Study of Medium Access Control (MAC) Layer Energy Efficient Protocol for Wireless Ad-Hoc and Sensor Networks

省電力無線アドホックセンサネットワークの MAC レイヤプロトコルに関する研究

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Graduate School of Global Information and Telecommunication Studies
Waseda University

Wireless Communication Systems II

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PREFACE

The work presented in this dissertation was carried out at SATO Wireless Communication Systems Laboratory, Graduate School of Global Information and Telecommunication Studies, Waseda University.

Acknowledgement

Upon completing my Ph.D., first and foremost, I would like to express my sincere gratitude to my supervisor, Prof. Takuro Sato. It is my privilege and honor to be able to work with Dr. Takuro Sato for the past two years and a half. It is him who guided me the way to high quality research work. I sincerely appreciate the freedom Dr. Sato gave me in research, and his insightful advices and heartfelt guidance are what I can benefit from for life. Beyond the materials, Dr. Sato also impresses me by his highly professional attitude in research, which is also critical for me to learn in the future.

I would like to express my heartfelt gratitude to Prof. Mitsuji Matsumoto who always inspires me and gives valuable suggestion about my research. I would like to extend my sincere thanks to Prof. Shigeru Shimamoto and Prof. Kenich Mase who give valuable suggestion about my research and all the faculty members and staff of GITS who have given me enormous help in both study and life.

During my Ph.D. research there have been many moments when I felt depressed. It was my family and friends who helped me out during these times. I would like to thank them for being so supportive.

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Summary

Wireless sensor networks (WSNs) is evolving areas of research due to its wide range of application in various domains, including health-care, assisted and enhanced-living scenarios, industrial and production monitoring, control networks, and many other fields. These application fields of wireless sensor network can be divided into three main categories: Monitoring space (applications in monitoring urban air quality, glaciers, forests, mountains etc); monitoring objects (home application, building application etc); and monitoring interactions between objects and space (monitoring environmental threats like floods and volcanic activities etc.).

Wireless Sensor Networks (WSNs) consists of a large number of wireless sensor nodes that are deployed randomly. The sensor nodes are typically small, and equipped with low-powered battery. Unlike other wireless networks, it is generally impractical to charge or replace the exhausted battery. Since prolonging lifetime of the sensor nodes is very important, energy efficiency becomes the most important attribute and a critical design objective for the design of the MAC layer protocol for energy constrained WSNs. In addition, the throughput and latency performance is also important for several sensor network applications. To simultaneously achieve the seemingly contradictory goals, this thesis proposes novel mechanisms for medium access control layer (MAC) protocols to optimize the energy consumption while maintaining high throughput and low latency.

In our work, first of all, we do an extensive analysis of diverse design choices for communication protocol from the energy consumption standpoint which motivates the design choices for our proposed energy efficient MAC protocols. We investigate four important design principles to achieve energy efficiency. They are namely application specific design vs general purpose design; cross

layer architecture vs layered architecture; cluster-based vs cluster-less design; and deliberation of the energy model of the targeted hardware i.e. considering the accurate and thorough energy model of the different components of the targeted hardware. In our first proposed mechanism, we present Intelligent Hybrid MAC (IH-MAC), a novel low power with quality of service guaranteed medium access control protocol for wireless sensor networks (WSNs). IH-MAC achieves high energy efficiency under wide range of traffic load. IH-MAC protocol achieves high channel utilization during high traffic load without compromising energy efficiency. IH-MAC does it by using the strength of CSMA and TDMA approach with intelligence. The novel idea behind the IH-MAC is that, it uses both the broadcast scheduling and link scheduling. Depending on the network loads, the IH-MAC protocol dynamically switches from broadcast scheduling to link scheduling and vice- versa in order to achieve better efficiency. The scheduling is done in IH-MAC with a novel decentralized approach where the nodes locally use the clock arithmetic to find the time slot, allocated for it. Furthermore, IH-MAC uses Request-To-Send (RTS), Clear–To-send (CTS) handshakes with methods for adapting the transmit power to the minimum level necessary to reach the intended neighbor. Thus, IH-MAC reduces energy consumption by suitably varying the transmit power. The typical example that we consider to evaluate of our proposed protocol is a building equipped with a WSN. The duty of sensor nodes are to monitor the power consumption of the appliance in the building. Another duty of the nodes is to work as a smoke detectors, and report alarms to fire monitoring hubs. So, in case of the communicating the later kind of data, it is desirable to ensure lowest possible latency. Our proposed IH-MAC protocol guarantees shorter latency for this type of critical and delay-sensitive packets. And thus IH-MAC is able to serve for the applications of wireless sensor network where it is really needed to ensure the priority services for the critical data.

