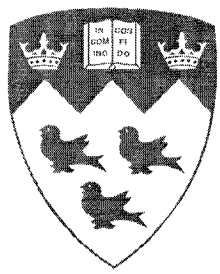
Low-Rate Wireless Personal Area Network Coordinator Design and Implementation

Miloš Prokić



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Before I put a sketch on paper, the whole idea is worked out mentally. In my mind I change the construction, make improvements, and even operate the device. Without ever having drawn a sketch I can give the measurements of all parts to workmen, and when completed all these parts will fit, just as certainly as though I had made the actual drawings. It is immaterial to me whether I run my machine in my mind or test it in my shop. The inventions I have conceived in this way have always worked. In thirty years there has not been a single exception. My first electric motor, the vacuum wireless light, my turbine engine and many other devices have all been developed in exactly this way.

—Nikola Tesla

Abstract

This thesis presents low-rate personal area network coordinator design and implementation on both hardware and software fronts.

It portrays integration techniques used to enhance the existing wireless sensor network infrastructure previously developed by the Microelectronics research group. The infrastructure was made for data collection and sharing during educational conferences and alike gatherings. The system is designed to be flexible and rapidly reprogrammable, while keeping low-power and low-cost as the primary design objectives.

Augmenting the hardware is the wireless network protocol specifically conceived for low-power and low-rate applications - IEEE 802.15.4. Both application and implementation aspects were covered in order to produce a portable and expandable embedded software design.

Résumé

Ce mémoire de maîtrise présente la conception et la réalisation d'un coordonnateur de réseau sans-fil personnel à bas débit et élabore sur les considérations reliées au matériel et au logiciel.

De plus, ce mémoire illustre les techniques d'intégration employées pour améliorer l'infrastructure existante du réseau de capteurs sans-fil précédemment développée par notre groupe de recherche en micro-électronique. L'infrastructure a été conçue pour rassembler des données et les disséminer dans le contexte d'une conférences ou d'une réunion similaire. Le système est conçu pour être flexible et rapidement reprogrammable, tout en respectant les objectifs principaux de conception: la faible consommation d'énergie et un faible coût.

Un protocole de réseau sans-fil basé sur le standard IEEE 802.15.4 et spécifiquement conçu pour la basse puissance et les applications à bas débit est intégré au matériel. Les divers aspects de l'application et les paramètres d'exécution ont été optimisés afin de produire un logiciel embarqué à la fois portable et extensible.

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Chapter 1

Introduction

Wireless communication dates back into the history of mankind. Even in ancient times, people used communication systems, which can be categorized as wireless. Examples are flags, flashing mirrors, smoke signals, fires, etc. It is reported that the ancient Greeks utilized a communication system comprising a collection of observation stations on hilltops, with each station visible from its neighboring one. It is very similar to what J.R.R. Tolkien described in his third book of the Lord of The Rings saga. Upon receiving a message from a neighboring station, the station personnel repeated the message in order to relay it to the next neighboring station. Using this system messages were exchanged between pairs of stations far apart from one another. However, it is more logical to assume that the origin of wireless networks, as we understand them today, starts with the first radio transmission. The first demonstration of a radio transmission took place in 1893, when Nikola Tesla, an American-Yugoslavian inventor, carried his first experiments with high frequency electric currents. It is the same year that Tesla described his radio apparatus in detail in his articles and lectures. In 1897 he registered the first patent on radio communication [4, 5]. Nevertheless, it was Guglielmo Marconi, an Italian inventor, that thrived on Tesla's 17 patents when he received the letter "S", telegraphed from England to Newfoundland in 1901. Over the years that followed Marconi's activities, radio-based transmission continued to evolve. The origins of radio-based telephony date back to 1915, when the first radio-based conversation was established between ships [6].

Currently the field of wireless communications is one of the fastest growing segments of the telecommunications industry. Wireless communication systems, such as cellular,

cordless and satellite phones have found widespread use and have become an essential tool in many peoples everyday life, both professional and personal. Wireless data networks, in particular, have led this trend due to the increasing exchange of data in Internet services such as the World Wide Web, e-mail, and data file transfers. The capabilities needed to deliver such services are characterized by an increasing need for data throughput in the network. Wireless Local Area Networks (WLANs) provide an example of this phenomenon. As the need for mobility and the cost of laying new wires increases, the motivation for a personal connection independent of location to that network also keeps increasing.

To support this mobile lifestyle, especially as work becomes more intensely information-based, companies are producing various portable and embedded information devices including cellular telephones, smart phones, PDAs and active badges. At the same time, recent advances in sensor integration and electronic miniaturization are making it possible to produce sensing devices equipped with significant processing memory and wireless communication capabilities. These devices can create smart environments where scattered sensors could coordinate to establish a communication network. These wearable computing devices and ad-hoc smart environments impose unique requirements on the communication protocol design such as low power consumption, frequent make and break connections, resource discovery and utilization and have created the need for Wireless Personal Area Networks (WPANs).

1.1 Wireless Personal Area Networks (WPANs) History

WPANs initially belonged to the category of relatively short-distance wireless networks specifically designed for interconnecting devices centered around an individual person's workspace. The objective of WPANs was to facilitate seamless operation among home or business devices and systems. A key concept in WPAN technology has been known as plugging in. In the ideal scenario, when any two WPAN-equipped devices come into close proximity (physical range of one another) or within a few kilometers of a central server, they can communicate as if connected by a cable. Another important feature is the ability of each device to lock out other devices selectively, preventing needless interference or unauthorized access to information.

Wireless Local Area Networks (WLANs), on the other hand, typically cover a moderately sized geographic area such as a single building, or campus. WLANs operate in the 100

meter range and are intended to augment rather than replace traditional wired LANs [7, 8]. They are often used to provide the final few feet of connectivity between the main network and the user. Users can plug into the network without having to look for a place to link their computer, or having to install expensive components and wiring.

WPANs are the next step down from LANs and target applications that demand low-power and relatively short range communications. Early research for PANs was carried out in 1996. However, the first attempt to define a standard for PANs dates back to an Ericsson project in 1994, which aimed to find a solution for wireless communication between mobile phones and related accessories (e.g. hands-free kits). This project was named Bluetooth [9, 10] (after the name of the king that united the Viking tribes). It is now an open industry standard that is adopted by more than 100 companies and many Bluetooth products exist and are appearing in today's market place. Bluetooth operates in the 2.4 MHz ISM band; it supports 64 kbps voice channels and asynchronous data channels with rates ranging up to 721 kbps. Supported ranges of operation are 10 m (at 1 mW transmission power) and 100 meters (at 1 W transmission power).

Another PAN project was HomeRF [11]; the latest version before discontinuing the project was released in 2001. This version offered 32 kbps voice connections and data rates up to 10 Mbps. HomeRF also operated in the 2.4 MHz band and supported ranges around 50 m. In 1999, IEEE joined the area of PAN standardization with the formation of the 802.15 Working Group [12, 13]. Due to the fact that Bluetooth and HomeRF preceded the initiative of IEEE, a target of the 802.15 Working Group was to achieve interoperability with these projects. Bluetooth was eventually standardized as IEEE 802.15.1 [14], has a raw data rate of 1 Mb/s; [15, 10], and IEEE 802.15.3, released in June 2003, has a maximum raw data rate of 55 Mb/s [16]. Both the 802.11 and 802.15 organizations have begun the definition of protocols with data throughputs greater than 100 Mb/s.

However, there are other potential wireless network applications. These applications, which have low data rate requirements and are often measured in a few bits per day, include industrial control and monitoring; home automation and consumer electronics; security and military sensing; asset tracking and supply chain management; intelligent agriculture; and health monitoring.[17] Because most of these low-data-rate applications involve sensing of one form or another, networks supporting them have been called wireless sensor networks (WSNs), or Low-Rate WPANs (LR-WPANs). Among recent IEEE standards, released in 2003, it is 802.15.4 [18] that defines an ultra-lightweight communication protocol that

transmits only the few required bytes per second per node, enough to satisfy application requirements but no more than that. The low data rate enables the LR-WPAN to consume very little power by realizing low duty cycles up to 15 ms in 252 s (active/sleep = 1/16400).

ZigBee technology is a *low data rate, low power consumption, low cost*, wireless networking protocol targeted towards automation and remote control applications. IEEE 802.15.4 committee started working on a low data rate standard a short while later. Then, in 2003 the ZigBee Alliance [19, 20] and the IEEE decided to join forces and ZigBee, HomeRF spinoff, emerged as the commercial name for this technology. ZigBee is to IEEE 802.15.4 what Bluetooth is to IEEE 802.15.1. ZigBee is expected to provide low cost and low power connectivity for equipment that needs battery life as long as several months to several years but does not require data transfer rates as high as those enabled by Bluetooth. In addition, the standard defines several types of network topologies in order to accommodate several hundreds of nodes.

Currently, two active task groups i.e. 802.15.4a and 802.15.4b are working on expanding as well as enhancing the standard. The 802.15.4b is in charge of specific enhancements and clarifications to the IEEE 802.15.4-2003 standard, whereas 802.15.4a concentrates on the physical layer aiming to increase throughput, reduce power consumption and scale down the overall cost. Since 802.15.4 task group ceased to exist in March of 2004, transferring all their activities to 802.15.4b, the two task groups will be used interchangeably in this document.

1.2 Contribution of the Thesis

Among the presented WPAN standards and industry groups in the previous section, special interest is devoted to the emerging IEEE 802.15.4 wireless standard. In fact, this project concentrates on both hardware and software design and implementation challenges revolving around the above mentioned standard - *low-power and low-cost.* For the simplicity in this thesis several terms denoting WPANs will be used interchangeably: PAN, Personal Area Networks, and IEEE 802.15 workgroup.

With recent advances in CMOS integrated circuits, the integration of an Radio Frequency (RF) front end onto the same die as the digital demodulation and media access control components became a common goal for many manufacturers. The high level of integration allows designers to add wireless networking capabilities to many embedded

systems for a few dollars in additional costs.

The work presented in this thesis is based on the design and integration challenges of latest Application Specific Integrated Circuits (ASICs) into a full wireless embedded system. The system's code name is McZub, and it stands for ***McGill ZigBee USB Board***, Figure 1.1. It is a dedicated embedded system that includes software and hardware components, designed to be a high performance, low-power IEEE 802.15.4 compliant network coordinator providing ubiquitous USB connectivity. It is meant to be a testbed prototype device for research in the domain of low-rate personal area networks (LR-WPANs). At the time when it was manufactured it was was the first of its kind in the world [1].

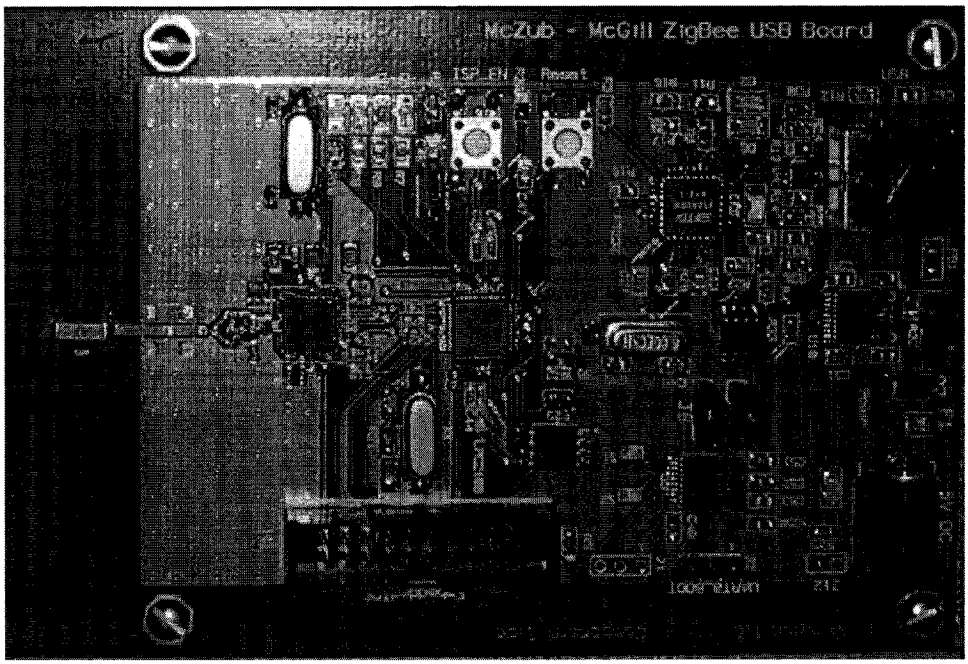


Fig. 1.1 McGill ZigBee USB Board

1.2.1 Design Goals and Research Problems

The central component of this thesis is the McZub board. Based on the specific setups available and the global research interests of the Microelectronics and Computer Systems (MACS) lab, a list of design goals was established on both hardware and firmware fronts.

[1] To the author's knowledge

These goals will be referred to as (DG) in the rest of this thesis. Note that firmware and embedded software will be used interchangeably throughout the thesis.

Hardware, Chapter 3:

(DG1) Partitioning: The partitioning design decisions are of paramount importance, especially at the start of a wireless node design. State the necessary decisions to balance current and future technological capabilities in order to meet all the requirements and at the same time achieve robust and easily upgradeable system.

(DG2) Low-Power: Required considerations as to the selection of a power sources, power regulators and other board components.

(DG3) Low-Cost: How to maintaining low-cost of the overall design - development and manufacturing costs, as well as operating costs.

(DG4) Compatibility: Maintain network/protocol compatibility with respect to existing hardware within the MACS research group.

(DG5) Reliability/Robustness: Board layout, testing and assembly techniques. Subtleties in achieving robust (RF) section - antenna layout, matching network.

Embedded Software / Firmware, Chapter 4:

(DG6) IEEE 802.15.4 MAC/PHY Implementation: Modular and expandable protocol stack implementation, according to IEEE specifications.

(DG7) Protocol Portability: Maintaining concise hardware abstraction layers in order to facilitate source code maintenance across different platforms.

(DG8) Real-Time Operating System (RTOS) selection: Exploring benefits and detriments among RTOS distributions, their complexity, memory requirements and ease of porting to different platforms.

1.2.2 Thesis Overview

In depth comparisons and features of both IEEE 802.15.4 and ZigBee are presented in Chapter 2. In addition, it discusses numerous applications of the technology that further strengthen and emphasize the motivation for the presented work. Chapter 3 presents the McZub hardware design decisions, implementation and testing challenges. Chapter 4, further elaborates on 802.15.4 MAC/PHY protocol implementation. Moreover, it shows

firmware design decisions such as low-memory footprint Application Programming Interface (API) realization, RTOS integration as well as inter PC communication protocol. The key metric used to evaluate the performance of the system involves integrating McZub with existing hardware platform - McGumps [21] and McZig [22]. These and other results are presented in Chapter 5.

Chapter 2

Background and Motivation

I never think of the future - it comes soon enough.

—Albert Einstein

Before describing the McZub hardware and firmware design and implementation decisions and subtleties, an in-depth presentation of IEEE 802.15.4 standard and ZigBee is in order. It is crucial to understand the motivation as well as the context in which this wireless technology is to be used. In Section 2.1, an overview of the LR-WPANs is given. Its goals, characteristics, relation to other widely adopted IEEE and industry standards are also described in this section. The impact on the society as well as potential application variety of LR-WPANs is given in Section 2.2. A short overview of the existing hardware platform is presented in Section 2.3.

2.1 IEEE 802.15.4 Standard for Low-Rate WPANs (LR-WPANs)

The IEEE 802.15.4 LR-WPAN task group has been put in charge to develop a standard for Low-Rate Wireless Personal Area Networks (LR-WPANs) [23]. It is a standard that was developed to convey information over short distances in a power efficient manner. This is a very new technology since the IEEE Standards board approved the IEEE 802.15.4 draft 18 on May 12, 2003. It is worth mentioning that ZigBee/802.15.4 related research within the MACS research group started shortly after, in September of 2003.

Until recently, the primary activity in networking technology has been focused on productivity and entertainment applications running on PCs. For wireless technologies, this

translates to high bandwidth. The attention of the wireless communications industry and researchers has now spread beyond the office and home to include new environments such as factories, hospitals, and agriculture. Furthermore, applications in these new areas are becoming increasingly dependent upon embedded systems. Traditional wireless technologies are often not suitable in this context due to reasons of practicality, hence the need for a new standard that focuses on these new special requirements.

Applications such as home automation, security, and gaming have relaxed throughput requirements. These applications cannot handle the complexity of heavy protocol stacks that impact power consumption and utilize too many computational resources. Naturally, this has a direct implication on cost. Consider a security device used as an identification tag for a piece of equipment or visitor to a plant. This security sensor may need to report the location of its host only after the movement has been detected. At other times, the device will be hibernating, hence saving power. Unsurprisingly, such security system would further require many of these devices and therefore they must have a very low selling point. This application is an excellent candidate for a low-throughput low-cost wireless communications link. In addition, it must be extremely low power, since frequent battery replacements are impractical and costly. It is evident that 802.11b or 802.11g is an overkill technology for this application that can only satisfy the connectivity requirement, jeopardizing low-power and low-cost. Bluetooth was originally engineered as a cable replacement and cannot be used in applications where connectivity of more than seven nodes is needed [9]. Please, refer to Section 2.1.2 and Table 2.3 for detailed comparison among the above mentioned IEEE standards.

2.1.1 Goals and Characteristics

Generally, the applications that IEEE 802.15.4 addresses are characterized by their requirements for low-power consumption and low-cost deployment [24].

Ultra-Low Power Consumption: On any wireless embedded system, the radio is often one of the largest consumers of energy–even more than the CPU. The embedded systems that are expected to utilize IEEE 802.15.4 for communication have extremely tight energy constraints, operating off of a small battery for a period of months and even years.

Very Low Cost: The final cost of the component implementing the IEEE 802.15.4 stan-

dard must be small compared to the cost of the rest of the component. The reason for this is that the deployed applications are envisioned to be composed of possibly numerous, inexpensive, and even disposable devices.

In order to achieve the low power and low cost goals established by IEEE 802.15.4 the following approaches are taken:

- Reduce the amount of transmitted data
- Reduce the transceiver duty cycle and frequency of data transmissions
- Reduce the frame overhead
- Reduce complexity
- Reduce range
- Implement strict power management mechanisms (power-down and sleep modes)

All of these design decisions contribute to lower power and lower cost requirements. They are directly reflected in the IEEE 802.15.4 Media Access Control (MAC) and Physical layers (PHY).

MAC Decision Highlights:

Network Topology: The common configuration of an LR-WPAN will be a star or star-cluster topology. The master node at the center of the star (or cluster-head, in the case of star-clusters) simplifies the control and synchronization of nodes participating in the network.

Homogeneous vs. Heterogeneous Devices: At the MAC layer, components may be identified as a fully functional (FFD) or reduced functional device(RFD). Therefore, if the application accommodates them, reduced functional devices may be attached to the network as leaf nodes, which simplifies their implementation and precludes these devices from forwarding messages, allowing them to save power.

Message Structure: The structure used is very simple compared to other WLAN/WPAN standards, allowing for very short messages to conserve power.

PHY Decision Highlights:

2.4 GHz band: This frequency is unlicensed and widely available for use. Existing low-cost designs for this band makes device manufacturing more affordable.

868/915 MHz band: Lower power consumption than 2.4 GHz and are freely available for use in Europe and the United States respectively.

Data Rate: Power can be saved by maximizing the data rate for any given amount of data that needs to be transmitted. Thus IEEE 802.15.4 allows up to 250kbs. However, the real power savings comes from transceiver duty cycling, which is expected to be about 0.33% for many applications. The high data rate allows the standard to accommodate applications that need higher throughput, but that can tolerate increased latency in order to save power.

Link Quality: Provides energy and link quality detection, clear channel assessment for improved coexistence with other wireless networks.

The main 802.15.4 characteristics are summarized in Table 2.1.

Table 2.1 High-level characteristics summary, adapted from [2]

Property	Range
Raw data rate	868 MHz: 20 kb/s; 915 MHz: 40 kb/s; 2.4 GHz: 250 kb/s
Range	50 - 300 meters
Channels	868MHz: 1 channel; 915 MHz: 10 channels; 2.4 Ghz: 16 channels
Frequency band	Two PHYs: 868 MHz/915 MHz and 2.4 GHz
Addressing	Short 16-bit or 64-bit IEEE
Channel access	CSMA-CA and slotted CSMA-CA
Temperature	Industrial temperature range -40 to +85 C

2.1.2 Relation to Other IEEE 802 Standards

Institute of electrical and electronics engineers (IEEE) has initiated numerous networking work groups over the years [13], some of which are still active, others that have matured or have been discontinued. The working groups are the driving force behind open standards that define both wireless and wired networking protocols. In addition, several groups have been established as discussion or study groups. Among the discussed topics is coexistence between standards, which are covered by 802.15.2 and 802.19.

The IEEE work groups cover an extended amount of networking concepts such as: Personal Area Network (PANs), Local Area Networks (LANs), Metropolitan Area Networks (MANs) and the most recently established - Regional Area Networks (RANs). Figure 2.1

depicts all of the above mentioned concepts, as well as provides concise information on how they are interrelated based on the operating frequencies and range.

