

# **Energy-Efficient Battery-Aware MAC protocol for Wireless Sensor Networks**

by

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# Abstract

Wireless sensor networks suffer from limited power resources. Therefore, managing the energy constraints and exploring new ways to minimize the power consumption during the operation of the nodes are critical issues. Conventional MAC protocols deal with this problem without considering the internal properties of the sensor nodes' batteries. However, recent studies about battery modeling and behaviour showed that the pulsed discharge mechanism and the charge recovery effect may have a significant impact on wireless communication in terms of power saving. In this thesis we propose two battery-aware MAC protocols that take benefit of these factors to save more energy and to prolong the lifetime of the nodes/network without affecting the throughput. In both protocols we measure the remaining battery capacity of the node and use that measurement in the back-off scheme. The first protocol gives the nodes with higher remaining battery capacity more priority to access the medium, while the other one provides more medium access priority to the nodes with lower remaining battery capacity. The objective is to investigate, through simulations, which protocol reduces the power consumption of the nodes, improve the lifetime of the network, and compare the results with the CSMA-CA protocol.

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# List of Acronyms

ACK	Acknowledgment
BAMAC	Battery Aware Medium Access Control
BE	Beacon Exponent
BEL-MAC	Battery-Aware Energy-Efficient Low-Latency Medium Access Control
BO	Beacon Order
BRANS	Battery and Redundancy Aware Node Scheduling protocol
CAP	Contention Access Period
CCA	Clear Channel Assessment
CDMA	Code Division Multiple Access
CFP	Contention Free Period
CR	Communication Request
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear To Send
CW	Contention Window
ECF	Election Control Frame
EMAC	Energy efficient Medium Access Control

FFD	Fully Function Devices
GTS	Guaranteed Time Slots
IP	Internet Protocol
L-MAC	Low-Latency Medium Access Control
LPDM	Low Power Distributed Medium access control
MAC	Medium Access Control
NB	Number of Back-offs
PAMAS	Power Aware Multi Access with Signaling
PAN	Personal Area Network
RF	Radio Frequency
RFD	Reduced Function Devices
RTS	Request To Send
S-MAC	Sensor Medium Access Control
SN-MAC	Sensor Network - Medium Access Control
SO	Superframe Order
STEM	Sparse Topology and Energy Management
TA	Time-out period Activity

TC	Traffic Control
TDMA	Time Division Multiple Access
T-MAC	Timeout Medium Access Protocol
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

# List of notations

$N_i, V_i$	Battery nominal voltage
$T_i$	Battery theoretical voltage
$R_{N_i, T_i}$	Recharge probability function

# Chapter 1 Introduction

## 1.1 Background

Wireless sensor networks (WSNs) are composed of tens to hundreds of small sensory nodes that are able to communicate wirelessly with each other in a multi-hop fashion. WSNs are used to provide a wide range of applications in various fields such as the medical domain, the transportation system, the environmental studies etc. A typical sensor-node device has a small processor to process data and control packets, a memory to save information needed by the node, an RF system that assures the communication with other nodes, and a small battery that represents the main (and most often the only ) source of power.

Designing and developing new effective protocols to overcome the different obstacles presented in the protocol layers has been the focus of the researchers in the past few years. However, how to conserve the power resources to prolong the lifetime of a node (and therefore the lifetime of the network) has always appeared as a big challenge. It is in fact the most important factor that should be taken into account while designing new protocols for WSNs, due to the limited capacity of batteries and the difficulty of frequent battery recharging or replacement in many situations.

Multiple key reasons stand behind the waste of energy in the sensor nodes such as (inspired from [MINE09]):

- The interference: it causes the reception of corrupted packets and the nodes then will waste energy trying to decode it.
- Overhearing: A node, located in the range of another transmitting node, receives packets that seek another destination. The Energy is wasted due to receiving and processing the wrong packets.
- Collision: This is a very common reason. When packets collide, the node has to retransmit them. So the node loses energy in the first transmission, in discarding the remaining of the packets, and in retransmitting them.
- Packet overhead: the lost of energy increases with the increase in the size of the packet overhead
- Idle listening: this is the major cause of energy dissipation, because usually the nodes in the wireless sensor networks spend most of their time in an idle state sensing the medium to check its availability.

A variety of protocols and techniques have been developed from different perspectives to mitigate the effect of these problems. For example, the cross-layer techniques ([FRAN11], [BOUA09]) in which the protocols residing in the different layers share some crucial information of the node, which lead to a better performance in terms of power consumption. Another approach is to reduce the amount of data transmitted by the mean of software-based solutions such as compression and data aggregations. There are also routing solutions based on energy efficient schemes, and others that consider the network topology and the power control such as fine-tuning the transmission power while maintaining network connectivity.

However in this report we focus mainly on schemes developed in the MAC layer protocol due to its particular relevancy to our work.

Most of the existing MAC protocols that try to maximize the lifetime of the WSN are based on switching off the Radio Frequency (RF) system while the node is not operating. All these MAC protocols fall under the title of power-aware protocols. Their basic mechanism is to let the nodes periodically listen to the medium and then sleep, instead of keeping them awake and listening all the time even in the absence of any activity like packets' transmission or reception. Therefore they aim to inactivate the node for a portion of time to save more power and extend its life.

However, these protocols do not take into account the characteristics of the node's battery. Only few studies available in the literature considered tackling the power saving challenge by including the battery's behavior in their MAC protocols.

The majority of the protocols that deal with power conservation in WSNs assume an unrealistic model of a battery. They assume that the battery is an ideal source of energy that drains power in a linear manner. They presume that the discharge of the batteries happens in a constant rate. In other words, they assume that the battery is just defined by a number of charge units and at every transmission of a packet a constant number of charges will be taken out. However, in a realistic situation, the battery behaviour is more complicated, the discharge process is nonlinear, and many other factors affect its operation.

Studying in depth the properties of the real battery is out of the scope of this report. However, it is important to briefly list some of the essential battery characteristics that will be used in our schemes:

- The remaining voltage of a battery depends on the intensity of the discharge current.
- The battery discharge is faster when the drained current is high (and vice versa).

- The capacity of a battery will increase if the battery is allowed to rest for some time (Charge recovery effect).
- The recovery process depends on the idle time duration.
- The recovery process depends on the state of the charge of the battery [CHIA99c], [DATT05].

Particularly, we shed light on two effects: The pulsed current discharge and the charger recovery mechanism due to their importance in our work as we will see later. We will discuss them in further details in chapter 3.

## 1.2 Motivation and Objective

Only few research studies, about energy-efficient MAC schemes, that take into consideration the real operation of the battery in their implementation have been submitted. Generally, the researchers tend to develop new duty-cycle mechanisms in the MAC sub-layer to conserve more energy.

In this thesis, we propose two new battery-aware energy-efficient MAC protocols based on two different approaches. These protocols exploit the internal properties of the battery to extend the lifetime of a node and to improve also the performance in terms of throughput and collision percentage. In both protocols, we introduce new wakeup/sleep schedules that include the actual battery voltage in their computations.

We call the first battery-aware MAC protocol: MAC-LV. This protocol gives priority to nodes with low battery voltage to access the medium before the nodes with higher battery voltage. In this case, the nodes with higher remaining voltage remain in the sleep mode longer than the

nodes with lower remaining voltage, and thus they will save more energy and they will recover more charges.

The second battery-aware energy-efficient protocol we propose is MAC-HV. The operation of this protocol is exactly the opposite. With this approach, the nodes with high battery residual capacity have the right to access the channel before the nodes with lower battery voltage. As a result the weaker nodes, in terms of power, have the opportunity to rest more and then to restore more power than the other nodes.

Eventually, the performance of these protocols will be studied and compared with each other as well as with the performance of the conventional CSMA-CA protocol through simulations.

We summarize the objectives of this thesis with the following points:

- To introduce the battery characteristics, precisely the charge recovery mechanism, in the design of a new MAC protocol for energy saving purpose.
- To verify that incorporating the capacity recovery effect of the battery in the implementation of a MAC protocol will add extra benefits to its performance.
- To provide a new active/idle scheme function of the current remaining voltage of the battery.
- To study the influence of giving the precedence right of channel access to the nodes with higher battery power on the overall performance of the network.
- To study the impact of allowing the nodes with lower battery voltage to gain access to the medium before the nodes with higher battery capacity on the general performance of the network.

- And to reach a conclusion about which approach is the best in terms of some performance metrics: is it the usual CSMA-CA protocol, or the approach that permits the powerful nodes to relax the most, or the approach that allows the weak nodes to rest more.

### 1.3 Thesis contributions

This thesis intends to provide innovative means to address the energy-efficiency problem in the wireless sensor networks. The design and implementation of these schemes led to new significant original work and novel results.

The contributions of this proposed study are as follows:

- The verification, through analytical study, of the importance and the benefits of including the real behaviour of the battery in the design of the MAC protocol in the wireless sensor networks has been achieved.
- New Back-off schemes that use the current battery state in their computations have been defined.
- A novel battery-aware MAC protocol that gives priority to powerful nodes (in terms of battery capacity) to use the channel has been designed and implemented.
- A novel battery-aware MAC protocol that allows weaker nodes to have the precedence in accessing the medium has been developed.
- A new comprehensive computer simulation program has been developed in C language to implement the proposed protocols

## 1.4 Thesis outline

This thesis consists of six chapters. Chapter 1 introduces the background of the energy-efficient protocols in WSNs, and focuses mainly on the protocols designed in the MAC sub-layer. It shows the background of the battery-aware MAC schemes by introducing the realistic behaviour of batteries. It also presents the motivation, the objectives and the contributions of this thesis.

Chapter 2 provides a review of the literature on the related work. It is basically composed of three main sections: the first section shows the studies about battery operations and properties. It presents many battery models that reflect the real internal behaviour of the battery and verifies the advantages of the pulsed current discharge and the charge recovery mechanism.

In the second section, we discuss the existing duty-cycle energy-efficient MAC protocols. And the third section talks about the few battery-aware MAC protocols reported to the literature.

Chapter 3 talks about two essential subjects which we used to develop our protocols. It consists of two main parts. The first part describes briefly the battery, its main parameters, its functions, the pulsed current discharge and the capacity recovery effect. The second part discusses the CSMA-CA protocol. It talks about its communication modes, its operations, and finally it represents it in a discrete Markov chain model.

Chapter 4 verifies the advantage of considering the internal battery properties and effects in the design of a MAC protocol in WSNs. In fact, it proves through analytical study, that modifying the CSMA-CA protocol by exploiting the charge recovery mechanism of the battery, has extended the lifetime of the nodes and the network.

Chapter 5 explains our proposed protocols MAC-HV and MAC-LV in details. It defines the new back-off functions which depend on the actual battery voltage. It presents the algorithms and flowchart of each protocol. And finally it shows and discusses the simulation results in terms of many performance metrics

Chapter 6 concludes our current research study and explores the future work we intend to target.

## 1.5 List of Publications

1. Yamen Nasrallah, Mouhcine Guennoun, Hussein T. Mouftah, Energy-Efficient Battery-Aware MAC Protocol for Wireless Sensor Networks, 2012 IEEE Wireless Communications and Networking Conference (WCNC 2012), Paris, France, April 2012.(to appear)
2. Y. Nasrallah, M. Guennoun and H.T. Mouftah, “Energy Efficient Battery Aware MAC protocol for WSN”, presented at 2011 WiSense Workshop, University of Ottawa, Ottawa, September 2011.

# Chapter 2      State-of-the-art of Energy- Efficient MAC Protocols

## 2.1 Introduction

Designing new MAC protocols to reduce the power consumption and to prolong the lifetime of the nodes in WSNs attracted the attention of many researchers. However, in most of the proposed work, the authors try to find the best duty-cycle schemes that effectively use the current energy, and the optimal ways to reduce the power spent during sending and receiving. They are known as power-aware MAC protocols. Their main drawback is that they do not consider the state of node battery in their design[YE04a], [CHIA02], [CHIA00], [DAM03].

The aim of this chapter is to review the existing MAC protocols in the literature that tackle the energy savings and power consumptions challenges in WSNs. This will includes those which take into consideration the battery characteristics and those which do not.

This chapter is divided into three main sections (in addition to the introduction and the summary): the first section discusses new battery representations that reflect its real functionality and reveal its actual advantage in a communication system. The second section talks about power-aware MAC protocol. The third section reviews a few existing battery-aware MAC protocol.

## 2.2 Models of real battery behaviours

Studying in depth the operation of the real battery, the internal chemical reactions and the details of its technical characteristics and properties is out of the scope of this project. However, since our proposed work is based on some important effects that take place in the battery, which influence positively the communication procedures in the sensor networks, we are obliged to give a brief overview about some studies reported in the literature related to these effects. Basically these effects are: the pulsed current discharge and the charge recovery mechanism.

We note that an overview section about the batteries operation and properties will be discussed in the Chapter 4.

The handbook of batteries [REDD10] is a modern, advanced and complete guide about batteries from theoretical perspectives to industrial applications. It covers the principles of the internal operations, it describes in details the electrochemical reactions, and it classifies the batteries to different categories based on different criteria. It is one of the best references about batteries nowadays.

The following research works [LAFO90], [PODH94], [FULL94], [NELS97] and [DOYL97] prove that draining the battery power with a sequence of current impulses is way better, in terms of lifetime and performance, than with a constant current discharge.

In what follows we will review some papers that propose new schemes to model the battery behavior taking into account the charge recovery capability. In [CHIA99b] an investigation is conducted about finding new ways to improve the energy efficiency of communication protocols that take advantage of the charge recovery mechanism.

The study starts with an overview about the battery behavior. It focuses mainly on the effect of the pulsed current discharge. In a communication system, two different battery models with pulsed discharge modes were assumed: the binary pulsed discharge and the generalized pulsed discharge. In both models the packet arrival process is considered to be Bernoulli.

The binary pulsed discharge process is illustrated in Figure 2-1. ( $N$  is the nominal capacity,  $N_s$  is a dummy state added to represent the start of the discharge,  $T$  is the theoretical capacity). The system transmits only one packet, if available, in each time slot. If there is no packet to send, the system recovers one charge unit. In case of a transmission, the system uses power during the whole duration of the time slot.

The probability that one packet arrives during one time slot (and thus the probability of a packet transmission a time slot) is defined as  $a_1$ . As a result, the charge recovery occurs with a probability of  $1 - a_1$  (in case of no transmission). The authors calculated the total estimated number of packet that can be transmitted before the theoretical capacity of the battery is exhausted, and then they determined the ratio of the mean transmitted packet under binary pulsed discharged and constant current discharge. The objective is to analyze the gain when varying the probability  $a_1$ .

The results showed that the performance of the system with binary pulsed current discharge surpass the performance of the system with the constant current discharge, especially when the probability of packet arrival is small (less than 50%), and that's obvious because nodes will have more time to rest in this case and thus more chance to recover charges.

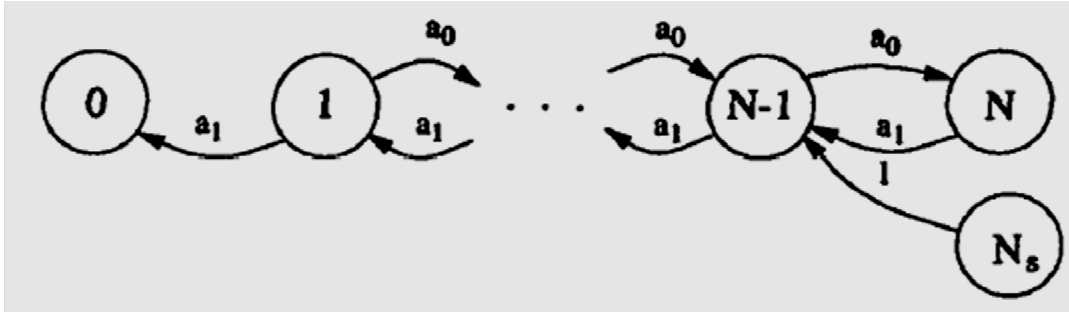


Figure 2-1. Binary pulsed discharge

In the generalized pulsed discharge, the node is allowed to send multiple packets in a time slot. The node relaxes in the remaining period of the time slot after completing the packets transmission. The system is presented in the Figure 2-2.

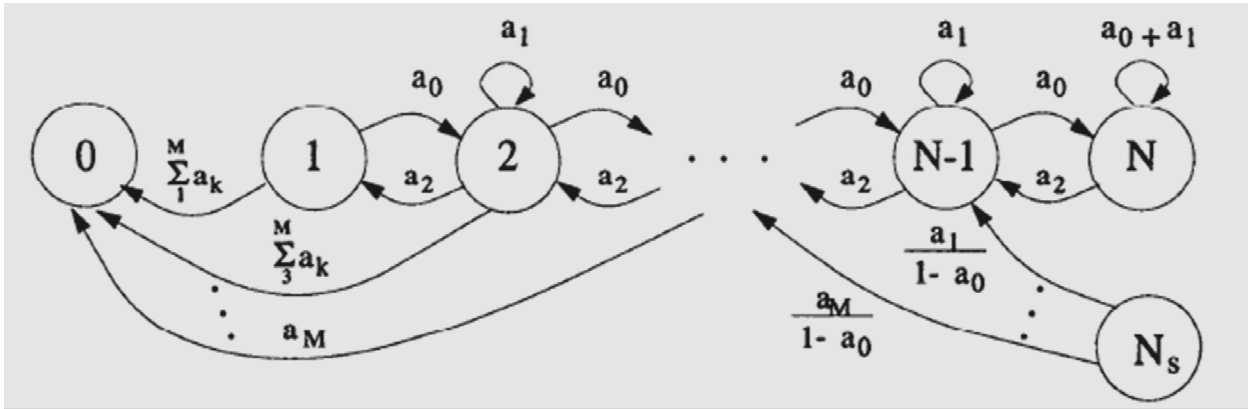


Figure 2- 2. Generalized pulsed discharge

$a_k$  : probability of the arrival of burst of packets in a time slot.

M is the maximum number of packet per burst.

The same concept of study followed in the previous case is applied in this system. A new gain fraction of packet arrival between the generalized discharge system and constant discharge system is calculated. And the results show a significant improvement, however as the number of packet transmitted increase the performance becomes worse.

We think that this research was one of first attempts of introducing the battery behaviour in the study of a communication system. It proved that such approach can be very useful and can achieve remarkable results in the future. However, it was not applied on a specific communication protocol; it was only based on an analytical scheme. We also think that it is incorrect to assume a fixed recharge probability; in fact the probability of recharge is variable and depends on the actual battery voltage.

A new model of the battery behaviour that takes into consideration the pulsed current discharge is presented in [CHIA99a]. It adopts the same Markov chain representation of the generalized pulsed current discharge discussed in [CHIA99b], however the main distinction is the definition of the charge recovery function: it is not a fixed parameter anymore, it is variable and depends on the battery state and on its discharge capacity. The new model was then applied on a new battery management technique based on the traffic shaping algorithm (leaky bucket) to get the most out of the battery capacity.

The authors identify the recovery probability as a decrementing exponential function of the battery current voltage and of its discharge operation. They adopt it from [ALZI97] where three recovery parameters were introduced  $\gamma_1$ ,  $\gamma_2$ , and  $\gamma_3$ . While the cell is discharged, the slope of the exponential function ranges over the value of these parameters.

They also assume that at each time slot, the battery may lose "i" charge units if it receives and sends "i" packets. If no activities were detected, the battery state may remain unchanged or it may increment by one charge unit.

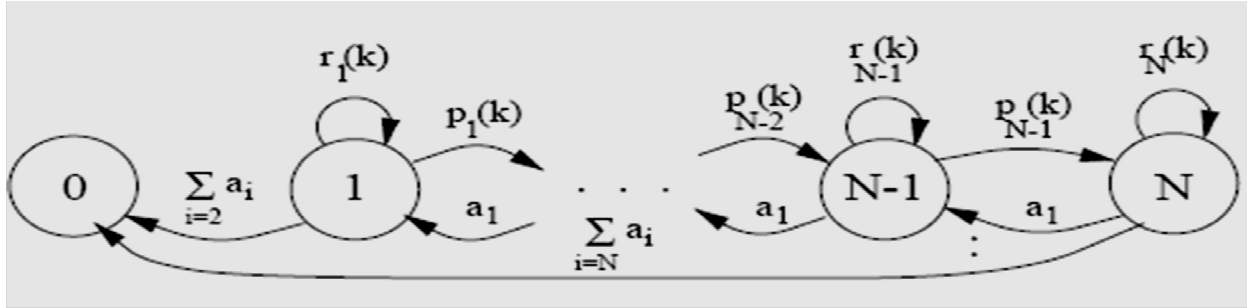


Figure 2- 3 Markov chain representation of a real battery behavior

The recovery probability function at state  $j$  after transmitting  $k$  packets is defined as the following:

$$p_j(k) = \begin{cases} a_0 e^{-\alpha_N(N-j) - \alpha_C(k)} & \begin{matrix} j=1, \dots, N-1 \\ k=0, \dots, \gamma_1 \end{matrix} \\ a_0 e^{-\alpha_N(N-j) - \alpha_C(k)\gamma_c} & \begin{matrix} j=1, \dots, N-1 \\ \gamma_c < k \leq \gamma_{c+1}; c=1, 2, 3 \end{matrix} \end{cases}$$

- $N$  is the nominal capacity ( we will talk about it in Chapter 3)
  - $\alpha_N$  and  $\alpha_c$  are parameters that depends on the recovery capability of the battery.
  - $\alpha_N$  is assumed constant
  - $\alpha_c$  is a piecewise constant function of the number of packets already transmitted, that changes value in correspondence with  $\gamma_c$  ( $c=1,2,3$ )
  - $a_i$  is the probability that a burst of  $i$  packets arrives in one time slot
  - $a_0$  is the probability to remain in state  $N$  when the initial state of the battery is  $N$ .
- $a_i = r_N(k)$ .

The authors choose the value of parameter so that the discharge process is as close as possible to the real operation of a battery.

Similar to [CHIA01], the authors define the ratio of the average number of packet transmitted during the discharge process over the initial maximum capacity of the battery ( $G_p$ ); and then they study the performance under two different arrival processes: Bernoulli arrival process, and Poisson arrival process.

