A COMPREHENSIVE STUDY OF ZIGBEE STANDARD WITH IEEE 802.15.4

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Abstract—This paper studies efficient and simple data broadcast in IEEE 802.15.4 based ad hoc networks (e.g., ZigBee). ZigBee technology was developed for a wireless personal area networks (PAN), aimed at control and military applications with low data rate and low power consumption. Zigbee is a mesh routing protocol used in large IEEE 802.15.4 based wireless sensor networks. This protocol is based on Adhoc On-demand Distance Vector (AODV) routing protocol. ZigBee is a standard defines a set of communication protocols for low-data-rate short-range wireless networking. ZigBee-based wireless devices operate in 868 MHz, 915 MHz, and 2.4 GHz frequency bands. The maximum data rate is 250 K bits per second. ZigBee is mainly for battery-powered applications where low data rate, low cost, and long battery life are main requirements. Since finding the minimum number of rebroadcast nodes in general ad hoc networks is NP-hard, current broadcast protocols either employ heuristic algorithms or assume extra knowledge such as position or two-hop neighbor table. It cannot provide position or two-hop neighbor information, but it still requires an efficient broadcast algorithm that can reduce the number of rebroadcast nodes with limited computation complexity and storage space.

Index Terms—Ad hoc network, Broadcast, IEEE 802.15.4, ZigBee.

INTRODUCTION

THE IEEE 802.15.4 standard [1] was approved in 2003 as a multiple access control (MAC) and physical (PHY) layer standard for low data rate, low power, and low cost wireless personal area networks (WPANs). The ZigBee Alliance [2] is a rapidly growing association of companies working together to enable reliable, cost-effective, low power, wirelessly networked monitoring and control applications. Zigbee standard is developed by ZigBee Alliance, which has hundreds of member companies, from the semi-conductor industry and software developers to original equipment manufacturers and installers. The ZigBee Alliance was formed in 2002 as a nonprofit organization open to everyone who wanted to join. The ZigBee standard has adopted IEEE 802.15.4 as its Physical Layer (PHY) and Medium Access Control (MAC) protocols. Therefore, a ZigBee compliant device is compliant with the IEEE 802.15.4 standard as well. The ZigBee specifications were ratified in December 2004 and the ZigBee network specification [3] is one of the first standards for ad hoc and sensor networks. A ZigBee device has limited computation and storage capacity. All the functionalities in MAC and upper layers are expected to be implemented in a single chip microcomputer, such as a 16-bit M16C [7]. So, it cannot afford to conduct sophisticated algorithms based on data structures that take a large memory space. 2) A ZigBee device should be of small size and low cost, so it cannot obtain accurate position information using extra hardware like GPS. 3) ZigBee networks are targeting low data rate and low power applications, so they cannot provide large communication bandwidth and power for exchanging position or neighbor information among neighbors. Given the above limitations, we are motivated to find a localized and light-weight broadcast algorithm for ZigBee networks. In a typical ZigBee network, the network addresses are organized in a hierarchical manner so that one node can easily identify addresses of its tree neighbors, including its parent and children.

ZigBee

The name ZigBee is said to come from the domestic honeybee which uses a zig-zag type of dance to communicate important information to other hive members. This communication dance (the "ZigBee Principle") is what engineers are trying to emulate with this protocol—a small bunch of separate and simple organisms that join together to tackle complex tasks. ZigBee standard consists of a whole suite of specifications designed specifically for wireless networked sensors and controllers. The physical (PHY) and medium access control (MAC) layers are standardized by the IEEE 802.15 wireless personal area network (WPAN) working group under the designation of 802.15.4 [4]. The standard mainly aims at low cost, low data rate and low power wireless network. The higher layers are specified by the ZigBee Alliance [5], which is an industry alliance consisting of a full spectrum of companies, ranging from ZigBee chip providers to solution providers. Compared to other wireless communication technologies, ZigBee is designed specifically for providing wireless networking capability for battery-powered, low-cost, low capability sensor and controller nodes, typically powered only by an eight-bit microcontroller. The ZigBee technology is designed to provide a simple and low-cost wireless communication and networking solution for low-data-rate and low power consumption applications, such as home monitoring and automation, environmental monitoring, industry controls, and emerging low-rate wireless sensor applications.
ZigBee can use so-called mesh networking, which may extend over a large area and contain thousands of nodes. Each FFD in the network also acts as a router to direct messages. The routing protocol optimizes the shortest and most reliable path through the network and can dynamically change, so as to take evolving conditions into account. This enables an extremely reliable network, since the network can heal itself if one node is disabled. This is very similar to the redundancy employed in the Internet. ZigBee networks are primarily intended for low duty cycle sensor networks (<1%). A new network node may be recognized and associated in about 30 ms. Waking up a sleeping node takes about 15 ms, as does accessing a channel or transmitting data. ZigBee applications benefit from the ability to quickly attach information, detach, and go to deep sleep, which results in low power consumption and extended battery life.