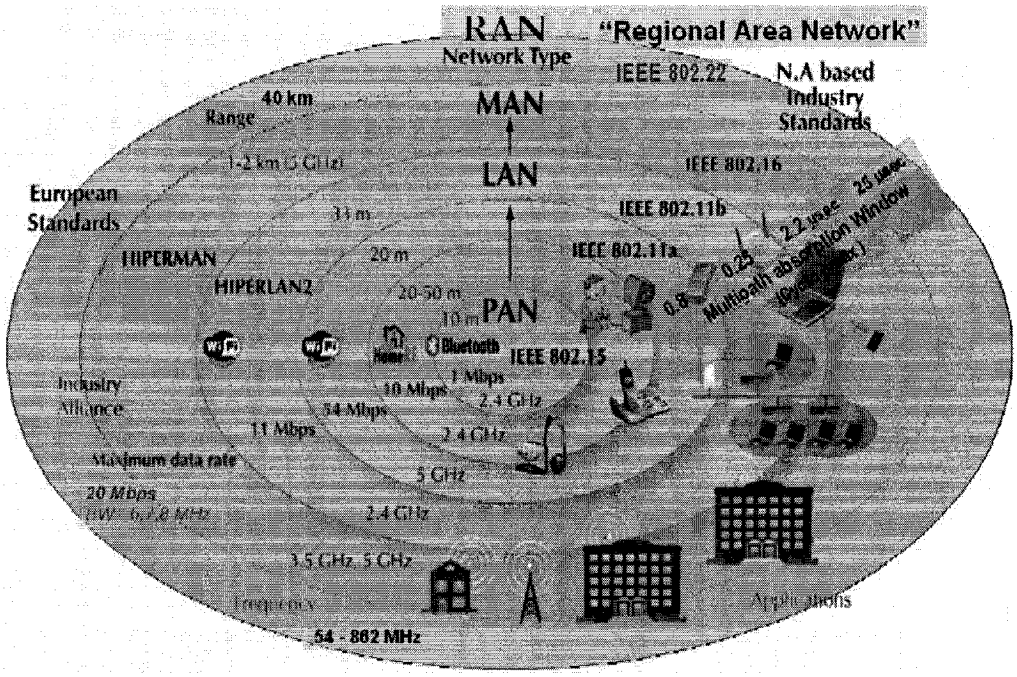


Fig. 2.1 IEEE standards, adapted from [1]

The IEEE 802.15 working group defines three classes of WPANs characterized by data rate, power usage, and quality of service:

802.15.1: Medium-rate: Voice applications, PDAs, etc. Known as Bluetooth.

802.15.3: High-data-rate, High quality of service. Good for multimedia applications.

802.15.4: Lower cost/power/data-rate/QoS than 802.15.1. Known as ZigBee.

The IEEE 802.15.2 task group tackles *coexistence issues* between WLANs (802.11) and WPANs (802.15). Table 2.2, shows the IEEE 802 hierarchy as well as the major industry players involved with its respective technology.

Among the existing network technologies WLANs are commonly being compared to WPANs mostly because they are currently the major player in wireless communications. Table 2.3 further breaks down the differences between WPANs and WLANs.

The IEEE 802.15.4 protocol was developed for a very different reason than 802.15.1 (BlueTooth). It features very low duty cycle and very long primary battery life by remaining

Table 2.2 802.15.4 in the context of other related IEEE standards

Standards Committee	**IEEE 802:** LAN/MAN Standards Committee			
Working Group	**IEEE 802.11:** WLAN	**IEEE 802.15:** WPAN		
Task Group	**802.11a/b/g**	**802.15.1:** WPAN/Bluetooth	**802.15.3a:** WPAN High Rate/UWB	**802.15.4:** WPAN Low Rate/Zigbee
Industry Alliance	**Wi-Fi:** Cisco, 3Com, Agere, Intersil, Compaq, Dell, Sony, Nokia, Symbol, etc.	**Bluetooth SIG:** Ericsson, 3Com, IBM, Intel, Motorola, Nokia, Agere, Toshiba, etc.	**Wi-Media:** Appairent, HP, Motorola, Philips, Samsung, Sharp, XtremeSpectrum, etc.	**Zigbee Alliance:** Chipcon, Ember, Honeywell, Mitsubishi, Motorola, Philips, Samsung, etc.

Table 2.3 Detailed overview of LR-WPAN vs. WLANs

	802.11	**802.15.1**	**802.15.4**
Range	~100 m	~10 m	~(70 - 300) m
Power profile	Hours	Days	Years
Nodes/Master	32	7	65536
Data rate	(11 - 54)Mbps	1Mbps	250Kbps
Security	SSID	64bit, 128bit	128bit AES
Modulation	Various	FSK	BPSK and O-QPSK
Size/Complexity	Larger	Smaller	Smallest
Cost ($US)	> 6	1	0.2

quiescent for long periods of time without communicating to the network. Furthermore, it benefits from more complex network topologies, such as: *static and dynamic mesh, cluster tree and star network structures* with potentially very large number (~ 65534) [1] of client units, Figure 2.2.

Bluetooth was conceived as a wire replacement for consumer devices that need moderate data rates with a very high quality of service (QoS) and guaranteed low latency. The network topologies are less complex, comparing to 802.15.4 with only a quasi-static star network structure with up to 7 clients (and ability to participate in more than one network simultaneously) [15]. It is generally used in applications where the batteries are frequently being recharged (headsets, cellphones) or constantly powered via an independent source

[1] A 16-bit address is assigned, where $0x0000$ and $0xFFFF$ are reserved.

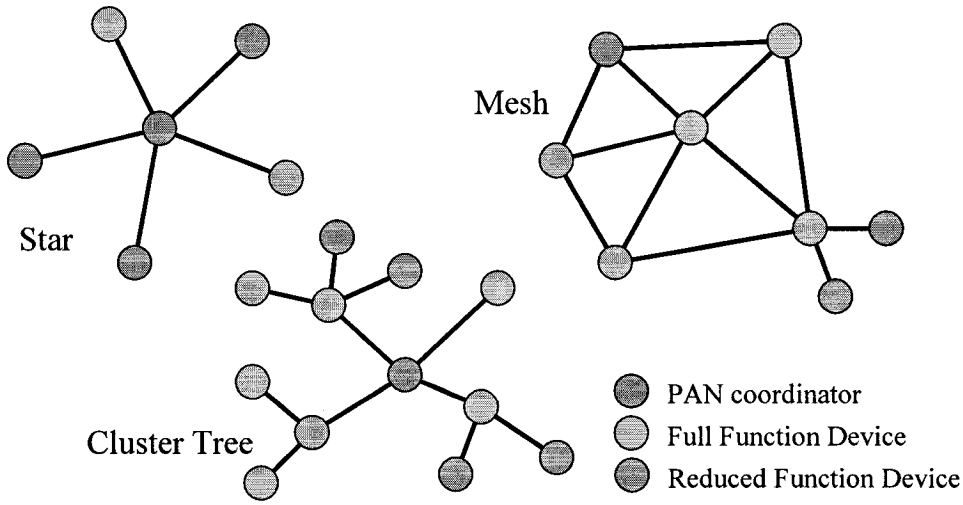


Fig. 2.2 IEEE 802.15.4 (ZigBee) Network Topologies

(printers, car kits).

2.1.3 ZigBee

IEEE and ZigBee Alliance [20] have been working closely to specify the entire protocol stack to be used in low-power and low-rate applications. As mentioned in Section 2.1.1, IEEE 802.15.4 focuses on the specification of the lower two layers of the protocol (physical and data link layer). On the other hand, ZigBee Alliance aims to provide the upper layers of the protocol stack (from network to the application layer) for interoperable data networking, security services and a range of wireless home and building control solutions, provide interoperability compliance testing, marketing of the standard, advanced engineering for the evolution of the standard [19], Figure 2.3. As any standard, ZigBee is no different - it will guarantee to its consumers that products purchased from different manufacturers will work together. A unique feature of ZigBee network layer is communication redundancy eliminating single point of failure in mesh networks [25].

2.2 Applications of LR-WPANs / ZigBee

ZigBee represents an industry initiative to enable the construction of business and residential network applications using low-cost, low-power sensors that run on batteries with very

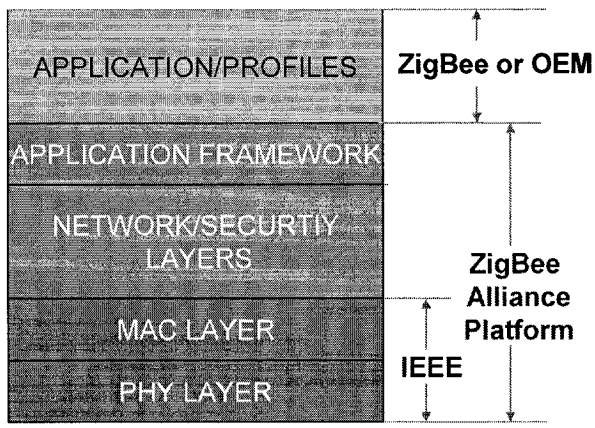


Fig. 2.3 General ZigBee network stack Overview

long lives. The standard is backed up by an industry consortium with more than 150 active members, called The ZigBee Alliance [20].

The likely applications may range from lighting control; heating, ventilating and air conditioning (HVAC) environmental management; industrial sensors and various consumer electronics. The following list captures the basic five domains in which wireless sensor networks (WSN) are used:

Control: Integrate and centralize management of lighting, heating, cooling and security; Improve complicated process control mechanisms.

Conservation: Capture highly detailed electric, water and gas utility usage data. Automate control of multiple systems to reduce power consumption.

Convenience: Install, upgrade and network home control system without wires. Configure and run multiple systems from a single remote control.

Safety: Deploy monitoring networks to enhance employee and public safety. Receive automatic notification upon detection of unusual events

Efficiency: Automate data acquisition from remote sensors to reduce user intervention

The following subsections explore how LR-WPANs, together with ZigBee, efficiently meet the above mentioned goals in more detail.

2.2.1 Home Automation and Consumer Electronics

The home is a very large application space for wireless sensor networks [24]. A home HVAC system equipped with wireless thermostats can effectively control the temperature throughout the house. Depending on the time of the day and the orientation of the house the temperature in the rooms can easily be adjusted to suit a sunny or a shady side. On the other hand, regular, wired thermostats, fall short if the overall complexity of the environment is taken into the account. In addition, home sensor networks could automatically determine when there's no one in the house and then turn off lights, heat and air conditioning to conserve energy.

A potential "killer application" is the universal remote control, a device that can control not only the home theater, stereo, and other home electronic equipment, but the lights, curtains, and locks that are also equipped with a WSN connection. An interesting scenario could be realized by combining multiple services. For example, having the curtains close automatically when the television is turned on.

Another application in the home is sensor-based information appliances that transparently interact and work symbiotically together as well as with the home occupant [26]. These networks are an extension of the information appliances proposed by Norman [27].

Toys represent another large market for wireless sensor networks [28]. The list of toys that can be enhanced or enabled by wireless sensor networks can range from conventional radio-controlled cars and boats to computer games employing wireless joysticks and controllers.

2.2.2 Social Event Tracking

While many sensing applications do not require the direct use of wireless units by humans, an interesting subset of applications would require an effective human interface, including sufficiently high-resolution touch-screen displays. Combining location-aware capabilities of WSNs, a diverse collection of consumer-related activities exist including tourism [29], shopping [30] and event tracking. Events and venues can be very different - social gatherings, sporting events, etc. One such system, has been developed in-house - Wireless Conference Manager (WCM), Section 5.2.

2.2.3 Security and Military Sensing

Security systems that employ proprietary communication protocol have existed for several years [31]. They can support multiple sensors relevant to industrial security, including magnetic door opening, smoke and broken glass sensors, passive infrared and others.

As with many technologies, some of the earliest proposed uses of wireless sensor networks were for military applications [32]. One of the great benefits of using wireless sensor networks is that they can be used to replace guards around defensive perimeters, keeping soldiers out of harm's way. In addition to such defensive applications, deployed wireless sensor networks can be used to locate and identify targets for potential attack, and to support the attack by locating friendly troops and unmanned vehicles [33].

Wireless sensor networks can also be effective in the monitoring and control of the population with the use of optical, audio, chemical, biological, and radiological sensors to track individuals and groups, as mentioned in Section 2.1. The control of WSNs and the data they produce in a free society is a topic of many discussions [34, 35].

2.2.4 Asset Tracking and Supply Chain Management

A very large unit volume application of wireless sensor networks is related to asset tracking and supply chain management. Radio Frequency Identification (RFID), which is a subset of LR-WPANs [36], is a main technology behind asset tracking that can take many forms. One example is the tracking of shipping containers and their storage within large warehouses or air terminals. Such warehouse facilities may have tens of thousands of containers, some of which are empty and in storage, while others are bound for many different destinations. An important factor in the shipper's productivity and consequentially profitability is how efficiently the orders can be organized so that they can be handled the fewest number of times and with the fewest errors.

Efficient inventory tracking, both quantity and its location is of paramount importance for any manufacturer or supplier. Knowing where a product is can mean the difference between making or not making a sale, but knowing the status of the entire supply chain from raw materials through components to final product can help a business operate more efficiently.

Accurate inventory information can also be used as a competitive advantage. By being able to tell a customer exactly where his product is in the supply chain, the customer's

confidence of on-time delivery and opinion of the seller's competence rises. This has already been used extensively in the package shipping industry a shipper that cannot tell a customer where his or her package is at any given time is rarely given a second chance [36].

2.2.5 Intelligent Agriculture and Environmental Sensing

The wireless sensor network could be widely used in various applications where accurate information about the current environment could result in natural resource savings. For example, large farms could deploy numerous sensors in order to monitor precipitation levels. If the irrigation may be omitted in certain parts of the farm, due to sporadic rain activity, the water savings could be immense. The amount of data sent over the network is minimal, hence perfect for LR-WPANs.

Other than soil moisture measurements, bio-chemical plants can benefit from low-power sensing of environmental contaminants such as mercury [37]. Integrated micro-cantilever sensors sensitive to particular contaminants can achieve parts-per-trillion sensitivities. These microelectromechanical (MEMS) sensors may be integrated with a wireless transceiver in a standard complementary metal oxide semiconductor (CMOS) process, providing a very low-cost solution to the monitoring of chemical and biological agents.

2.2.6 Health Monitoring

A market for wireless sensor networks that is expected to grow quickly is the field of health monitoring [38].

Two general classes of health monitoring applications are available for wireless sensor networks. One class is athletic performance monitoring, for example, tracking one's pulse and respiration rate via wearable sensors and sending the information to a personal computer for later analysis [38]. The other class is at-home health monitoring, for example, personal weight management [39]. Other examples are daily blood sugar monitoring and recording by a diabetic, and remote monitoring of patients with chronic disorders [35].

An interesting and developing field in the health monitoring market is that of implanted medical devices. These types of systems can be used for a number of purposes, for example, monitoring pacemakers and specialized drug delivery systems.

Wireless disaster relief systems, especially the avalanche rescue beacons, have been on the market for some time now. These devices continuously transmit signals that rescuers

can use to locate the victim. They are naturally used by "avalanche skiers" in avalanche-prone areas. The present systems have their limitations since they only provide location information, and give no information about the health of the victim. In a large avalanche, where several beacons are present, the rescuers have no way to decide who should be assisted first due to the lack of additional health sensors. Given the additional information about victim's life signals, the probability of saving a life increases dramatically [40].

2.2.7 Industrial Control and Monitoring

The final, and most widely accepted applications of wireless sensor networks are within the industrial control and monitoring.

An example of wireless industrial control is the control of commercial lighting [41]. From a simple hand held unit the lights can be turned on or off eliminating the need to physically flip a switch. Furthermore, the hand held controller can be programmed to control the lighting in many different ways - synchronously turning lights on and off, dimming of the lights, etc.

Industrial safety applications are another major example. WSNs may employ sensors to detect the presence of dangerous materials, providing early detection and identification of leaks or spills of chemicals. For example, workers on an oil platform carry devices that signal increased levels of certain gases. However, due to sudden release of these gases the workers sometimes simply do not have time to act accordingly and could get poisoned. Currently these sensor boxes, carried by the workers, are not linked to the main control tower and therefore help cannot be sent immediately after the incident. By replacing the existing local sensors with wireless sensors many lives across oil platforms could be saved.

As in the home applications mentioned in Section 2.2.1, the manufacturing industry can benefit from wireless sensor networks that would monitor heat and therefore control ventilation, and air conditioning (HVAC) of buildings. The efficiency of any HVAC system is directly proportional to number of installed thermostats and humidistats. However, the number of these thermostats and humidistats is limited by the costs associated with their wired connection to the rest of the HVAC system. Therefore, WSNs are gaining tremendous ground in this area [18].

2.3 Existing Low-Power Hardware Platforms

Considering the novelty of the wireless protocol and the availability of compliant hardware, the choices among the existing platforms were limited.

Shortly after the project was conceived, Moteiv [42] released their first WSN IEEE 802.15.4 compliant platform - Telos, Figure 2.4. It is an ultra low power wireless module designed for use in sensor networks, monitoring applications and rapid prototyping. Moteiv, being closely related with University of California at Barkeley, provides full TinyOS support for their Telos platform, which greatly reduces development and deployment time. However, since it features an ultra-low power and memory limited microcontroller, TI MSP430, it is an ideal solution for a reduced function device (RFD), rather than an FFD - PAN coordinator. Needless to say that Telos, can be closely compared with our own existing WSN platform - McGumps + McZig, described in Chapter 3, since the microcontroller and transceiver components are identical.

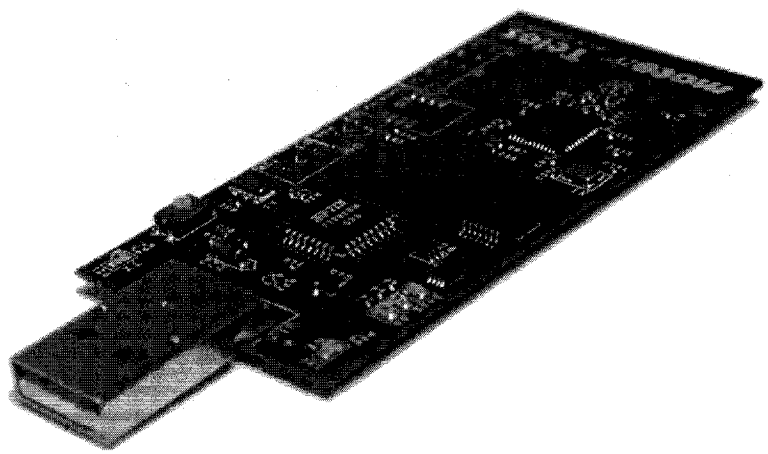


Fig. 2.4 Telos

2.4 Previous IEEE 802.15.4 MAC Implementations

During the last two years since the adoption of the standard only two MAC/PHY implementations have been publicly announced none of which are fully and freely available. In the first quarter of 2005 Chipcon and Freescale, the two industry rivals, announced semi-open 802.15.4 libraries i.e. sources for the physical layer and binaries in case of the

media access control that are being distributed with their respective development kits. The only implementation available for comparison was a "Zigbee implementation on McGumps evaluation board", by Kin Lam [43].

Unfortunately, the McGumps implementation lacked numerous essential features described in the standard. Moreover, the implemented routines lacked robustness and efficiency, both on the CPU as well as power usage fronts. This is clearly present throughout the firmware design where countless `while` loops are used to poll software, as well as hardware flags thus wasting CPU cycles and hence the power. Both software and hardware flags are usually set as a result of a coordinated hardware interfacing routine. Therefore, such blocking loops, in addition to being power inefficient, are likely to cause permanent program stalls if hardware misbehaves that can be resolved only by system reset. Any such blocking loop should always have a timeout associated with it in order to prevent the unrecoverable firmware halts.

Chapter 3

Hardware Selection, Acquisition and Configuration

Little by little, one travels far.

—J. R. R. Tolkien

This chapter covers the hardware portion of this project. A generic wireless node design is covered in Section 3.1. Several aspects were explored in order to come up with an optimal design in order to meet our four hardware DGs, Section 1.2.1. A more in-depth look into the McZub implementation as well as necessary hardware troubleshooting is overviewed in Section 3.2.

3.1 Wireless Node Design

The design of wireless network node is of primary importance in the design of a wireless sensor network. The most important factors that determine the success of a wireless sensor network are its *low-cost, low-power, size and reliability.* The network protocol does play a significant role in the overall reliability and low power usage, however, this chapter concentrates on examining hardware design decisions that were employed to achieve the set objectives. At the start of the McZub project, the MACS research group had already developed the low-power hardware platform to be used in teaching as well as wireless sensor

node research[1]. The overall design strategies as well as compatibility issues (DG4) between the two platforms are considered in this section.