With Bernoulli arrival process, the probability of the arrival of one packet in one time slot is fixed and equal to  $q$ . However with Poisson arrival process the probability of  $i$  packets arrival is defined by  $\alpha_i = \frac{q^i e^{-q}}{i!}$ .

The results show the real benefit of pulsed current discharge, the performance increases with the higher recovery capabilities. It also proves that the current intensity has a big impact on the recovery process whatever the internal properties of the battery are.

The second step the authors have discussed is applying the previous discharge model on the leaky bucket technique [SCHW96]. Their goal is to be able to return the battery voltage level to its initial value under different traffic load. They define a threshold state of the battery  $B$ . When the battery capacity reaches this threshold it stops transmitting packets, and the remaining packets will be stored in a data buffer big enough to not lose any of them. During the recovery period, the battery recovers one charge unit in one time slot. In the absence of any packet in the queue, it continues recovering. However, when new packets arrive, the node starts transmitting as long as the battery level is greater than  $B$ .

They study the performance, with Bernoulli arrival process, in terms of throughput, average packet delay and average number of queued packets. The pro is that the battery capacity can be maximized, but this is at the cost of packet transmission delay. However, by choosing the suitable size for the token in accord to the battery recovery properties, we can attain an optimized solution.

In [CHIA01], the authors revisited the earlier work with same processes, functions, assumptions and schemes but with a new mathematical approach. They investigate the real battery activities and the benefit of the pulsed current discharge through stochastic models. And they achieve the same results attained previously.

We limit our survey in this subsection to this end, because the majority of the other papers reported to the literature that discuss this subject delve deep into batteries internal functions and material characteristics [RAHM10], [SUBR09], [PODH94] and [FULL94], which is far away from our main field of interest.

In the next subsection, we discuss power-efficient MAC protocols. We mainly talk about protocols based on new duty-cycle schemes aimed to reduce the power dissipation.

## **2.3 Power-Aware MAC protocols**

In general, MAC protocols can be classified as either contention-based or contention free protocols. TDMA is an example of a contention-free MAC protocols and CSMA is an example of contention-based MAC protocols. It is true that the use of the TDMA technique in the MAC layer will prevent the collisions of packet and will solve the hidden node problem; however it encounters various disadvantages (documented in [YE04b]) such as the need of a centralized

node, a very precise synchronization clock, a very tight schedule with high degree of concurrency etc. which make it a bad option for wireless sensor networks. On the other hand, what concern us in this report are the MAC protocols that aim to extend the operation life of a network. The conventional contention based MAC protocols for wireless networks such as WLAN are not suitable for WSNs, because they require the nodes to listen to the channel continuously [SELV08] and as a result consume too much energy. In what follows we will focus on the CSMA-CA based protocols designed to reduce the idle listening time using new duty cycle techniques, however we will first present briefly two energy efficient TDMA-based protocol.

### **2.3.1 TDMA-based energy-efficient MAC protocols**

The Energy efficient Medium Access Protocol (EMAC) [NIEB03] is a TDMA-based protocol that aims to decrease the energy consumption of a sensor node. The authors identified major sources that cause the waste of energy, and then they identified numerous novel mechanisms to mitigate their effects.

This protocol divides time into frames and each frame into time slots and then it assigns one time slot to each node. The node has possession of the timeslot and controls it alone without any competition with any other node. For efficient use and distribution of these timeslots, the network is composed into cells; each cell consists of neighbor nodes. Two nodes located in two different cells cannot communicate with each other, because the range of communication of one node does not reach the second. Therefore a common time slot can be used by these nodes.

The timeslot in its turn is divided to three sections: Communication Request (CR), Traffic Control (TC) and Data section. In the CR section, the node controlling the timeslot accepts

requests from other node. For example the nodes can ask for data or inform the owner node that there are data available for it (very similar to the RTS packet in CSMA-CA based protocols). In the CR period a small probability of collision exists.

Each node retains a schedule table where it saves the schedule of the neighbor nodes located in its cell. In TC section the owner transmits its schedule and broadcasts important information to the neighbors such as the timeslots of surrounding nodes, and it also tells them about what kind of communication will take place in the data section.

In the data section, the actual data will be transmitted to the target.

In the CR period, the nodes that do not have a request for the current slot owner will keep their transceiver in a low power state. When a time slot is not controlled by any node, all nodes will remain in sleep state. If a node is not addressed in the TC section nor its request was approved, it will resume a standby state during the entire data section [VAN06].

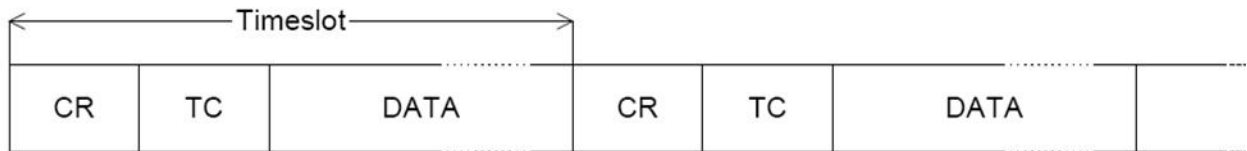


Figure 2- 4 EMAC frame format

This protocol shows good results in terms of energy efficiency; however that is in the expense of latency.

The authors of EMAC protocol developed a new protocol called: Lightweight Medium Access Control protocol (L-MAC) for wireless sensor networks based on ideas derived from the EMAC protocol. It is also an energy-efficient TDMA-based scheme.

Similar to EMAC, the frame is composed of time slots and one time slot is assigned to one node to control over it. However, unlike EMAC the time slot in this case has only two sections: the control message section and data unit section.

In the control section, the node transmits a control message defined in the table 2-1.

<b>Description</b>	<b>Size (bytes)</b>
Identification	2
Current Slot Number	1
Occupied Slots	4
Distance to Gateway	1
Collision in Slot	1
Destination ID	2
Data size (bytes)	1
<b>Total</b>	<b>12</b>

Table 2-1. Contents of the control message

During this section, the node which owns the time slot exchanges important information with the neighbors. For example, it informs them the id of the current time slot, the distance in hops to the gateway, the size of the data that will be sent etc. It also sends an indication to the destination node about the data length so it prepares to receive the data in the next section. It also uses this section to maintain synchronization with other nodes.

All the nodes, except the one indicated as a destination, will switch to sleep mode to save energy. And after completing the data transfer, both nodes (the source and the destination) power off their transceiver.

The main advantage over EMAC protocol is that LMAC tries to minimize the overhead of the physical layer. And in contrast to EMAC, LMAC is a contention free protocol.

Simulation results were compared to EMAC and S-MAC protocols (S-MAC will be discussed later in this section). LMAC protocol was able to extend more the network lifetime compared to EMAC and S-MAC respectively [VAN04].

Z-MAC [RHEE05] is a hybrid TDMA-CSMA protocol. It is designed to take the advantages of both TDMA and CSMA-based schemes and to avoid their weaknesses.

Under low contention conditions, Z-MAC operates like a CSMA-based protocol and thus it accomplishes high throughput and low latency communication among the nodes. In contrast, it functions as a TDMA-based protocol under high contention situations, and as result its performance achieves high channel utilization and nearly eliminates collisions among two-hop neighbors.

Z-MAC succeeded to solve the problems of synchronization, network topology variations and time varying channel conditions. However, it requires a long initial setup phase in which the nodes should execute multiple tasks in order to establish their links.

There are many other proposals made for TDMA in wireless sensor networks [GOBR09], [ARIS02], [LI04], and [VENK06] , but we restrict our review to what we presented so far, because the solutions based on TDMA alone has been neglected in wireless ad hoc networks for its failure to resolve their fundamental challenges, such as scalability, energy constraints etc.

### **2.3.2 CSMA-based energy-efficient MAC protocols**

The Sensor Medium Access protocol (S-MAC) proposed in [YE04a] is a contention based protocol that assumes a fixed duty-cycle scheme. Its goal is to shorten the duration of the idle time to save more energy and to decrease the number of collisions in the network.

It switches periodically the transmission system between two modes: sleep and active. In fact, the frame in S-MAC is divided into two parts: an active part and a sleeping part. During the sleeping part the radio of the node is turned off, and it keeps all the packets ready to be sent in a queue. These packets are sent out once the node switches to the active mode, and therefore the energy wasted on idle listening is reduced. The active-sleep schedule created initially by the node is broadcasted to the neighbors; this schedule should be updated periodically among different nodes, thus synchronization is always required.

To overcome the hidden node problem, S-MAC protocol applies the RTS/CTS/DATA/ACK handshake scheme.

The main advantage of the S-MAC protocol is the energy savings due to the long sleeping period. But this comes at the expense of the network throughput and packets latency. Moreover, a fixed duty cycle scheme does not adapt to the traffic variation in sensor networks. Another problem is the data forwarding interruption which takes place when packets need to go over multiple hops to reach their destination.

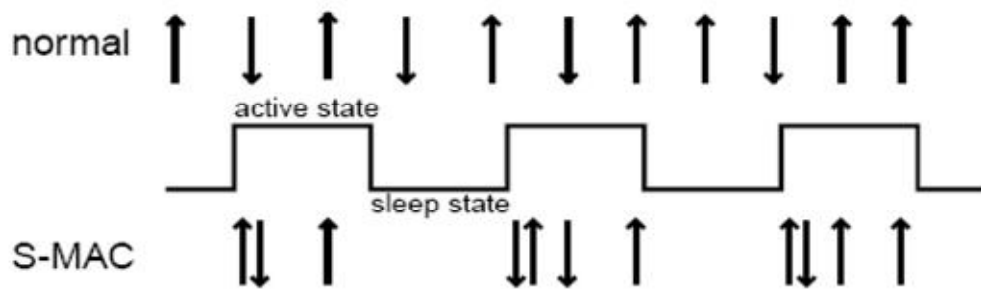


Figure 2-5. The S-MAC duty cycle: the arrows indicate transmitted and received messages

D-MAC protocol [LU04] was designed to avoid the data forwarding problem. It is an energy efficient and low latency protocol based on data gathering trees where the flow of packets is

directed in one predetermined way from source nodes to one coordinator or sink node which is the only destination in the network.

The tree architecture is divided into levels (Figure2-6). Each level consists of a set of nodes that receive data from the nodes of lower level and forward them to the nodes in the higher level. The frame is divided into three main modes: transmitting, receiving and sleeping, and the schedule proposed is designed in a way so when a node at a given level is sending data, the neighbor node in the upper level will be in the receiving mode. The nodes at each successive level up the tree follow a receive-transmit-sleep sequence shifted to the right [SHEL08].

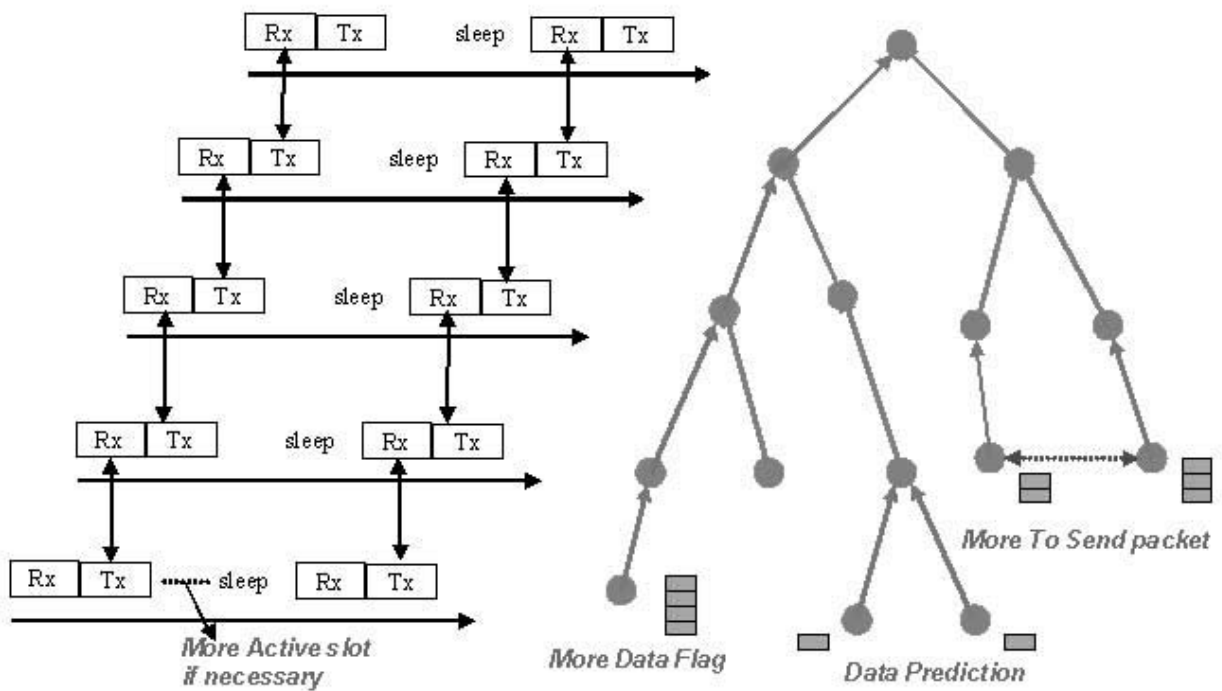


Figure 2-6 D-MAC tree structure and the sequence receive-transmit-sleep

This protocol comprises multiple advantages. The latency is reduced because the nodes involved in the communication wake up in a sequence manner from bottom up to the destination. Another

pro is that the nodes which are not on the path of communication operate in a low duty cycle, and thus they save energy.

The main shortcoming is that D-MAC protocol can be applied only on this type of networks (unidirectional gathering trees).

A similar approach has been adopted in [WANG07] [L-MAC protocol] with almost the same network assumptions and topology. However, the author implements an adaptive sleeping scheme (inspired from a protocol called T-MAC which we will discuss later), to mitigate the effect of unbalanced traffic problem. In fact, he introduces a time interval within which if a node, in receiving mode, does not sense any communication, it changes to sleep mode.

In contrast to S-MAC protocol, the Timeout MAC protocol (T-MAC) [DAM03] introduces a new adaptive duty-cycle mechanism that dynamically terminates the active mode. Its main goal is to reduce the idle listening time to save more energy.

To achieve this goal, T-MAC protocol allows the node to send the entire messages it possesses in bursts of different sizes, and to sleep after that. The key feature of T-MAC protocol is the introduction of a new time out policy that helps to adapt to the variations in traffic by ending dynamically the active period.

A Time Out (TA) interval is defined. The node terminates its active time if within the period of a TA no activities were detected, such as transmitting or receiving DATA/ACK packets, listening to the medium during a collision, sending an RTS or CTS signal. In this case the node assumes that no neighbor is willing to communicate so it switches to sleep mode. On the other hand, if a node is involved in a communication, it starts a new time-out period after it completes the communication.

Figure 2-7 shows a basic comparison between the operation of S-MAC, T-MAC and CSMA-CA protocols

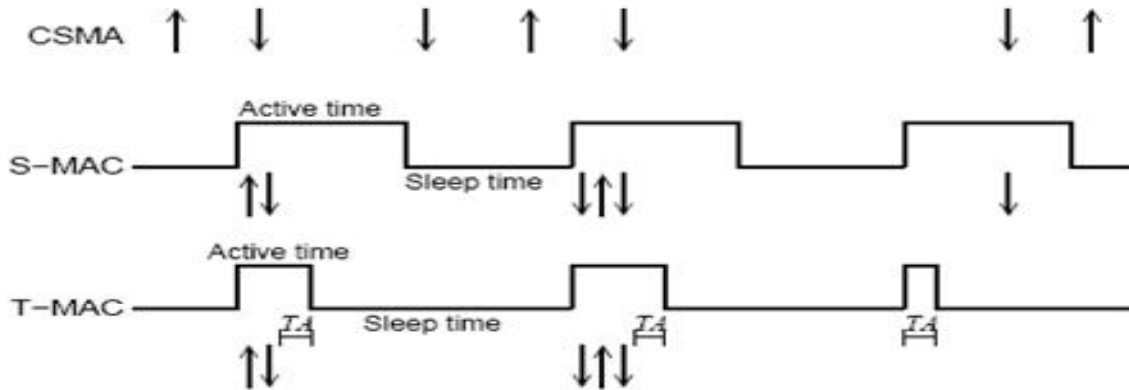


Figure 2-7 Duty cycles of S-MAC and T-MAC protocols compared to CSMA-CA protocol

The results of T-MAC protocol exceed those with S-MAC protocol, especially in reducing the energy consumption of the nodes. In addition to that, the dynamic aspect of its design makes it more suitable to WSNs than S-MAC which uses a fixed duty-cycle scheme.

Other protocols, such as PAMAS [SING98], LPDM [GUO01] and STEM [SCHU02] use a radio system with dual channels: the data channel and the signaling channel. The data channel remains most of the time in a sleep mode. It just wakes up for data transmission once it receives a wakeup signal by the control (signaling) channel.

We note finally that there are so many other protocols that propose new duty cycle schemes ([JURD08], [ANAS09b] and [YUAN11]), and novel energy efficient approaches ([SUN08], [ALIP09], and [YIN10]), others developed based on the conventional S-MAC protocol ([HAMA10] and [EZZE09] for example), trying to enhance its performance or to avoid some of its drawbacks. But since this is not the main concern of our study, we will limit this subsection to this point.

## 2.4 Battery-aware energy-efficient MAC protocol

In [JAYA04] the authors propose a new battery-aware MAC protocol for ad hoc wireless networks, based on a novel distributed scheduling scheme to increase the lifetime of the nodes and the network by exploiting the charge recovery effect of the battery. They refer to this protocol as BAMAC(k). k represents the number of packet that the node should send once it gains access to the medium.

Their main goal is to ensure a near round-robin scheduling and a uniform discharge of their batteries to outperform the conventional IEEE 802.11 CSMA-CA protocol.

The proposed scheduling scheme depends on the current residual battery voltage. It schedules the nodes, using a round-robin scheduler, in a way that the back-off period decreases with the decrease of the remaining battery capacity. In order to achieve this target, the authors suggested that each node saves a table in which it keeps the following information about the batteries of its neighbor nodes: the remaining theoretical voltage, the remaining nominal voltage and the last time the battery was used. The table is arranged in descending order of its theoretical capacity of the nodes. Every node sends the current battery information to the neighbor nodes with every packet: RTS, CTS, DATA, and ACK.

They define the back-off period as:

$$back - off = uniform[0, (2^x * CW_{min}) - 1] * rank * (T_{SIFS} + T_{DIFS} + T_t)$$

Where: -  $CW_{min}$  is the minimum size of the contention window.

- rank is the position of that entry in the information table

- $T_{SIFS}$  and  $T_{DIFS}$  the short inter-frame spacing and the DCF inter-frame spacing durations
- $T_t$  is the longest possible time required to transmit a packet successfully including the RTS-CTS-Data-ACK handshake

To demonstrate the operation of the protocol, an example was introduced. It is illustrated in Figure 2-8. A and B are the source and the destination nodes. In the first step, A sends an RTS signal to B. The battery information of A are attached to RTS. The nodes C, I and B update their battery table. In step two, B sends back a CTS signal including the battery information of A and of itself, as a result the nodes D, I and A add the new entries to their battery table. Same procedure occurs with the Data and the ACK packets. After step 4, node B will have the right to access the channel before the other nodes because its rank is the smallest.

Their results showed that this protocol outperforms IEEE 802.11 in terms of power consumption and the lifetime of the nodes and network.

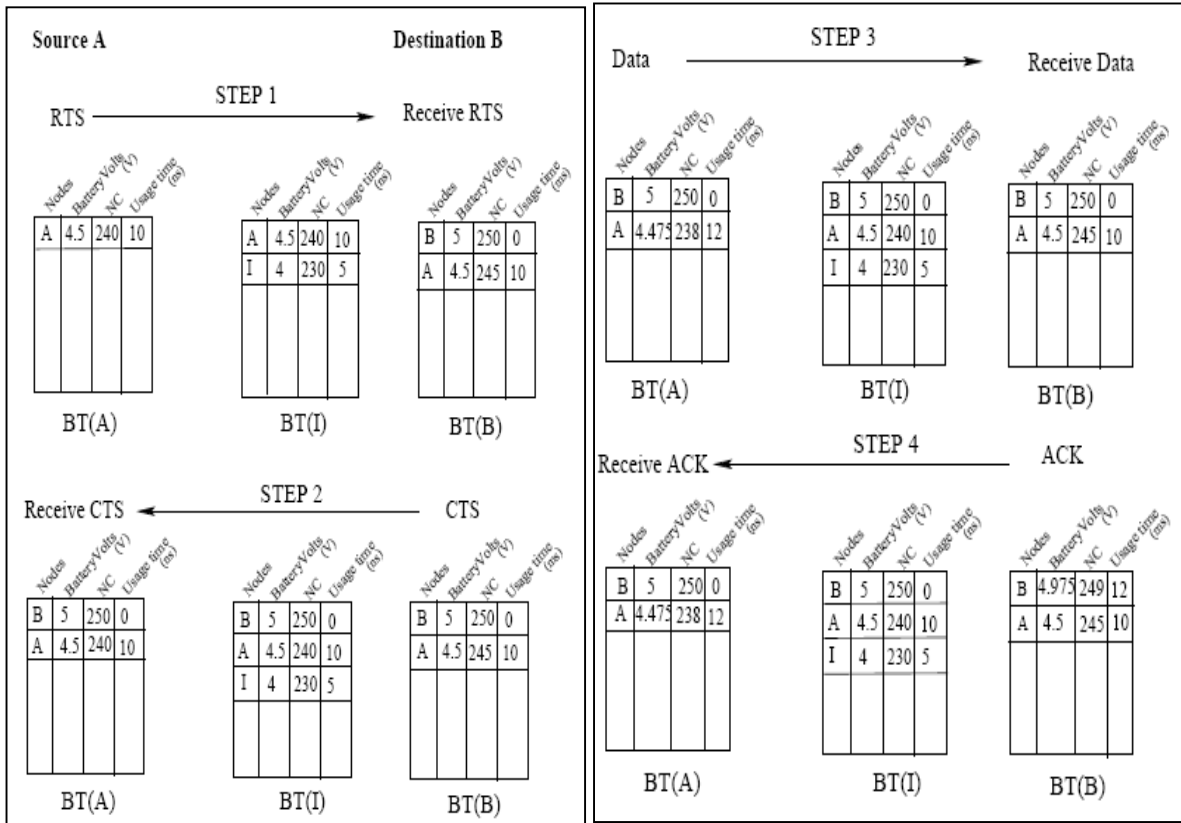
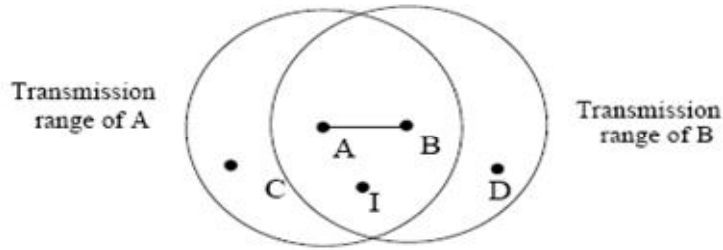


Figure 2-8. Example of BAMAC(k) Operation

In our opinion, this approach was very successful, however there is a network security question since all essential information about the batteries are exchanged between the nodes. Other drawbacks are noticed: the big overhead attached to every packet sent, all the nodes need to continue listening to the medium all the time so they can update their battery table, additional memory and processing capabilities are required.

