Any node within the vicinity of the source node which receives correctly the original data packet with the sending timer information automatically becomes a cooperative transmitting node. When the sending timer expires, all the *M* transmitting nodes send the data packet cooperatively to the *N* cooperatively receiving nodes. Each node in the receiving group receives the data packet and forwards it to the destination. To avoid collision, each receiving group performs CSMA with a random back-off before forwarding the data. The process of forwarding all the packets from the *N*-1 receiving nodes to the destination is denoted as a collection process.

The final decoding is done by the destination with a simple majority decision rule. The destination chooses the highest SNR among multiple received data packets. In case of a tie, the destination will take its own reception as the correct one. The basic operation of the MAC is shown in Figure 11. The algorithms of the $CMAC_{ON}$ protocol are presented in Algorithm 1 to Algorithm 5.

Performance evaluation of the $CMAC_{ON}$ protocol in terms of energy consumption and packet latency was done in (Yang et al., 2007). Performance of the $CMAC_{ON}$ protocol is compared to that of a SISO scheme. The SISO scheme employs RTS-CTS signalling prior to data transmission and feedback ACK to ensure reliability. Also the transceivers of the sensor nodes are always on. For simple notation, we denote the SISO scheme with such a MAC protocol as a SISO always on protocol or $SISO_{ON}$ protocol.

The energy model of a sensor node consists of two parts: successful and unsuccessful transmissions. The authors only consider transmission energy and neglect the impact of circuit energy on the MAC performance. The energy for an unsuccessful transmission attempt is given as:

$$E_u = E_{rts} + E_{Br} + E_{cts} + E_{Bs} + M \cdot E_{data} + (N-1) \cdot E_{col} \tag{11}$$

where E_{rts}, E_{cts}, E_{Bs}, E_{Br}, E_{data} and E_{col} are the energy consumption of RTS, CTS, broadcast packet at the transmitting side (BCASTdata), broadcast packet at the receiving side (BCASTrecv), DATA and collection energies. The energy for a successful transmission attempt is given as:

$$E_s = E_{rts} + E_{Br} + E_{cts} + E_{Bs} + M \cdot E_{data} + (N-1) \cdot E_{col} + E_{ack} \tag{12}$$

where E_{ack} is the energy consumption of ACK packet transmission. We can observe that the unsuccessful attempt occurs with the absence of the ACK packet. The total energy consumption is modelled as a function of the retransmission rate and it is given as:

$$E = \left(\frac{PER}{1 - PER} \right) E_u + E_s \tag{13}$$

where PER is the packet error rate of the cooperative MIMO system. Also the packet latency model consists of two parts: successful and unsuccessful transmission attempts. The duration of a successful transmission attempt is given as:

$$T_s = T_{rts} + T_{cts} + T_{Br} + T_{Bs} + T_{data} + T_{col} + T_{ack} \tag{14}$$

where T_{rts}, T_{cts}, T_{Br}, T_{Bs}, T_{data}, T_{col} and T_{ack} are the time required to send RTS, CTS, broadcast packet at the receiving side, broadcast packet at the transmitting side, DATA and ACK packets. The duration of an unsuccessful transmission attempt is given as:

$$T_u = T_{rts} + T_{cts} + T_{Br} + T_{Bs} + T_{data} + T_{col} + T_{wfack} \tag{15}$$

where T_{wfack} is the duration during which the sender waits for an ACK. The values used for the performance evaluation are given as T_{rts} = 0.353 ms, T_{cts} = 0.305 ms, T_{ack} = 0.32 ms, T_{data} = 6 ms, T_{wfack} = 70 ms, T_{Br} = 0.69 ms, T_{Bs} = 7.7 ms and T_{col} = 22.3 ms.

$CMAC_{ON}$ provides a less complex operation by eliminating the need to pre-select the cooperative nodes compared to the MIMO-LEACH MAC. $CMAC_{ON}$ is more scalable without any need for fixed cluster formation and synchronisation. The cooperative groups are formed when there is a data packet to be sent. Also, a collision avoidance mechanism is provided by RTS-CTS signalling. Furthermore, $CMAC_{ON}$ reduces transmission energy and increases link reliability by the exploitation of the spatial diversity gain when compared to the $SISO_{ON}$ protocol. However, we note that all the sensor nodes are always on which makes the issues of idle listening and overhearing still to be addressed. The $CMAC_{ON}$ protocol should deploy a duty cycle mechanism to reduce further the total energy consumption.

6. Conclusion

This chapter has examined various important low duty cycle MAC protocols and the two most important MAC protocols designed specifically for cooperative MIMO transmission. In most cases, the low duty cycle MAC protocols trade off latency for energy efficient operation. Also, we observed that asynchronous MAC protocols are more scalable than synchronous MAC protocols.