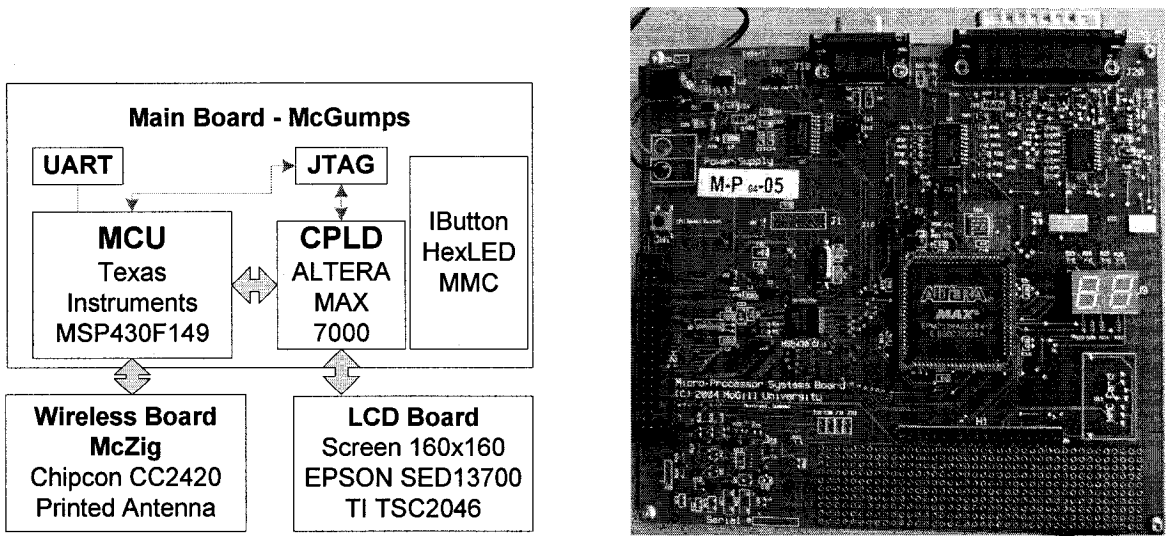
3.1.1 Existing Low-Power Hardware Platform

The existing hardware platform, McGill Microprocessor Systems board (McGumps) has been designed to be expandable and to facilitate complex research and teaching goals [21, 44]. The platform benefits from the complex programable logic device (CPLD) that is used to rapidly prototype any external hardware [45]. The ultra-low power 16-bit RISC type microcontroller MSP430 from Texas Instruments provides sufficient computing resources while keeping power consumption in the neighborhood of 1mW/MIPS [46] or less. Since analog as well as digital lines from the MSP430 are routed to the expansion headers sensor or actuator modules can be easily added. Choosing this family of microcontrollers for the embedded nodes certainly was also heavily influenced by its low cost. Figure 3.1, depicts main components as well as an example WSN node configuration with a liquid crystal display (LCD) and touch screen (TS). The example featuring LCD and TS - *Wireless Conference Manager* is further described in Section 5.2. In addition, board features an interface to the Dallas iButton that allows access to a vast array of compatible devices: temperature switches and sensors, digital potentiometers, etc. So far, three different expansion boards were designed, one of which is used for wireless communication - McGill ZigBee Board - McZig, Figure 3.2. The module is based on the Chipcon CC2420 integrated radio transceiver. The background and rationale behind choosing this particular transceiver is covered in Section 3.1.3. In addition, the board features an integrated printed antenna, removing fragile parts and hence providing a low-cost module. The reader wanting to know more about the the novel methodology for designing nodes in which a robust antenna is realized by printed circuit traces may consult *Design Methodology for Wireless Nodes with Printed Antennas* [22].

3.1.2 General Design Strategy

The common-off-the-shelf (COTS) microcontroller-based system architecture was considered as the implementation technology of choice. The generic structure of both the WSN

[1]The members of the MACS group that developed the platform are: Jean-Samuel Chenard, Milos Prokic, Rong Zhang, Usman Khalid and Zeljko Zilic



System Diagram Photo

Fig. 3.1 McGumps hardware platform

nodes (McGumps + McZig) and the PAN coordinator (McZub) is depicted in Figure 3.3. This design has many benefits and it came about when the world's first IEEE 802.15.4 compliant chip was released. By keeping the RF front-end constant throughout the design cycle it allows for experimentation with different microcontroller architectures to accommodate multiple application platforms. Moreover, it guarantees their seamless integration into the already existing network. Furthermore, the RF chip non-binding architecture can provide a smooth transition to a different device if changing the operating band is required (DG1).

As shown in Figure 3.3, a single processor architecture is used for both protocol handling and application data processing. Naturally, wireless sensor networks are assumed to have relatively low data throughput and total amount of processing required to be fairly low. In addition, it reduces complexity and power consumption which is one of the main characteristics of wireless sensor networks. An attractive approach could have been to employ a dedicated protocol handler to off-load the host processor, and use the resources of the host processor for application data processing. This could have been a more elegant approach, but would have inflicted unnecessary cost, which would directly be at odds with DG3 (low-cost).

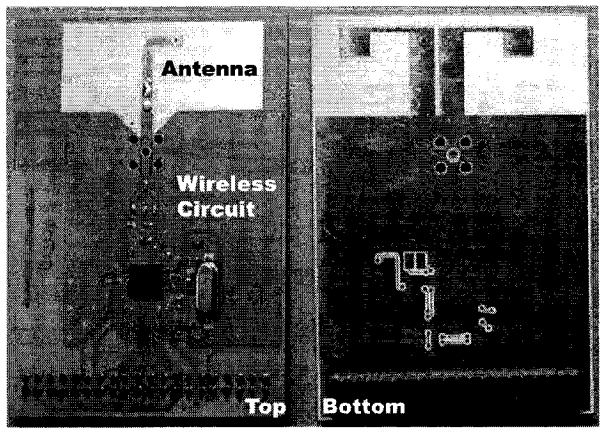


Fig. 3.2 McGill ZigBee board (McZig) - McGumps peripheral board

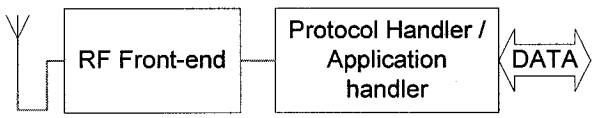


Fig. 3.3 Wireless node generic architecture model

The IEEE 802.15.4 standard [2] specifies two types of devices: a Full Function Device (FFD) and a Reduced Function Device (RFD). The difference between the two types is that the FFD or PAN coordinator, must have enough memory and computing power to manage all the devices, RFDs, present in the network. An FFD can take the role of a ZigBee Coordinator, Router or End Device depending on the ZigBee logical device type configuration. An RFD can act as a ZigBee End Device and cannot serve as a ZigBee Coordinator or ZigBee Router [47].

During the design stages of the McGumps platform several processor architectures were explored. The Texas Instruments' MSP430 processor is among the most energy efficient ones to date. Nonetheless, since low-power systems are inherently RAM and MIPS-limited, the embedded software component needed to be optimized to compensate for these shortcomings, Section 4. Among the members of the MSP430 family, MSP430F149 has been chosen, featuring 60K FLASH and 2K RAM. Since, this device only requires a fraction of the full 802.15.4 MAC layer (as RFD) the above specifications proved to be sufficient.

The PAN coordinator (FFD), needing to have more computational power and memory had to belong to a different family of processors. The architecture examination as well as

other aspects of the McZub design are presented in Section 3.2.

3.1.3 Wireless Transceiver

Zigbee compliant hardware was the top choice, as offered by Freescale [48] and Chipcon [49]. The main decisive factor was the availability of engineering samples at the time the project was conceived. Therefore, Chipcon CC2420 single-chip 2.4 GHz IEEE 802.15.4 transceiver became the heart of the wireless communication of both McZig and McZub as the more stable of the two offered ICs. CC2420 includes a digital direct sequence spread spectrum base band modem providing a spreading gain of 9 dB and an effective data rate of 250 kbps [50]. Its main advantages are in its design for low-power and low-voltage wireless applications (DG2). In addition, the CC2420 provides extensive hardware support for packet handling, data buffering, burst transmissions, data encryption and for authentication. Other useful capabilities include clear channel assessment, link quality indication and packet timing information. The configuration interface and transmit / receive FIFOs of CC2420 are accessed via the Serial Peripheral Interface (SPI) interface. The development kit provided by Chipcon included a simple yet powerful 802.15.4 network analyzer device - the "packet sniffer". This piece of equipment combines CC2420 with powerful software frontend to provide detailed graphical overview of the network activity. It greatly facilitated protocol debugging, as shown in Section 5.1.

3.2 McZub - Personal Area Network (PAN) Coordinator

The general hardware design goals were stated in the Introduction. Some of them, such as partitioning (DG1), low-power (DG2), low-cost (DG3) and compatibility (DG4) were briefly covered in the previous section of this Chapter. The remaining sections of this chapter will further emphasize and cover the outstanding ones. Other than stating the design goals a crucial step in the design process is to outline important characteristics.

3.2.1 Design Characteristics

- The design (McZub) shall be used as an IEEE 802.15.4 PAN Coordinator, hence it shall be a single purpose device, without the extendability present within the McGumps;

- The McZub shall have "USB device" capabilities. Universal Serial Bus (USB) shall serve as a link between the McZub and a host PC for application data passing, debugging and bootstrapping, Section 3.2.5;
- The design shall have nonvolatile memory for storing device and network settings as well as for data buffering, Section 3.2.6;
- The board shall feature a simple user interface (UI) by incorporating light emitting diodes (LEDs).
- The design shall have three power sources: USB bus, a wall-mounted transformer and direct soldered connections (ex: batteries), Section 5.1.3;
- To provide simple and flexible programming and debugging, the design shall be "Embedded ICE" ready, Section 3.2.3.
- An alternative RS232 link shall be present for debugging, Section 3.2.4.
- For extended signal range the design shall have the SMA connector for an external antenna in addition to the on-board one, Section 3.2.8.
- The microcontroller shall provide sufficient memory and computing power to support the full IEEE 802.15.4 MAC and PHY layers, applicable application and communication protocol with the host PC, Section 3.2.2;

After all the design characteristics have been laid out, one starts to sketch out the logical overview of the design. Figure 3.4 illustrates major components coupled with an interconnection overview.

Since the wireless transceiver has been chosen previously, Section 3.1.3, the next considered component is the microcontroller. A pin count estimate is presented in Table 3.1. Several components could be differently interfaced with the controller:

- USB chip could either benefit from full set of modem pins (Hardware control: Request-To-Send (RTS), Clear-To-Send(CTS), etc), which would result in total of 7 pins. On the other hand, abandoning any kind of flow control would save 4 I/O lines;
- Depending on the flavor of the serial memory: SPI or I^2C, this interconnection may require additional 3 or 2 I/O lines respectively;
- LEDs have secondary importance, therefore the design will utilize as many lines as needed or available.

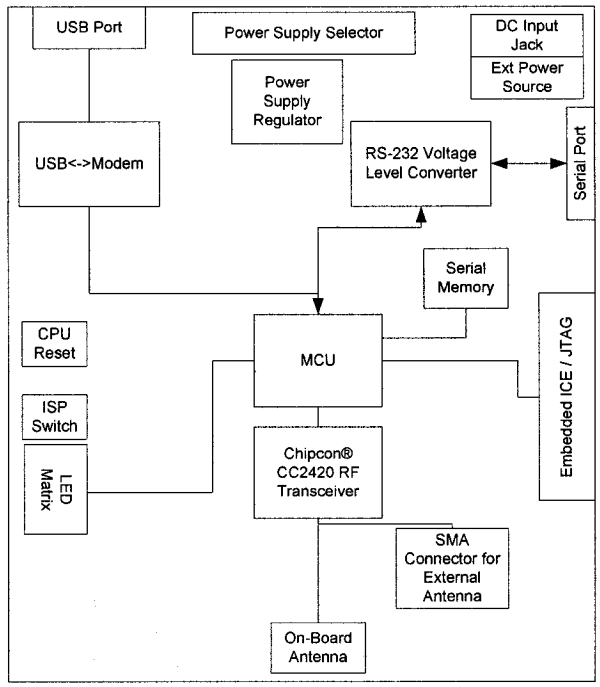


Fig. 3.4 McZub Logical Overview

3.2.2 Microcontroller and Memory

Nowadays, the choice of microcontrollers is very extensive, one needs to devote ample amount of research time before choice is made. By having completed the pin count analysis presented in the previous section, the aim was to find a controller for which the I/O lines would be maximally utilized and not wasted on NCs ("Not Connected").

The memory requirements, both ROM and RAM, are considered next. The structure of the controlling software has to be explored at this stage as it has direct impact on the initial RAM estimates. The rough outline of the anticipated software layers is shown in Figure 3.5. A Real-Time Operating System (RTOS) will be used in conjunction with low level software (firmware), that will be providing handlers for interaction with the application layer. Depending on the amount of tasks and intertask communication structures an RTOS can take anywhere from $\sim$ 400 bytes as presented in Table 3.2 to an application specific number of bytes. Further software implementation details are covered in Chapter 4.

The random access memory (RAM) requirements of a network coordinator (FFD) are significantly higher comparing to an end device (RFD) due to packet buffering (128B packet

Table 3.1 McZub Min/Max I/O pin count

	Min	Max
Chipcon)	7	7
USB	3	7
SPI	3	3
Ext. Memory	2 (SPI)	3 (I2C)
RS232	2	2
LEDs	2	4
TOTAL	19	26

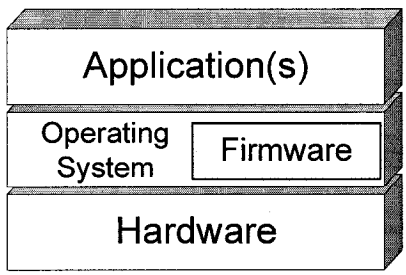


Fig. 3.5 McZub Software Layers Overview

size [2]), storing network nodes' information and running a more demanding user application. The number of network nodes that can be handled by the coordinator is directly proportional to the amount of available RAM. Considering that the MACS wireless network currently features only a dozen of nodes, providing support for a maximum total of 2^{16} nodes, proved to be a non-issue. If the device is to be used in teaching, with average enrollment of 50 students, the expected node count can reach up to one hundred.

The high memory capacity can be easily achieved by employing additional support circuitry - memory controllers. Designs providing support for external memory usually benefit from easier expendability, but consequentially higher power consumption. Keeping both RAM and ROM on-chip, results in a simpler, power efficient but less expandable design.

Summary of explored microcontrollers is presented in Table 3.3.

From Table 3.3, it was deduced that LPC210x family of devices will satisfy all of the

Table 3.2 RAM/ROM initial estimates [3]

	RAM (bytes)	ROM (Kbytes)
ZigBee Stack	specific	40
RTOS		4.4
Scheduler	83	
Queue	45 + queue storage area	
Task	20 + the task stack size	
Binary Semaphore	45	
Application code		specific
Firmware		2

related design goals and characteristics. In addition, this specific Philips family of chips features three devices LPC2104/5/6 with 16, 32 and 64 kilobytes of RAM respectively. Having the identical packages and pinout, the chips can be swapped at different stages of the development. Higher RAM capacity accelerates the debugging stages of the design development; once completed, the LPC2106 can be swapped with its "younger brothers" if saving on cost and power is the key requirement. The MSP430 is a great candidate when it comes to power consumption and price, but choosing this specific processor will result in constraints with respect to memory, both ROM and RAM. Being at the high-end spectrum of the MSP430 family, it does not make it a good choice since future expansions are not possible.

At the core of the LPC210x family is an ARM7 [51]. The key philosophy behind the ARM design is simplicity. The ARM7 is a RISC-type CPU with a small instruction set and consequently a small gate count. This makes it ideal for embedded systems. It has high performance, low power consumption and it takes a small amount of the available silicon die area [52]. It is one of the most widely used CPU IP cores today.

At the heart of the ARM7 CPU is the instruction pipeline, featuring three stages [53]. The pipeline is used to process instructions taken from the program store. A three-stage pipeline is the simplest form of pipeline for CPUs and does not suffer from the kind of hazards such as read-before-write seen in pipelines with more stages [54]. The pipeline has hardware independent stages that execute one instruction while decoding a second and fetching a third. The pipeline speeds up the throughput of CPU instructions so effectively

Table 3.3 Relevant microcontroller comparison chart (Nov. 2004)

	MSP430 F1611	Atmel AT91 (ARM7)	ColdFire MCF5206	LPC210x (ARM7)
Program Memory (KB)	48	FLASH[a]	FLASH[1]	128
RAM (KB)	10.24	256	DRAM[1]	16 – 64
Max Frequency (MHz)	8	75	33	60
I/O Pins	48	32	144	32
SPI	✓	✓	✓	✓
I^2C	✓		✓	✓
UART (Modem)			✓	✓
UART (Basic)	✓	✓	✓	✓
ADC/DAC	✓			
DMA	✓			
Timers	2:16bit	1:16bit	2:16bit	2:32bit
Power Usage				
Idle	4.3uA	8.2mA	30mA	5mA
Active	4.8mA	38.4	77.6mA	30mA
Package	64LQFP	100LQFP	160QFP	48LQFP
Cost ($US)	~ 14	~ 20	~ 22	9.4 – 11.8

[a]Via the memory controller

that most ARM instructions can be executed in a single cycle.

Although the ARM7 is a 32-bit processor, it has a second 16-bit instruction set called THUMB. The THUMB instruction set is really a compressed form of the ARM instruction set. This allows instructions to be stored in a 16-bit format, expanded into ARM instructions and then executed. Although the THUMB instructions will result in lower code performance compared to ARM instructions, they will achieve a much higher code density. So, in order to build a reasonably-sized application that will fit on a small single chip microcontroller, it is vital to compile the code as a mixture of ARM and THUMB functions, as it will be explained in Chapter 4. This process is called interworking and is easily supported on all ARM compilers. By compiling code in the THUMB instruction set

a space saving of 30% is achieved, while the same code compiled as ARM code will run 40% faster [52].

3.2.3 EmbeddedICE / JTAG

LPC2106 provides maximum on-chip debug support. There are several levels of support. The simplest is a JTAG debug port.

The JTAG port allows for real-time debugging of hardware and software by providing access to the internals of the processor and, through it, the rest of the computer system. It allows single or multi stepping through code running directly on the target system; individually toggle signal lines of the processor to test external subsystems, also known as boundary scan [55]. Even though JTAG is principally used for debugging purposes, it is also used for reprogramming the internal flash memory. LPC210x provides two JTAG ports - primary and secondary.

In addition, Philips has included the ARM embedded trace module (ETM). The embedded trace module provides much more powerful debugging options and real time trace, code coverage, triggering and performance analysis toolsets [51, 53]. In addition to more advanced debug tools, the ETM allows extensive code verification and software testing which is just not possible with a simple JTAG interface.

The only downside of the ETM module is relatively high pin utilization. When LPC210x is placed in the *primary debug mode*, by setting *DBGSEL* pin [51], 15 general I/O ports are reserved: 5 for *primary JTAG* and 10 for *Embedded Trace Macrocell (ETM)*. Considering the low pin count, the design proves to be unfeasible with 15 I/O lines reserved for debugging purposes.

However, designs that require additional I/O lines can benefit from the *secondary JTAG* functionality. The user has an option to redirect JTAG communication to pins P0.27 to P0.31. While the JTAG communication can be redirected to the *secondary JTAG* pins in software, ETM module becomes unavailable, since ETM and secondary JTAG interfaces are sharing the same pins and consequently are excluding one another [51]. This simple yet powerful option provides access to an additional 10 I/O lines compared to the default *primary debug mode*. Secondary JTAG has one downside - it is disabled by default and can only be engaged by bootstrapping the controller with the appropriate pin setup code via the UART and by maintaining the same setup throughout the design process. This was an

acceptable shortcoming because debug functionalities provided by the JTAG are sufficient for vast number of embedded systems, including the McZub. The code verification features provided by the ETM are useful but not essential.

3.2.4 RS-232

The simplest form of serial interface is that of the Universal Asynchronous Receiver Transmitter - UART. RS-232 is a serial communication interface standard used for interfacing serial devices over cable lengths of up to 25 meters and data rates up to 115kbps. The interface is primarily used to connect to other computers and terminal emulators as well as for microcontroller programming and possibly debugging in case when JTAG fuse has been blown.

RS-232 voltage levels of the transmitted bits is referenced to local ground. Moreover, a logic high is in the range from $-5V$ to $-15V$, and logic low is between $+5V$ and $+15V$. Typically the voltage levels are $-12V$ and $+12V$ for logic high and logic low respectively [56].

Since UART is incorporated within the LPC210x, all that is required is an external level shifter to convert the serial transmissions to and from RS-232 levels. A generic MAX3223 chip has been chosen form Texas Instruments. Adding the chip is trivial, since the only external support components are capacitors for the internal charge pumps. These pumps generate the necessary $-12V$ and $+12V$ required voltages. The capacitor values are shown in the Appendix C, Figure A.1.

The main usage will be initial JTAG bootstrapping, as explained in Section 3.2.3, and as backup communication medium in case USB connection on the host computer is not available or broken. Considering the purposes of this link only the simplest form of the RS232 will be used - signals Tx, Rx and signal ground.

3.2.5 USB

The above subsection covers an older standard that is gradually becoming obsolete. In addition, RS-232 suffers from numerous problems and limitations. Communication parameters such as data rate, parity and handshaking have to be manually set. Connectors vary as well.

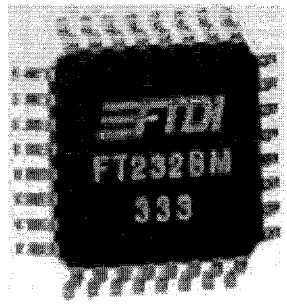
The main rational behind USB incorporation was to make the device as easy to use as possible. Universal Serial Bus (USB) allows peripherals and computers to interconnect in a

standard way with a standard protocol providing "plug and play" possibilities. Additionally, USB bus provides power via its $5V$ line [57] that eliminates the need for an external power supply or cable.

By directly interacting with the host computer's OS without the need for manual setup USB provides ease of use. Conversely, it requires an extra layer of complexity on the firmware side, since the device must interact with the host in the appropriate way. The protocol and specifications of USB are fairly elaborate, therefore the actual implementation and overview are beyond the scope of this thesis. Fortunately, USB hardware is widely available, in particular UART to USB ASICs.

Currently the two most popular solutions that provide full (hardware control) UART to USB connectivity are CP2102 from Silicon Laboratories [58] and FT232BM from Future Technology Devices [59]. The former IC requires no external components and provides internal nonvolatile memory for device ID and product description strings. The latter, requires numerous external components (oscillators, capacitors and resistors) and external EEPROM for storing description strings. Both devices are USB 2.0 compliant, Figure 3.6.

SiLabs CP2102



FTDI FT232BM

Fig. 3.6 USB to UART bridges

To avoid possible soldering difficulties with the Silicon Lab's lead free 28-pin MLP package during in house assembly the FTDI solution provides a viable alternative. Since the devices are functionally the same, for the purposes of this thesis the FTDI chip has been chosen. The full schematic of the USB section is provided in the Appendix C, Figure A.3.