BEL-MAC protocol [DHAN05] introduces a new duty-cycle scheme that exploits the internal properties of the battery to minimize the end-to-end delay and maximize the network's lifetime.

The throughput and the latency of BEL-MAC were compared with S-MAC, D-SMAC, T-MAC and CSMA-CA outcomes, and the results showed that BEL-MAC is the best among them.

In this study, it is assumed that the node is equipped with two batteries: primary and secondary. The secondary battery is always active and it is used to activate the primary battery, which is shut off most of the time (during the sleep mode). It is also assumed that the sensor node periodically switches between sensing and computing modes all the time.

BEL-MAC protocol is designed in a way to keep the remaining voltage level in the battery as close as possible to the initial value of the nominal voltage. In order to achieve this goal, the author introduces new dynamic active slots in every frame. After the contention period, the node that succeeded to access the medium sends the entire packets it possesses. However the node is not permitted to continue transmitting in multiple time slots. The node saves the remaining packets and toggles to sleep state by putting off the primary battery, while the secondary battery stays awake and listens to the medium. This sleeping period allows the main battery to recover some charge units.

The major difference between BEL-MAC and S-MAC and D-SMAC protocols is that the former insert an optimum number of additional active slots to achieve a compromise between the latency and the energy recovery.

The first figure of Figure 2-9 shows the difference between the various protocols in term of Wakeup/sleep schedule. As we can see, in S-MAC protocol the node is active just for a short period of time and sleeps most of the time which will increase the latency. D-SMAC protocols uses more time in transmitting then in sleeping. In T-MAC protocol, the nodes transmit all the packets once it has access to the medium and thus the battery will be discharge so quickly. And

finally BEL-MAC protocol adds, in an optimal way, some active time slots in the frames to gain the advantages of S-MAC and T-MAC and neglects their disadvantages

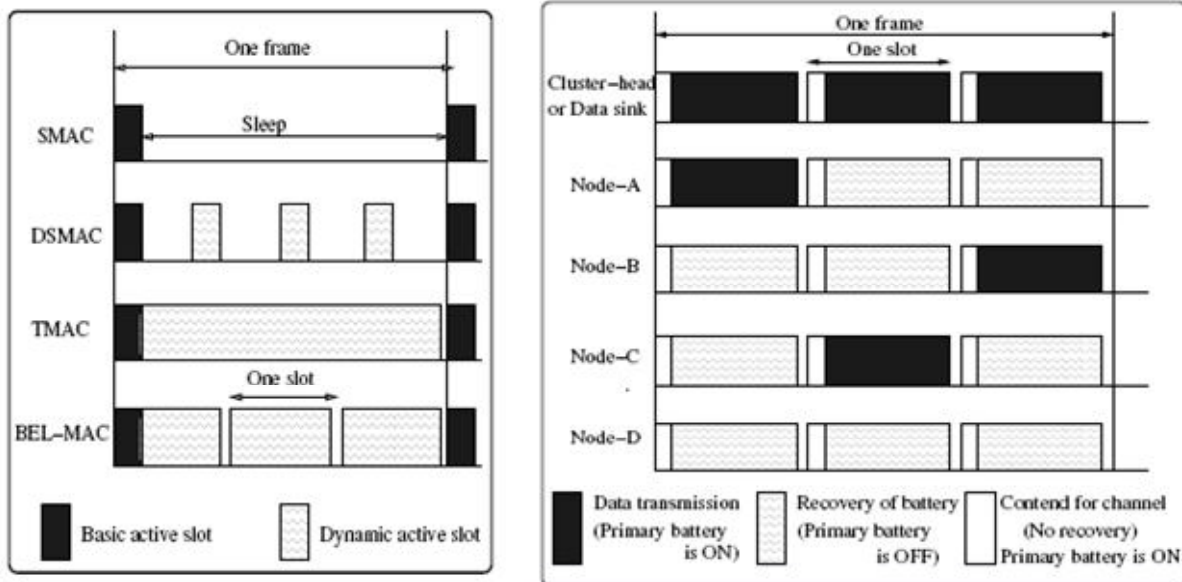


Figure 2-9. a) Wakeup/sleep schedules of S-MAC, DSMAC, T-MAC and BEL-MAC protocols  
b) communication process of BEL-MAC protocol

In the second figure of Figure 2-9 the authors show the communication process in a one-hop network. A cluster head is connected to four nodes. As we can see, a node can transmit only in one active time slot in each frame and relaxes for the remaining time.

The simulation demonstrates promising results, however there are some disadvantages related to this protocol: the extra size of the node and its extra cost due to the usage of an extra battery.

An interesting study about exploiting the battery recovery effect in the sensor networks was described in [CHAU10]. The author conducted experiments on a sensor network test-bed. The results demonstrated a considerable increase in the lifetime of the node due to the charge recovery effect, and it provided evidence that there is a time saturation threshold after which the node will not recover any charge units.

A remarkable protocol that exploits the battery charge recovery property to extend the lifetime of the network is designed in [SELV08]. It is the Battery and Redundancy Aware Node Scheduling protocol [BRANS]. The interesting factor that distinguishes this protocol from the previous ones is the introduction of the node level redundancy with respect to sensing. It schedules the sensor nodes (Wake up/sleep) based on the sensing level redundancy information and exploits the battery charge recovery mechanism in order to attain an increased network lifetime with controlled latency [SELV08].

The basic assumptions and variables that characterize this protocol are summarized as follows:

- The sensing coverage area of the node is defined as a circle with radius  $R_s$ .
- The communication range of the node is determined by a circle with a radius  $R_c$
- Every node is at the same time a source of information and a relay that forwards the data sent by neighbor nodes to the sink node.
- Redundancy with respect to the sensing should be guaranteed. To assure that, the authors assume the operation of a large number of nodes distributed randomly in a precise area.
- Every node is equipped with two batteries. The big battery, denoted the primary battery, is responsible to supply the node with the required power to be fully functional. The small battery, denoted the secondary battery, is used only to generate an activation signal to wake up the primary battery on termination of a timer.
- All nodes are aware of their locations.

As describe in BEL-MAC protocol, the primary battery switches to sleep mode whenever the active period is expired. Sleep mode means a complete shutoff of the battery, which will allow it to recuperate a portion of its charges.

The BRANS protocol is implemented in 4 phases: Virtual Grid Foundation, Initialization, Periodic active node election and routing neighbor updating. It starts by dividing the area where the nodes are deployed, into virtual grids with equal surfaces. The size of each square unit of this grid depends on the application, it could be for example  $2R_s * 2R_s$ . After exchanging the location information, the nodes will be able to identify their neighbor nodes which are located within their range of sensing (a grid) (Check Figure2-10). The nodes which reside in the same grid are assumed redundant. Then each node will create a neighbor table that contains information about their neighbors.

In the second phase, in each grid the node with the lowest node id remains active while the other go to sleep mode. The sink node communicates then with all active nodes to create a routing table (Table 2-2).

In the third phase, every active node in a grid should choose a successor node to be active. In fact, in every predefined period of time all the nodes wake up and wait for an Election Control Frame (ECF) (Table 2-3) to update their neighbor table and to be aware of the next active node. The node with nominal capacity higher than a predetermined threshold will be chosen to be the next active node. And finally the routing table should be updated based on the new active nodes in all grids that form the actual network.

The simulation results showed great increase in the lifetime of the network compared to IEEE 802.11 CSMA-CA and T-MAC. The implementation of the protocol is quite interesting; however the latency is still a problem that needs to be resolved especially in high network loads. We should consider also the additional size and cost of the nodes due to the dual battery setup.

Exchanging crucial information among nodes presents a big challenge in term of security. And finally the use of this protocol is limited to a network with redundant nodes.

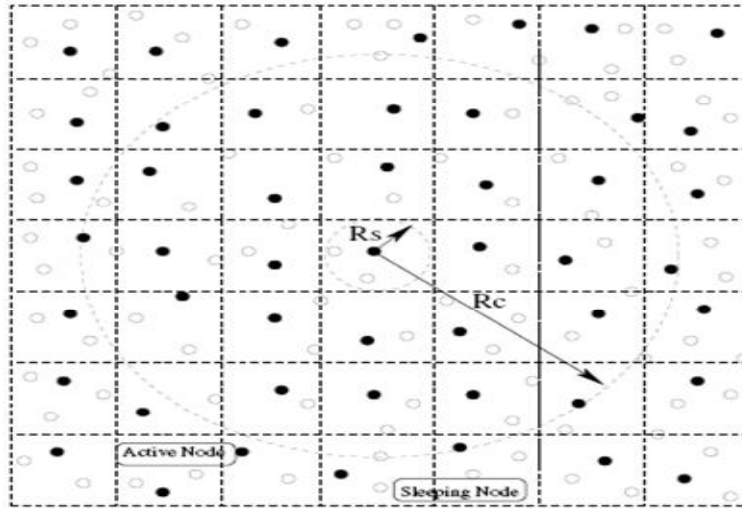


Figure 2-10 Virtual Grid

Node ID	T	N	Q-length	sleepSlots
3	200	25	0	0
7	180	18	2	3
14	180	20	1	2
..	..	..	..	..

Table 2-2 Battery Table

Current Active Node	T	N	Next Active Node (NAN)	Forwarding Node (FN)	Q-length

Table 2-3 Election Control Frame  
Q-Length: length of queue in MAC buffer

SN-MAC protocol [WATF10] is a recent MAC protocol that makes use of the chemical properties of the battery to increase the lifetime of the network. The authors assume a cluster-based network, in which the nodes are assembled in groups characterized by the presence of one cluster head which controls and manages the internal and external communications. The cluster head of every set of nodes is unique, i.e. that it does not circle and switch places with other nodes for the sake of load distribution in terms of energy. On the other hand, all cluster heads are in turn organized in multiple levels, each level is one hop away from the other, and it is selected

based on the battery state of the nodes and based on information transmitted in the packets issued by a priority function at each cluster head. The highest level is connected directly to the main base station. As a consequence the network will be considered virtually hierarchal.

CDMA-based communication scheme is applied inside of each cluster, where every new node joining the cluster gets a code that allows it to transmit at the same time and frequency with other nodes. Conversely, the cluster heads communicates with the base station based on an adaptive TDMA schedule mechanism.

The main objective behind the design of this protocol is to increase the channel utilization and reduce the end-to-end packet transmission delay in addition to extending the life duration of the network.

The author designed a new battery model represented in a discrete Markov chain process. It is composed of "M" states, starting from the state M where the battery is considered full and ending with the state 0 (zero) where the battery is considered empty. This model assumes the following:

- The time frame is split into time slots.
- $P_{rec\_i}$  : This is the probability that a node, in state "i", returns to state M if it remains idle for one time slot
- $P_{rec\_total} = 1$ . This is the probability that a node, in state "i", returns to state M if it remains idle for  $\Delta$  time slots.
- $\Phi$  the energy wasted in the battery during the process of transmission

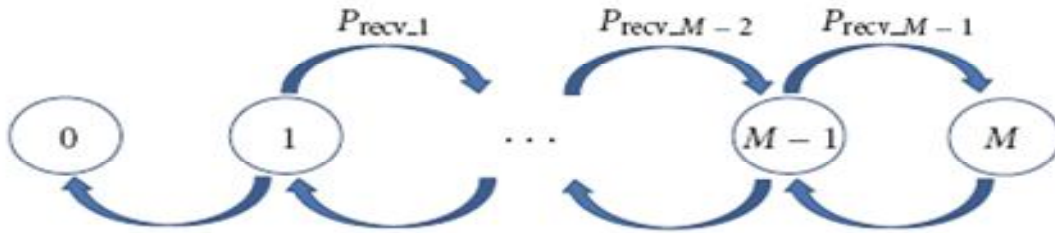


Figure 2-11. Proposed battery model

The question here is to evaluate  $\Delta$  in order to take decisions on how long to remain idle. After calculating  $\Delta$ , the algorithm will use its value to compute the node's priority in being selected as a routing candidate towards the base station.

We will briefly present the basic design and setup steps followed by SN-MAC protocol:

- 1- Initial phase after deployment: this is the first step, it includes neighbor discovering, communication establishment, node levels identification, codes spreading and formation of clusters
- 2- Second phase is the implementation of the CDMA and TDMA protocols among nodes and clusters.

SN-MAC offers the following properties: it can be applied on any type of cluster-based networks, it can adopt any spreading code mechanism, it is capable of overcome the challenges derived from the collisions, nodes overhearing, idle listening and protocol overhead. It can be simply integrated with different upper layer protocol due to its flexible and proper cross-layer design.

However it presents some drawbacks: it is only applicable on cluster-based networks and it does not consider a realistic model of the battery.

## 2.5 Summary

In this chapter, recent works in the MAC sub-layer about reducing the power consumption and increasing the energy savings have been discussed. We have started the survey with an overview about the importance and the benefits of incorporating the real battery behaviour in the design of a communication protocol. We have proceeded with a study about the current energy-efficient power-aware MAC protocols, in which the focal point was about developing new duty-cycle schemes that force the nodes to switch to sleep mode whenever it is inactive. And we terminated our review by presenting the MAC protocols that consider the battery state to restore more energy and to extend the lifetime of the network.

# Chapter 3      **Battery Characteristics and**

## **CSMA-CA Modeling**

### **3.1 Introduction**

In this chapter, we will describe two important subjects related to our study: the battery characteristics and the IEEE 802.15.4 CSMA-CA. In fact, in the next chapters, we will build on top of these concepts to provide our new propositions.

This chapter is organized in four main sections: The current introduction presents its first section. In the second section we explain the charge recovery mechanism; we start by an overview about the battery operation, we then focus on the pulsed current discharge and the charge recovery mechanism, and finally we present the recharge probability function which will be used in our proposed protocols.

The third section provides detailed description of CSMA-CA protocol; it includes its operation, its modes of communication and its algorithm. The most important part in this section is the representation of CSMA-CA protocol in a discrete Markov chain model. In this subsection, we study analytically (through mathematical equations) the operation of the CSMA-CA protocol, and later (in Chapter 4) we will develop on top of this model our new enhanced schemes.

And finally, section five concludes this chapter.

## 3.2 Charge Recover Mechanism

### 3.2.1 Introduction

Without any doubt, energy resources and power consumptions present a major challenge in wireless sensor networks. The majority of the applications in wireless sensor networks require the usage of sensors that rely on batteries as their main source of power. Therefore, understanding the characteristics of the batteries, knowing their discharge behaviours and exploiting their special effects and mechanisms may lead to promising results in terms of prolonging its life and reducing its discharge rate.

We will start this section by talking about the main properties of a battery, and then we will mainly focus on two important effects: the charge recovery mechanism and the pulsed current discharge. These two concepts are the bases on which we developed our new idea.

### 3.2.2 Basics of a battery

The battery is an electrical device that stores chemical energy and provides electrical energy. It is an electro-chemical container usually composed of one or multiple cells organized as an array, that converts the stored chemical power into useful electrical power.

Every cell consists of two electrodes: an anode and a cathode, and of an electrolyte.

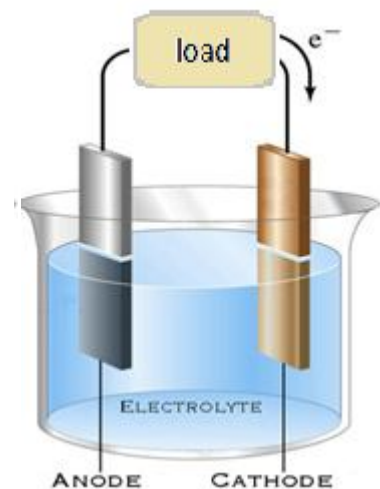


Figure3-1. Battery basic components

The main role of the electrolyte is to separate the two electrodes and to allow the transfer of electrons between them.

A battery is characterized by the following parameters

- Theoretical capacity: we refer to it as T.

It is the maximum voltage that can be extracted from a battery. It is directly related to the type and amount of material contained in the battery. So two batteries possess two different substances will have dissimilar theoretical capacities because of their different internal electrical characteristics. And two batteries with the same kind of materials but with different sizes will have different theoretical capacities since the amount of materials (or their weights) is not equal.

- Standard or Nominal capacity: we refer to it as N.

It is the energy that a battery can provide under standard load conditions at a specific constant current discharge. The nominal capacity can never go beyond the theoretical capacity.

- Actual Capacity:

It is the energy that the battery delivers under a given load [DHAN05], and it is usually used as a metric to judge the battery efficiency for constant loads.

### 3.2.3 Battery discharge behaviour

The following description is based on the information presented in [CHIA99b]. In the absence of any current, the concentration of the active material in the electrolyte is uniform and equal to its average value. In the presence of current, and due to an electrochemical reaction, the active species will be consumed at the electrolyte-electrode interface and will be replaced by other new active materials that move from the electrolyte solution to the electrode.

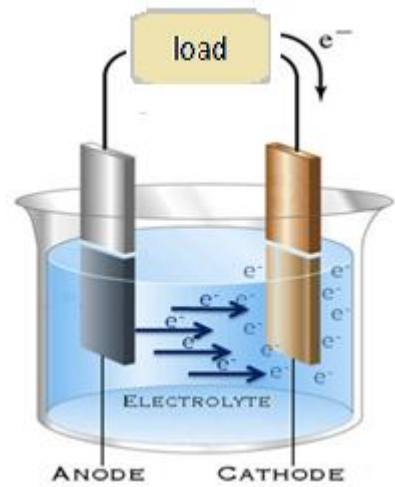


Figure 3-2 Battery basic discharge process

#### 3.2.3.1 Constant current discharge

In constant current discharge, and as the intensity of the discharge current grows, the concentration of the active material around the electrode will drop. As a consequence, the state of the charge of the electrode as well as the battery voltage decreases. And very quickly the electrolyte next to the cathode will run out of active materials that assure the electrochemical conversion, and thus the battery will expire in a relatively short period of time.

At this point, even though a portion of the active material still exists in the battery, the battery will not be able to provide more electrical energy due to the distance of these active materials from the cathode. In fact, the theoretical capacity in this case has not been exhausted, but the nominal capacity is considered zero.

It is important to mention that if the discharge current rate increases, the battery will be drained faster due to the fast decrement of the active material concentration around the electrodes.(see Figure3-3 taken from [CHIA99b])

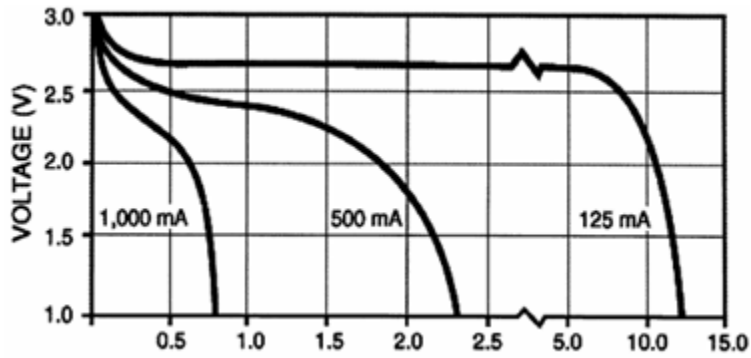


Figure 3-3 Discharge time with different current intensities

### 3.2.3.2 Pulsed current discharge and charge recovery mechanism

With pulsed current discharge, the battery is drained by a train of current impulses. So periodically, the battery will be utilized for a short period of time and then it takes a rest time.

With pulsed current discharge, we can overcome some of the drawbacks presented by the constant current discharge.

In fact, when the battery is allowed to stay idle for sometime after usage, the distribution of the active materials in the electrolyte may return to be uniform and the concentration may get back to its average value. Therefore, more active species will be involved in the electrochemical conversion, and as a result more electrical power can be extracted from the battery. So, in idle time the nominal voltage of the battery increases, however the theoretical capacity remains the same and always greater than the nominal voltage.

Figure 3-4, taken from [JAYA04], shows how the pulsed current discharge operates. We can see that after every current impulse, the battery recovers a portion of its charges, although the new energy level is slightly lower the previous level.

However we should note that the relation between the numbers of charge recovered and the remaining voltage is directly proportional. It means that the battery will be able to recharge more if the remaining voltage is higher, and the amount of charges recovered will decrease with lower level of battery voltage. And that's because with low voltage, the battery contains a small amount of active materials, which reduces the supply of charges.