On the one hand, when sensor nodes join or leave a group or a cluster, the MAC needs to re-synchronise the network over and over in such protocols as LEACH and S-MAC. Frequent re-synchronisation can lead to higher energy consumption. The situation becomes more complex when global synchronisation is required instead of local synchronisation. Thus a balance must be made between frequent synchronisation and scalability in synchronous MAC protocol design. On the other hand, in some cases with asynchronous MAC, the higher scalability comes at the cost of higher transmission energy due to the implementation of a long preamble and overhearing in such protocols as RF Wake-up and B-MAC. However, the burden of long preamble transmission is reduced gradually by the introduction of short packet techniques such in SpeckMAC and X-MAC.

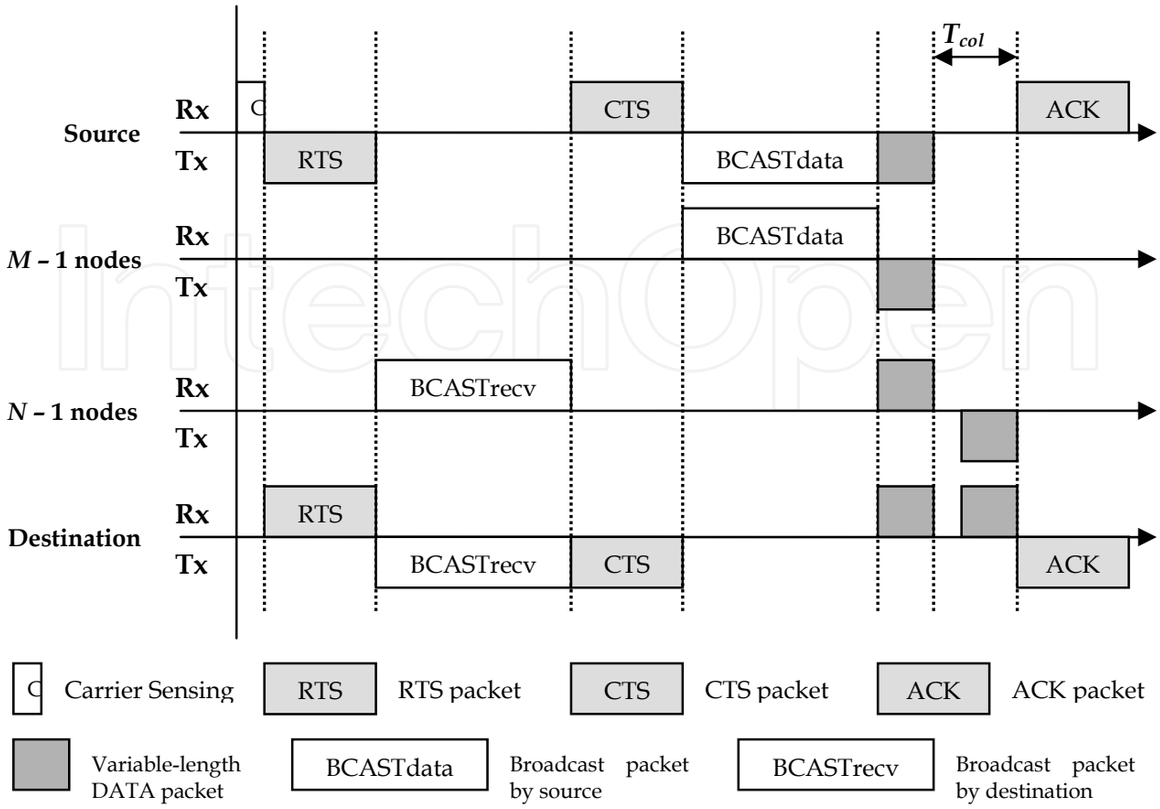


Fig. 11. Basic operation of $CMAC_{ON}$ with *M* transmitting and *N* receiving cooperative nodes.

Moreover, it is important to note that little attention has been paid to increasing the link reliability in SISO systems. The only mechanism used is the ACK packet feedback in protocols such IEEE 802.15.4 MAC and WiseMAC.

The MIMO-LEACH and $CMAC_{ON}$ protocols provide measures to increase link reliability and at the same time reduce transmission power by exploiting spatial diversity gain. On the one hand, the MIMO-LEACH protocol employs a duty cycle mechanism through TDMA time slots assignments which reduces the total energy consumption. Furthermore, multi-hop communication between cluster heads is introduced to replace the direct communication which reduces further the total energy consumption. Also, collisions can be avoided with the distinct time slot assignment to each sensor node. The benefits come at the cost of higher latency (multi-hop communication). In addition, the scalability issue is not addressed at all.