3.2.6 External Memory

Common embedded system peripherals, such as real-time clocks, nonvolatile memories for parameter storage, touchscreen controllers connect to microcontrollers via two simple interfaces - Serial Peripheral Interface (SPI) and Inter-Integrated Circuit (I^2C). The wireless chip used in this project, CC2420, connects to the system via the SPI, as mentioned in Section 3.1.3.

As Philips originally invented the I^2C bus standard, it is not surprising to find the LPC2000 equipped with a fully featured I^2C interface. The I^2C interface can operate in master or slave mode up to 400K bits per second and in master mode it will automatically arbitrate in a multi-master system.

The SPI was developed by Motorola to provide a low-cost and simple interface between microcontrollers and peripheral chips. It is sometimes called three or four wire interface. Unlike the UART, SPI is a synchronous protocol in which all transmissions are referenced to a common clock, generated by the SPI master. The slave device uses the clock to synchronize to an incoming bit stream. Many chips may be connected to the same SPI bus, however each must have its own chip select input controllable by the SPI master. The LPC210x has the hardware SPI interface built-in.

Like the I^2C the SPI interface is a simple peripheral interface which can write and read data to the SPI bus, but is not intelligent enough to manage the bus. It is up to the code to initialize the bus interface and then manage the transfers.

Since we have the option of running the external memory and the wireless chip on separate busses in order to avoid arbitration difficulties the design decision was to utilize I^2C compatible memory device. A 64KB EEPROM device from Microchip Technologies was chosen.

Peripheral memory usually comes in two flavors - EEPROM and Flash. Flash is a more recent ROM technology, usually featuring higher capacities than EEPROMs. A subtle difference between the two technologies is the rewrite cycle. Normally flash is organized in fixed size sectors that may be individually erased and rewritten [60]. Since the device is used for storing network parameters, configuration settings and possible simple packet buffering the capability of rewriting single bytes wins over higher memory capacity.

3.2.7 Power Supply

McZub board can operate via three different types of power sources: AC adapters, batteries and $5V$ USB bus line. Selector jumper 4 (J4) in Figure A.4 is used to select between the power obtained from the USB bus and other remaining sources.

The Philips LPC2100 family of devices is a wave of new microcontrollers based on a low-power, cost effective ARM7TDMI-S core. As such, they require a dual power supply: one for the CPU core and one for the I/O lines. The CPU operating voltage range of $1.65V$ to $1.95V$ ($1.8V \pm 8.3\%$) while the I/O power supply range of $3.0V$ to $3.6V$ ($3.3V \pm 10\%$). The pads are 5 V tolerant [53, 51].

To provide the correct and constant operating voltage to the system, the design must employ a voltage regulator. It is a device that converts a range of input DC voltages to a fixed-output DC voltage. Since our supplied voltages are assumed to be higher than the highest required voltage by the system ($3.3V$) a *linear regulator* has been selected. A switching regulator or a charge pump has been considered, but since boosting the voltage was not required, and by topically costing more and needing more external components than linear regulators, they were quickly disregarded.

Selecting a linear regulator is not an easy task since there is literally hundreds of them offered by a single manufacturer, for example Texas Instruments. To save on the chip count and therefore cost (DG3) a relatively new breed of dual-output low-dropout voltage regulators has been selected. They provide dual output voltages ($1.8V$ and $3.3V$) for split-supply applications with ultra-low 190μA quiescent current [61]. Quiescent current is a byproduct of the inefficient conversion process, however the TPS707xx family of devices benefits from the lowest quiescent current among the products of its class.

Within the split-supply systems, it is crucial to respect the order during power up. LPC210x requires the I/O lines to be excited before powering up the core and releasing the system reset [51]. Texas Instruments TPS70751 provides the designer with this important power sequencing capabilities. The regulator features selectable power-up sequencing i.e. by driving a control line (SEQ) low or high, the $3.3V$ line can appear before or after the $1.8V$ line respectively.

After consulting all the devices' datasheets and performing "back of the envelope calculations" it has been established that $250mA$ and $150mA$ provided on the $3.3V$ and $1.8V$ lines respectively will satisfy both the continuous and peak loads [61].

Furthermore, the board features self-resettable fuse and a protection diode as illustrated in schematics of Appendix C, Figure A.4.

3.2.8 Antenna

Since the establishment of the design methodology for wireless nodes with printed antennas [22] numerous different antennas were realized using copper traces. For this design it has been decided to try out an off-the-shelf 2.4GHz compact chip antenna as an on-board solution. Moreover, a surfacemount SMA connector has been added to provide connectivity to an external, potentially more efficient antenna. The reader may consult Figure A.2 in Appendix C. The matching network has been kept the same as on the McZig.

3.3 McZub Printed-Circuit Board (PCB)

The whole infrastructure design was done using only 2-layer PCBs to reduce the development and production cost. The main drawback of a 2-layer approach is that more attention must be paid to the signal routing and power distribution [62], [63]. The use of ground return traces and ground area fill are especially critical in the RF section, where any discontinuity in the trace impedance can considerably affect the performance of the design.

The PCB designed was carried using Mentor Expedition PCB. The design databases were set-up to include prototype and production part numbers, allowing the generation of Bill of Materials (BOM) in a single command. The BOM could then be directly imported in a spreadsheet for on-line ordering of prototype components while production part numbers were used for larger orders, Figure A.5. Strong emphasis was put on the Design Rule Checking (DRC) to obtain hazard-free board in a single iteration.

Noise generated by the electromagnetic interference can be a significant problem in digital systems [63]. Naturally, digital signals suffer degradation and noise to analog effects because the system is inherently analog in operation. Degradation and noise leads to corrupted data and possibly a system crash. Furthermore, power lines are equally susceptible to noise as digital lines. Techniques used to minimize noise through careful design and board layout are presented next.

3.3.1 Eliminating Noise

In any circuit, there is a wire carrying current in and a wire carrying current out. Current flowing through a wire generates a magnetic field around that wire. Such a magnetic field can be a source of electromagnetic interference (EMI). When current flows through a system it flows via the power and signal connections and back to the power supply through ground. To minimize the magnetic fields generated by the currents in the wires one must aim to minimize the length of the *current return path.* This task is also known as *minimizing the current loop area* [62]. An effective method to minimize the current loop area is to introduce ground planes, which was done over the entire area of the board on both layers, Figure A.6. In addition, ground planes help reduce *capacitive coupling*, thus lowering the probability of possible *crosstalk.* Crosstalk is an effect when a signal on one wire capacitively induces a signal in an adjacent line.

Keeping the power lines "noiseless" is slightly harder than signal lines. The principle of short current loops applies in this situation as well, however keeping them short is difficult since power must be distributed throughout the circuit and thus resulting in long copper traces. The common solution to this problem is to provide a path to ground for any noise present in the power supply. In an effort to circumvent the problems created by power distribution wiring *decoupling capacitors* are added between power and ground for each integrated circuit, as close as possible to the power pins, Figure 3.7. Moreover, multiple capacitors are used for each power pin in order to ensure that all frequencies that may affect the circuit have a low impedance path to ground. Figure A.1 illustrates several capacitors (100nF and 10nF) placed on $3.3V$ and $1.8V$ rails. Placing multiple capacitors is the concept known as the *multilayered power distribution system* [62].

The bigger capacitor generally has the advantage of acting as a current source for the device during intense switching activity. To that end the McZub board has been decoupled by a large 33μF tantalum capacitor (C55), Figure A.4.

In order to cope with possible ground and power noise at high frequencies, an additional bypass capacitance was obtained by distributing the ground plane on both layers as mentioned earlier. The capacitance present between ground and power lines can be described by Equation 3.1, where ε_r is relative electric permeability of insulator; A - area of shared

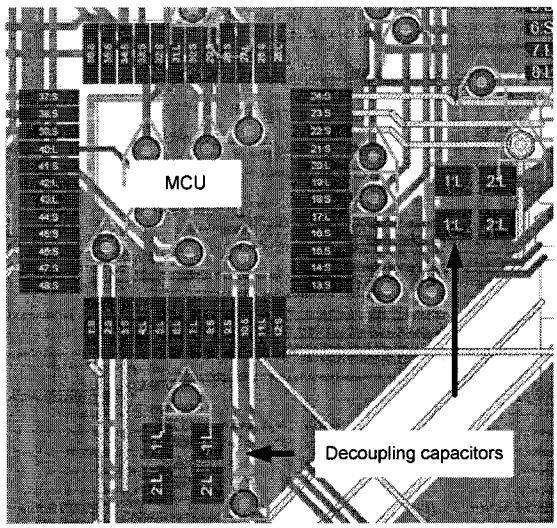


Fig. 3.7 LPC210x decoupling capacitors

power-ground planes; d - separation between planes.

$$C_{plane} = \frac{0.225 \times \varepsilon_r \times A}{d} \tag{3.1}$$

Employing all the above mentioned techniques resulted in an error free and stable hardware platform while satisfying all the current requirements in the field of low-rate personal area networks.

Chapter 4

Embedded Software (Firmware)

Hardware is part of the computer that you can hit, but software you can only scream at.

—Unknown

This chapter presents an overview of a highly portable and expandable IEEE 802.15.4 MAC/PHY implementation as well as other supporting services that provide foundation for 802.15.4 compliant application development. The embedded software development has been carried out using "ANSI C" and assembly. The firmware has been ported and tested on two different hardware platforms (ARM7 and MSP430). Moreover, the MSP430 variation of the code is available for both MSPGCC[1] and Rowley[2] compilers.

The IEEE standard and its background were briefly introduced in Section 2.1.1 and will be covered in this chapter in more detail, Section 4.1. For better understanding of the protocol specifics the reader should consult the IEEE Standard's publication on 802.15.4^{TM} [2]. The design strategies and specifics regarding overall firmware implementation, such as general approach, hardware abstraction layer (HAL) and real-time operating system (RTOS) use are presented in Section 4.2. Sections 4.4 and 4.3 discuss Medium Access Control (MAC) and Physical (PHY) layers respectively.

[1] `http://mspgcc.sourceforge.net`
[2] `http://www.rowley.co.uk`

4.1 IEEE 802.15.4 Background

The main features of this standard are network flexibility, low cost, very low power consumption, and low data rate in an adhoc self-organizing network among inexpensive fixed, portable and moving devices. As mentioned in previous chapters, a device can be a full-function device (FFD) or reduced-function device (RFD). A network shall include at least one FFD, operating as the PAN coordinator. The FFD can operate in three modes: a personal area network (PAN) coordinator, a coordinator or a device. An RFD is intended for applications that are extremely simple and do not need to send large amounts of data. An FFD can talk to RFDs or FFDs while an RFD can only talk to an FFD [24].

4.1.1 Network Topologies

Figure 4.1 shows 2 types of topologies that the IEEE 802.15.4 standard defines: a star topology and a peer-to-peer network topology.

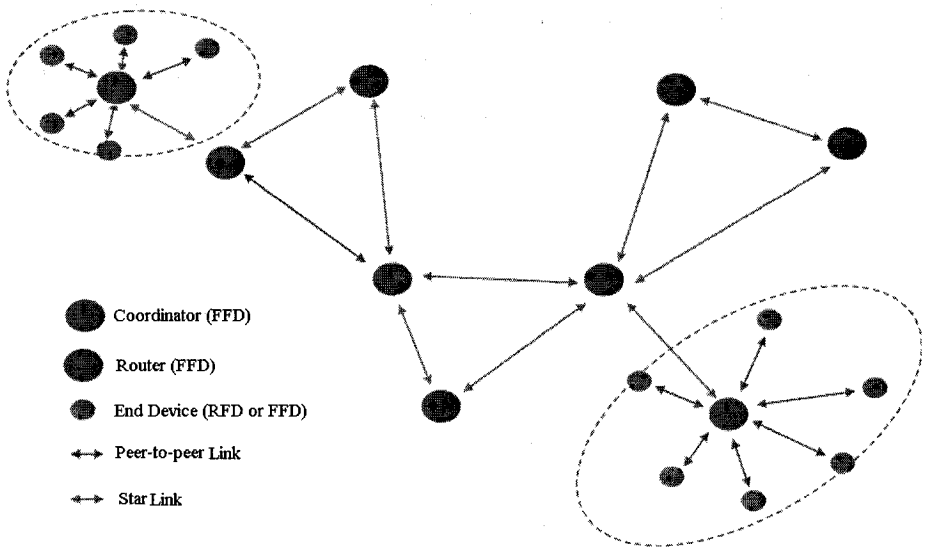


Fig. 4.1 Network topology - global prospective

Star Topology

In the star topology, the communication is established between devices and a single central controller, called the PAN coordinator. The PAN coordinator may be mains-powered [3] while the devices will most likely be battery powered. Applications that benefit from this topology include home automation, social event tracking, personal computer (PC) peripherals, toys and games. After an FFD is activated for the first time, it may establish its own network and become the PAN coordinator. Whenever a new PAN is started by the coordinator it must choose a PAN identifier, which is not currently used by any other network within the range of its radio signal. This allows each star network to operate independently.

Peer-to-peer Topology

In a peer-to-peer topology, there is also one PAN coordinator. In contrast to star topology, any device can communicate with any other device as long as they are in range of one another. A peer-to-peer network can be ad hoc, self-organizing and self-healing. Applications such as industrial control and monitoring, wireless sensor networks, asset and inventory tracking would benefit from such a topology. It also allows multiple hops to route messages from any device to any other device in the network. It can provide reliability by multipath routing [64].

4.1.2 Network Operation

The PAN coordinator, being the principal controller of the network, maintains a list of devices that are currently in its network. If a device wants to join an 802.15.4 network it must associate itself with its respective PAN coordinator. A device can only be associated with one PAN coordinator. PAN coordinator, if properly configured, can provide synchronization services to its devices through the transmission of beacon frames.

A network can operate in either beacon mode or non-beacon mode. In beacon mode, all coordinators within the network transmit beacon frames (synchronization frames) to its associated devices and all data transmissions between the coordinator and its associated devices occur in the active period following the beacon frame, as shown in Figure 4.2.

[3] Powered via the main electric grid

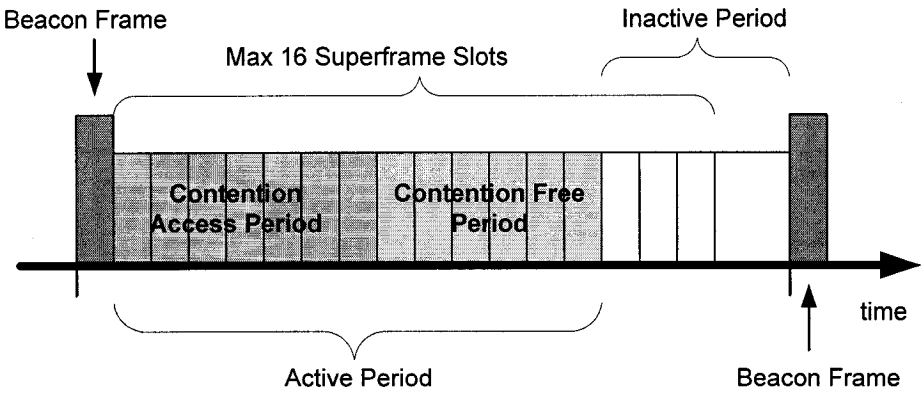


Fig. 4.2 IEEE 802.15.4 Superframe structure timing

The superframe can have an active and an inactive portion. During the inactive portion, a device shall not interact with its PAN coordinator and may enter a low-power mode. The active portion consists of contention access period (CAP) and contention free period (CFP). Any device wishing to communicate during the CAP shall compete with other devices using a slotted CSMA-CA mechanism. On the other hand, the CFP contains guaranteed time slots (GTSs). The GTSs always appear at the end of the active superframe starting at a slot boundary immediately following the CAP. The PAN coordinator may allocate up to seven of these GTSs and a GTS can occupy more than one slot period.

In non-beacon mode data transmissions can take place at any time. For both non-beacon and beacon networks, the application can chose to transmit data in two ways:

Direct Data Transfer: Data exchanged between a device and a coordinator in a non-beacon network using direct data transfer takes place as soon as the channel is free using CSMA-CA.

Indirect Data Transfer: Data from a device to a coordinator in a non-beacon network using indirect data transfer takes place as soon as the coordinator receives data poll request and the channel is free using CSMA-CA.

4.2 Firmware Design Overview

The classical layered model has been chosen as the design implementation choice. Figure 4.3 depicts a block diagram of the software system. The nature of the design allows for rapid

prototyping and deployment of 802.15.4 compliant applications by fully abstracting the physical and medium access control layers.

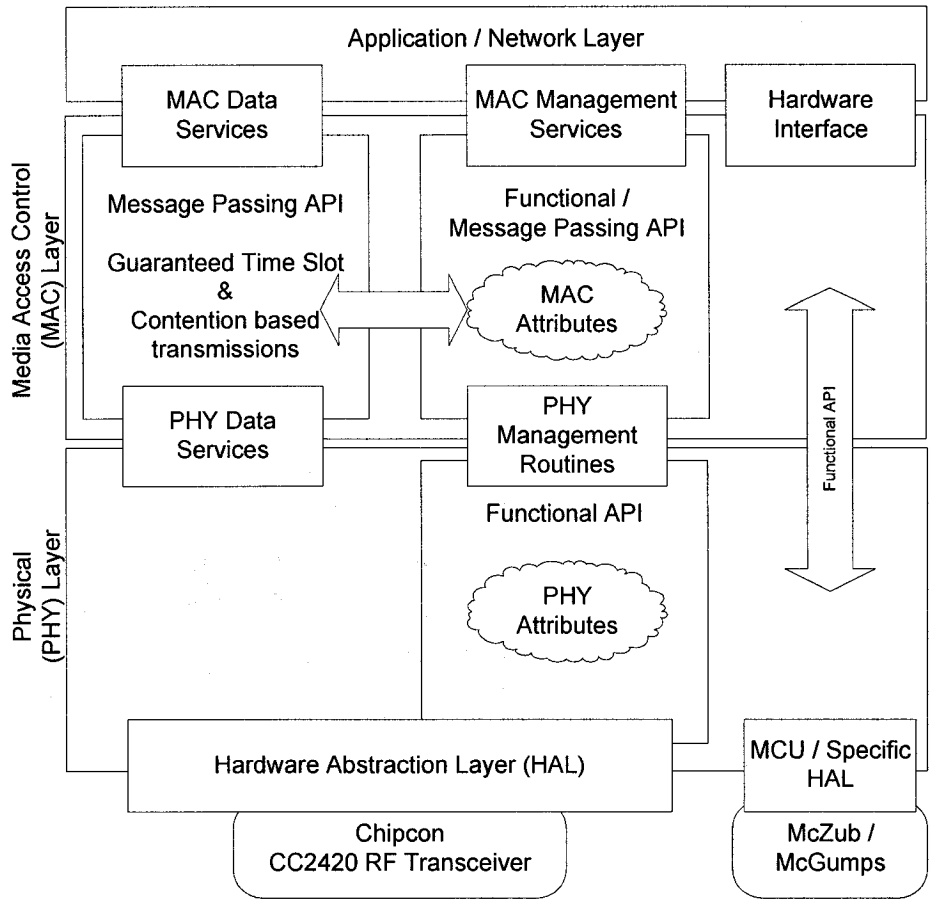


Fig. 4.3 Embedded software model of extendable MAC / PHY layers

The key to layered approach is dependency management [65]. Components in one layer are allowed to interact only with components from lower levels. This helps reduce the dependencies between components on different layers. Initially a *strictly layered* approach was considered. In such scenario, a layer can only interact with layer directly below it. However, in a memory-limited embedded system such approach proves to be inefficient and memory hungry since simple calls need to be forwarded from one layer to the next. A *relaxed layered* approach loosens the constraints such that a component can interact with components from any lower layer if need be. It eliminates the level of isolation between the layers, but tremendously improves efficiency. This is especially useful in case when the

MAC layer needs to access hardware features, such as timers in order to satisfy hard timing requirements by the network protocol.

The possible applications can range from ZigBee Network (NWK) layers to dedicated MAC applications. In the ZigBee configuration it is the IEEE 802.2 logical link control (LLC) that accesses the MAC sublayer through the service specific convergence sublayer (SSCS) [66], Figure 4.4.

The MAC layer, Section 4.4, provides three interfaces to the application:

Data (MAC Common Part Sublayer - MCPS) Services: This interface provides services for all data related primitives. The application must use this interface in order to send and/or receive data. The interface is defined in the IEEE 802.15.4 specification.

Management (MAC Sublayer Management Entity - MLME) Services: This interface provides services for all MAC management functions - MAC commands. This interface is defined in the IEEE specification.

Hardware Interface: Depending on the hardware used, this interface provides means for the application to access hardware specific features: real-time clock, low power modes, LEDs, etc.

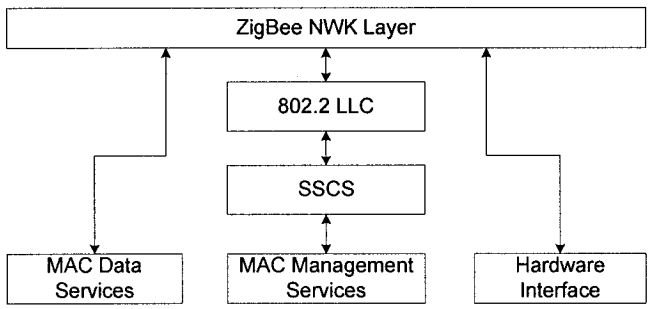


Fig. 4.4 ZigBee upper layers overview

The PHY layer contains low-level control mechanism of the RF transceiver that are presented in Section 4.3.

4.2.1 Hardware Abstraction Layer (HAL)

Hardware abstraction layer functions as an interface between a systems hardware and software, providing a consistent hardware platform on which to run applications. When

a HAL is employed, applications do not access hardware directly but access the abstract layer provided by the HAL. Applications become device-independent, which is crucial when they are intended to run on different platforms as in our situation.