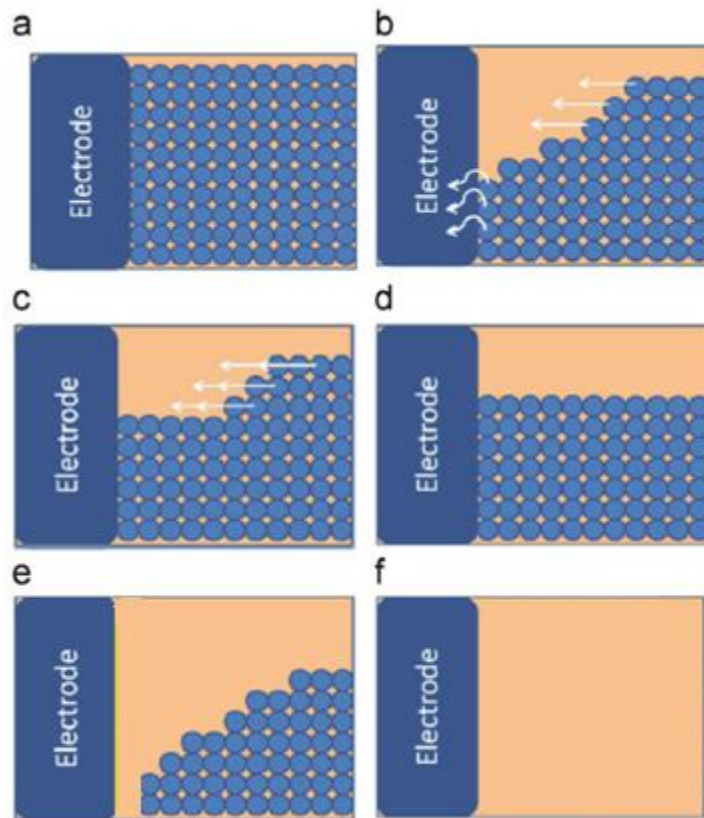


Figure 3-4 Operation of the pulsed current discharge

In a) the battery is full. It discharges in b). It switches to an idle state in c) and recover charges in d). In e) the battery loses more charges and it is incapable of recovering more charges. And finally it gets empty in f).

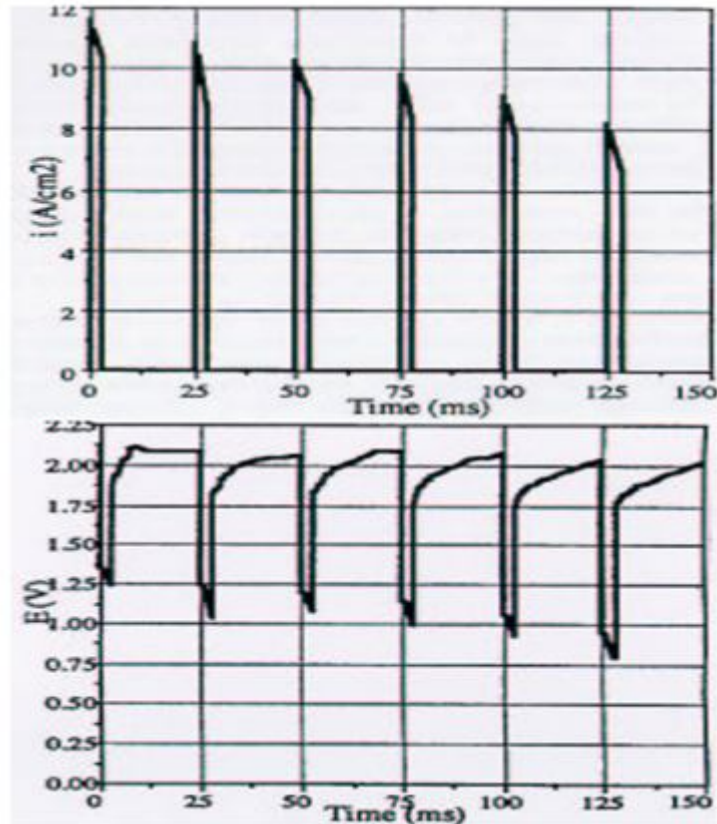


Figure 3-5 Pulsed current discharge

In Figure 3-5 we can see the pulsed current discharge. The battery drains power by a sequence of current impulses followed by an inactive period. As we can notice in the lower part of Figure 3-5 the battery recuperates most of its power. However with time, and with the reduction of voltage level, the battery recovers less and less charges.

### 3.2.4 Markov chain representation

The behaviour of the battery under pulsed current discharge may be presented in a discrete time Markov process (Figure 3-6). Every state is identified by the couple  $\langle N_i, T_i \rangle$  where  $N_i$  is the current nominal voltage and  $T_i$  is the current theoretical voltage. The initial state would be  $\langle N, T \rangle$  where  $N$  and  $T$  are the maximum values of the nominal and the theoretical voltage, and



$T_i$	$\Phi(T_i)$
200 to 196	0.0
195 to 101	0.0025
100 to 6	0.008
5 to 0	15.6

Table 3- 1 Piecewise constant function of the charge units delivered

### 3.2.5 WSNs and battery operations

Batteries, as they are the main source of power in most of the cases, are perhaps the most important devices in wireless sensor nodes. That's why it is wise to study their activities and to try to exploit all the benefits they may offer.

In fact, The operation of a sensor node can take the most advantage of pulsed current discharge effect, because a sensor node usually sends its packets, then it goes back to its back-off period waiting to access the medium again. During this period, the node will be in idle or sleep mode, and thus the battery will rest, and it will be able to gain additional capacity.

We note finally that we will use the recharge probability function  $R_{NiTi}$  and the piecewise constant function  $\Phi(T_i)$  defined in the previous part, in our new protocol.

## 3.3 CSMA-CA Overview

### 3.3.1 Introduction

The primary set of protocols that deals with low power and low data rate wireless sensor networks is defined in the Zigbee standard. This standard is mainly designed to provide some key features for sensor networks such as the simplicity of implementation, low cost of device

installation and maintenance, reliability of data transfer, and most importantly low power consumptions and thus efficient use of the battery so it can stay alive for long time (months or even years).

The Zigbee protocol stack is illustrated in the following figure

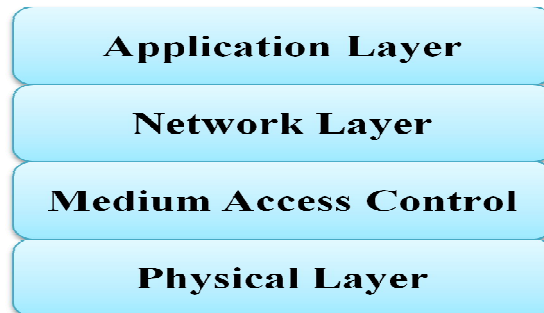


Figure 3- 7 Zigbee protocol Stack

The actual Zigbee standards are located in the Network and the Application layers, and the IEEE 802.15.4 standard is implemented in the physical and MAC layer [ZIGAL08]

A WSN can be composed of tens to hundreds of devices; one or multiple source nodes may send packets to one or multiple destination nodes at the same time. To avoid collisions and miscommunications between the various nodes, the Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) algorithm (which is already implemented in IEEE 802.15.4 MAC sub layer) is used. Basically, every source node will have to compete to access the transmission channel with other nodes that decide to send data in its range of communication. This competition for channel access is totally controlled and managed by CSMA/CA protocol.

### 3.3.2 CSMA-CA Communication Modes

There are two main communication modes provided by the MAC sub-layer of IEEE 802.14.5 CSMA-CA protocol: the beacon enabled mode and the non-beacon enabled mode.

### 3.3.2.1 Beacon enabled mode

In the beacon enabled data transfer model, the communication between the nodes is executed in a superframe structure which is presented in Figure 3-8. A superframe is usually bordered by two interval periods called beacons, and it is divided into two sections: the active period and the inactive period. The length of the time interval between two beacons is:  $aBaseSuperframeDuration * 2^{BO}$ . The “aBaseSuperframeDuration” parameter is defined as the minimum superframe duration. BO is the Beacon Order. The value of BO can vary from 0 to 14.

The length of the active period section of the superframe is defined by:  $aBaseSuperframeDuration * 2^{SO}$ . The parameter SO is Superframe Order. The value of SO can vary between 0 and 14.

The active mode of the superframe is in turn divided into two sections: the Contention Access Period (CAP) and the Contention-Free Period (CFP). In the CFP period, the coordinator is totally in control, it gives the exclusive access rights on a channel to the nodes. It may dedicate a portion of the active superframe to one node. These free time portions are called Guaranteed Time Slots (GTSs). It may assign up to seven GTS for a node, and each GTS may take more than one slot period. If a node wants to transmit, it has to request the GTS from the coordinator in a specified time slot, then the coordinator will check if a free GTS is available (not used by another node). If it is free, then the coordinator updates the superframe structures and assigns a GTS as long as the minimum CAP length is not reached.

In the CAP period, the slotted CSMA-CA protocol will be used to arrange the communication between two devices in the network. In this period, all the nodes have the right to access the channel by competing with other nodes using CSMA-CA. If a node cannot finish its transmission

before the CAP ends, it has to cancel its transmission. The total time slots allocated for the CFP and the CAP periods is 16 time slots.

During the inactive period, the coordinator and the other devices can be switched to sleep mode to reduce power consumption.

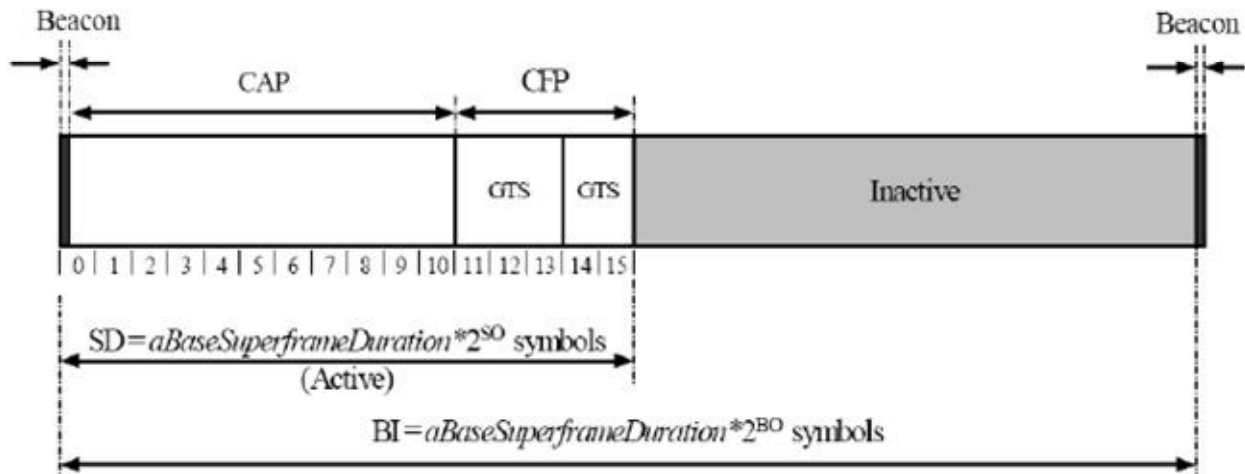


Figure 3-8 Superframe structure

### 3.3.2.2 Non-beacon enabled mode

The other mode of communication is the non-beacon enabled mode. In this case there are no beacons to be transmitted; there is no superframe structure to be used. It simply consists of a CAP section in which the nodes will contend to access the channel using unslotted CSMA-CA protocol.

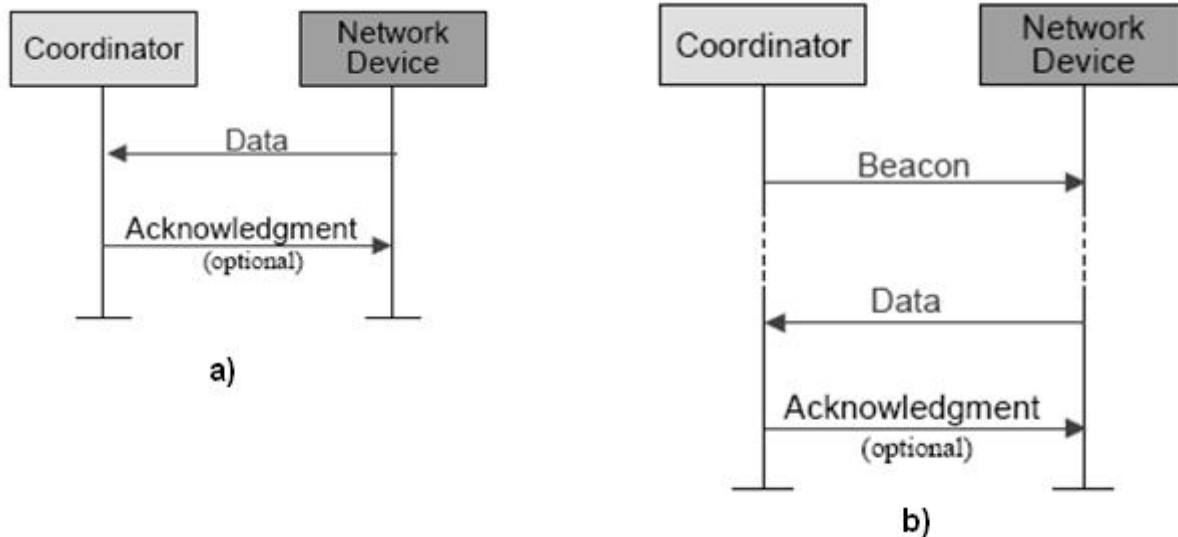


Figure 3-9 a. Non-beacon network communication, b. Beacon network communication

In the beacon enabled network, the coordinator indicates in the beacon that the data is pending. The device periodically listens to the beacon and transmits a MAC command request using slotted CSMA/CA if necessary.

In the non-beacon enabled network, a device transmits a MAC command request using unslotted CSMA-CA. If the coordinator has its pending data, it will transmit the data frame using unslotted CSMA/CA. Otherwise a data frame with zero length payload will be transmitted.

### 3.3.3 CSMA-CA operation

It is important to mention first that there are two versions of CSMA-CA algorithm. First one is used in non-beacon enabled networks and the second one is used in beacon enabled networks. In both cases, there are basic parameters and variables defined in the implementation of the algorithm.

- The basic time unit is the back-off period: it is identified by 20 symbols. The actual duration of the back-off period depends on the frequency band in which Zigbee is

operating. In beacon enabled networks, this period is related to the internal clock of the coordinator.

- The Beacon Exponent (BE): this variable is related to how many back-off periods a node shall wait before attempting to access the channel. The waiting period may be a random value between 0 to  $2^{\text{BE}} - 1$ .
- The Number of Back-offs (NB): it is the number of times CSMA-CA algorithm is required to back-off before trying to access the channel. If this number reaches a certain threshold defined by the algorithm, the communication terminates with a failure
- The Contention Window (CW): it is the length of the contention window, it defines the number of back-off periods that needs to be clear of activity before transmission can be launched. This parameter is only used with slotted CSMA-CA protocol (Beacon enabled network)

### 3.3.3.1 CSMA-CA in a beacon enabled network

As we mentioned before, superframes are used to perform the communication between the nodes, and packets will be exchanged during the active section using slotted CSMA/CA algorithm.

The operation of CSMA-CA algorithm in the CAP period is schematically shown in Figure3-10. It first initializes the parameter NB and CW to the value 0 and 2 respectively. The parameter *macBattLifeExt* indicates whether the node is operating on battery power or not. If it is the case, the parameter BE will be set to 2 or to the constant *macMinBE*, whichever is less.

Next step is to locate the boundary of the next back-off period, because all remaining operations need to be synchronized to back-off time units. A random waiting time  $k$  within the range of 0 to  $2^{BE}-1$  back-off periods will be generated. And then at each back-off period the value of  $k$  will be decremented by 1. Once  $k$  reaches zero, the device listens to the channel to make sure that the medium is clear before attempting to transmit any frame. This procedure is known as Clear Channel Assessment (CCA). CCA must be repeated two successive times. If the channel was found busy, the values of NB and BE will be incremented by one (BE should not exceed a predefined value *macMaxBE*) and the value of CW will be set to 2, and then it checks the number of retries, if it is above to a certain predefined threshold *macMaxCSMABack-offs*, the communication will be terminated with a channel access failure status. If the number of retries is less or equal to *macMaxCSMABack-offs*, the algorithm returns to the point where the node waits for a new random number of back-off periods.

If the channel is found idle in both CCA, the node starts transmitting. But in case the channel is found busy in the second CCA, the algorithm checks whether the remaining time within the CAP area of the current superframe is sufficient. If it is, the algorithm proceeds, if not it simply stops and waits the next superframe and resumes the execution from the point it stopped.

In the CFP portion, the communication is totally controlled and managed by the coordinator; the communication from/to the nodes should be performed by requesting the right of access to the channel from the coordinator. Therefore the algorithm CSMA-CA will not be used; instead the coordinator will assign some free slots to nodes that need to transmit, within the area of the CFP portion.

### 3.3.3.2 CSMA-CA in a non-beacon enabled network

The operation of CSMA-CA algorithm in the beaconless network is schematically shown Figure3-10. It is very similar to the algorithm in the CAP portion of a beacon enabled network. The algorithm starts by initializing the parameters NB and BE to 0 and  $macMinBE$ , and then it waits for a random number of back-off periods units within the range  $0 - 2^{BE}-1$ . After that it needs to assure that the medium is not in usage by other nodes, therefore it waits two CCA periods and listens to the medium. If it is idle, the node may transmit, however if the channel is busy, the NB and BE parameters will be incremented by one. If the value of NB becomes greater than  $macMaxCSMABack-offs$  then the transmission will fail, if not the node waits again for a new random number of back-off periods and repeats the whole process.

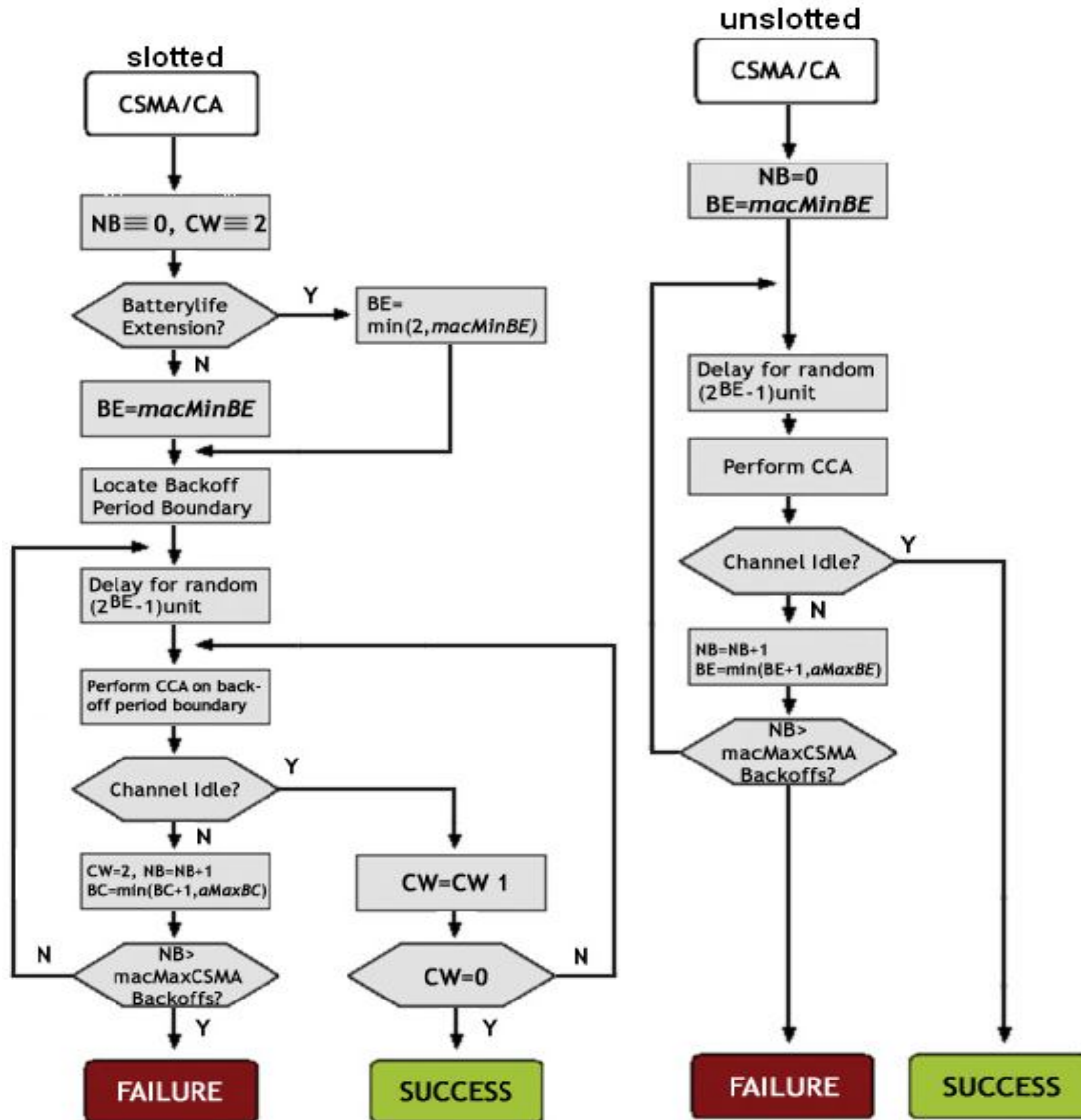


Figure 3-10 CSMA-CA operations in beacon and non-beacon enabled modes

### 3.3.4 Markov-chain Modeling

This is the most important part of this section. We will first represent the operation of the CSMA-CA algorithm in a Markov chain-based model. Then we will determine the mathematical equations that define it.

The Markov chain-based model of the MAC sub-layer proposed by Pollin et al. [POLL08] is a very accurate model that succeeded to represent the main properties, characteristics and operation of CSMA-CA, that's why our analytical study will be based on it.