Applications

The major applications of ZigBee are focused on sensor network and automatic control, such as personal medical assistance, industrial control, home automation, remote control and monitoring [6]. It is particularly suitable for biotelemetry applications because of low power consumption, e.g., the personal medical monitoring device for senior citizens. Rather than the traditional wired monitoring equipment, the biotelemetry techniques, allow electrical isolation from data processing devices and power lines.

One of the intended application of ZigBee is in-home patient monitoring. A patient’s vital body parameters, for example blood pressure and heart rate can be measured by wearable devices. The patient wears a ZigBee device that interfaces with a sensor that gathers health related information such as blood pressure on a periodic basis. Then the data is wirelessly transmitted to a local server, such as a personal computer inside the patient’s home, where initial analysis is performed. Finally the vital information is sent to the patient’s nurse or physician via the internet for further analysis.

Another example of a ZigBee application is monitoring the structural health of large scale building and structures. In this application, several ZigBee enabled wireless sensors like accelerometers can be installed in a building and all these sensors can form a single wireless network to gather the information that will be used to evaluate the building structural health and detects the signs of possible damage. After an earthquake, for example, a building could require before it reopens to the public. The data gathered by the sensors could help further and reduce the cost of inspection. Home automation is one of the major application areas for ZigBee wireless networking. The typical data rate in home automation is only 10Kbps. Some of the possible ZigBee applications in a typical residential building are light control systems, security systems, meter reading systems, irrigation systems, multizone Heating, Ventilation, and Air Conditioning (HVAC) systems.

IEEE 802.15.4

The 802.15 is an IEEE working group that specializes in Wireless Personal Area Networks. Though all the standards under this group are defined for networks that are smaller in size, they are bifurcated based on the data rate required for different communications. Standards are defined for Bluetooth, very high data rates and very low data rate networks. Under the very low data rate category comes the 802.15.4/Zigbee standard. This is an infant protocol and is making great progress in the recent years. Optimization and efficiency are the main concerns of this protocol especially because of the constraint of power consumption. There has been constant changes being made to the protocol and thus be considered as one of the fastest growing protocols in the industry. The goal IEEE had when they specified the IEEE 802.15.4 standard was to provide a standard for ultra-low complexity, ultra-low cost, ultra-low power consumption and low data rate wireless connectivity among inexpensive devices. The raw data rate will be high enough (maximum of 250 kb/s) for applications like sensors, alarms and toys.

Components of the IEEE 802.15.4

IEEE 802.15.4 networks use three types of devices:

- The network Coordinator maintains overall network knowledge. It is the most sophisticated one of the three types, and requires the most memory and computing power.

- The Full Function Device (FFD) supports all IEEE 802.15.4 functions and features speci_ed by the standard. It can function as a network coordinator. Additional memory and computing power make it ideal for network router functions or it could be used in network-edge devices (where the network touches the real world).

- The Reduced Function Device (RFD) carries limited (as speci_ed by the standard) function and requires the most memory and computing power. It can function as a network coordinator. Additional memory and computing power make it ideal for network router functions or it could be used in network-edge devices (where the network touches the real world).
uses the layered architecture similar to the OSI model. Each of these layers is responsible to carry out a specific function. The layers could be perceived as a chain in which the layer below functions in a way in which it could provide services for the layer above. The services are provided through what are known as the service access points. These points are present between any two layers of the stack. 802.15.4 itself describes the lower layers namely the Physical layer and the MAC layer. Zigbee however describes the network and the application layers over the foundation built by 802.15.4.

**Relationship between ZigBee and IEEE 802.15.4 standard**

ZigBee wireless networking protocols are shown in Figure 3. ZigBee protocol layers are based on the Open System Interconnect (OSI) basic reference model. As shown in Figure 3, the bottom two networking layers are defined by IEEE 802.15.4 standard. This standard is developed by IEEE 802 standards committee and was initially released in 2003. IEEE 802.15.4 defines the specifications for PHY and MAC layers of wireless networking, but it does not specify any requirements for higher networking layers. The ZigBee standard defines only the networking, applications and security layers of the protocol and adopts IEEE 802.15.4 PHY and MAC layers as a part of the ZigBee networking protocol. Therefore, ZigBee-compliant device conforms to IEEE 802.15.4 as well. IEEE 802.15.4 was conceived due to the unsuitability of current wireless standards such as Wi-Fi and Bluetooth for low data rate battery powered ad-hoc networks. The standard specifies the MAC and PHY layers of the open standards interconnection (OSI) network model while leaving the development of the upper layers to the designer. The standard defines three types of network nodes, PAN coordinators, Full Function Devices (FFDs) and Reduced Function Devices (RFDs). The PAN coordinator is responsible for creating the network and is often used as a gateway to other networks such as Ethernet. There must be only one PAN coordinator per network. FFDs are capable of communicating with all device types as well as creating sub networks and managing routing and addressing of RFDs. RFDs are intended to be extremely simple devices with minimal hardware and software resources. RFDs can only communicate with FFDs or the PAN coordinator, not with another RFD.