The HAL for the wireless transceiver has been adopted from Chipcon, device manufacturer, and ported to the two architectures of interest - Philips LPC210x and Texas Instruments MSP430 (DG7). This layer consists exclusively of "C" macros and provides access to transceiver's registers and receive/transmit buffers.

Additionally this abstraction layer provides convenient macros to initialize hardware components - port pins, modules (real-time clock, timers) and interrupts. Few macros are presented below:

```
#define FASTSPI_WAIT() \
    do { \
        while (!(rSPSR & BM(SPIF))); \
    } while (0)

#define MEM_WP_ENABLE()     (rIOSET = BM(MEM_WP))
```

4.2.2 Real-Time Kernel / Operating System (RTOS)

Low complexity and small memory systems are generally designed without multitasking capabilities, i.e. without the use of a kernel. These systems are called foreground/background or super-loops. An application usually consists of an infinite loop that calls modules to perform the desired operations (background) while the Interrupt Service Routines (ISRs) handle asynchronous events (foreground) [67]. Critical operations must be performed by the ISRs to ensure that they are dealt with in a timely fashion. Because of this, ISRs tend to take longer than they should and require more stack space. To insure atomical execution of a critical section, ISR nesting must be disabled, leading to possible failure of servicing a pending interrupt. Also, information for a background module made available by an ISR (acquired data, set flag, etc.) is not processed until the background routine gets its turn to execute. Moreover, if a code change is made, the timing of the main loop is affected. A typical execution sequence of a foreground/background implementation is shown in Figure 4.5.

The IEEE 802.15.4 protocol heavily relies on precise timing to achieve ultra-low power usage. After associating with the PAN coordinator, a device starts to periodically track beacons in order to maintain synchronization with the PAN as well as for the coordinator

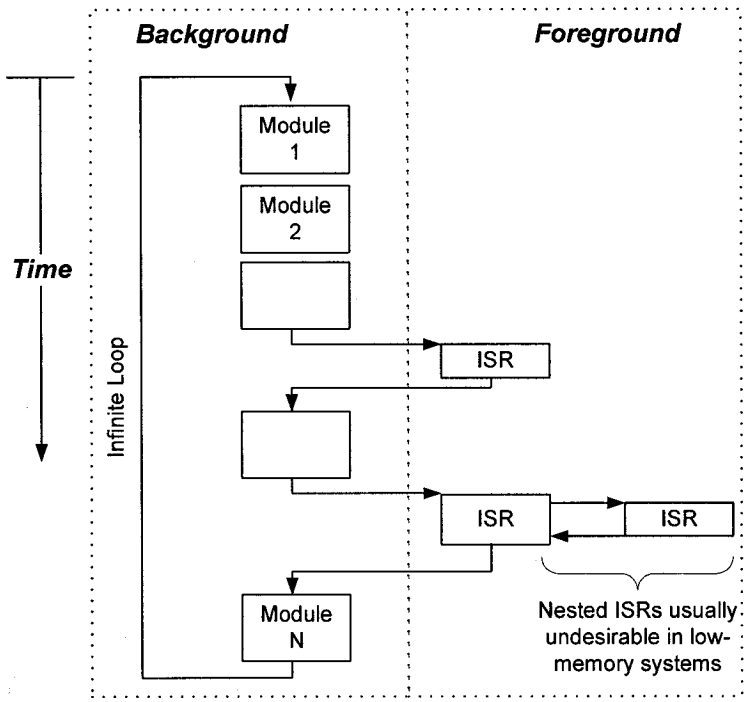


Fig. 4.5 Foreground / Background system implementation

to transmit data indirectly to the device. For a device to avoid beacon losses, the PAN coordinator must guarantee timely transmissions of the beacon frames, Figure 4.2. Furthermore, prompt processing of the incoming packets helps reduce the probability of moving the transmission to the next superframe, thus conserving power. For these reasons and for other benefits a real-time kernel is considered.

Multitasking is the process of scheduling and switching the MCU (Microcontroller Unit) between several tasks. It allows for maximum utilization of the MCU and provides for modular construction of applications. Moreover, it helps manage the complexity of real-time applications by providing intertask communication tools such as message queues, semaphores and events. The only downside of running a kernel is additional RAM usage due to the individual task control blocks and stack spaces, as shown in Figure 4.6.

Considering the availability of RAM on the McZub system (64KB), several real-time kernels were explored, both proprietary (ucOS-II) and open source. The open source solution, FreeRTOS [3] turned out to be more appealing mainly due to freely available updates, possi-

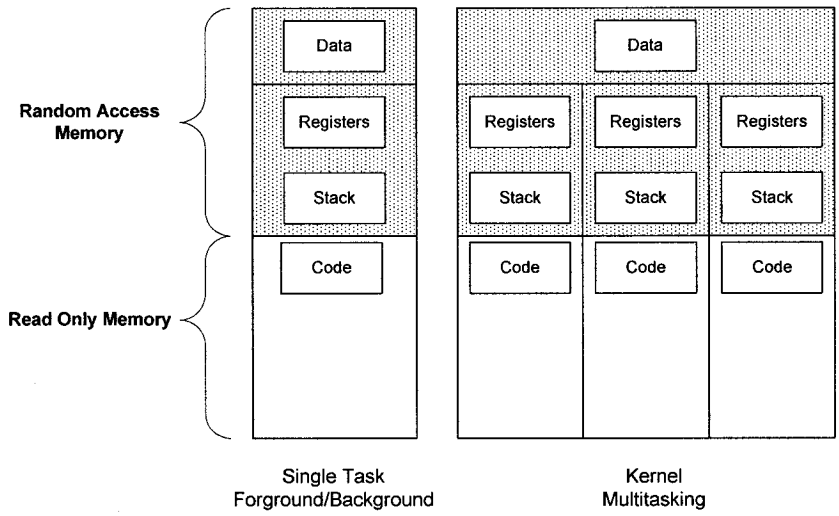


Fig. 4.6 Multitasking versus single tasks

bility of contributing to the project[4] and far less restrictions on code distribution. The RAM requirements are virtually the same as with the ucOS-II, providing higher degree of configurability and slightly better performance. Due to the open source nature, the full MAC and PHY layers are currently maintained on SourceForge at `http://mczub.sourceforge.net`.

4.2.3 OS Abstraction Layer

Even though FreeRTOS has been chosen as the main kernel for this project, an OS abstraction layer has been implemented to provide smoother transitions to other kernels, such as ucOS-II. All structures and function calls have been abstracted to generic ones by use of "C" macros. These can be easily converted to function calls if a target kernel requires additional functionality.

4.3 IEEE 802.15.4 Physical (PHY) Layer

The PHY provides two services: the PHY data service and PHY management service interfacing to the physical layer management entity (PLME). The PHY data service enables the transmission and reception of PHY protocol data units (PPDU) across the physical radio channel. The features of the PHY are activation and deactivation of the radio transceiver,

[4]The MSP430 Crossworks port

energy detection (ED), link quality indication (LQI), channel selection, clear channel assessment (CCA) and transmitting as well as receiving packets across the physical medium.

Physical layer management and data services have been implemented using functional application programming interface (API). The approach was favored over message passing since all the commands provided by the PHY are executed at call time, providing return values in a timely manner. Message passing APIs are appropriate in situations where requests cannot be completed instantaneously, that is they require scheduling and reporting for later times. Message passing is generally avoided unless it is absolutely needed because of the increased memory requirements and lower performance compared to functional APIs.

The PPDU packet structure is illustrated in Figure 4.7. Each PPDU packet consists of the following basic components:

- SHR, which allows a receiving device to synchronize and lock onto the bit stream
- PHR, which contains frame length information
- A variable length payload, which carries the MAC sublayer frame.

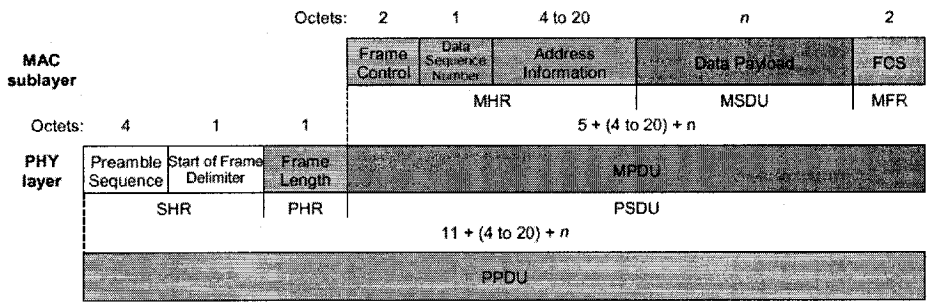


Fig. 4.7 IEEE 802.15.4 MAC / PHY network packet breakdown layers

The CC2420 wireless transceiver, being IEEE 802.15.4 compliant, abstracts most of the PHY services to on-chip registry accesses. In addition, it provides automatic generation of preamble sequence and start of frame delimeter (SFD).

4.4 IEEE 802.15.4 Media Access Control (MAC) Layer

Similarly to the PHY, the MAC sublayer provides two services: the MAC data service and the MAC management service that interfaces to the MAC sublayer management entity (MLME) service access point (SAP) (MLMESAP). The MAC data service enables the

transmission and reception of MAC protocol data units (MPDU) across the PHY data service, Figure 4.7. Among the major features of MAC sublayer are beacon management, GTS management, channel scanning, association and disassociation. The Chipcon RF transceiver provides numerous other important MAC layer services including: frame validation, acknowledged frame delivery, channel access and encryption.

Figure 4.8 depicts a high-level overview of the MAC/PHY internal composition. As shown, up to 4 tasks are used to control protocol execution as well as process incoming data from the physical and network (application) layers.

When the FFD is configured as a PAN coordinator, the "Beacon Network" task, having the highest priority, commences beacon frame transmissions. The subsequent beacon transmissions are scheduled using the hardware timer, thus providing necessary transmission accuracy. Moreover, the task implements superframe timings for both contention based (CAP) and guaranteed time slot (GTS) periods and carries necessary data sending. At the end of the active period, before putting the PAN coordinator to low-power mode, the task engages service maintenance functions: new beacon generation, GTS slot defragmentation and reports to higher layers any untransferred data.

The "Device Task" is present in both RFD and FFD firmware configurations. This task can run in conjunction with "Beacon Network" to provide beacon transmissions if the FFD acts as a router, rather than the PAN coordinator. In simpler network configurations (star topology), the FFD device would either act as an RFD or a PAN coordinator, thus limiting total number of running tasks to three. After proper configuration has taken place, the "Device Task" begins synchronization process by tracking the beacon frame. Given that the expected packet has been received, the task enters the CAP period followed by the GTS, if available, to finally enter the MAC sublayer maintenance period. If the synchronization process has failed, the task would report loss of beacon to the upper layers.

Handler tasks used for inter-layer communication run at the second-highest level of priority. Processing of data and MAC management requests have been consolidated into a single task "Handle NWK to MAC Messages". As mentioned previously, the message passing architecture is only used for messages that might require longer processing times to complete. These are requests for data transfers or network control messages requiring packet transmissions.

As shown in Figure 4.8, the message requests are stored in queues that are provided by the operating system, thus facilitating overall inter-task communication.

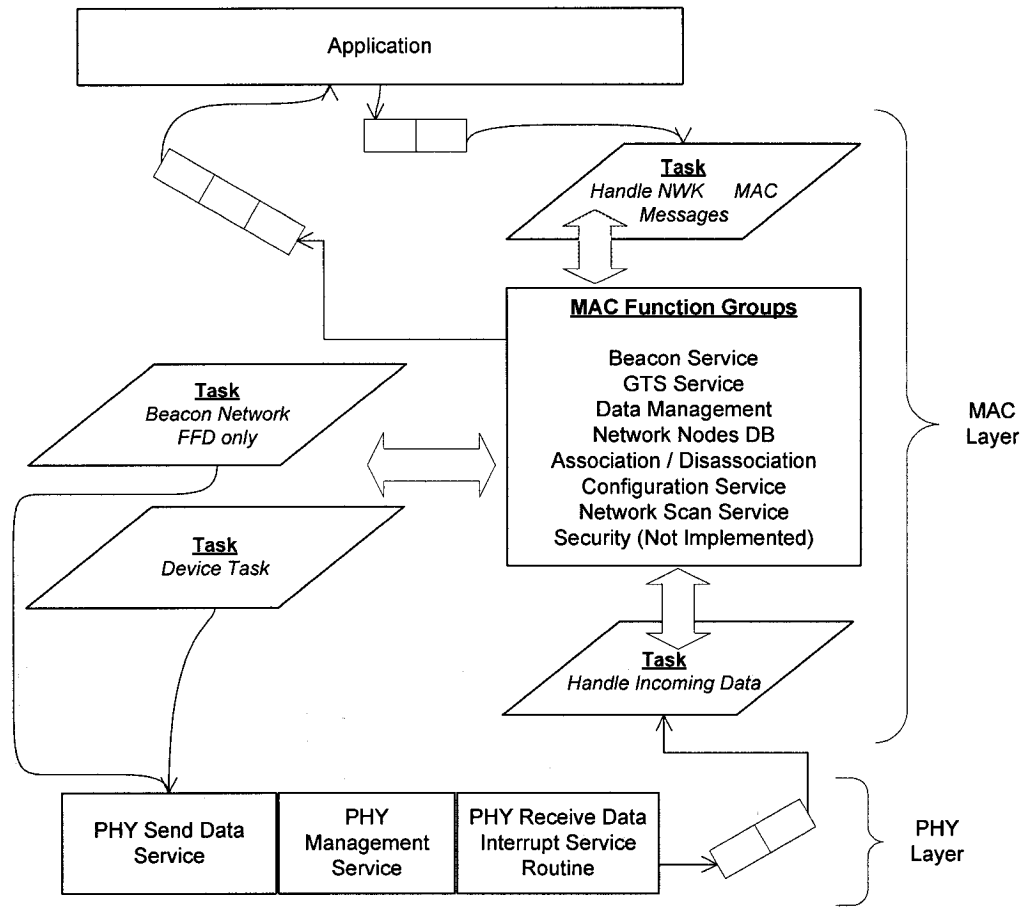


Fig. 4.8 IEEE 802.15.4 MAC / PHY Internals

4.4.1 Higher Layer Interface Overview

The interface between any applicable higher layers (for example: Network - NWK) and the MAC Logical Management Entity Layer (MLME) or MAC Common Part Sublayer (MCPS) is based on service primitives passed from one layer to the other through a layer of "Service Access Point". All the SAPs have been implemented and the application only needs to use the applicable message queues to receive or send inter-layer messages. They are presented herein.

```
void vMLMEMessageSendMacToNwk (MLME_Message_t *pxMessage);
MLME_Message_t* xMLMEMessageReceiveNwkFromMac (UINT16 usMSecBlockTime);

void vMCPSMessageSendMacToNwk (MCPS_Message_t *pxMessage);
```

```
MCPS_Message_t* xMCPSMessageReceiveNwkFromMac (UINT16 usMSecBlockTime);

void vMLMEMessageSendNwkToMac (MLME_Message_t *pxMessage);
MLME_Message_t* xMLMEMessageReceiveMacFromNwk (UINT16 usMSecBlockTime);

void vMCPSMessageSendNwkToMac (MCPS_Message_t *pxMessage);
MCPS_Message_t* xMCPSMessageReceiveMacFromNwk (UINT16 usMSecBlockTime);
```

Because the NWK and MLME/MCPS interfaces are based on messages being passed to a few SAP', each message needs to have an identifier. The message identifiers as well as the data types used are defined in the interface header files called `mac_mlme.h` and `mac_mcps.h`. Quick overview of data primitives are presented in Appendix B, Section B.1.

4.5 Implemented MAC Services

4.5.1 Beacon Generation

Depending on the parameters of the request message to the MAC management services (MLME-START.request primitive), the FFD may either operate in a beaconless mode or may begin beacon transmissions either as the PAN coordinator or as a device on a previously established PAN. An FFD that is not the PAN coordinator shall begin transmitting beacon frames only when it has successfully associated with a PAN. This primitive also includes macBeaconOrder and macSuperFrameOrder parameters that determine the duration of the beacon interval and the duration of the active and inactive portions, Figure 4.2.

4.5.2 Guaranteed Time Slot (GTS) Management

A GTS allows a device to operate on the channel within a portion of the superframe that is dedicated exclusively to that device. A device shall attempt to allocate and use a GTS only if it is currently tracking the beacons. A GTS is only used only for communications between the PAN coordinator and a device. A single GTS can extend over one or more superframe slots. The PAN coordinator may allocate up to *seven GTSs* at the same time, provided there is sufficient capacity in the superframe.

For each GTS, the PAN coordinator stores its starting slot, length, direction and associated device address. The GTS direction is specified as either transmit or receive. Each device may request one transmit GTS and/or one receive GTS.

A device is instructed to request the allocation of a new GTS through the GTS request command, with GTS characteristics (direction, length,...) set according to the requirements of the intended application.

The PAN coordinator checks if there is available capacity in the current superframe based on the remaining length of the CAP and the desired length of the requested GTS. The superframe shall have available capacity if the maximum number of GTSs has not been reached and allocating a GTS of the desired length would not reduce the length of the CAP to less than aMinCAPLength. The PAN coordinator may take up to aGTSDescPersistence-Time superframes to allocate the GTS. During that time the pending GTSs are kept in the "pending buffer" size of which is set depending on the available memory. The allocated GTS descriptor is advertised in the beacon frame for aGTSPersistenceTime superframes. On receipt of the beacon frame, the device processes the descriptor and notifies the next upper layer of the success.

In the same way, a device is instructed to request the deallocation of an existing GTS through the GTS request command using the characteristics of the GTS it wishes to deallocate. The PAN coordinator ensures that any gaps occurring in the CFP, appearing due to the deallocation of a GTS, are removed to maximize the length of the CAP during the GTS maintenance - GTS defragmentation.

4.5.3 Data Buffering

Due to the nature of 802.15.4 protocol i.e. indirect transmissions and specific timings of the CAP and CFP periods, the pending packets are in most cases buffered prior to their release. Packets awaiting transmission must be arranged in order in which they were passed from the higher layers and preferably sorted according to their destination address to facilitate their maintenance within the PAN itself. The proposed data structure is presented in Figure 4.9. According to the protocol specifications only seven addresses can be pending for transmission at any time in either CAP or CFP periods.

Every time a packet is passed via the MCPS service access point or it is generated within the MAC layer, the buffer for the specific packet is picked from the pool of the statically allocated data blocks. Static allocation of memory is more preferable in the embedded systems than dynamic due to its deterministic and error free performance. After the free memory block was found, the packet is inserted into one of the seven queues depending on

its destination address. The proposed data structure considerably facilitates extrapolation

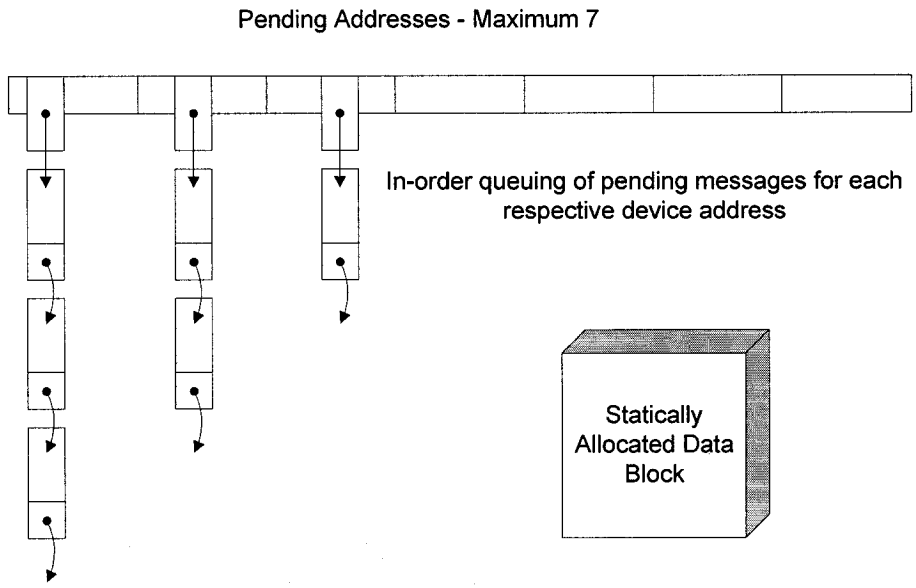


Fig. 4.9 CAP and GTS message buffering data structure

of pending addresses that need to be included as part of the beacon frame, thus providing notifications to respective devices of pending data at the PAN coordinator.

4.5.4 Channel Scanning

Channel scanning allows a device to locate any active coordinators transmitting beacon frames within its personal operating space (POS). A device may execute a passive or an active channel scan. The difference between the two scans is that during the active scan a device transmits a beacon request command whereas the passive scan simply listens for an incoming beacon.

An energy detection scan, used only by the FFD allows it to measure peak energy of each requested channel. This function should always be called prior to starting a new PAN in order to pick least "noisy" channel.

The passive scan, like an active scan, allows a device to locate any coordinator transmitting beacon frames within its POS whereas there beacon request command is not required for passive scan.

4.5.5 Association and Disassociation

Association of a device starts after having completed either an active channel scan or a passive channel scan.

Following the selection of a PAN with which to associate, the next higher layers request that MLME configures the phyCurrentChannel to the appropriate logical channel on which to associate, macPANId to the identifier of the PAN with which to associate and macCoordExtendedAddress or macCoordShortAddress to the address of the coordinator with which it associates. A device association is initiated by sending an associate request command to the coordinator of an existing PAN.