### 3.3.4.1 System description

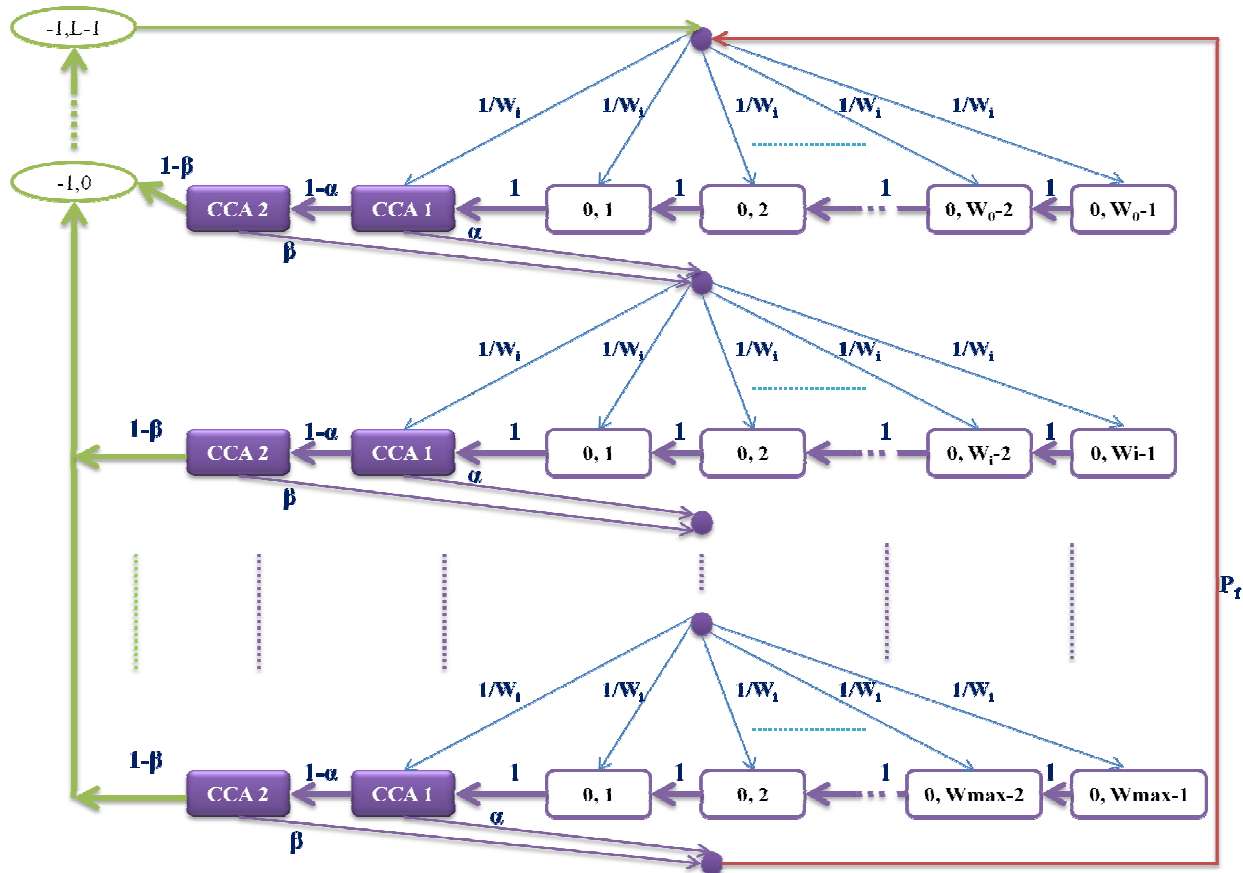


Figure 3-11 Discrete Markov chain representation of CSMA-CA protocol

In Pollin's study, a network composed of a fix number of devices ( $N$ ) is assumed. This network is supposed to be in a saturated traffic conditions, it means that every node of the network is always considered having packets to be transmitted.

Two stochastic processes are defined:

- $c(t)$ : the stochastic process representing the delay line and transmission duration counters of the device
- $s(t)$  : the stochastic process representing the delay line stages or the transmission stage.

These processes describe all the possible states that a node could experience to transmit frames.

If the value of  $s(t)$  is in the range of  $\{0..NB\}$ , it represents the delay line stage. However if  $s(t) = -1$ , it represents the transmission stage.

When the decrementing delay counter reaches zero, the values  $c=-1$  and  $c=-2$  correspond to the first CCA and the second CCA respectively.

An important assumption to represent these processes in a Markov chain-based model, is that the probability to start sensing the medium is independent of all other nodes.

The main goal here is to determine a set of equations that uniquely defines the network operation. We start by studying the behaviour of a single node. We define first the following variables:

- $\Phi$ : the probability that a node attempts its CCA for the first time within a slot.
- $\alpha$  : the probability of assessing the channel busy during the first CCA.
- $\beta$  : the probability of assessing the channel busy during the second CCA.

### 3.3.4.2 Mathematical equations

The two-dimensional Markov chain is characterized by the following transition probabilities:

- $P\{i, k | i, k + 1\} = 1, \quad k \geq 0 \dots \text{eq 3.1}$

- $P\{0, k|i, 0\} = \frac{(1-\alpha)(1-\beta)}{W_0}$ ,  $i < NB$ ... eq 3.2
- $P\{i, k|i-1, 0\} = \frac{\alpha+(1-\alpha)\beta}{W_i}$ ,  $i \leq NB$ ,  $k \leq W_i - 1$ ... eq 3.3
- $P\{0, k|NB, 0\} = \frac{(1-\alpha)(1-\beta)}{W_0} + P_f/W_0$ , ... eq 3.4

Eq 3.1 presents the condition to decrement the delay line counter per slot.

Eq 3.2 presents the case where the channel was sensed idle two consecutive times (during the first and the second CCA) and the node was able to transmit packets.

Eq 3.3 presents the case where the channel was sensed busy in one of the CCA time slots, and the node selects a new state in the next delay level

Eq 3.4 gives the probability of starting a new transmission attempt when leaving the last delay line, following a successful or failed packet transmission attempt.

$P_f$  is the probability of transmission failure. In fact the number of transmission attempts is limited, after exceeding this number the node will move to a state of transmission failure.

$W_i$  is the delay window. Its initial value is  $W_0 = 2^{aMinBE}$ , and then this value will be doubled every state until it reaches the maximal value :  $W_i = W_{max} = 2^{aMaxBE}$  ( $aMaxBE - aMinBE \leq i \leq NB$ ).

Between  $W_0$  and  $W_{max}$ ,  $W_i$  is defined as:  $W_i = W_0 * 2^i$  ... eq 3.5

Assume now that the Markov chain's steady-state probability is  $b_{i,k} = P\{(s(t), c(t)) = (i, k)\}$  for  $i \in \{-1, NB\}$  and  $k \in \{-2, \max(L-1, W_i-1)\}$

$$b_{i,k} = \lim_{t \rightarrow \infty} P(s(t) = i, c(t) = k).$$

Our aim is to determine the system of equations that define the Marko chain model. The variables that defines this system are  $\Phi$ ,  $\alpha$  and  $\beta$ .

The node can be in one of the following states:

- Back-off stage : where the node waits before listening to the channel to check if it is busy or not
- First CCA: once the back-off counter reaches zero, the node checks if the medium is free for the first time
- Second CCA: if in the first CCA the channel was free, the node will listen for the second time to verify that no other node is transmitting
- The node is transmitting: the duration of transmission is measured in slots. L is the total number of slots.

The sum of all probabilities should be equal to one.

$$\sum_{i=0}^{NB} \sum_{k=1}^{W_i-1} b_{i,k} + \sum_{i=0}^{NB} b_{i,-1} + \sum_{i=0}^{NB} b_{i,-2} + \sum_{i=0}^{L-1} b_{-1,i} = 1 \dots \text{eq 3.6}$$

Using the equations eq 3.1 to eq 3.4 we can get:

$$b_{i-1,0} * (\alpha + (1 - \alpha)\beta) = b_{i,0} \quad 0 < i \leq NB \dots \text{eq 3.7}$$

$$b_{i,k} = \frac{W_i - k}{W_i} \left\{ (1 - \alpha)(1 - \beta) \sum_{j=0}^{NB} b_{j,0} + P_f \right\} \quad \text{for } i = 0 \dots \text{eq 3.8}$$

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \quad \text{for } i > 0 \dots \text{eq 3.9}$$

The probability of the transmission failure  $P_f$  is calculated as:

$$P_f = b_{NB,0}(\alpha - \alpha\beta + \beta) \dots \text{eq 3.10}$$

From eq 3.5 we can get:

$$b_{i,0} = [(\alpha + (1 - \alpha)\beta)]^i * b_{0,0} \quad 0 < i \leq NB \dots \text{eq 3.11}$$

In order to calculate eq 3.6 we will substitute the parameter  $W_i$  and the variables  $b_{i,k}$  by their values from the equations: eq 3.5, eq 3.7 to eq 3.11, the equation eq 3.6 becomes:

$$\begin{aligned} \frac{b_{0,0}}{2} \left\{ [1 + 2(1 - \alpha) + 2xL] * \left[ \frac{1 - y^{NB+1}}{1 - y} \right] \right\} \\ + \frac{b_{0,0}}{2} \left\{ [2^{aMaxBE - aMinBE} * W_0] * \left[ \frac{y^{aMaxBE - aMinBE + 1} - y^{NB}}{1 - y} \right] \right\} \\ + \frac{b_{0,0}}{2} \left\{ W_0 * \left[ \frac{1 - [2y]^{aMaxBE - aMinBE + 1}}{1 - 2y} \right] \right\} = 1 \dots \text{eq 3.12} \end{aligned}$$

Where  $x = (1 - \alpha) * (1 - \beta)$ ; and  $y = \alpha + (1 - \alpha) * \beta$ .

Eq 3.12 is the first equation to define the two-dimension Markov chain, what remains are the equations related to  $\Phi$ ,  $\alpha$  and  $\beta$ .

The equation that derives the probability of the node to attempt its CCA for the first time within a slot is:

$$\phi = \sum_{i=0}^{NB} b_{i,0} \dots \text{eq 3.13}$$

Using eq 3.11 and eq 3.13 we obtain:

$$\phi = \sum_{i=0}^{NB} y^i * b_{0,0} \dots \text{eq 3.14} .$$

Eq 3.14 represents the second equation to define the system.

The calculation and the explanation required to determine the probabilities  $\alpha$  and  $\beta$  are too long and they are out of the scope of this report, therefore we will just use the equations presented in [POLL08].

$$\alpha = L * [1 - (1 - \phi)^{N-1}] * x \text{ or } \phi = 1 - \left[1 - \frac{\alpha}{L * y}\right]^{\frac{1}{N-1}} \dots \text{eq 3.15}$$

$$\beta = \left[1 - \frac{1}{1 + \frac{1}{1 - (1 - \phi)^N}}\right] * [1 - (1 - \phi)^N] \text{ or } \phi = 1 - \left(1 - \frac{\beta}{1 - \beta}\right)^{\frac{1}{N}} \dots \text{eq 3.16}$$

If we replace the value of  $b_{0,0}$  (eq 3.12) in eq 3.14, we obtain a system of three non-linear equations (eq 3.14, eq 3.15, and eq 3.16) that defines the network operation point. The values of these three variables ( $\alpha$ ,  $\beta$  and  $\Phi$ ) are sufficient to determine all the performance metrics of the network, such as throughput, collision percentage, energy consumption, end-to-end delay, energy recovered and the lifetime of the network as we are going to prove later in the next chapter.

### 3.4 Summary

Battery characteristics and IEEE 802.15.4 CSMA-CA protocol are the basis of our new work. In this chapter we have overviewed their theories and their Markov chain representation. In the next chapter we will use them develop the battery-aware CSMA-CA protocol.

## Chapter 4 Battery-Aware CSMA-CA Protocol

### 4.1 Introduction

In this chapter, we will introduce the basics of our novel approach, and we will prove that the modifications we suggest to add on the CSMA-CA protocol will improve its performance by increasing the average lifetime of the node and the total life duration of the network.

In fact the network lifetime is a key characteristic for evaluating sensor networks; it includes especially the availability of nodes, the sensor coverage, and the connectivity of the nodes [DIET09]. That's why many researchers investigated via simulations and experiments the estimation of WSNs lifetime [NGUY11], [KERA10], [BARB08].

We will extend the previous Markov chain representation to define our new model that includes the charge recovery mechanism. Then we will validate our idea by solving numerically the mathematical equations in C language and we will demonstrate that the performance of the algorithm has been improved in many aspects.

This chapter consists of five main parts. The first part is the current introduction. The second part is about the system description. We present our algorithm in the third part. We show and discuss our results in part four and we summarize in part 5.

## 4.2 System description

As we previously explained in the preceding chapter, a battery may gain some charge units if it remains unused for some period of time, which means that the node power will grow if this node is in idle or sleep mode (back-off period).

According to the conventional CSMA-CA, the node has  $W_i$  possible idle state, and in each state there is a probability that the remaining voltage of the node battery will increase due to the recovery capacity effect. This probability is defined by:

$$\left\{ \begin{array}{ll} R_{N_i T_i} = e^{-g*(N-N_i)-\phi(T_i)} & \text{if } (1 < N_i < N_i) \\ & 1 < T_i < T) \\ R_{N_i T_i} = 0 & \text{otherwise} \end{array} \right\}$$

Then the node listens to the medium. Depending on the availability of the channel, the battery may lose energy in the first CCA, in the second CCA and/or in the L time slots of packet transmission, before going back to the next level of back-off stage where it will probably recover more charges.

Figure 4-1 illustrates the behaviour of the node battery when applying CSMA-CA algorithm.

We assume that during this back-off period the losses of battery power are very minimal so we neglect them. Therefore we assume that the battery at every state during this period may keep the same voltage value or it may recover one charge unit. However the voltage level cannot exceed at any time the current nominal neither the theoretical value of the battery voltage.

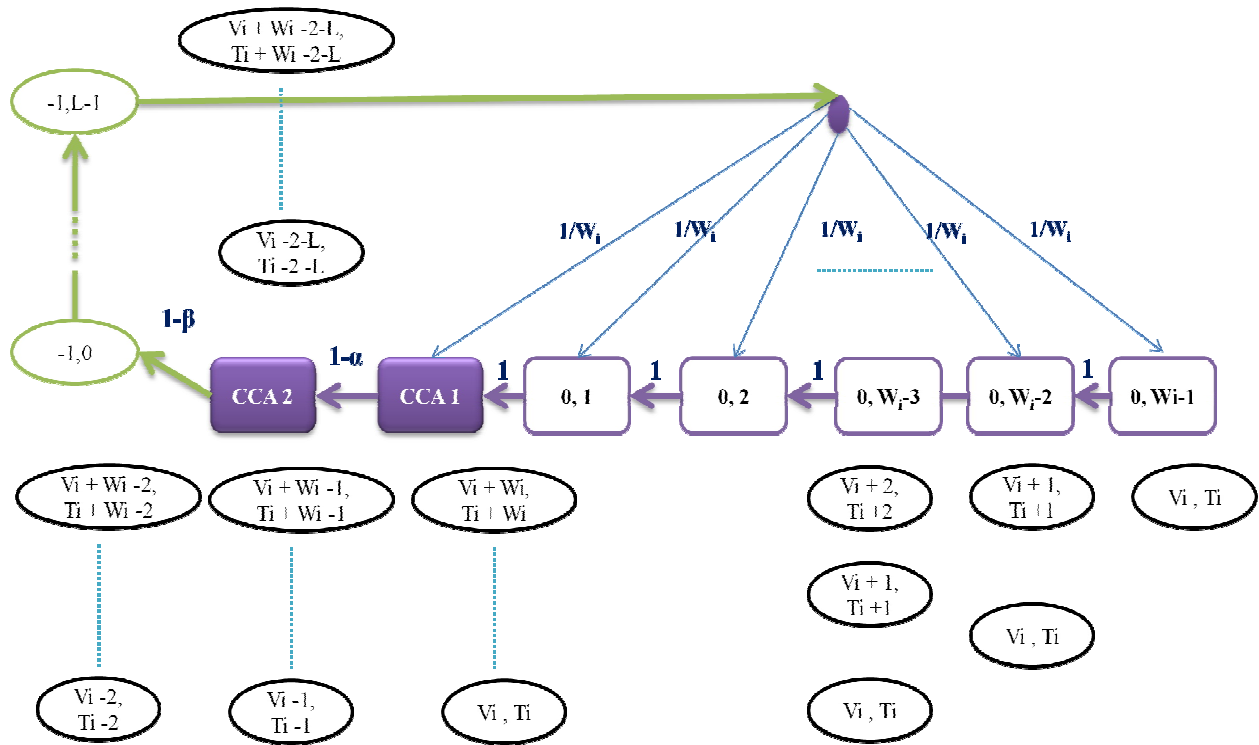


Figure 4-1 Real battery behaviour of a node during CSMA-CA protocol execution

In Figure 4-1, the initial state of the battery at the beginning of the back-off period is  $\langle V_i, T_i \rangle$ . After one time slot, the battery may recover one charge unit and its state changes to  $\langle V_i + 1, T_i + 1 \rangle$  or it may stay in its initial state without gaining any new charges  $\langle V_i, T_i \rangle$ . Again the same process repeats after each time slot in the back-off phase, the battery voltage level may increase with an additional charge unit or it may keep the current voltage value. Then it loses one charge unit after CCA1 and CCA2 (if the channel was clear), and drops by  $L$  charge units when the node transmits the packet.

### 4.3 Algorithm

We assume first that the discharge rate of the node battery in each of the following state is one charge unit per state: the first CCA, the second CCA and each of the  $L$  states.

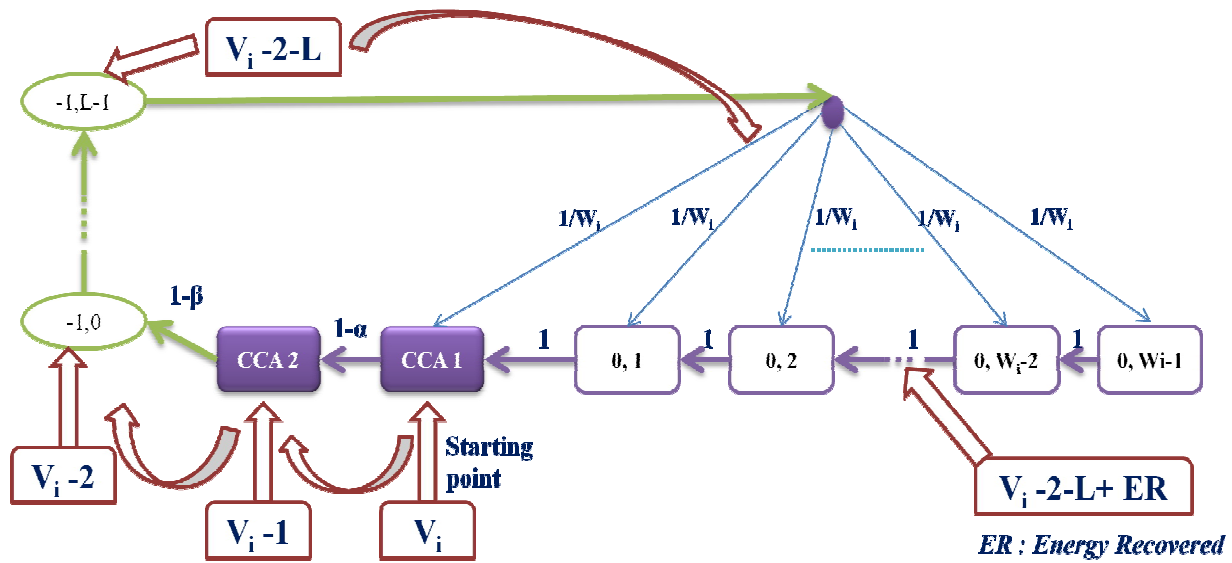


Figure 4-2 Battery nominal voltage at every stage of CSMA-CA protocol

In Figure 4-2 we summarize our algorithm. For the sake of simplicity, we only illustrate one cycle of operation and we assumed the best case scenario in which the channel is sensed free in two consecutive CCA, and in which the node succeeded to transmit its packets.

We assume that our cycle starts at a point where the node is at the first CCA. We assume that  $V_i$  is the nominal voltage of the battery at that state. The node will then check the medium, if the medium is free, the new node state will be in the second CCA and the battery voltage will drop by one charge unit. The new nominal voltage will be:  $(V_i-1)$  charge units.

The probability to reach the second CCA is  $(1-\alpha)$ . The node will sense the channel again, and there is a probability of  $(1-\beta)$  that the channel is free; if it is, the node will jump then to the transmission state and the battery voltage will drain an additional charge unit. The new nominal voltage will be:  $(V_i-2)$  charge units.

The node will start transmitting the packet. The duration of the transmission is assumed to be  $L$  time slots, at each slot the capacity of the battery will decrease one charge unit. At the end of the transmission the new nominal voltage will be:  $(V_i - 2 - L)$  charge units.

The node will return to the back-off period in one of these three cases:

- After the first CCA, if channel was sensed busy.
- After the second CCA, if channel was sensed busy.
- or After transmitting the packets

There are  $W_i$  states, and the probabilities to be in one of these state are equal and uniform  $(1/W_i)$ , Therefore, in order to simplify the calculation, we assume that the number of charges that can be recovered during this period is the average value:

$$\frac{W_i}{2} * R_{N_i, T_i} = \frac{W_i}{2} * e^{-g*(V-V_i)-\phi(T_i)}$$

The new nominal voltage will be:  $(V_i - 2 - L + ER)$  charge units, where  $ER$  is the energy recovered.

What follows is our detailed algorithm.