**Figure 2**: 802.15.4/Zigbee Protocol Stack

**ZigBee/IEEE 802.15.4 - General Characteristics**

- Data rates of 250 kbps (@2.4 GHz), 40 kbps (@915 MHz), and 20 kbps (@868 MHz)
- Dual PHY (2.4GHz and 868/915 MHz)
- Optimized for low duty-cycle applications (<0.1%)
- CSMA-CA channel access
  - Yields high throughput and low latency for low duty cycle devices like sensors and controls
- Low power (battery life multi-month to years)
- Addressing space of up to:
  - 18,450,000,000,000,000,000 devices (64 bit IEEE address)
  - 65,535 networks
- Multiple topologies: star, peer-to-peer, mesh
- Fully hand-shaked protocol for transfer reliability
- Optional guaranteed time slot for applications requiring low latency
- Range: 50m typical (5-500m based on environment)

**THE IEEE 802.15.4 PHY AND MAC ALONG WITH ZIGBEE’S NETWORK AND APPLICATION SUPPORT LAYER PROVIDE:**

- Ease of implementation
- Reliable data transfer
- Appropriate levels of security
- Short range operation
- Extremely low cost
- Very low power consumption

There are two physical device types for the lowest system cost

To allow vendors to supply the lowest possible cost devices the IEEE standard defines two types of devices: full function devices and reduced function devices

- Full function device (FFD)
  - Can function in any topology
  - Capable of being the Network coordinator
  - Capable of being a coordinator
  - Can talk to any other device

- Reduced function device (RFD)
  - Limited to star topology
  - Cannot become a network coordinator
  - Talks only to a network coordinator
  - Very simple implementation

An IEEE 802.15.4/ZigBee network requires at least one full function device as a network coordinator, but endpoint devices may be reduced functionality devices to reduce system cost.

- All devices must have 64 bit IEEE addresses
- Short (16 bit) addresses can be allocated to reduce packet size
- Addressing modes:
  - Network + device identifier (star)
  - Source/destination identifier (peer-peer)

Frame Structure

The frame structures have been designed to keep the complexity to a minimum while at the same time making them sufficiently robust for transmission on a noisy channel. Each successive protocol layer adds to the structure with layer-specific headers and footers.

The IEEE 802.15.4 MAC defines four frame structures:

- A beacon frame, used by a coordinator to transmit beacons.
- A data frame, used for all transfers of data.
- An acknowledgment frame, used for confirming successful frame reception.
- A MAC command frame, used for handling all MAC peer entity control transfers.

The Physical Protocol Data Unit is the total information sent over the air. As shown in the illustration above the Physical layer adds the following overhead:
- Preamble Sequence 4 Octets
- Start of Frame Delimiter 1 Octet
- Frame Length 1 Octet
- The MAC adds the following overhead:
  - Frame Control 2 Octets
  - Data Sequence Number 1 Octet
  - Address Information 4 – 20 Octets
  - Frame Check Sequence 2 Octets

In summary the total overhead for a single packet is therefore 15 -31 octets (120 bits); depending upon the addressing scheme used (short or 64 bit addresses). Please note that these numbers do not include any security overhead.

Super Frame Structure

The LR-WPAN standard allows the optional use of a superframe structure. The format of the superframe is defined by the coordinator. The superframe is bounded by network beacons, is sent by the coordinator (See Figure 4) and is divided into 16 equally sized slots. The beacon frame is transmitted in the first slot of each superframe. If a coordinator does not wish to use a superframe structure it may turn off the beacon transmissions. The beacons are used to synchronize the attached devices, to identify the PAN, and to describe the structure of the superframes. Any device wishing to communicate during the contention access period (CAP) between two beacons shall compete with other devices using a slotted CSMA-CA mechanism. All transactions shall be completed by the time of the next network beacon.

For low latency applications or applications requiring specific data bandwidth, the PAN coordinator may dedicate portions of the active superframe to that application. These portions are called guaranteed time slots (GTSs). The guaranteed time slots comprise the contention free period (CFP), which always appears 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 may occupy more than one slot period. However, a sufficient portion of the CAP shall remain for contention based access of other networked devices or new devices wishing to join the network. All contention based transactions shall be complete before the CFP begins. Also each device transmitting in a GTS shall ensure that its transaction is complete before the time of the next GTS or the end of the CFP.

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Figure 4 - Data Frame

Figure 5 - Super Frame Structure
CONCLUSIONS

This paper does not aim to bring the novel results from of Zigbee. Instead it aims to serve as the guideline for the student and researchers that want to do comparative study of Zigbee network and IEEE 802.15.4. This paper show that, in single sink IEEE 802.15.4/Zigbee wireless networks non beacon mode gives the longest battery life (lowest power consumption) and the best delivery ratio at all tested data rates in both computer simulations and the experimental investigation. IEEE 802.15.4 in beacon mode in a single sink wireless network results in significantly lower battery life (higher power consumption) and a poorer delivery ratio. However it is likely that in applications where there is bidirectional traffic, the synchronisation provided by beacon mode could be an advantage and could result in fewer collisions than in non beacon mode.

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