If sufficient resources are available, the coordinator allocates a short address to the device and generates an association response command containing the new address. If there are not enough resources, the coordinator generates an association response command containing a status indicating failure. This response is sent to the device using indirect transmission.

The disassociation of a device may be initiated by either the coordinator or the device itself. When a coordinator wants one of its associated devices to leave the PAN, it sends the disassociation notification command to the device using indirect transmission. If an associated device wants to leave the PAN, it sends a disassociation notification command to the coordinator during the CAP period.

As suggested by the protocol standard, higher layers should be responsible for short address allocation. However, this feature is currently seen as a part of the MAC layer. In addition to storing basic information regarding the associated node, the implemented database contains the node's security material [2] that is used for packet encryption. Considering the possibility of having several hundreds of nodes associated with a single PAN linear searches through simple array structures resulting in $O(n)$ access times is simply unacceptable. One of the most efficient ways to access out-of-order elements is to use a *hash table*. When correctly implemented searching a specific element within the table is performed in $O(1)$ time. Every element of the table must have a unique key that will map into an integer range $[0, N-1]$, where N is the total number of available array slots. The node's short address, having to be unique by nature perfectly suits the main requirement for the mapping key.

To find the *hash code* for the given key one must use a *hash function*. One simple hash

function is $h(k) = k \bmod N$, where N is a prime number and is equal to the total number of nodes that the PAN coordinator can handle within its database. Choosing the N to be a prime number, helps "spread out" the distribution of hashed values, thus reducing the number of collisions [68]. The collision within the hash table occurs when two different keys map into the same array slot.

Usual collision resolution rule is *chaining*, which places the collided elements in a link list of a specific array slot [68]. However, in our application this resolution rule is unacceptable, because it will result in $O(n)$ execution time, thus defeating the purpose of the hash table. To overcome this problem, a *"reverse hash function"* method was used instead. When a collision occurs, a linear search is used to find an empty slot within the database array. Heaving the desired *hash code* (z), a new key (k) is computed such that it will satisfy the equation

$$z = k \bmod N \tag{4.1}$$

The key (k) is a newly allocated short address. As mentioned previously, the PAN coordinator randomly allocates the address from a predetermined pool of numbers during the device association process. Therefore, as long as the address falls within the range defined by the pool and provides unique network identification the requirements are met. Hence, the procedure for obtaining the correct key is to generate a random 16-bit number from the allowed range. Afterwards, a linear adjustment is performed by doing addition or subtraction in order to satisfy equation 4.1.

The "reverse hash function" method provides $O(n)$ execution time during node allocation, but $O(1)$ during the acquisition of necessary node information.

4.5.6 Firmware Libraries

Considering the two device types defined by the IEEE, RFD and FFD, it is expected that at least two library flavors will be available. However, using preprocessor statements the 802.15.4 MAC / PHY can be further customized. In particular, the `CONFIG_802_15_4.h` header file allows for three major subtypes of firmware per device type in addition to providing full function exclusion / inclusion capabilities. The generic subtypes as well as the respective code sizes are presented in Table 4.1. For detailed overview of included / excluded MAC functions the reader is encouraged to consult Table B.2, Appendix B.

Table 4.1 Firmware code size summary

Description	Code size
Full function device excluding security features	35K
FFD excluding GTS capability	30K
FFD excluding beacon and GTS capability	20K
Reduced function device excluding security features	25K
RFD excluding GTS capability	22K
RFD excluding beacon and GTS capability	18K

4.6 Comparison With Previous Implementation

The implementation introduced and described in section 2.4 is independent of an operating system and therefore requires periodic executions of the "main task" in order to process incoming packets as well as send out pending ones. The design is fully functional, i.e. no message passing providing lower memory footprint, but resulting in less scalable and hardly extendible protocol stack. The supported MAC primitives are summarized in Table 4.2.

Table 4.2 Supported services by previous implementation

	Ind	Rqt	Rsp	Cnf
MLME-ASSOCIATE	✓	✓	✓	✓
MLME-DISASSOCIATE	✓	✓		
MLME-BEACON-NOTIFY	✓			
MLME-SCAN		✓		✓
MLME-START		✓		
MLME-SYNC		✓		
MCPS-DATA	✓	✓		

The overall code size didn't exceed 12KB, which is expected considering the nature of the implementation. The design could definitely be improved upon and should only be considered for purposes of the reduced function device (RFD).

Chapter 5

Testing Results and Applications

No thing happens in vain, but everything for a reason and by necessity

—Leucippus

In this chapter, the network protocol testing procedures are presented. Section 5.1 overviews major handshaking scenarios between the PAN coordinator and the device. Furthermore, power consumption is investigated. In Sections 5.2 a full wireless sensor network platform is described featuring McZub device as its network hub - coordinator. Section 5.3 outlines contributions to the overall teaching experience of Microprocessor Systems course.

5.1 Testing

The goal of this section is to verify correct operation of the four major IEEE 802.15.4 services, previously described in Section 4.5 - beacon generation, association, GTS allocation and consequentially indirect transmission.

To effectively test and verify the network handshaking a device called "packet sniffer" was used to capture IEEE 802.15.4 MAC packets. It is a software solution developed by Chipcon [69] that runs on their proprietary development platform CC2420DK. The overall solution is capable of individually decoding the packets and later displaying them in a convenient way. The packet sniffer, being a transparent RF channel listener, was simply installed within the RF range of the PAN coordinator and its respective devices while they were in the midst of exchanging MAC management and data packets.

5.1.1 Association

After the PAN coordinator has been successfully started on a full function device, the FFD starts broadcasting beacon packets containing information regarding the capabilities of the coordinator as well as specifications of the current superframe. As shown in Figure 5.1, the first captured packet is the beacon frame specified by the type subfield within the "Frame control field". It informs the listening devices of the PAN ID, PAN coordinator's short address and superframe specification. One can observe that the beacon order (BO) is 9, superframe order (SO) 8 and that the device transmitting the beacon frame is indeed a PAN coordinator ($Coord = 1$) that is ready to accept new association requests ($Assoc = 1$).

After processing the information contained within the beacon frame a device, willing to join the PAN, transmits its request before the final Contention Access Period (CAP) slot has been reached ($F.CAP = 4$). The association request belongs to a MAC command and as such it carries a different frame type. Furthermore, the device always requests an acknowledgement from the PAN by setting the necessary bit within the frame control field ($Ack.req = 1$). As mentioned in the previous chapters, each device has a unique hard-coded 64-bit address. Device must always use this address during the association process. Moreover, as part of the association message the device informs the PAN coordinator of its capabilities, in particular: capability of starting a PAN coordinator ($Alt.Coord$ and FFD), security support (Sec), receiver state during idle times ($IdleRX$) and the nature of the its power source (battery or alternating current mains - $Power$). Finally, a device can chose to request a short address by setting *Alloc addr* bit.

Upon reception of the acknowledgement frame, a device continues to track the beacon frames expecting an indirect transmission from the coordinator. Regardless of the association outcome, the coordinator will place the device's extended address in the address pending field of the beacon frame which will cause a device to issue a data request packet.

The association process concludes when the PAN coordinator transmits an association response message. Figure 5.1 depicts a successful association and short address allocation. For the subsequent data transmission the device starts to use its newly allocated 16-bit short address.

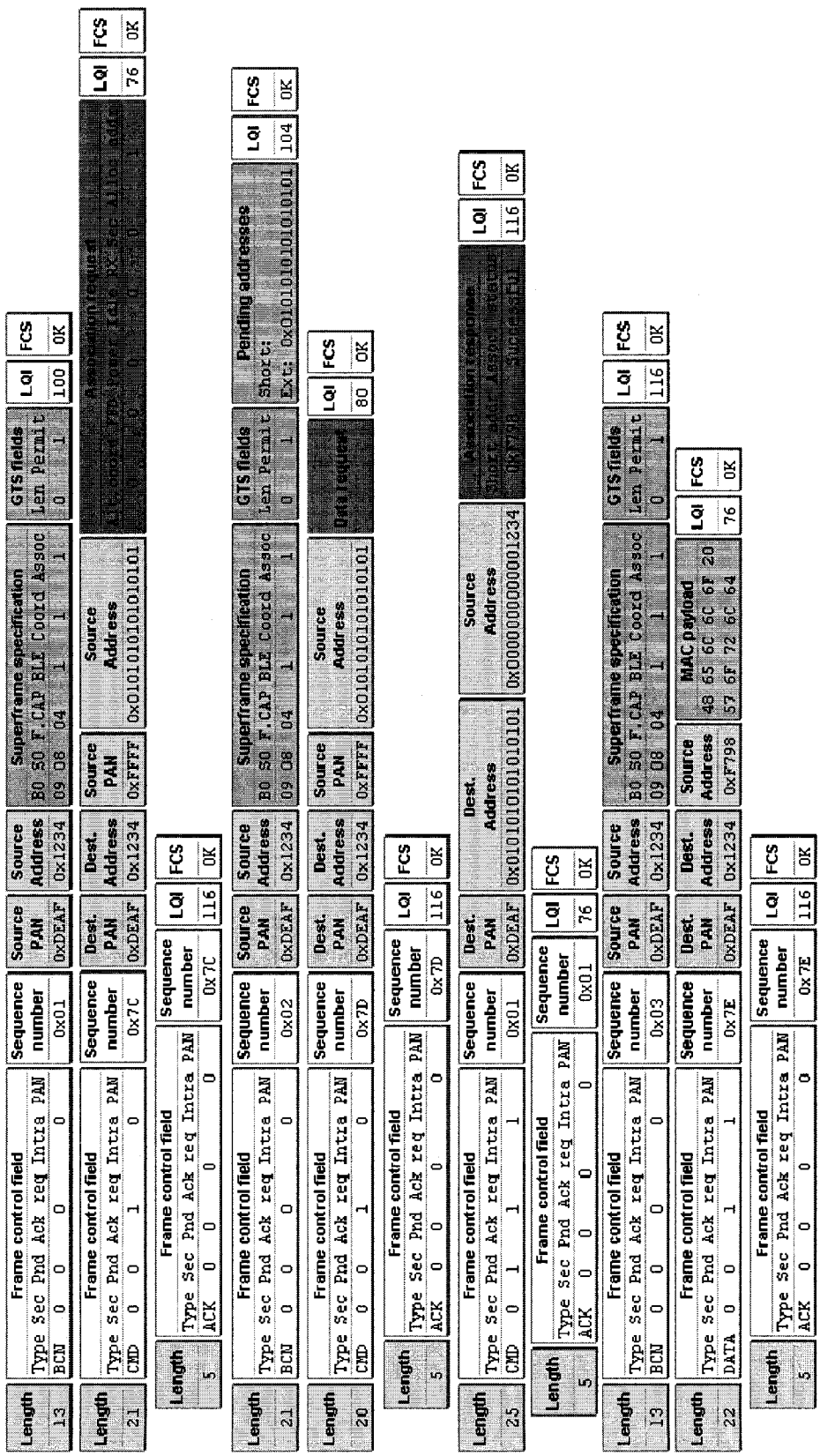


Fig. 5.1 Network activity during association

5.1.2 GTS Allocation

The guaranteed time slot (GTS) allocation requires less network overhead compared to a device association, as presented in Figure 5.2. In addition to the superframe specifications, the beacon frame carries information that instructs devices to either engage in GTS allocation or to refrain from it - *Permit* bit within the $GTSfields$. Initially, the PAN coordinator does not advertise any GTS slots, hence the *Len* field being zero. After the PAN coordinator successfully receives a GTS request MAC command packet, it attempts to allocate desired GTS length and direction specified by the *Length* and *Direction* bits in the GTS request field. If the operation deems to be successful the PAN coordinator will begin to advertise newly allocated GTS slot as part of the beacon frame - the starting slot, length and the address of the device currently in ownership of that slot.

Figure 5.2 additionally depicts further network operation showing subsequent beacon transmissions as well as including short address within the address pending fields.

5.1.3 Power Consumption

To measure the power consumption an external discrete difference amplifier circuit was built. The amplifier is fed by the signal voltage across a current-sense resistor circuit. This circuit configuration is known to provide precise current measurements by sampling the voltage across the current sense resistor [70].

The measurement results are presented in Figure 5.3 where three different modes of operation are explored - transmission, reception and idle (transceiver off) mode. It can be observed that the transceiver power consumption is highest during receive hence it is crucial to keep the receiver off during idle times. Table 5.1 portrays overall system power consumption during different modes of operation. The respective operating state of the CPU, wireless transceiver and USB module provide additional insight with respect to the individual modes.

5.1.4 Wireless Link Quality

The Chipcon transceiver, as mentioned in Section 3.1.3, provides the radio link quality indication. This feature was used to establish important relations among network parameters such as signal range and its dependance on the output power.

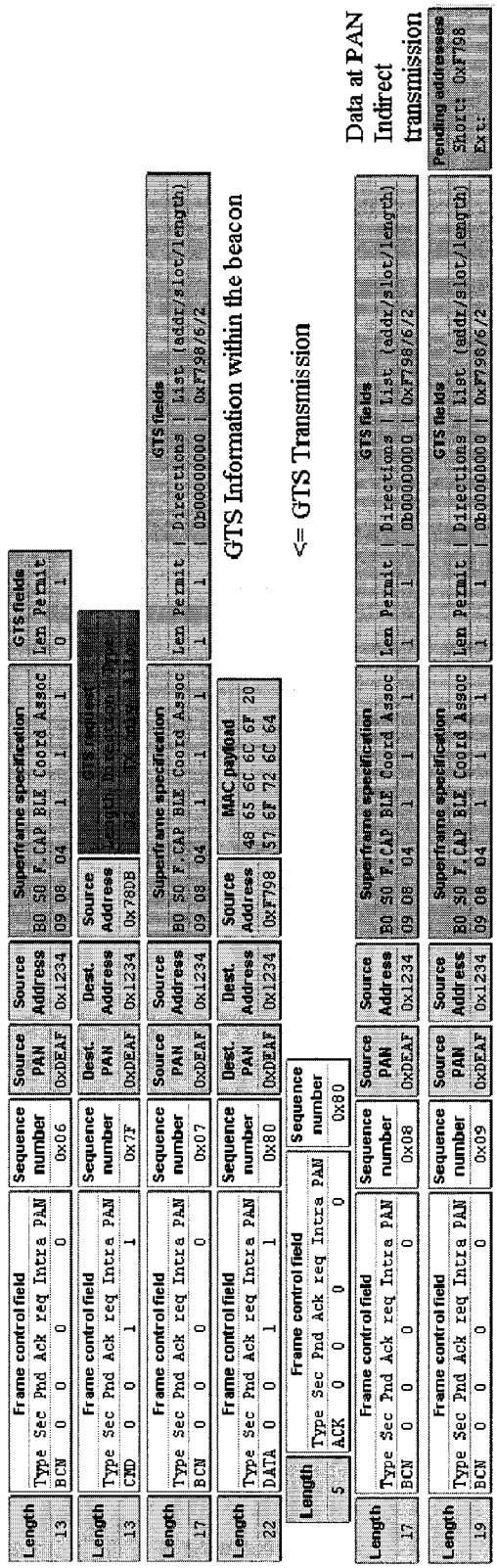


Fig. 5.2 Network activity during GTS allocation

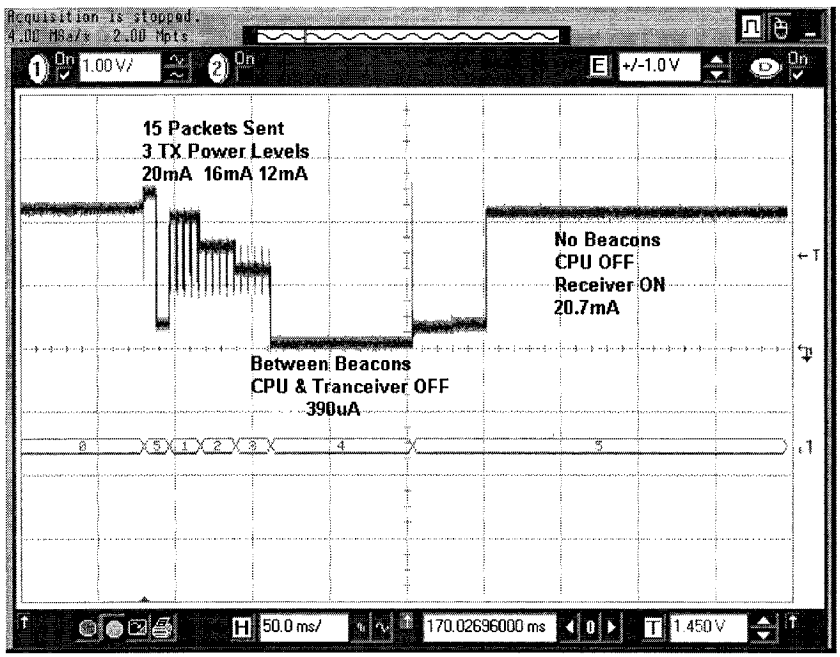


Fig. 5.3 Power utilization in different scenarios

The equipment was tested indoors, where the presence of metallic objects was excessive. Such harsh radio environment results in lower performance but provides necessary insight as the equipment is intended mainly for indoor use - homes, warehouses and industrial buildings.

Figure 5.4 depicts LQI measurement results collected within the MACS lab between the McZub and one of the existing network nodes (McGumps + McZig). The results proved to be consistent across a range of output power levels.

However, it is the reception rate that ties together the above mentioned parameters. This measure is crucial in assessing any wireless network i.e. determining how will the packet error rate change as a function of the distance and the output power. Figure 5.5 illustrates the obtained results.

5.2 A Wireless Conference Manager

A full wireless sensor network platform has been developed. The platform is suitable for the rapid deployment of various large scale social events [71]. The platform consists of

Table 5.1 Operating modes and their associated power consumption

Mode	CPU	CC2420	USB	I(mA)
Online packet reporting	ON	RX ON	ON	75.6
Packet reception	ON	ON	Suspend	50.4
Active PC Comm.	ON	OFF	ON	55.7
Beacon generation	ON	Tx ON	Suspend	45.3
Periodic PC Comm.	Idle	OFF	ON	29.8
Quick startup	Idle	ON	Suspend	25.3
Slow startup	Power down	ON	Suspend	21.9
RTC on	Idle	OFF	Suspend	5.6
Inactive	Power Down	OFF	Suspend	0.39

low power embedded nodes, a PAN coordinator that acts as a hub in star topology, and a remote (host) database controller with middleware (bridging software) for presenting the status of the tracked events on WWW or locally via a projector.

The system aims to help conference organizers and managers to maintain and provide real time conference status information. The user has the option of fetching the relevant data i.e. authors and paper titles. For the ongoing presentation, the user is given the option to update the status of the paper that will be displayed on the projector or WWW in real time 5.6. The application falls under "Social Event Tracking" applications described in Section 2.2.2.

The handheld unit, Figure 5.7 provides the conference session chair with a score sheet that is used for evaluations, all accessible via the touchscreen-based graphical user interface (GUI). By having the applicable options available at a touch of the stylus using the system is intuitive and efficient. The UI consists of three main screens, which provide the following functionality:

- Loading the paper information from the database for the specific conference room
- Updating the status of the paper: started, discussion in progress and ended
- Sending the current attendance for the specific session
- Grading the paper according to the four different categories: technical content, interest, visual and verbal

A terminal console, always present in the bottom of the screen, displays network status

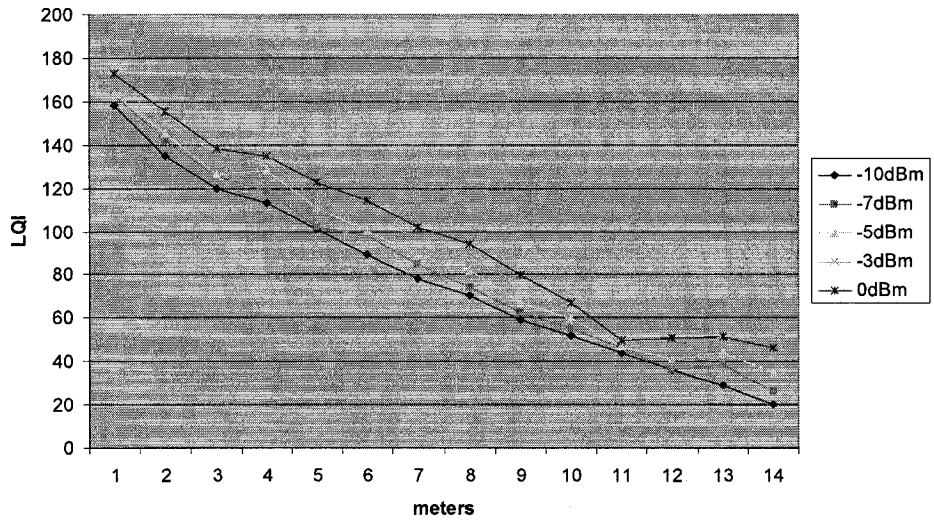


Fig. 5.4 Link Quality Indicator at different distances across different transmit power levels

information as well as broadcast messages sent from the PAN coordinator.

For the conference management application, a general structure of the conference is assumed but is not a binding restriction on the overall operation of the system. The database assumes that the conference would be divided into sessions and can be spread over multiple days. It is also assumed that the duration of each presentation is known along with its title and the names of the authors. The tables in the database, thus, store the above information.

While the status of the conference can be managed via the handheld units, an automated system has been developed in PHP that can automatically update the status of the presentations not being monitored by the handheld users. Based on the start and end times of the presentation, the PHP script automatically updates the status of the presentation in the database. The script also formats the data such that it can be viewed on a web-browser. This is accomplished by execution of the PHP script on the Apache web server. The web-browser can be displayed to the audience at hand using a projector or webcast in real time on the WWW.