**% Definition of the parameters**

```

N = 50; % Number of nodes in the network
aMinBE = 3; % Minimal value of BE
aMaxBE = 8; % Maximal value of BE
macMAXCSMABack-offs = 5; % Maximum number of Back-offs before the transmission is
%considered a failure

L = 14; % 14 time slots duration of transmission
g = 0.025; % constant related to the characteristics of the materials in
%the battery

```

```

Vmax=65,000;           %Initial value of the nominal voltage: 65000 charge units
Tmax=100,000;         % Initial value of the theoretical voltage: 100,000 charge
                      %units

% Variable Declaration
Int i;                 % index

V[i];                 % Remaining nominal voltage in the battery
                      % V[0] is assumed to be the initial nominal voltage ( $V_{max}$ )

T[i];                 % Remaining theoretical voltage in the battery
                      %T[0] is assumed to be the initial theoretical voltage ( $T_{max}$ )

PhiT[i]               % The variable that defines the piecewise constant function
                      % included in the recharge probability function

Alpha; Beta, Phi;    % the variables that define the Markov chain model
ELost;                % Energy lost at each state
ER;                   % Energy recovered
Per;                  %Recover probability function

p1, p2, p3;          % Variables to calculate the probabilities
BE;                   % Back-off Exponent
NB;                   % Number of back-offs
W0, W;               %Back-off parameter

TimeSim[i]           % Simulation time
TR;                   % Number of retries in case of a collision
fail;                 % Boolean variable. In case of transmission failure,
                      %fail=1;

% Body of the algorithm

1. Solve the nonlinear equation system to calculate Alpha, Beta and Phi;

2. Define the function that helps to determine PhiT

function ValueofV(double v){

    if v is greater than 0.975 then return 0;
    if v is between 0.5 and 0.975 then return 0.0025;
    if v is between 0.025 and 0.5 then return 0.008;
    if v is less than 0.025 then return 15.6;

}

```



*else*

*p2 is less than 1-Betta, in another word if the channel was not clear at the second CCA, so the node failed to transmit,*

*Update fail*

**fail = 1;**

*} else*

*p1 is less than 1-Alpha, in another word if the channel was not clear at the first CCA, so the node failed to transmit,*

*Update fail*

**fail =1;**

*In case of a transmission failure*

**If fail==1 then**

**{**

*Increment NB by one*

**NB = NB + 1;**

*Then check if NB exceeds macMaxCSMABack-offs*

**If NB>maxMaxCSMABack-offs then**

**{**

*Reset the values of NB and BE*

**BE=aMinBE;**

**NB=0;**

**}**

**Else**

*If it is less then macMaxCSMABack-offs*

*Increment the value of BE by one as long as it is less then aMaxBE*

*Update the value of BE*

**BE = min(BE+1,aMaxBE);**

**}**

*Reset the parameter fail*

**fail =0;**

*Update the value of W0*

**W0 = 2^BE;**

*The new nominal voltage of the node battery is decreased by Elost,*

*Update V[i]*

**V[i] = V[i-1] - Elost;**

The new theoretical voltage of the node battery is decreased by **Elost**,

Update **T[i]**

**T[i] = T[i-1] - Elost;**

Whether the node failed at the first CCA, failed at the second CCA, failed during transmission (collision), or transmitted successfully, it is now at the back-off stage,

Set the back-off period **W**, it is a random value between **1** and **W0**

**W=random();**

Now at every state of the back-off period, there is a probability **Pre** to gain back one charge unit,  
At every state of the back-off period do the following

**for W states do**

{

Calculate the function **Phik[i]** to be able to determine the probability of recharge

Update **Phik[i]**,

**Phik[i]=ValueofV(T[i]/T[0]);**

Calculate **Pre**

**Pre = exp(-g\*(V[0] - V[i]) - Phik[i]);**

Create a probability **p3** and compare it to **Pre**,

if **p3** is greater than **Pre**, then the node recuperate one charge unit

**If p3 < Pre then {**

Increment the energy recovery variable **ER** by one

**ER = ER + 1;**

The sum of the current nominal energy and the energy recovered should be less then **Vmax** and less then **Tmax**,

**If ( (V[k]+ER <= V[0]) && (V[k]+ER <= T[k]) ) then**

{

The new battery capacity is

**V[k] = V[k] + ER;**

}

}

}

**}%end of the while loop**

## 4.4 Results and validation

To validate our scheme, we implemented our mathematical model in C language. To reveal the benefits of introducing the charge recovery mechanism into the plain CSMA-CA protocol, we calculate the following performance metrics and we compare them with the conventional CSMA-CA: Average charge recovery, average lifetime of a node and total lifetime of the network.

### 4.4.1 Average charge recovery

It is the average amount of charges recovered by the network. In the usual CSMA-CA protocol, the capacity recovery effect is not considered and thus no charges are recovered. However, in our proposed model, the nodes of the network are able to re-gain a portion of the charges when they become idles.

Figure 4-3 illustrates the average quantity of charges recuperated by the nodes in networks with different sizes. We note that the initial nominal and theoretical voltages are 65,000 charge units and 100,000 units respectively when the battery of the node is full. Therefore the maximum number of charges we can recover is the difference between these two values which equal to 35,000 charge units. The average number of charges recovered with the network consisting of 50 nodes is 11,356 charge units which is equivalent to 32.5% of the total amount.

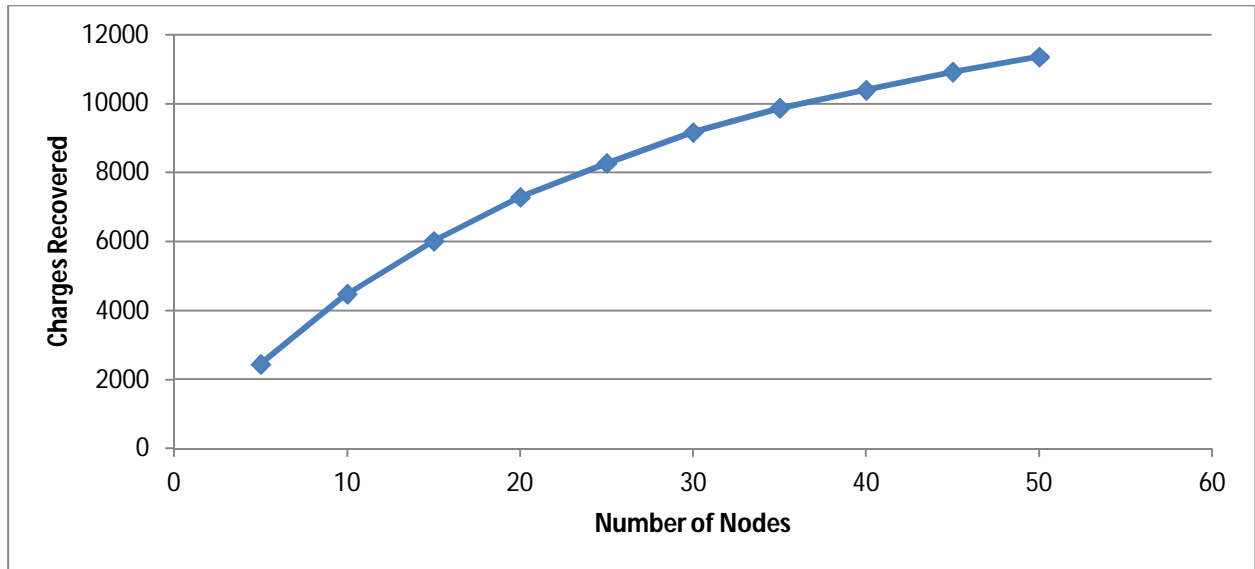


Figure 4-3 Charges recovered with the new scheme

#### 4.4.2 Average lifetime of a node

The lifetime of the node is the period of time during which the node has power. It starts with the first moment the node is activated and ends when the battery is completely drained out of energy.

We proved in the previous part that the number of charges used by the nodes is greater with the new scheme than with CSMA-CA, therefore we expect that the average lifetime of the node to be extended accordingly.

In Figure 4-4 we show the average lifetime of a node in different networks, and we compare the results of the new scheme with CSMA-CA. At N=50 nodes, the average lifetime of a node with CSMA-CA is 335 seconds, and 392 seconds with the new scheme. This presents an enhancement of 17.2%.

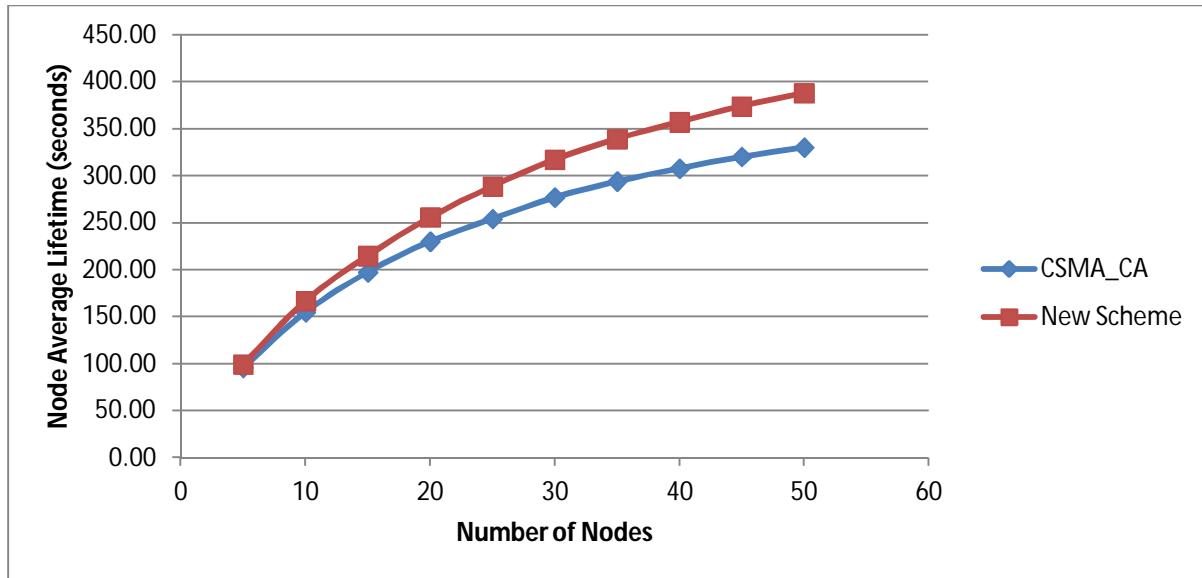


Figure 4-4 Average lifetime of a node

#### 4.4.3 Lifetime of the network

We define the lifetime of the network as the duration of time in which at least one node is still alive. It begins when all the nodes are activated and running and terminates when the last node of the network expires.

Figure 4-5 clearly demonstrates that the network with our proposed scheme survive longer than the network with CSMA-CA protocol. In fact, there is an improvement of 17.2%.

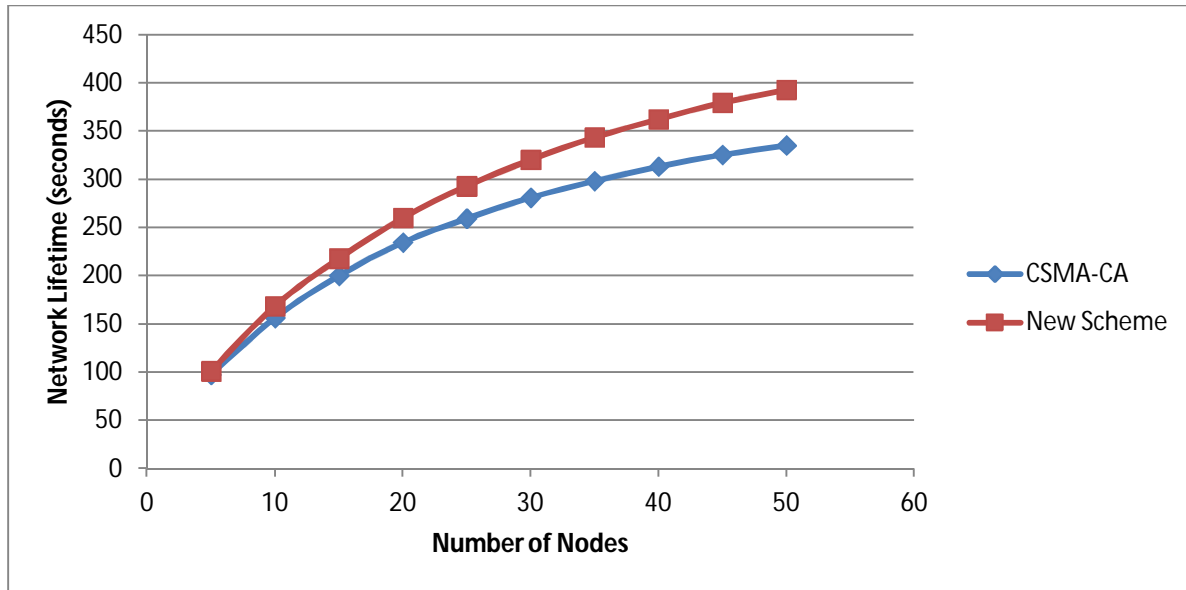


Figure 4-5 Total Lifetime of the network

We achieve the same conclusion in Figure 4-6 and Figure 4-7 which compute the number of remaining alive nodes in case of  $N=25$  nodes and  $N=50$  nodes.

The results presented in Figure 4-6 show that all the nodes of the network become inactive after 259 seconds and 293 seconds with CSMA-CA and with the new scheme respectively. So, the number of alive nodes has incremented by 13%.

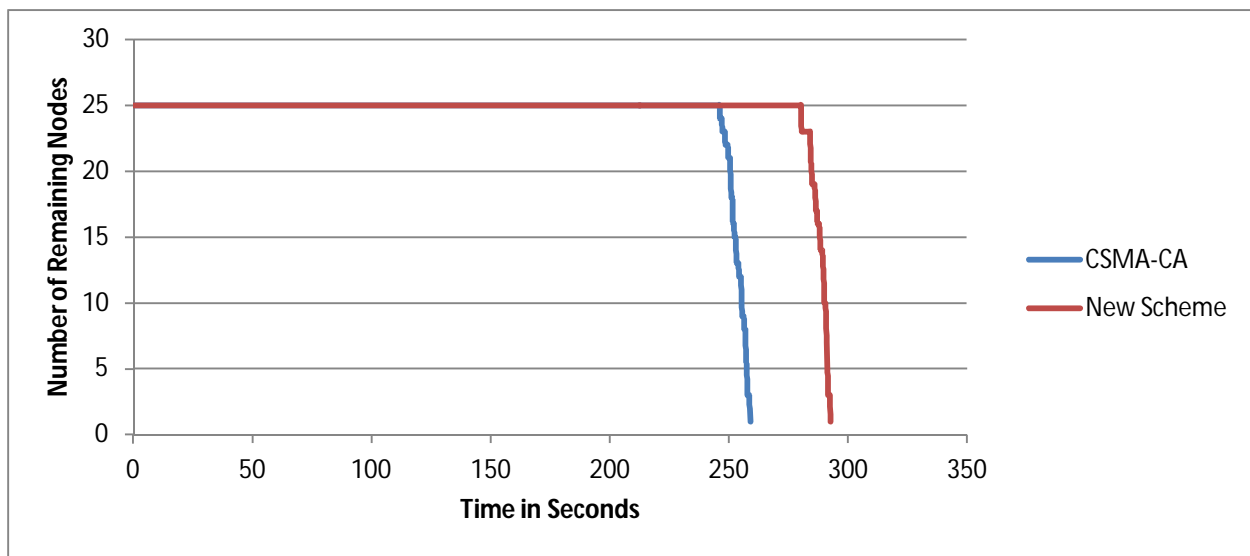


Figure 4-6 Number of remaining alive nodes ( $N=25$ )

With a bigger network composed of 50 nodes, the improvement is higher. The number of remaining alive nodes over time has increased by 17.2% (see Figure 4-7)

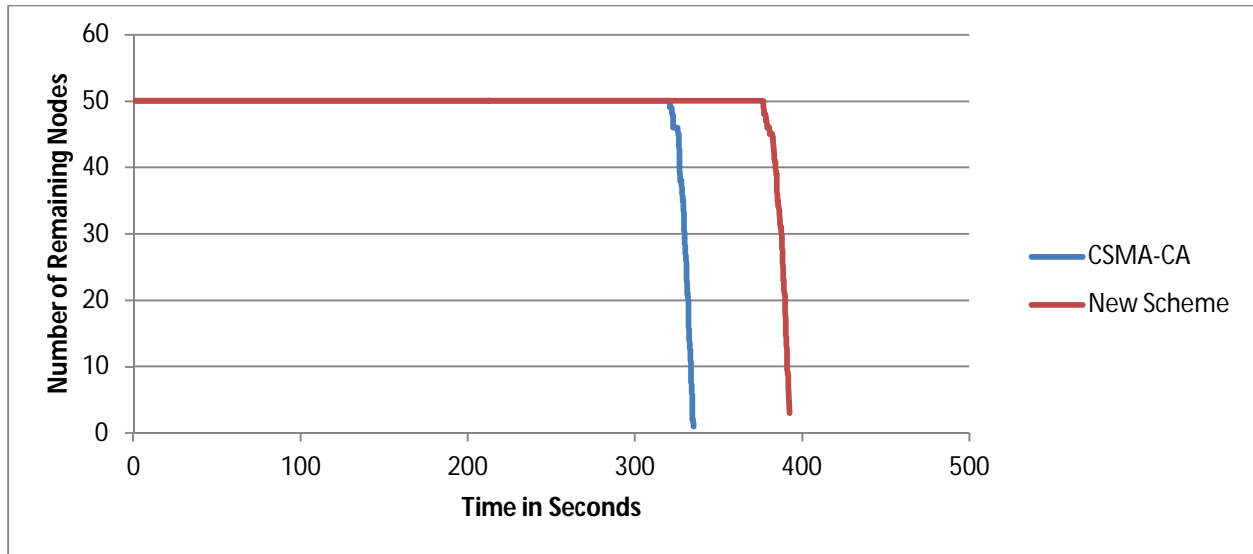


Figure 4-7 Number of remaining alive nodes (N=50)

## 4.5 Summary

In this chapter, we demonstrated that incorporating the battery characteristics, precisely the pulsed current discharge and the energy recovery mechanism, in the design of CSMA-CA protocol had a great impact on the overall lifetime of the network and on the average life duration of the nodes. In fact, we verified through analytical simulation, that the total lifetime of the network has raised by more than 17% compared to the plain CSMA-CA, after considering the battery effects. Moreover, we proved that the nodes could recover more than 32% of the unused charges.

These results present evidence that new approaches can be developed in the MAC sub-layer of the WSNs protocol stack to save more energy, to optimize the usage of power and to increase the lifetime of the network. We refer to these approaches as "Battery-aware MAC protocols". In the

following chapter, we will propose two new Battery-aware MAC protocols, in which the MAC sub-layer take into account the battery state in its computation to attain superior outcomes.

# Chapter 5      **Battery-Aware Energy-Efficient**

## **MAC Protocols**

### **5.1 Introduction**

As we stated earlier in this thesis, only few battery-aware MAC protocols that consider battery characteristic factors have been reported. The majority of the existing MAC protocols that deal with the power consumption matter and the energy conservation subject are founded on the development of new duty-cycle schemes in the MAC sub-layer, without any connection to the actual status of the battery. Moreover, all these protocols do not consider the real charge/discharge operations that take place in the battery, and they don't take advantage of the existing effects and mechanisms that occur during these processes.

For example, in a large network, where the number of sensor nodes exceeds 50, the node's idle time can be higher than 97% of the time. This means that the node transmits packet in less than 3% of the time and rests for the remaining period. Therefore, taking into consideration the pulsed current discharge effect and the charge recovery mechanism of the battery will firstly show a realistic performance of the nodes, secondly it will allow a better modeling of the wireless sensor network behaviour, and thirdly it will demonstrate enhanced results in terms of power savings and network lifetime.

In this chapter, we propose two battery-aware MAC schemes, and investigate their advantages and disadvantages in the context of the CSMA-CA protocol. The target is to exploit the capacity recharge effect in order to extend the lifetime of the node/network, and enhance the throughput.

Therefore, we propose two new back-off methods that consider the battery's current capacity in their functionalities. In another word, the back-off period defined in CSMA-CA protocol will be changed in our proposed protocols; it will be related to the remaining battery voltage at the actual time of operation, and thus the back-off duration before attempting to access the channel, will depend on the current battery state.

And eventually we explore, through simulations, the performance of our approaches compared to each other, and compared to the conventional CSMA-CA protocol in terms of node/network lifetime, throughput, percentage of collisions, and energy recovered.

## 5.2 Our proposed protocols

Based on the results we attained in the previous chapter, we know now that introducing the probability of battery recharge in the functionality of the CSMA-CA protocol will improve its performance in terms of power recovery and lifetime extension. So the question is how to exploit this conclusion to design a new enhanced protocol?

In addition to that, we know also from the previous chapters two important things:

- The amount of charges that the battery gains, depends on the duration of the resting time. The longer the battery remains unused (in idle or sleep mode), the higher is the amount of charges it recovers

- The amount of charges that the battery recovers, depends on the current remaining voltage. The battery recuperates more charges in case of high residual voltage than with small remaining energy.

The abovementioned points led us to think about the following:

In order to achieve better network performance, which nodes should have higher priority to rest more? Should we give priority to the nodes with higher residual voltage to relax longer than the nodes with lower voltage level? Or should it be the opposite way?

In fact, based on the first point, we should offer more relaxing time to the nodes with low battery level so they can recover more charges and live longer. However, the second point implies that these nodes will not be able to gain enough power due the lack of active materials in the batteries.

Conversely, the second point suggests that we should provide the nodes with higher residual capacity the priority to rest longer, because their batteries will be capable of gaining the maximum amount of charges. However, the other nodes with low battery power will be intensively used and they will be exhausted so quickly, then the overall operation of the network will be affected.

Based on this brief discussion, we propose two battery-aware MAC protocols:

- The first protocol let the nodes with lower battery power to stay idle longer than the nodes with higher battery power. It means that the nodes with higher remaining voltage will access the medium faster. We refer to it as MAC-HV.

- The second protocol allows the nodes with higher remaining voltage to relax more than the nodes with lower remaining voltage. It means that the nodes with lower remaining voltage will access the medium faster. We refer to it as MAC-LV.

And then we will study the performance of both protocols, explore their impacts on the overall operation of the network, and finally compare their results with the IEEE 802.14.5 CSMA-CA protocol.

### 5.2.1 MAC-HV Protocol

In this protocol, we propose that the nodes with higher remaining voltage in their batteries have the priority to access the medium before the nodes with lower remaining voltage. In other words, with this protocol, the nodes with lower remaining voltage will stay in idle or sleep mode longer than the nodes with higher remaining voltage.

Consequently, we need to define a new back-off function that takes into account the current residual voltage in the battery, and use it to extend the idle period of the nodes with lower residual voltage, and thus give them low priority to access the medium. We refer to this back-off function as BP-HV.

Assume that  $V$  is the initial value of the voltage when the battery is full, and  $V_i$  is the current remaining value of the voltage after some time of operation. We define the back-off period function of MAC-HV as:

$$BP - HV = Uniform(1: 2^{BE} + 2^{BE} * (1 - \frac{V_i}{V}))$$

It is clear here that when  $V_i$  is closer to  $V$  (high voltage) the value of the BP-HV decreases. This means that the node with higher value of voltage will wait less time to access the medium than the other nodes. And if  $V_i$  is much smaller than  $V$  the value of BP-HV increases (low voltage), so the node with low value of voltage will wait longer to access the medium.