$CMAC_{ON}$ is more scalable and does not require pre-selection of cooperative nodes. $CMAC_{ON}$ does not suffer from tight synchronisation and overhead of cluster formation. Also, collision avoidance is provided through RTS-CTS signalling. Moreover, an ACK mechanism is used as a double measure of link reliability. However, we note that all the sensor nodes are always on which makes the issues of idle listening and overhearing still to be addressed. The $CMAC_{ON}$ protocol should deploy a duty cycle mechanism to reduce further the total energy consumption. Also, circuit energy must be included to get a better picture of the overall energy usage in the network.

Algorithm 1: Cooperative MIMO MAC Protocol

STATE: IDLE node is idle and listens to the channel
if Packet ready to be sent **then**
  go to **algorithm 2**
end if
if receive RTS packet **then**
  go to **algorithm 3**
end if
if receive BCASTdata packet **then**
  go to **algorithm 4**
end if
if receive BCASTrecv packet **then**
  go to **algorithm 5**
end if

Algorithm 2: Node is the source

STATE: RTS node sends RTS packet
if CTS not received **then**
  repeat **STATE: RTS**
end if
STATE: BCASTdata send data to transmitting group with low power, set sending timer
STATE: Data send MIMO data when the timer expires
if receive ACK packet **then**
  go to **STATE: IDLE**
else
  go to **STATE: RTS**
end if

Algorithm 3: Node is the destination

STATE: BCASTrecv broadcast recruiting packet with low power
STATE: CTS send CTS packet
if MISO data received **then**
  go to **STATE: Collection**
else if
  go to **STATE: IDLE**
end if
STATE: Collection set timer to wait for receiving group nodes to send packet
if packet not received correctly **then**
  go to **STATE: IDLE**
end if
STATE: ACK send ACK packet
go to **STATE: IDLE**

Algorithm 4: Cooperative sending node

STATE: Cooperative Sending nodes transmit data packet when sending timer expires
go to **STATE: IDLE** listens for channel activity

Algorithm 5: Cooperative receiving node

STATE: Cooperative Receiving set expiration timer
if MISO data packet received **then**
  go to **STATE: Collection**
else if
  go to **STATE: IDLE**
end if
STATE: Collection send data to destination after random back-off
go to **STATE: IDLE**

7. References

Buettner, M.; Yee, G.; Anderson, E. & Han, R. (2006). X-MAC: A Short Preamble MAC Protocol for Duty-Cycled Wireless Sensor Networks, *Proceedings of ACM Conference on Embedded Networked Sensor Systems (SENSYS)*, Baltimore, Maryland, USA, 2006.

Dam, T.V. & Langendoen, K. (2003). An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks, *Proceedings of ACM Conference on Embedded Networked Sensor Systems (SENSYS)*, Los Angeles, California, USA, 2003.

El-Hoiydi, A. (2002a). Aloha with Preamble Sampling for Sporadic Traffic in Ad-hoc Wireless Sensor Networks, *Proceedings of IEEE International Conference on Communications (ICC)*, New York City, USA, 2004.

El-Hoiydi, A. (2002b). Spatial TDMA and CSMA with Preamble Sampling for Low Power Ad-hoc Wireless Sensor Networks, *Proceedings of IEEE International Symposium on Computers and Communications (ISCC)*, Taromina, Italy, 2002.

El-Hoiydi, A.; Decotignie, J.D. & Hernandez, J. (2004). Low Power MAC Protocols for Infrastructure Wireless Sensor Networks, *Proceedings of European Wireless Conference*, Barcelona, Spain, 2004.

Gerla, M.; Kwon, T. & Pei, G. (2000). On Demand Routing in Large Ad-hoc Wireless Networks with Passive Clustering, *Proceedings of IEEE Wireless Communications and Networking (WCNC)*, Chicago, USA, 2000.

Heinzelman, W.B.; Chandrakasan, A.P.; & Balakrishnan, H. (2002). An Application-specific Protocol Architecture for Wireless Microsensor Network, *IEEE Journal on Wireless Communications,* Vol. 1.

Hill, J. & Culler, D. (2002). A Wireless Platform for Deeply Embedded Networks. *IEEE Journal on Micro,* Vol. 22, pp. 12-24.

IEEE Standard (2006). 802.15.4-2006 IEEE Standard for Information Technology-Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Low Rate Wireless Personal Area Networks (LR-WPANs).

IEEE Standard (2008). IEEE 802.15 Wireless Personal Area Network (WPAN) Task Group 5 (TG5) electronic documents at http://ieee802.org/15/pub/TG5.html, 2008.

Karl, H. & Willig, A. (2007). MAC Protocols, In: *Protocols and Architectures for Wireless Sensor Networks,* pp. 111-148, John Wiley & Sons, 978-0-470-09510-2, West Sussex, England.