Wireless Conference Manager (WCM) has already been deployed at two high-profile IEEE[1] international conferences [71]. Testing and verification results collected at these

[1]International Conference on Parallel Processing and International Test Conference

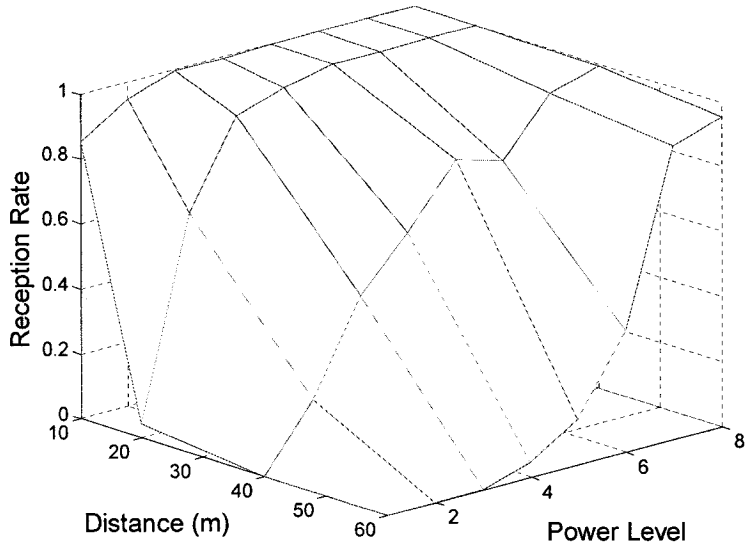


Fig. 5.5 Reception rate vs. distance vs. different output power levels

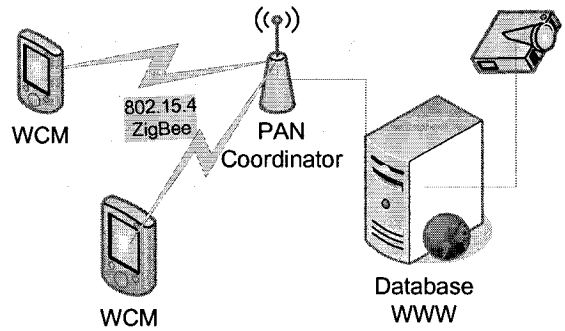


Fig. 5.6 Wireless Conference Manager System high level overview

events demonstrate its suitability as well as expendability for new requirements and applications.

5.2.1 Database and Backend Software

To facilitate the overall application by which events are tracked in real time, various software components were designed for a remote host computer. The application-level software comprises of a MySQL database server, an Apache web server, and a control application created in "C++" that is responsible for communication between the PC and the PAN coordinator. The main design goals were to build the application that is flexible and

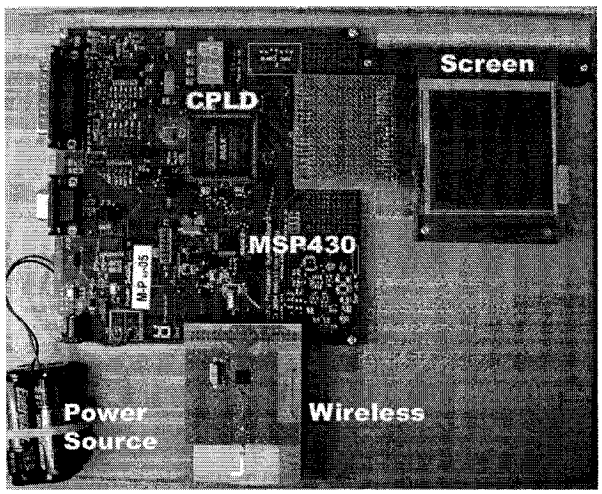


Fig. 5.7 WCM (Handheld unit) - Photo

scalable enough to accommodate different types of end-user applications as well as for the in-field testing of the hardware. By working with only open standards low-cost and reliable application software were achieved

The process of entering the information in the database has also been streamlined with the use of a small TCL based GUI. The GUI parses text files containing the pertinent information to the MySQL database. The GUI also allows a direct entry to the MySQL tables [72]. This serves to abstract the database and MySQL commands from the conference administrator.

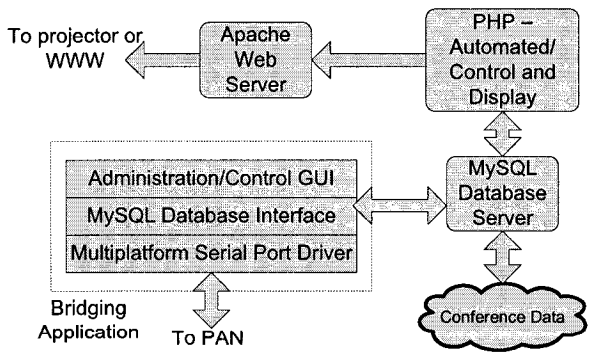


Fig. 5.8 Application-level architecture

Hardware and software are seamlessly integrated via USB by platform independent

middleware. It has a dual role of providing communication between the PAN coordinator and the PC-side software applications as well as to provide administrative capability over the entire system.

It is an application that works on Windows as well as Linux-based computers. In both cases the application uses threads for reading and writing to the port. A TCL based GUI is used to provide interaction with the user.

5.3 Teaching

Widespread use of microprocessor systems and the rapid introduction of new processors, computer interfaces and communication standards requires state-of-the art laboratory teaching practices that elude obsolescence. The hardware platform consisting of "McGumps", "McZig", "McZub"and other boards[2] facilitates efficient learning of relevant hardware and software design techniques that will not get outdated soon [21].

The Microprocessor Student Kit achieves relevance, possibility to generate a large set of exercises, including complex SW/HW projects, as well as overall robustness and ease of use, Figure 5.9.

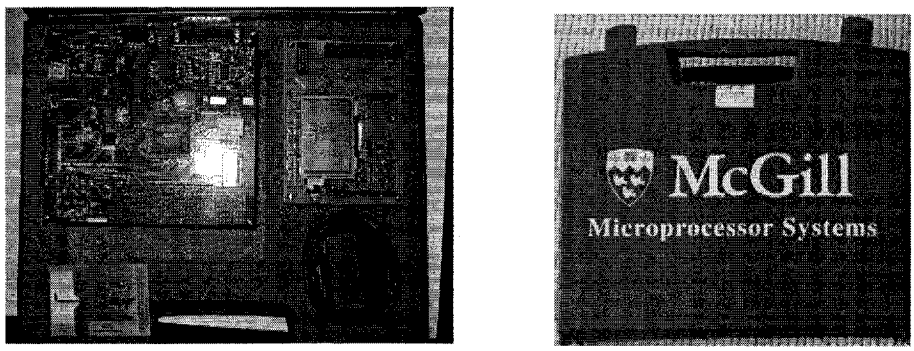


Fig. 5.9 Microprocessor lab kit

Over the past few semesters that the equipment has been used the student evaluations showed that the overall course appreciation has increased mainly due to more reliable equipment and challenging projects.

[2]McGuld - McGill LCD/TS board

Chapter 6

Conclusions and Future Work

6.1 Conclusions

A LR-WPAN IEEE 802.15.4 compliant coordinator was successfully designed, manufactured and tested. Furthermore, the IEEE 802.15.4 PHY/MAC layers were developed and ported to two different architectures running in conjunction with an open source real-time kernel. Here is a short summary of the contributions:

1. Robust and low-cost PAN coordinator hardware platform for current and future research and teaching needs.
2. Fully compatible with the existing wireless devices used within the MACS lab.
3. IEEE 802.15.4 MAC/PHY implementation using multitasking capabilities of a real-time kernel.
4. Layered design approach guaranteeing expendability of protocol layers.
5. Hardware abstraction layer providing easily portable embedded software.
6. Real life deployment and presence at two international conferences.

The design, testing and integration into the existing network has been accomplished during an 8-month period. Overall, the project entailed numerous design techniques of both hardware and embedded software (firmware) in order to achieve a modern, robust

and low-power hardware platform on top of which further network topologies can be built and tested.

At the time of this writing, several manufacturers (Chipcon and Freescale) have announced SoCs (systems on chip) that would combine the RF front-end (ex: CC2420) and a microcontroller. These advancements would further lower the power consumption and price - the two driving factors behind any LR-WPAN. With the increasing reliability and costumer satisfaction the LR-WPANs are here to stay and have a tremendous impact on our everyday life.

6.2 Future Work

Continuous testing and optimization of the IEEE 802.15.4 stack is a never-ending process. Considering the topicality and significance of the research as well as expanding opportunities in the market place the author intends to continue to maintain the SourcForge.net project[1] as well as develop new LR-WPAN compliant hardware.

The immediate question that needs to be addressed is integration of the MAC security layer. As mentioned in Chapter 4, the software features all the necessary hooks within the MAC layer as well as all the low-level function calls providing access to the hardware encryption module.

Furthermore, as the number of nodes in the network grows, the number of collisions would increase leading to longer synchronization times and thus resulting in higher power consumption. Therefore, further testing with hundreds/thousands of nodes is something that would fully stress the network and yield valuable results.

Overall, the current state of the LR-WPAN research is very diverse with many big players offering numerous attractive prototyping solutions from ultra-low microcontrollers such as TI, Atmel and Philips to compliant radio modems by RFM, Chipcon, Freescale, Nordic and others. It is evident that a lot of synergy could be gained if a convergence to a single prototype could be achieved. We believe that the current developments in the IEEE 802.15.4 and ZigBee standardization process will create sufficient pressure towards unification.

[1] `http://mczub.sourceforge.net`

Appendix A

McZub Schematics

The appendix provides McZub design details on a schematic level. In addition, it presents the bill of materials (BOM), Figure A.5, where component pricing is established in small quantities [1] and quoted in Canadian dollars. Furthermore, it depicts final PCB layout in Figure A.6.

[1] Less than 10.