It is important to note that  $V$  and  $V_i$  represent the nominal voltage of the battery, not its theoretical voltage.

### **5.2.1.1 Flow chart**

The following flow chart illustrates how MAC-HV protocol operates in the case of CSMA-CA protocol. We highlighted in green the blocks where we include our modifications.

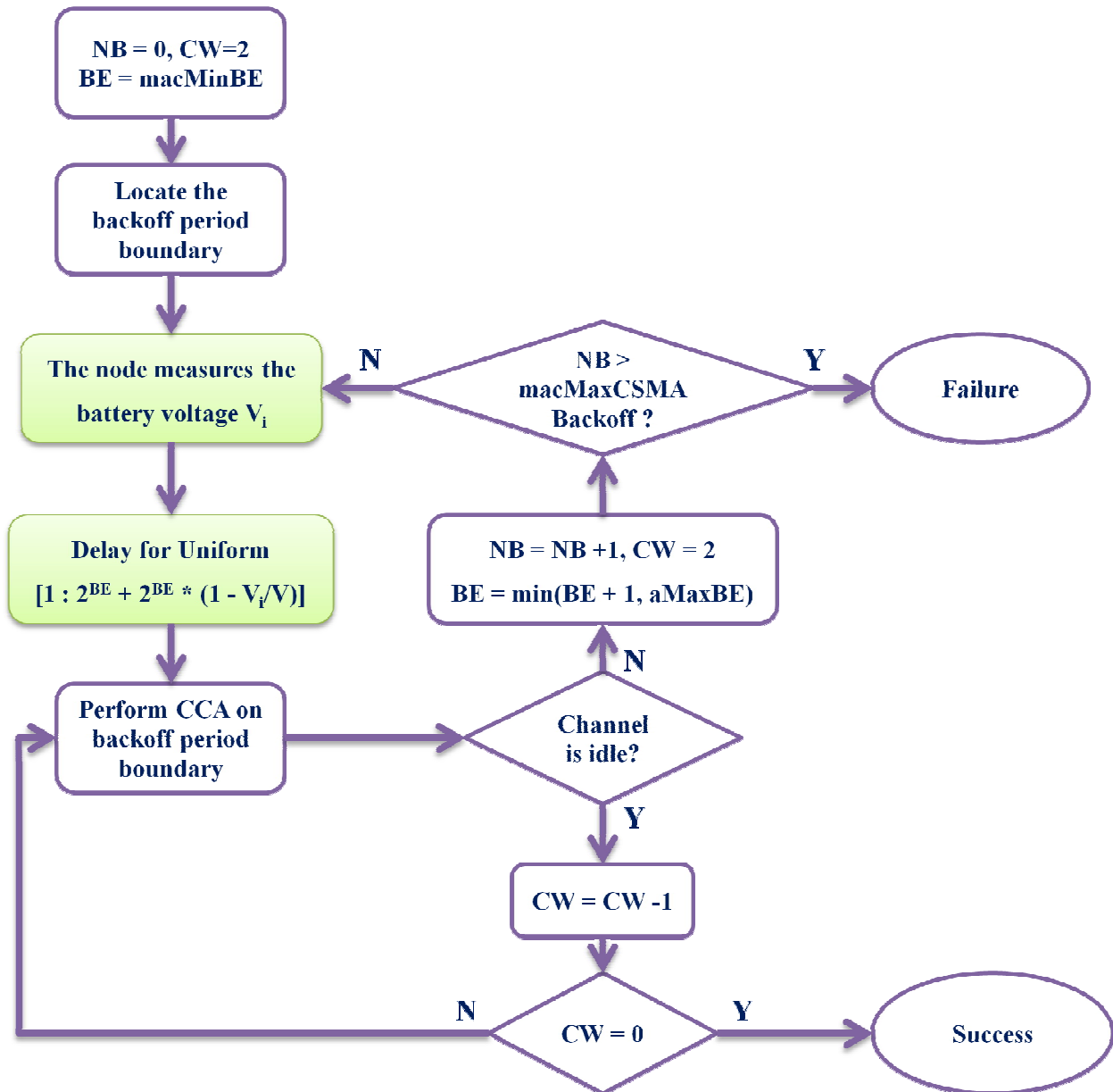


Figure 5-1 Flow chart of MAC-HV protocol

### 5.2.1.2 Algorithm

The protocol MAC-HV operates as follows:

```

% First step is the initialisation
If a node wants to transmit a packet then
{

```

*Initialise the local parameters, BE, NB and CW.*

***BE = macMinBE;***

***NB = 0;***

***CW = 2;***

***}***

***% Second step (after locating the back-off period boundary in case of slotted CSMA-CA) is to read the current battery voltage***

*Read the current remaining voltage of the battery;*

***V<sub>i</sub> = current voltage;***

***% Third step is to calculate the back-off period and stay idle during this period***

*Calculate Back-off-period*

***Back-off -period=random(1 : 2<sup>BE</sup> + 2<sup>BE</sup> \* (1-V<sub>i</sub>/V));***

***While (back-off-period > 0) do***

***{***

*Stay idle;*

*Decrement back-off-period;*

***Back-off-period = back-off-period - 1;***

***}***

***% forth step is to perform the double clear channel assessment***

*Perform CCA1;*

***If the channel is idle then***

***{***

*Decrement CW by one*

**$CW = CW - 1;$**

***If  $CW = 0$  then***

***{***

*Transmit the packets*

***}***

***Else***

***{***

*Return to the forth step*

***}***

***}***

***Else***

***{***

*Update the parameter values.*

**$BE = \min (BE + 1, aMaxBE);$**

**$NB = NB + 1;$**

**$CW = 2;$**

*Check now if the number of retries is higher than the threshold value*

***If  $NB > macMaxCSMABack-off$  then***

***{***

*Packet transmission has failed;*

***}***

***Else***

```

    {
        Return to the second step;
    }
}
% End of the algorithm

```

### 5.2.2 MAC-LV Protocol

This protocol grants access to the medium to the nodes with low remaining capacity, these nodes will have the precedence right to use the channel before the nodes with higher power. This means that, in this approach, the nodes with higher remaining capacity will have the chance to relax more than the other nodes.

As a consequence, we should identify a new back-off function that considers the actual battery voltage in its computation, and that allows the low power nodes to transmit their packets before the high power nodes. We refer to this back-off function as BP-LV.

BP-LV is defined as:

$$BP - LV = Uniform(1: 2^{BE} + 2^{BE} * \frac{V_i}{V})$$

$V_i$  and  $V$  are always the current nominal voltage and the initial nominal voltage respectively

In this case, BP-LV decreases when  $V_i$  decreases and increases when it does. A node with weak battery ( $V_i$  is too small) will guarantee access to the medium before the nodes with high battery voltage.

### 5.2.2.1 Flow chart

We demonstrate the protocol MAC-LV functions in the next flow chart. The green blocks present the changes we applied to the conventional CSMA-CA protocol. The main difference with MAC-HV protocol is the calculation of the back-off function.

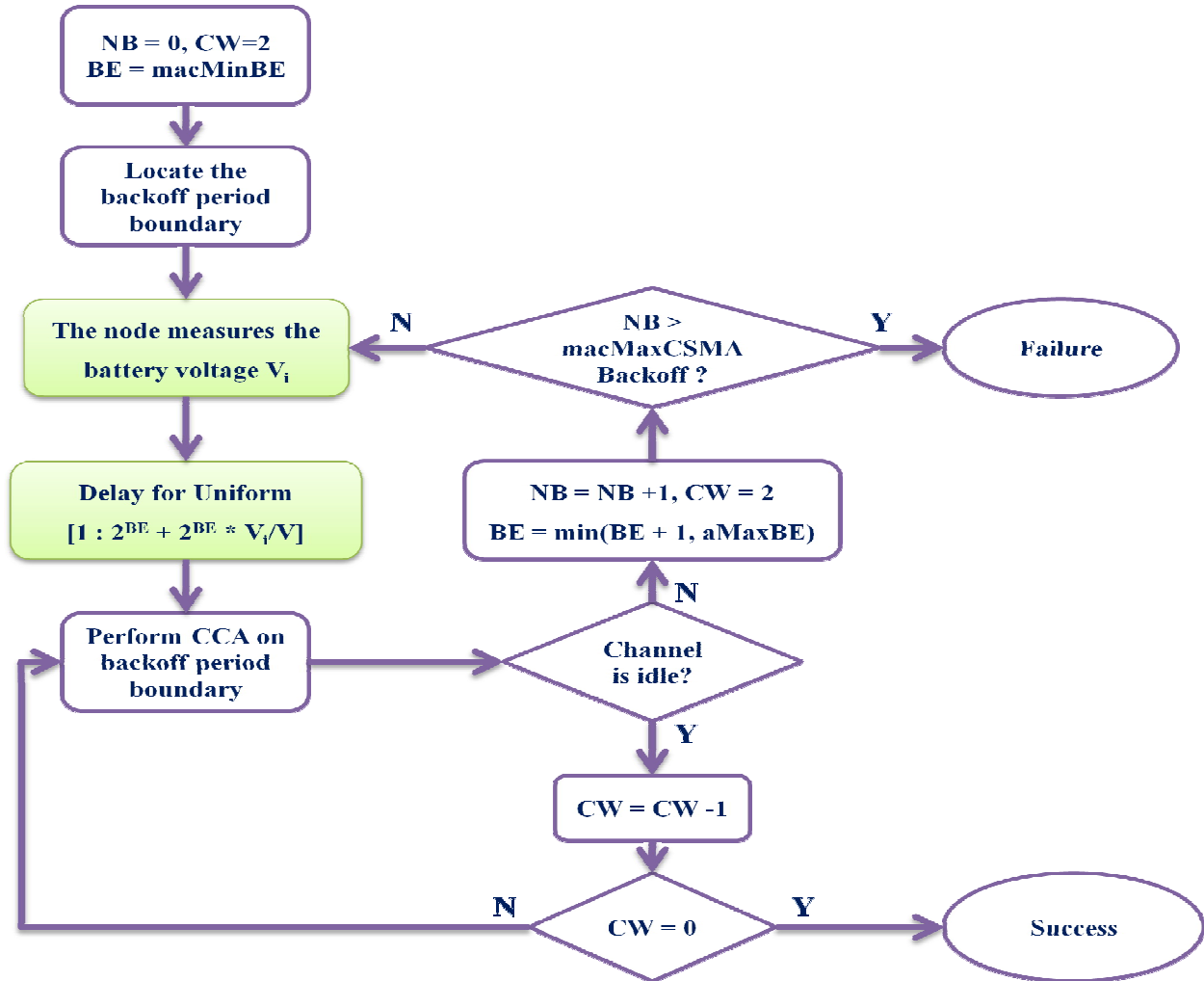


Figure 5-2 Flow chart of the MAC-LV protocol

### 5.2.2.2 Algorithm

The algorithm of the protocol MAC-LV is very similar to the algorithm of MAC-HV described in details in the previous section. The main difference is the calculation of the back-off period.

**% First step is the initialisation**

***If a node wants to transmit a packet then***

***{***

*Initialise the local parameters, BE, NB and CW.*

***BE = macMinBE;***

***NB = 0;***

***CW = 2;***

***}***

***% Second step (after locating the back-off period boundary in case of slotted CSMA-CA) is to read the current battery voltage***

*Read the current remaining voltage of the battery;*

***V<sub>i</sub> = current voltage;***

***% Third step is to calculate the back-off period and stay idle during this period***

*Calculate Back-off-period*

***Back-off -period=random(1 :  $2^{BE} + 2^{BE} * V_i/V$ );***

***While (back-off-period > 0) do***

***{***

*Stay idle;*

*Decrement back-off-period;*

```

Back-off-period = back-off-period - 1;
}
% forth step is to perform the double clear channel assessment

Perform CCA1;
If the channel is idle then
{
Decrement CW by one
CW = CW -1;
    If CW = 0 then
    {
        Transmit the packets
    }
    Else
    {
        Return to the forth step
    }
}
Else
{
    Update the parameter values.
BE = min (BE + 1, aMaxBE);
NB = NB + 1;
}

```

```
CW = 2;
```

```
Check now if the number of retries is higher than the threshold value
```

```
If NB > macMaxCSMABack-off then
```

```
{
```

```
Packet transmission has failed;
```

```
}
```

```
Else
```

```
{
```

```
Return to the second step;
```

```
}
```

```
}
```

```
% End of the algorithm
```

### 5.3 Simulation and performance analysis

In this section we study the performance of our proposed schemes and compare them with the performance of the conventional CSMA-CA protocol. We implemented a simulator for the energy efficient battery aware MAC protocols in the C programming language. We verified first the accuracy of the simulator by running it over multiple networks, with different sizes, using the conventional CSMA-CA protocol, and we found that the outcomes are totally compatible.

We obtained our results by executing the simulator over ten networks with the following sizes: 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 nodes.

The simulator stops only when all the nodes of the network run out of power.

We assume the following:

- Each node with enough power can participate in the communication process
- In case of packet transmission, two possible actions may occur: the transmission is completed successfully or there was a collision during the transmission.
- If the transmission was successful, an ACK packet will be generated by the destination

The performance is studied in terms of the following parameters: channel utilization, percentage of collisions, average idle time, average energy recovered by a node, average lifetime of a node, the total lifetime of the network, and the number of remaining alive nodes over time.

We define these metrics as follows

- The channel utilization (or the throughput) is the fraction of the total successful transmission time over the total time of the simulation.
- The collision is the fraction of the total collision time over the total time of the simulation.
- The average idle time is the fraction of the time when the channel was idle over the total time of the simulation.
- The average energy recovered by a node is the sum of energy recovered by all nodes divided by the number of nodes
- The average lifetime of a node is the ratio of the total life time of all nodes in the network over the total number of nodes
- The total lifetime of the network is the period of time that starts at the beginning of the simulation and ends when the last node of network expires

- The number of remaining alive nodes over time is the number of nodes in the network that are still involved in the communication over time.

The energy consumed by a node during the simulation includes the following:

- The energy consumed during the clear channel assessments (CCA 1 and CCA 2)
- The energy consumed during the successful transmission
- The energy consumed during failed transmission (collision)
- The energy consumed during receiving data
- The energy consumed during ACK

The energy consumed during idle time was neglected.

### 5.3.1 Simulation Parameters

Our simulation parameters are adopted from [JAYA04], [CHIA99c] and [POLL08], and listed in Table 5-1 and Table 5-2.

Parameter	Value
g (Battery parameter)	0.05/mJ
Theoretical capacity (c.u)	100,000 charge units
Nominal capacity (c.u)	65,000 charge units
Theoretical capacity (j)	0.4 Joules
Nominal capacity (j)	0.2 Joules
Energy recovery	0.05 mJ /idle timeslot

Table 5-1 Simulation parameters

<b>Power Consumed (mW)</b>	Rx	40
	Tx	30
	CCA	40
	Sleep	0.8
<b>Durations</b>	1 timeslot	0.32 ms (80 bits)
	Packet Length (L)	14 timeslots
	ACK Packet Length (LACK)	2 timeslots
	Simulation Time	320 s
<b>802.15.4 Parameter Settings</b>	macMaxCSMABack-offs	5
	macMinBE	3
	macMaxBE	8

Table 5-2 Simulation parameters

We note that every time a node sends a packet, it loses one charge unit. On the other hand, every time a node rests for one time slot, there is a probability  $R_{NiTi}$  that it will recover one charge unit.

In the following subsections we show our results along with our analysis and discussions.

### 5.3.2 Channel utilization

In Figure 5-3 we show the performance in terms of channel utilization. We can clearly see that our proposed schemes outperform the CSMA-CA protocol in terms of this parameter. Also, we can see that MAC-LV performs much better than MAC-HV. In fact, the CSMA-CA protocol does not rely in its computations on the battery's remaining voltage. This is in contrast to the other two proposed schemes. In these schemes, the battery recovers partially its capacity, and therefore, it allows the node to conserve more energy and send more packets. We can notice from Figure 5-3 that the channel utilization under the MAC-LV protocol surpasses that of the CSMA-CA protocol by 18.75%, while it surpasses the MAC-HV protocol by 13.74%.

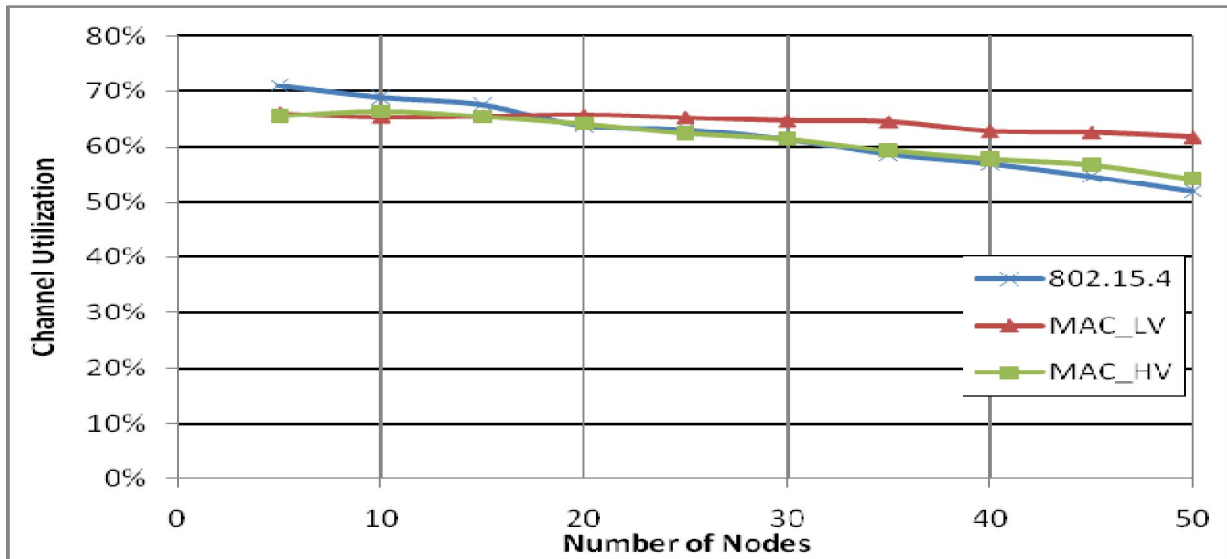


Figure 5-3 Channel utilization (Throughput)

### 5.3.3 Percentage of collisions

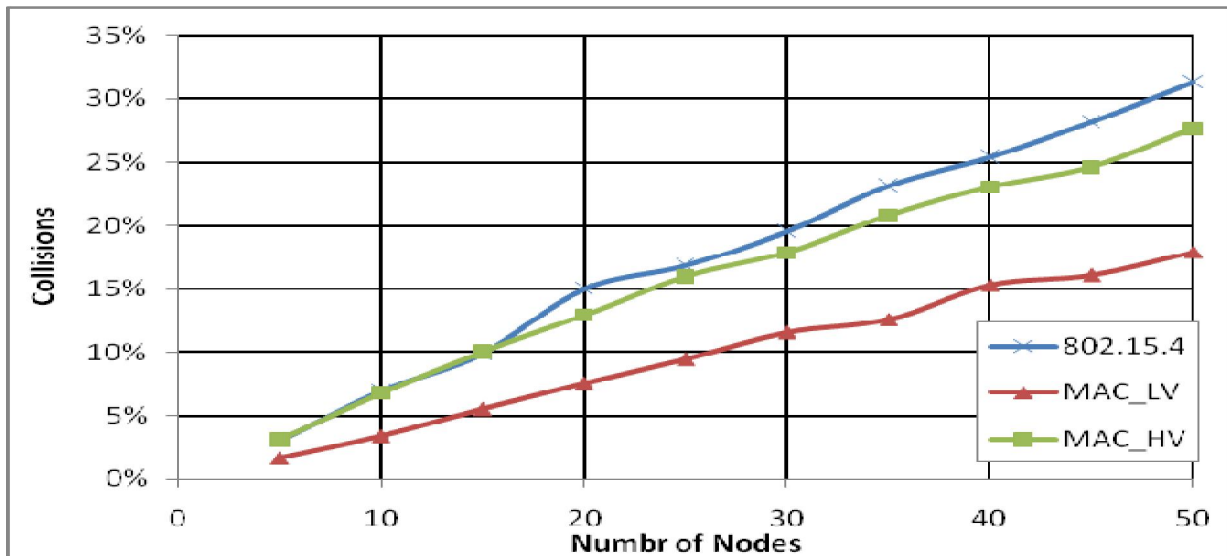


Figure 5-4 Percentage of collisions

In Figure 5-4 we illustrate the performance in terms of the percentage of time the channel is in the collision state. This figure can explain the results we showed for the channel utilization. As we can see, the percentage of collisions under the CSMA-CA protocol is higher than that of both MAC-LV and MAC-HV. The fact that MAC-LV and MAC-HV allow the nodes to send more

packets, and that they achieve lower percentage of collisions, result in the enhancement we see in the channel utilization. Figure 5-4 proves that the collisions under the MAC-LV protocol are reduced by 42.77% compared to the CSMA-CA protocol, while the reduction is by 35.2% compared to the MAC-HV protocol.

### 5.3.4 Channel idle time

In Figure 5-5 we show the performance in terms of the achieved channel idle time. This figure explains the reason behind that that MAC-LV is performing better than MAC-HV. We can clearly see that the idle time of the nodes under MAC-LV is greater than that under MAC-HV. This means that the nodes with MAC-LV have the opportunity to rest longer, and therefore, recover more charges. This enables the nodes to send more packets and extend their lifetime. The channel idle time under the MAC-LV protocol exceeds that under the CSMA-CA protocol by 21.87%, while it exceeds that under the MAC-HV protocol by 12.6%.