Kohvakka, M.; Kuorilehto, M.; Hannikainen, M. & Hamalainen, T.D. (2006). Performance Analysis of IEEE 802.15.4 and Zigbee for Large-scale Wireless Sensor Network Applications, *Proceedings of ACM International Workshop on Performance Evaluation of Wireless Ad hoc, Sensor, and Ubiquitous Networks,*, pp. 1-6, Malaga, Spain, 2006.

Kuorilehto, M.; Kohvakka, M.; Suhonen, J.; Hamalainen, P.; Hannikainen, M. & Hamalainen, T.D. (2007). MAC Protocols, In: *Ultra-Low Energy Wireless Sensor Networks in Practice,* pp. 73-88, John Wiley & Sons, 978-0-470-05786-5, West Sussex, England.

Lu, G.; Krishnamachari, B. & Raghavendra, C.S. (2004). An Adaptive Energy-Efficient and Low-latency MAC for Data Gathering in Wireless Sensor Networks, *Proceedings of Parallel and Distributed Processing Symposium (IPDPS)*, 2004.

Mainwaring, A.; Polastre, J.; Szewczyk, R.; Culler, D. & Anderson, J. (2002). Wireless Sensor Networks for Habitat Monitoring, *Proceedings of ACM International Workshop on Wireless Sensor Networks and Applications*, 2002.

Pei, G. & Chien, C. (2001). Low Power TDMA in Large Wireless Sensor Networks, *Proceedings of IEEE Military Communications Conference (MILCOM)*, Washington DC, USA, 2001.

Polastre, J.; Hill, J. & Culler, D. (2004). Versatile Low Power Media Access for Wireless Sensor Networks, *Proceedings of ACM Conference on Embedded Networked Sensor Systems (SENSYS)*, pp. 95-107, Baltimore, Maryland, USA, November 2004.

Rajendran, V.; Obraczka, K. & Gracia-Luna-Aceves (2003). Energy-efficient, Collision-free Medium Access Control for Wireless Sensor Networks, *Proceedings of International Conference on Embedded Networked Sensor Systems (SenSys)*, Los Angeles, USA, 2003.

Rhee, I.; Warrier, A.; Aia, M. & Min, J. (2005). A Hybrid MAC for Wireless Sensor Networks, *Proceedings of International Conference on Embedded Networked Sensor Systems (SENSYS)*, New York, USA, 2005.

Wong, K.J. & Arvind, D. (2006). Low Power Decentralized MAC Protocols for Low Data Rate Transmissions in Specknets, *Proceedings of ACM International Workshop on Multihop Ad-hoc Networks: From Theory to Reality*, Florence, Italy, 2006.

Wong, K.J. & Arvind, D. (2007). A Hybrid Wakeup Signalling Mechanism for Periodic-Listening MAC Algorithms, *Proceedings of IEEE International Conference on Networking (ICON)*, Adelaide, Australia, 2007.

Wu, T. & Biswas, S. (2005). Low Power TDMA in Large Wireless Sensor Networks, *Proceedings of International Conference on Information Processing in Sensor Networks (IPSN)*, Los Angeles, USA, 2005.

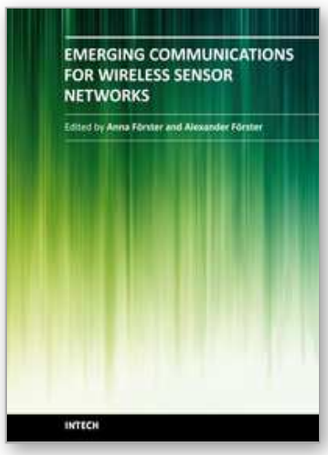
Yang, H.; Shen, H.-Y. & Sikdar, B. (2007). A MAC Protocol for Cooperative MIMO Transmissions in Sensor Networks, *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM)*, pp. 636-640, Washington, USA, 26-30 November 2007.

Ye, W.; Heidemann, J. & Estrin, D. (2002). An Energy-Efficient MAC Protocol for Wireless Sensor Networks, *Proceedings of IEEE Infocomm*, New York, USA, 2002.

Ye, W.; Heidemann, J. & Estrin, D. (2004). Medium Access Control with Coordinated, Adaptive Sleeping for Wireless Sensor Networks, *Transactions of IEEE/ACM on Networking*, 2004.

Yuan, Y.; Chen, M. & Kwon, T. (2006). A Novel Cluster-based Cooperative MIMO Scheme for Multi-hop Wireless Sensor Networks. *EURASIP Journal on Wireless Communications and Networking,* Vol. 2006, pp. 1-9.

Zigbee Alliance Document 053474r06 (2004). Zigbee Specification, Version 1.0, 2004.



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

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