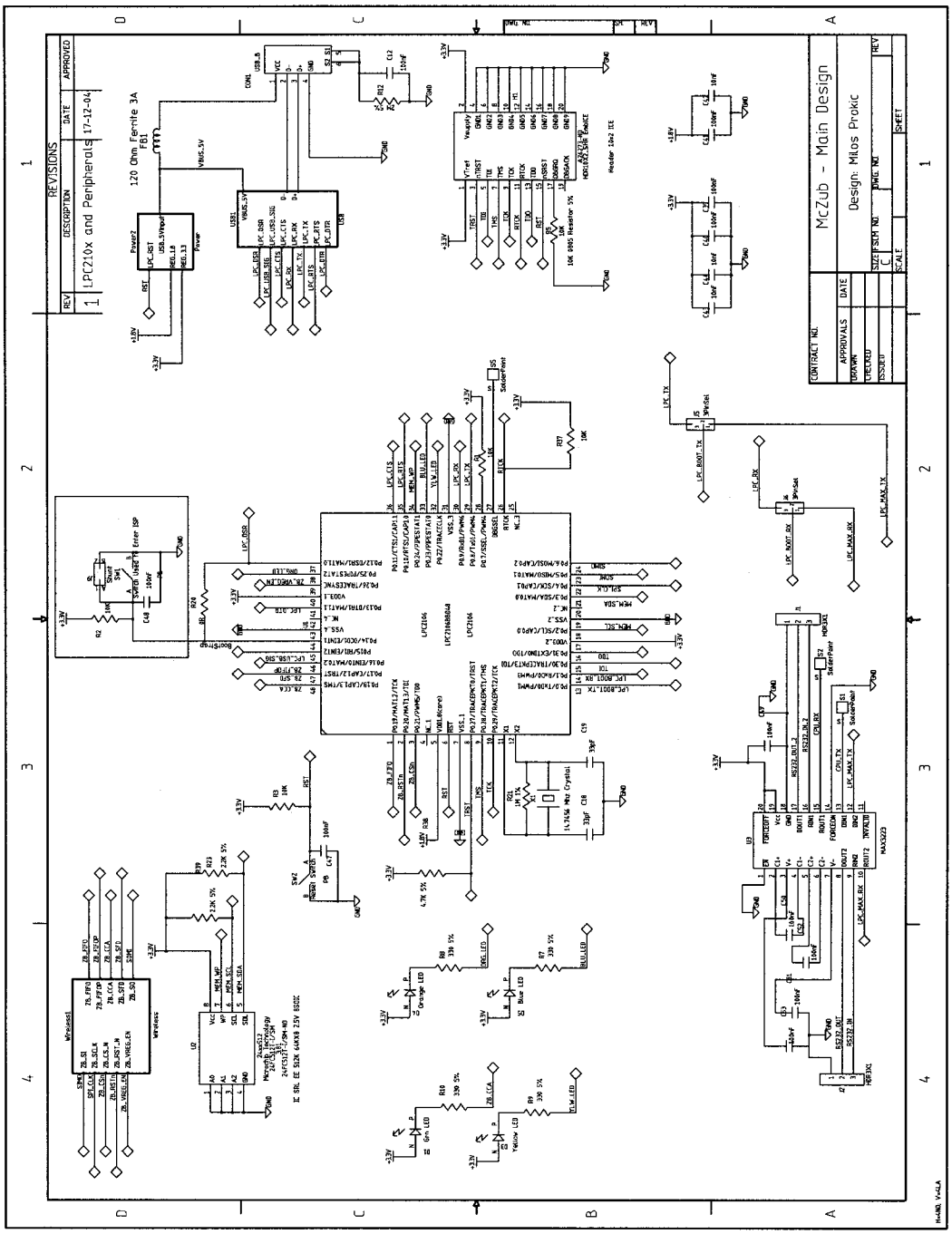


Fig. A.1 McZub Schematics - Main

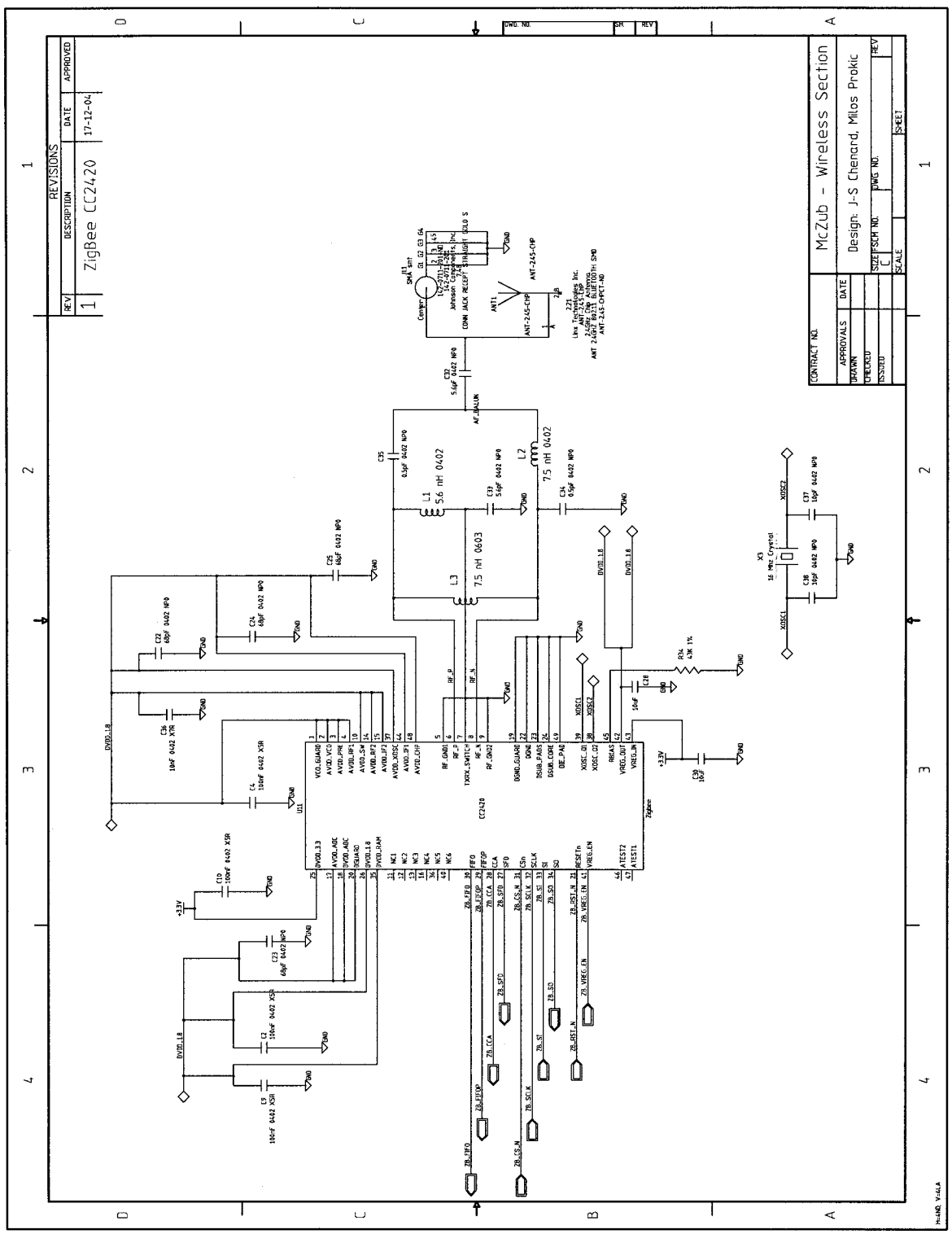


Fig. A.2 McZub Schematics - Wireless Section

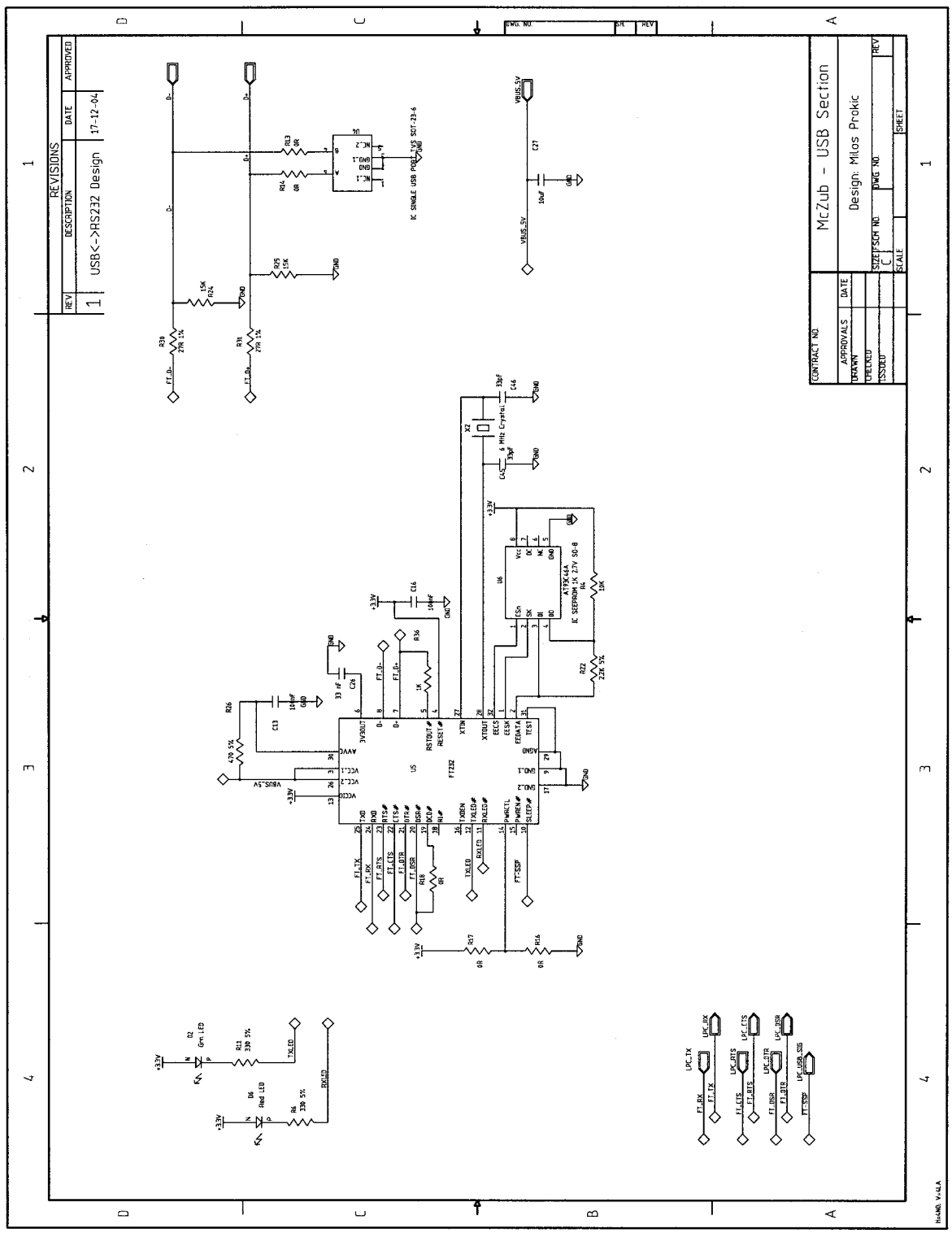


Fig. A.3 McZub Schematics - USB Section

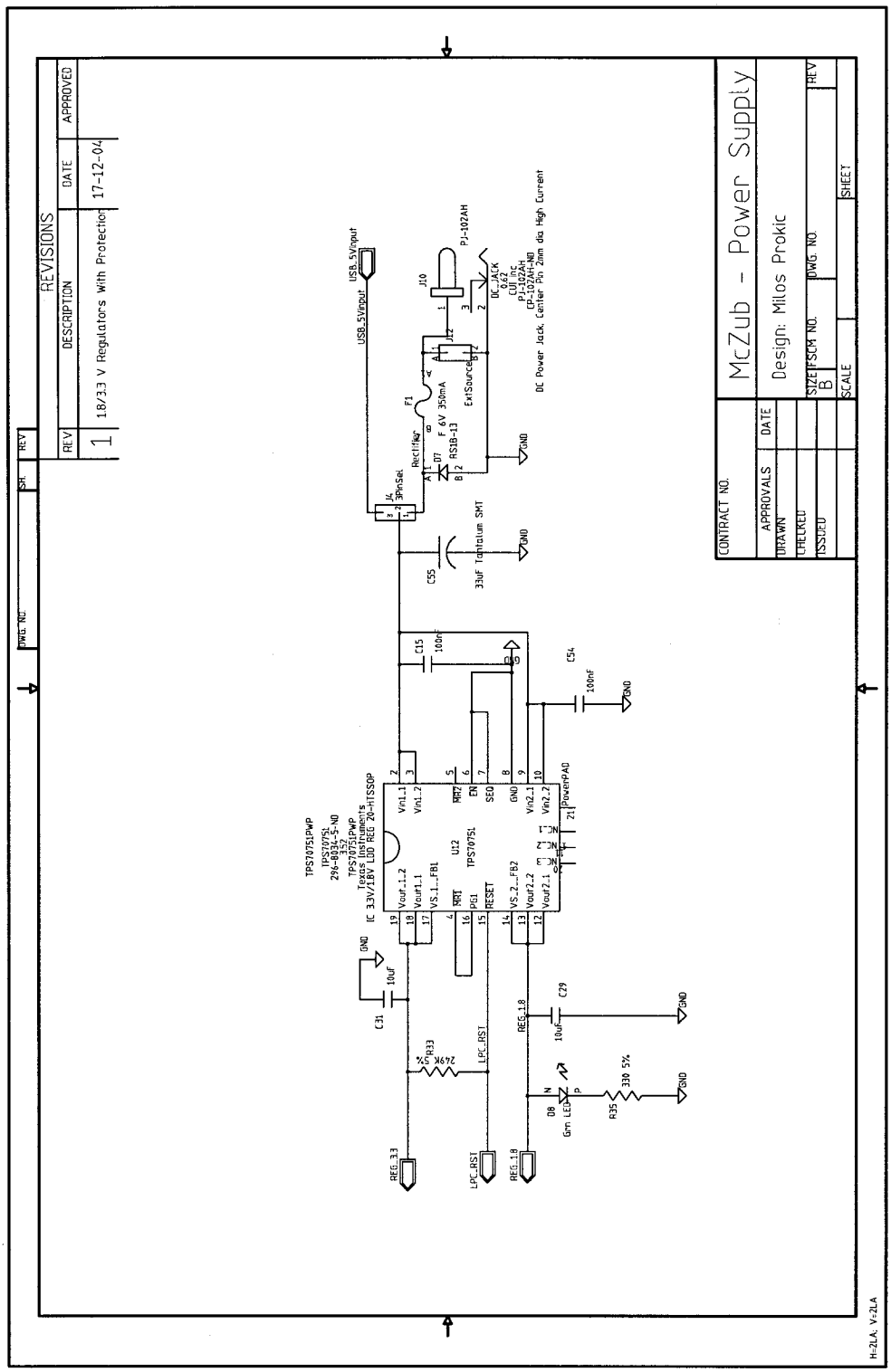
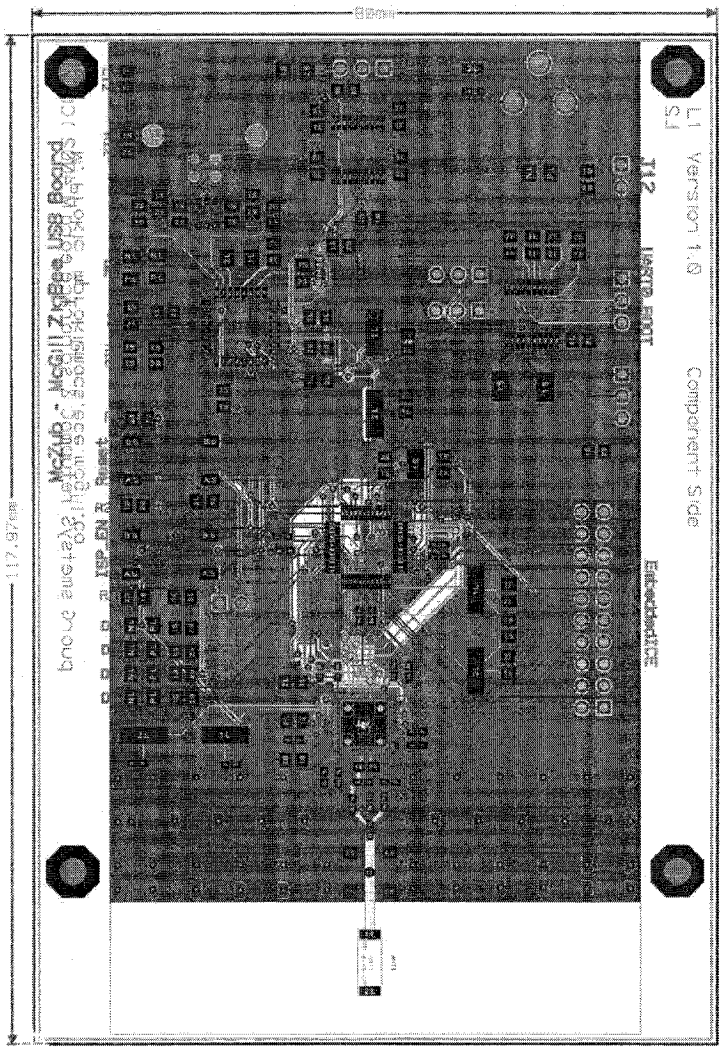


Fig. A.4 McZub Schematics - Power Section

Item	Qty	References	Description	Manuf Name	Manuf Part Num	Prototype	Cost	Total
1	1	ANT1	ANT 2.4GHZ 802.11 BLUETOOTH SMD	Linx Technologies Inc.	ANT-2.45-CHP	ANT-2.45-CHPCT-ND	2.21	$2.21
2	1	U6	IC SEEPROM 1K 2.7V SO-8	Atmel	AT93C46A-10SI-2.7	AT93C46A-10SI-2.7-ND	1	$1.00
3	1	H1	CONN HEADER	AMP/Tyco	103308-5	A26273-ND	0.728	$0.73
4	1	FB1	120 Ohm 3000mA ferrite bead	Murata	BLM31PG121SN1L	490-1056-1-ND	0.14	$0.14
5	1	U11	Single Chip Zigbee 802.15-4 Transceiver	Chipcon	CC2420		6.8	$6.80
6	2	C34-C35	0.5pF Ceramic NP0 0402 Capacitor 50V	Yageo America	0402CG508C9B200	311-1001-1-ND	0.035	$0.07
7	2	C32-C33	5.6pF Ceramic NP0 0402 Capacitor 50V	Yageo America	0402CG569D9B200	311-1011-1-ND	0.033	$0.07
8	4	C36,C42-C44	10nF Ceramic X7R 0402 Capacitor 25V	Kemet	C0402C103K3RACTU	399-1278-1-ND	0.017	$0.07
9	2	C37-C38	10pF Ceramic NP0 0402 Capacitor 50V	Kermet	C0402C100J5GACTU	399-1011-1-ND	0.0158	$0.03
10	5	C27-C31	10 uF Ceramic 0805 X5R Capacitor 6.3V	Murata	GRM21BR60J106ME19L	490-1718-1-ND	0.199	$1.00
11	1	C26	CAP Low Leakeage 33 nF 16V 5% 1206	Panasonic - ECG	ECH-U1C333JX5	PCF1202CT-ND	0.349	$0.35
12	4	C18-C19,C45-C46	CAP CERAMIC 33PF 50V NP0 0805	Yageo America	0805CG330J9B200	311-1105-1-ND	0.111	$0.44
13	1	C55	CAP 33UF 16V TANTALUM TE SMD	Panasonic - ECG	ECS-T1CC336R	P11318CT-ND	0.82	$0.82
14	4	C22-C25	68 pF Ceramic NP0 0402 Capacitor 50V	Panasonic - ECG	ECJ-0EC1H680J	PCC680CQCT-ND	0.112	$0.45
15	7	C2,C4,C9-C10,C39-C41	100nF Ceramic X5R 0402 Capacitor 10V	Kemet	C0402C104K8PACTU	399-3027-1-ND	0.026	$0.18
16	12	C12-C13,C15-C16,C47-C54	CAP CER 100NF 50V 20% X5R 0805	Kermet	C0805C104M5UACTU	399-1176-1-ND	0.0239	$0.29
17	2	SW1-SW2	PushButton Momentary SPST	E-Switch	TL3301AF260QG/TR	EG2527CT-ND	0.273	$0.55
18	1	U5	FT232BM USB UART (USB - Serial) I.C.	FTDI	FT232BM	FT232BM - Kotrade.ca	7.7	$7.70
19	1	D5	LED 428NM BLUE DIFF 1206 SMD	Agilent Technologies	HSMB-C150	516-1447-1-ND	1.72	$1.72
20	3	D1-D2,D8	LED Green Clear	Chicago Miniature	CMD15-21VGC/TR8	L62205CT-ND	0.32	$0.96
21	1	D4	LED 605NM ORANGE DIFF 1206 SMD	Agilent Technologies	HSMD-C150	516-1441-1-ND	0.45	$0.45
22	1	D6	LED Red Clear Lens	Chicago Miniature	CMD15-21VRC/TR8	L62201CT-ND	0.35	$0.35
23	1	D3	LED 589NM YELLOW DIFF 1206 SMD	Agilent Technologies	HSMY-C150	516-1442-1-ND	0.45	$0.45
24	1	U1	32bit CPU, ARM Core	Philips	LPC2106BBD48	LPC2106BBD48-S	6.58	$6.58
25	1	L1	Inductor 5.6 nH	Murata	LQP15MN5N6B02D	490-1133-1-ND	0.131	$0.13
26	1	L2	Inductor 7.5 nH	Murata	LQW15AN7N5J00D	490-1143-1-ND	0.281	$0.28
27	1	L3	INDUCTOR 7.5NH 750MA 0603	Murata	LQW18AN7N5D00D	490-1166-1-ND	0.0281	0.28
28	1	U3	IC DRVR/RCVR MLTCH RS232 20TSSOP	Texas Instruments	MAX3223IPWR	296-13091-1-ND	2.92	$2.92
29	1	F1	FUSE RESETTABLE .35A HOLD SMD	Bourns Inc.	MF-USMD035-2	MF-USMD035CT-ND	1	$1.00
30	1	J10	DC Power Jack, Center Pin 2mm dia	CUI inc	PJ-102AH	CP-102AH-ND	0.62	$0.62
31	1	D7	RECT FAST RECOVERY 100V 1A SMA	Diodes Inc.	RS1B-13	RS1BDICT-ND	0.81	$0.81
32	6	R13-R14,R16-R18,R20	Zero Ohm Resistor 0805	Yageo	9C08052A0R00JLHF	311-0.0ACT-ND	0.0227	$0.14
33	1	R36	Resistor SMT 0805 1K 5%	Yageo America	9C08052A1001JLHFT	311-1.0KACT-ND	0.0227	$0.02
34	1	R21	Resistor SMT 0805 1Meg 1%	Yageo America	9C08052A1004FKHFT	311-1.00MCCT-ND	0.023	$0.02
35	3	R22-R23,R39	RES 2.2K OHM 1/8W 5% 0805 SMD	Yageo America	9C08052A2201JLHFT	311-2.2KACT-ND	0.111	$0.33
36	1	R12	Resistor SMT 0805 2Meg 5%	Yageo America	9C08052A2004JLHFT	311-2.0MACT-ND	0.0227	$0.02
37	1	R38	RES 4.7K OHM 1/8W 5% 0805 SMD	Yageo America	9C08052A4701JLHFT	311-4.7KACT-ND	0.111	$0.11
38	6	R1-R5,R37	Resistor SMT 0805 10K 5%	Yageo America	9C08052A1002JLHFT	311-10KACT-ND	0.0227	$0.14
39	2	R24-R25	RES 15K OHM 1/8W 5% 0805 SMD	Yageo America	9C08052A1502JLHFT	311-15KACT-ND	0.111	$0.22
40	2	R30-R31	RES 27 OHM 1/8W 1% 0805 SMD	Rohm	MCR10EZHF27R0	RHM27.0CCT-ND	0.052	$0.10
41	1	R34	Resistor SMT 0805 43K 1%	Yageo America	9C08052A4122FKHFT	311-41.2KCCT-ND	0.0239	$0.02
42	1	R33	RES 249K OHM 1/8W 1% 0805 SMD	Yageo America	9C08052A2493FKHFT	311-249KACT-ND	0.0227	$0.02
43	7	R6-R11,R35	RES 330 OHM 1/8W 5% 0805 SMD	Yageo America	9C08052A3300JLHFT	311-330ACT-ND	0.111	$0.78
44	1	R26	RES 470 OHM 1/8W 5% 0805 SMD	Yageo America	9C08052A4700JLHFT	311-470ACT-ND	0.111	$0.11
45	3	S1-S2,S5	Solder Test Point				0	
46	1	J11	CONN JACK RECEPT STRAIGHT GOLD S	Johnson Components, Inc.	142-0711-201	142-0711-201-ND	7.48	$7.48
47	1	U4	IC SINGLE USB PORT TVS SOT-23-6	Texas Instruments	SN65220DBVR	SN65220DBVR	1.23	$1.23
48	1	U12	IC 3.3V/1.8V LDO REG 20-HTSSOP	Texas Instruments	TPS70751PWP	296-8034-5-ND	3.52	$3.52
49	1	CON1	USB_B Connector SMT	Assmann Electronics, Inc	AU-Y1007	AE1085-ND	3.09	$3.09
50	2	J1-J2	Header 3x1 0.1 Gold Plated	Molex	22-28-4033	WM6503-ND	0.18	$0.36
51	1	X2	CRYSTAL 6.00MHZ 32PF SMD CSM-7	ECS Inc	ECS-60-32-5P-TR	XC679CT-ND	0.63	$0.63
52	1	X1	CRYSTAL 14.7456MHZ 20PF SMD	ECS	ECS-147.4-20-5P-TR	XC692CT-ND	1.07	$1.07
53	1	X3	CRYSTAL 16 MHZ 20PF SMD CSM-7	ECS	ECS-160-20-5P-TR	XC694CT-ND	0.634	$0.63
54	3	J4-J6	Header 3x1 0.1 + 1 Shunt for Select	Molex	22-03-2031	WM4001-ND	0.53	$1.59
55	1	U2	IC SRL EE 512K 64KX8 2.5V 8SOIC	Microchip Technology	24FC512T-I/SM	24FC512T-I/SM-ND	3.81	$3.81
56	2	J9,J12	Shunt 0.1 2 pins Tin	AMP/Tyco Electronics	382811-5	A26229-ND	0.137	$0.27
						TOTAL		$65.16

Fig. A.5 McZub Bill of materials (BOM)



Through Holes						
Symbol	Diameter (in)	Tolerance (in)	Plated	Punched	Hole Name	Quantity
A	0.0120	+0.0000 / -0.0020	Yes	No	Rnd 12 +Tol 0 -Tol -2	100
B	0.0160		Yes	No	Rnd 16	52
C	0.0362		Yes	No	Rnd 0.92	4
D	0.0420		Yes	No	Rnd 42	39
E	0.0860		Yes	No	Rnd 86	3
F	0.0906		Yes	No	Rnd 2.3	2
G	0.1250		No	No	Rnd 125 Non-Plated	4

Fig. A.6 McZub PCB Layout

Appendix B

IEEE 802.15.4 MAC/PHY

B.1 Message Primitives and Data Types

B.1.1 MLME Message Structure/Union

```
/* MLME-SAP to higher level queued message */ typedef struct
MLME_Message_lbl {
  MLME_Msg_Type_t xMsgType;
  union {
    MLME_AssociateInd_t       xAssociateInd;
    MLME_AssociateRsp_t       xAssociateRsp;
    MLME_AssociateRqt_t       xAssociateRqt;
    MLME_AssociateCnf_t       xAssociateCnf;

    MLME_DisassociateInd_t    xDisassociateInd;
    MLME_DisassociateRqt_t    xDisassociateRqt;
    MLME_DisassociateCnf_t    xDisassociateCnf;

    MLME_BeaconNotifyInd_t    xBeaconNotifyInd;

    MLME_GtsInd_t             xGtsInd;
    MLME_GtsCnf_t             xGtsCnf;
    MLME_GtsRqt_t             xGtsRqt;

    MLME_OrphanInd_t          xOrphanInd;
    MLME_OrphanRsp_t          xOrphanRsp;

    MLME_ScanRqt_t            xScanRqt;
    MLME_ScanCnf_t            xScanCnf;

    MLME_CommStatusInd_t      xCommStatusInd;
    MLME_SyncLossInd_t        xSyncLossInd;
```

```
    MLME_PollRqt_t          xPollRqt;
    MLME_PollCnf_t          xPollCnf;
  } uMsgData;
} MLME_Message_t;
```

B.1.2 MCPS Message Structure/Union

```
/* MCPS-SAP to higher level queued message */ typedef struct
MSPC_Message_lbl {
  MCPS_Msg_Type_t xMsgType;
  union {
    MCPS_DataInd_t   xDataInd;
    MCPS_DataCnf_t   xDataCnf;
    MCPS_DataReq_t   xDataRqt;
  } uMsgData;
} MCPS_Message_t;
```

B.1.3 MAC Messages

Table B.1 Mapping of message or function identifiers to 802.15.4 primitives

Type	Identifier (Message Passing) / Function Name	802.15.4 Primitive
M	MLME_ASSOCIATE_RQT_MSG	MLME-ASSOCIATE.Request
M	MLME_ASSOCIATE_IND_MSG	MLME-ASSOCIATE.Indication
M	MLME_ASSOCIATE_RSP_MSG	MLME-ASSOCIATE.Response
M	MLME_ASSOCIATE_CNF_MSG	MLME-ASSOCIATE.Confirm
M	MLME_DISASSOCIATE_RQT_MSG	MLME-DISASSOCIATE.Request
M	MLME_DISASSOCIATE_IND_MSG	MLME-DISASSOCIATE.Indication
M	MLME_DISASSOCIATE_CNF_MSG	MLME-DISASSOCIATE.Confirm
M	MLME_ASSOCIATE_IND_MSG	MLME-BEACON-NOTIFY.Indication
F	ConfirmStatus_t macMLME_GET_request (PIB_Attribute_t, void*)	MLME-GET.Request
M	MLME_GTS_RQT_MSG	MLME-GTS.Request
M	MLME_GTS_IND_MSG	MLME-GTS.Indication
M	MLME_GTS_CNF_MSG	MLME-GTS.Confirm
M	MLME_ORPHAN_IND_MSG	MLME-ORPHAN.Indication
M	MLME_ORPHAN_RSP_MSG	MLME-ORPHAN.Response
F	ConfirmStatus_t macMLME_RESET_request (BOOL)	MLME-RESET.Request
F	ConfirmStatus_t macMLME_RX_ENABLE_request (BOOL, UINT32, UINT32)	MLME-RX-ENABLE.Request
M	MLME_SCAN_RQT_MSG	MLME-SCAN.Request
M	MLME_SCAN_CNF_MSG	MLME-SCAN.Confirm
M	MLME_COMM_STATUS_IND_MSG	MLME-COMM-STATUS.Indication
F	ConfirmStatus_t macMLME_SET_request (PIB_Attribute_t, void*)	MLME-SET.Request
F	ConfirmStatus_t macMLME_START_request (MLME_StartRqt_t*)	MLME-START.Request
F	void macMLME_SYNC_request (UINT8, BOOL)	MLME-SYNC.Request
M	MLME_SYNC_LOSS_IND_MSG	MLME-SYNC-LOSS.Indication
M	MLME_POLL_RQT_MSG	MLME-POLL.Request
M	MLME_POLL_RQT_MSG	MLME-POLL.Confirm
M	MCPS_DATA_RQT_MSG	MCPS-DATA.Request
M	MCPS_DATA_IND_MSG	MCPS-DATA.Indication
M	MCPS_DATA_CNF_MSG	MCPS-DATA.Confirm
F	void macMCPS_PURGE_request (UINT8)	MLME-PURGE.Request

B.1.4 MAC Device Types - Detailed Overview

Table B.2 Device types and the respective functions

Description	Code Name
Full function device excluding security features	FFD
Reduced function device excluding security features	RFD
Device excluding GTS capability	DNG
Device excluding beacon and GTS capability	DNBNG

	FFD				RFD				DNG				DNBNG			
	Ind	Rqt	Rsp	Cnf	Ind	Rqt	Rsp	Cnf	Ind	Rqt	Rsp	Cnf	Ind	Rqt	Rsp	Cnf
MLME-ASSOCIATE	✓	✓	✓	✓	NA	✓	NA									
MLME-DISASSOCIATE	✓	✓		✓	✓	✓										
MLME-BEACON-NOTIFY	✓				✓											
MLME-GET		✓		✓		✓		✓								
MLME-GTS	✓	✓		✓	NA	✓		✓	NA	NA		NA	NA	NA		NA
MLME-ORPHAN	✓		✓		NA		NA									
MLME-RESET		✓		✓		✓		✓								
MLME-RX-ENABLE		✓		✓		✓		✓								
MLME-SCAN		✓		✓		✓		✓								
MLME-COMM-STATUS	✓				✓											
MLME-SET		✓		✓		✓		✓								
MLME-START		✓		✓		NA		NA								
MLME-SYNC		✓				✓								NA		
MLME-POLL		✓		✓		✓		✓								
MCPS-DATA	✓	✓	✓	✓	✓	✓	✓	✓								
MLME-PURGE		✓		✓		NA		NA								

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