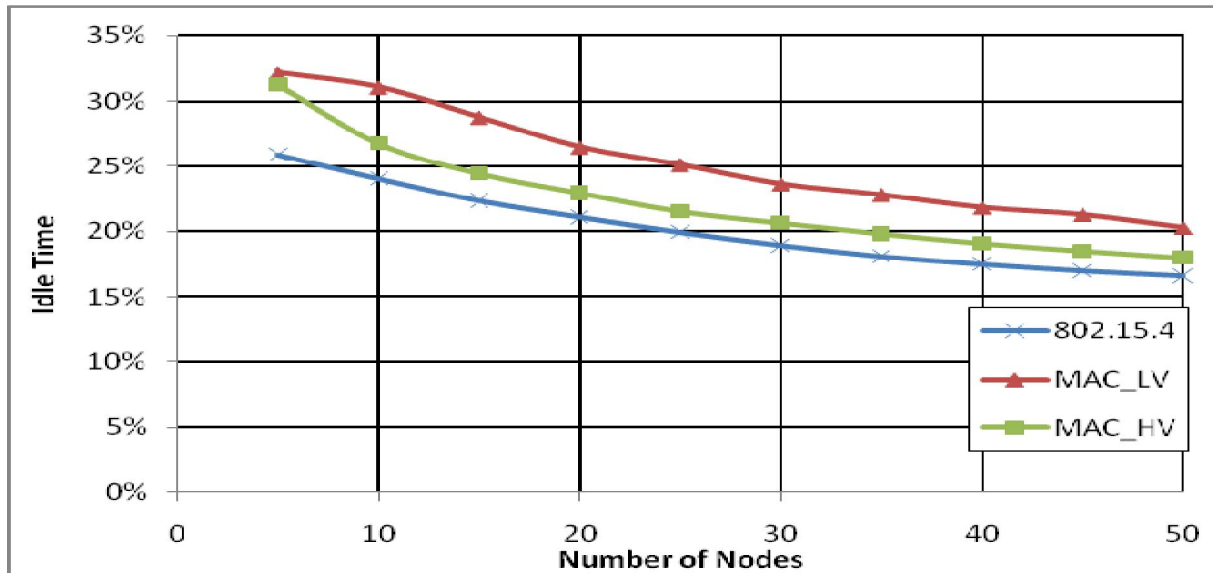


Figure 5-5 Channel idle time

### 5.3.5 Average energy recovered

In Figure 5-6 we show the performance in terms of the average energy recovered per node. Surprisingly, MAC-HV recovers, on average, more energy than MAC-LV. However, most of this energy is lost in retransmitting packets, due to the high collision percentage shown in Figure 5-4.

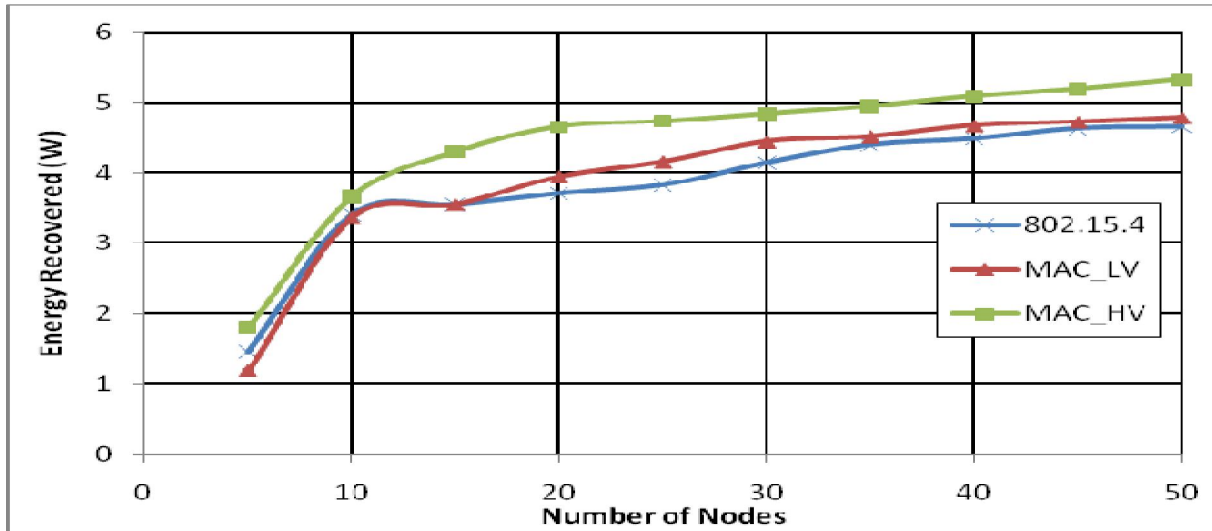


Figure 5-6 Average energy recovered per node

### 5.3.6 Average lifetime of a node

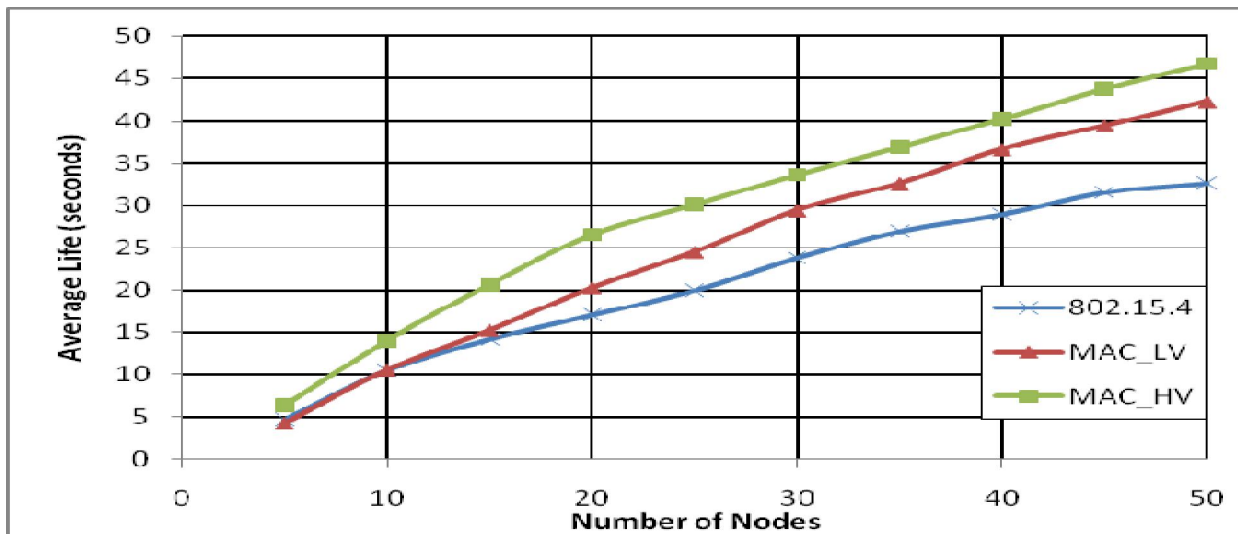


Figure 5-7 average lifetime of a node

In Figure 5-7 we show the performance in terms of the average lifetime of a node. As expected, the average lifetime of the nodes under the CSMA-CA protocol is shorter than that under our proposed schemes. Interestingly, we can observe that the average lifetime of the nodes with MAC-HV goes beyond that with MAC-LV. We can explain this behavior by referring to the results shown in Figures 5-9 and 5-10 (which we will detail more in the next subsection). In these figures, we can observe that most of the time, the number of the remaining alive nodes with MAC-HV is more than that with MAC-LV, even though MAC-LV eventually outperforms MAC-HV. Consequently, if we calculate the average value of both curves in both graphs, we will find that the average value of MAC-HV exceeds that of MAC-LV.

According to Figure 5-7, at  $N = 50$ , the maximum value of the node's average lifetime with CSMA-CA, MAC-LV, and MAC-HV is around 33 seconds, 42 seconds, and 47 seconds, respectively. Based on these numbers, MAC-LV and MAC-HV are superior to CSMA-CA by 29.56% and 43.08%, respectively. Meanwhile, MAC-HV is superior to MAC-LV by 9.44%.

### 5.3.7 Lifetime of the network

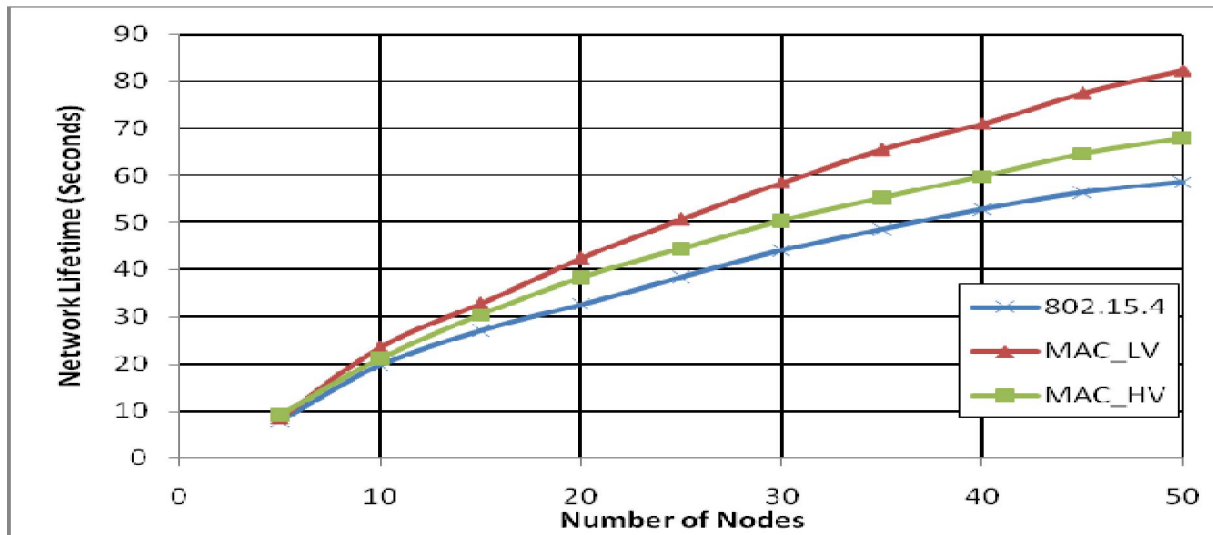


Figure 5-8 Total lifetime of the network

In Figure 5-8 we show the performance in terms of the total lifetime of the network. This figure proves that MAC-LV can prolong the lifetime of the network more than MAC-HV and CSMA-CA. In fact, the network lasts around 82 seconds with MAC-LV, around 68 seconds with MAC-HV, and around 59 seconds with CSMA-CA. This is an improvement by 40.31% for MAC-LV over CSMA-CA and by 21.14% for MAC-LV over MAC-HV.

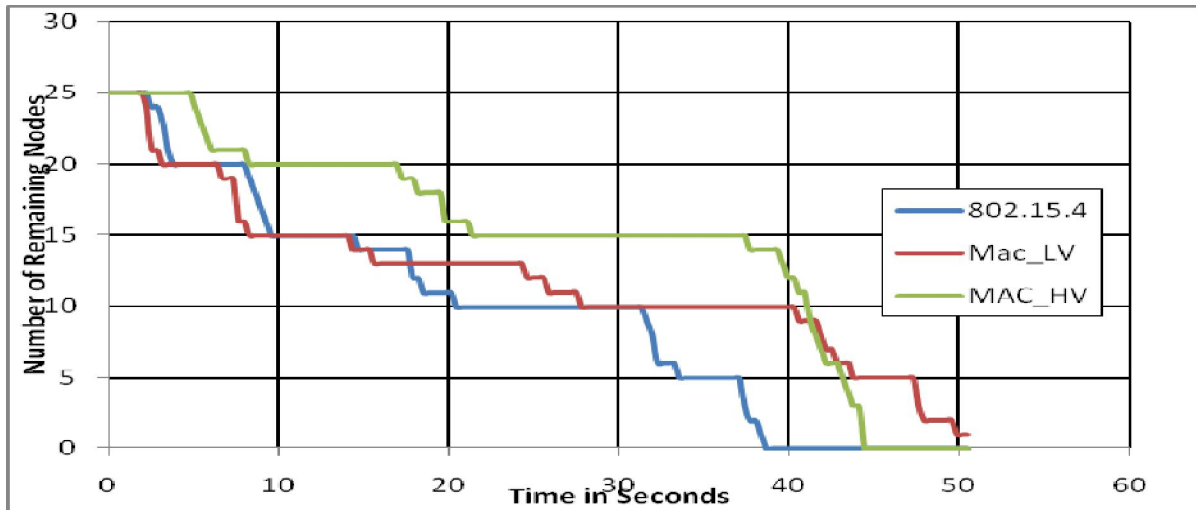


Figure 5-9 Number of remaining alive nodes (N=25)

The same conclusion is drawn from Figures 5-9 and 5-10. They clearly show that with the *MAC-LV* protocol, the number of remaining alive nodes is superior, especially for bigger networks.

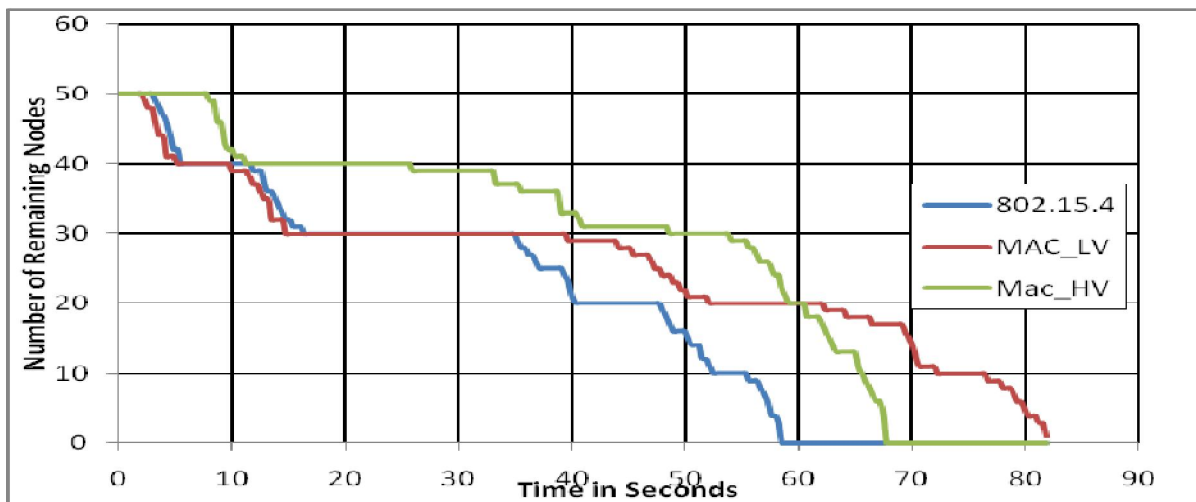


Figure 5-10 Number of remaining alive nodes (N=50)

In the case of  $N=25$  (Figure 5-9), all the nodes become disabled after 38s, 44s, and 51s have passed, with CSMA-CA, MAC-HV and MAC-LV, respectively. Therefore, the number of alive nodes with MAC-LV is increased by 31.71% compared to CSMA-CA, and it is better by 14.66% compared to MAC-HV. With bigger networks (Figure 5-10), the enhancement over CSMA-CA is 40% and over MAC-HV is 20.87%.

Moreover, as we mentioned earlier, the charge recovery mechanism shows that this effect will be higher (lower) when the battery has higher (lower) remaining capacity. *MAC-LV* exploits this effect by giving priority for medium access to the batteries that have low power, and leaving the nodes with high remaining capacity to rest more. In fact, having a battery with low power indicates that the remaining quantity of active material in it is very small. Therefore, that battery will not be able to recover more charges, and so leaving it idle for some period of time will not add any benefit in terms of conserving energy. In contrast, nodes with high voltage batteries can recover more charges if they rest longer.

## 5.4 Summary

In this chapter we have presented our proposed versions of battery-aware energy-efficient MAC protocol for wireless sensor networks: MAC-HV and MAC-LV. Unlike most of the reported power-aware and energy-efficiency MAC protocols, our protocols incorporate the actual voltage of the battery in their computations, and they take advantage of the charge recovery effect that extend significantly the lifetime of the battery.

With MAC-HV the nodes with higher battery voltage gain the precedence to access the medium by prolonging the back-off period of the nodes with lower battery voltage, which give them the chance to rest and recover charges.

On the contrary, with MAC-LV the nodes that have low battery capacity have the priority to use the channel before the nodes with high battery capacity. In this case, the nodes with high battery power back-off for longer duration, and thus they earn more energy.

We run both protocols, in addition to the usual CSMA-CA protocol, through extensive simulations focusing on some important performance metrics such as energy gained, lifetime of the network, throughput and collision rate. Both protocols proved better performance than CSMA-CA, and the results confirmed that the best performance is achieved when allowing the nodes with higher remaining voltage to relax more than the nodes with low remaining voltage. (MAC-LV is better than MAC-HV).

These results are completely compatible with the conclusions attained in the battery behavior studies: the charge recovery increase with longer period of relaxation and the amount of charges recovered augments with higher voltage values.

## Chapter 6      **Conclusions and Future Work**

### **6.1 Summary and Concluding Remarks**

In this thesis we propose two novel schemes of battery-aware MAC protocols, namely, MAC-HV and MAC-LV that take into account the real complex behavior of the sensor node's battery. The motivation behind these schemes is to exploit the charge recovery mechanism of the battery such that more energy is conserved. The direct benefit of that is prolonging the lifetime of the WSN. Both schemes showed significant improvement over CSMA-CA in terms of throughput, energy recovered and the average lifetime of the nodes/network.

In these protocols, we identified two new back-off functions that depend on the current remaining voltage of the battery, we called them BP-HV and BP-LV. The back-off function BP-HV decreases with higher values of the remaining voltage and increases with smaller values. So with BP-HV, the nodes with high remaining power back off for shorter duration than other nodes, and thus they grant access to the channel before the other nodes.

On the contrary, BP-LV function is directly proportional to the battery residual voltage, it increments when the voltage increments and vice versa. With this back-off function, the nodes with small current battery capacity wait less during the back-off stage, and therefore they gain the right to use the medium before the other nodes.

Prior to designing the new protocols, we presented an analytical study to demonstrate the gain that can be offered by the charge recovery concept of the battery. In fact, we applied that concept to the conventional CSMA-CA protocol, we included the probabilities of gaining or losing charges by the battery during the different stages (back-off stage, first and second clear channel assessment and packet transmission/reception/collision stages), and finally we verified that considering the capacity recovery effect in the communication protocol in WSNs increase the life duration of the network.

At the end of the thesis, we run our proposed protocols through extensive simulations focusing on the performance in terms of channel utilization, collisions rate, average energy recovered per node, and the lifetime of the network. We provide head-to-head comparison of MAC-LV, MAC-HV and conventional CSMA-CA protocol. We proved that providing longer idle times to nodes with higher battery capacity leads to enhanced performance. In other words, we showed that giving the priority to access the medium for the nodes with low residual voltage, while leaving the other nodes to rest (MAC-LV), offered a superior performance over the other schemes.

## **6.2 Future Research**

This thesis has outlined the development of new algorithms and protocols in the MAC layer of WSNs. As an extension to the work carried out herein, we believe that potential future research can be undertaken on the following subjects:

- Analytical study

In this thesis, we implemented our protocols and provided results through simulations. The next normal step is to confirm the results via analytical studies. A new mathematical model for each proposed protocol should be developed, and then an analytical study should be conducted.

The theory of new mathematical models will be like the one proposed in chapter 3. The same discrete Markov chain representation of the CSMA-CA protocol proposed in [PARK10] should be adopted with essential changes. The analytical study will be similar; we expect to apply modifications to the following parameters and variables:

- The delay window ( $W_i$ ) will not depend only on the back-off exponent (BE) parameter anymore, it will also depend on the current battery voltage  $V_i$ . So the number of states during the back-off state will be a function of  $V_i$  as well. As a result, the number of back-off stages with MAC-HV (MAC-LV) will be less with greater  $V_i$  (with smaller  $V_i$ ).
- The probability parameters ( $\alpha$ ,  $\beta$ , and  $\Phi$ ) that define the Markov chain will not be constant anymore; they will be functions of  $V_i$ .
- The recovery probability function  $R_{N_i, T_i}$  will have the additional factor  $(V_i/V)$  in the case of MAC-LV and the factor  $(1 - V_i/V)$  in the case of MAC-HV.

- Collaborative battery-aware MAC protocol

In the current study we did not consider exchanging information between the nodes. Indeed, the back-off function depends only on local data (current battery capacity). As a matter of fact, previous studies in many fields of the WSNs proved that sharing some crucial information

among neighbor nodes enhance greatly the entire performance of the network especially in terms of extending the lifetime of the network.

As future work, a new battery-aware MAC protocol based on collaborative work can be designed with a new back-off scheme that takes into account the state of the batteries in the neighboring nodes to improve the power control and management, and to increase the energy savings and the lifetime of the nodes/network.

- Adaptive battery-aware MAC protocol

As we stated previously in this thesis, the concept of packet collisions is one of the aspects that contribute to the energy expenditure. Our proposed protocols do not take this factor into consideration.

An enhancement to our schemes will be the development of a new version of the battery-aware MAC protocol adaptable to the state of the channel. In other words, in the new approach the nodes will attempt to avoid transmitting packets in case of high channel utilization, and then less power will be dissipated.

- Battery-aware Routing protocol

The main function of routing protocols in WSNs is to ensure reliable multi-hop communication among nodes. Selecting the proper routing algorithm that the nodes will use to choose the paths on which the data will be transmitted, has a great impact on the functionality of the WSN; because the communication unit consumes most of the battery power during sending/receiving packets. For example, if long routes have been selected, more energy will be consumed and then the nodes expire sooner.

Multiple routing methods have been reported, some of them are topology based, and some are based on proactive strategies, others on reactive techniques, and several consider the geographic location of the node. Most of these protocols do not consider the battery state in their computations; they do not exploit the pulsed current discharge and the charge recovery effects (we found only one proposed protocol, very recent, it was published in October 2011 [MA11]).

In the future, a new design of a new routing protocol that takes into consideration the remaining voltage in the battery can be developed. Similar to our approach in the MAC sub-layer, two versions can be developed: one algorithm that allow that the nodes with higher voltage to rest more than the nodes with lower remaining energy, and a second algorithm that operates in an opposite way.

- Cross-layer design

Another important design we think it is possible to realize in the future, is a novel cross layer system that combine a battery-aware MAC protocol with a battery-aware routing protocol. In this system, battery state and effects will be used in a collaborative way between the different layers to attain better performance at each level of the protocol stack.

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