In our second work, we present a novel medium access control protocol, (Efficient MAC with Parallel Transmission, named as EP-MAC) for wireless sensor networks (WSNs) which is basically based on TDMA approach. The proposed EP-MAC protocol achieves high energy efficiency and high packet delivery ratio under different traffic load. The power of CSMA is used in order to offset the fundamental problems that the stand-alone TDMA method suffers from i.e., problem like lack of scalability, adaptability to varying situations etc. Novel idea behind the EP-MAC is that, it uses parallel transmission concept with the TDMA link Scheduling. EP-MAC uses the methods for the transmission power adjustment i,e, uses the minimum level power necessary to reach the intended neighbor within a specified BER target. This reduces energy consumption, as well as further enhances the scope of parallel transmission of the protocol. Simulations show that both the IH-MAC and EP-MAC protocols are energy efficient MAC layer protocol for WSNs. Moreover they significantly outperform other duty cycling protocols in terms of latency and throughput as well.

Chapter 1

Introduction

1.1 Motivation

Wireless sensor networks (WSNs) is evolving areas of research due to its wide range of application in various domains, including health-care, assisted and enhanced-living scenarios, industrial and production monitoring, control networks, and many other fields. These application fields of wireless sensor network can be divided into three main categories: Monitoring space (application in monitoring urban air quality, glaciers, forests, mountains etc); monitoring objects (home application, building application etc); and monitoring interactions between objects and space (monitoring environmental threats like floods and volcanic activities etc.)[1,2]. Considering the most promising and practical applications of WSN, IETF ROLL has identified the four potential applications of WSN namely industrial, urban, building, and home applications [3].

In most of its applications, the WSN consists of a large number of wireless sensor nodes that are deployed randomly. The sensor nodes are typically small, and equipped with low-powered battery. Unlike other wireless networks, it is generally impractical to charge or replace the exhausted battery. Since prolonging lifetime of the sensor nodes is very important, energy efficiency becomes the most important attribute of design of communication protocol of sensor networks. Other attributes are fairness, latency, delivery ratio, and bandwidth [4]. Many WSNs are based on proprietary standards for wireless networking, but the recent trend has been increasingly towards the standardization of low power wireless communication. The first step of standardization for such WPAN with low energy communication was established with the approval of IEEE 802.15.4. IEEE 802.15.4 standard specifies only the lowest part of OSI communication model: PHY layer and MAC sub-layer. With 802.15.4, IEEE had a goal in mind for low-cost, low-power and short-range wireless communications. This standardization process continued and went through an enhancement process. As a result, newer versions like IEEE 802.15.4b, 802.15.4a, 802.15.4c and 802.15.4d were released subsequently. But unlike 802.11 WLAN cards where MAC is usually included as part of the chipset, in WSNs the MAC designer has absolute control on the design of MAC layer. So, on the basis of IEEE 802.15.4 standard a lot of MAC protocols for sensor networks have been proposed in recent years.

In case of most of the applications of wireless sensor network, idle listening is identified as the major source of energy wastage [5]. Idle listening happens when a node has its radio transceivers turned on but it has communication activities like transmission, reception etc. Since idle listening consumes energy at almost the same rate as receptions one of the important design goal of MAC protocol for sensor network is to minimize the idle listening. Overhearing is another cause of energy wastage for sensor nodes. Overhearing happens when nodes are receiving packets not destined for them due to the broadcast nature of the wireless medium. Since energy consumption during overhearing is same as energy consumption during reception, minimizing overhearing is another design challenge for WSNs.

Therefore, in sensor network, nodes do not wake-up all the time rather prefer energy preservation by going to sleep time to time. After the sleep scheduling, nodes could operate in a low duty cycle which can significantly save energy and extend the network lifetime at the expense of increased communication latency and synchronization overhead. In [6], different sleep scheduling schemes are analyzed and a scheduling methods that can decrease the end to end delay is proposed. But this method does not provide an interference free scheduling. One obvious approach is TDMA MAC which can naturally support low duty cycle operation. Besides TDMA has inherent advantage of contention and collisions free transmission. To be interference free, a straightforward approach can be to assign each communication link a slot, and thus the number of slot is equal to the number of communication links of the network. However, this scheme requires much more slots than necessary, which enhance delay and reduces the channel utilization. Moreover, minimizing the number of slot assignment for producing an interference free link scheduling is a NP complete problem [7]. On the other hand performance of broadcast scheduling is worse than link scheduling in WSNs, in terms of energy conservation. In addition to that, existing MAC layer protocols for WSNs trade off energy efficiency with performance degradation in throughput and latency. But throughput and latency are also important metrics for various applications like event tracking and surveillance. In this thesis, we try to address the challenges involving different above mention aspects in designing the MAC protocol of WSNs.

1.2 Thesis contribution

The main contribution of this thesis is a detailed study of the MAC layer protocol for WSNs. And proposals of energy efficient MAC layer protocols for wireless sensor networks. We also propose protocol for addressing the QoS for home applications of WSNs. We provide analytical model and simulation study to analyze and validate the performance efficiency of our proposed protocols.

1.3 Organization of the Thesis

The rest of the thesis is organized as follows. In Chapter 2, the Wireless Sensor Networks and its different applications are described. In Chapter 3 different classes of MAC protocols and design constrained for the WSNs MAC protocol are described. In Chapter 4, we focus on the related work. The design and elaboration of the proposed IH-MAC protocol with Quality of Service (QoS) is presented in chapter 5 and a detailed performance evaluation is done for the protocol. In Chapter 6, we explain our proposed EP-MAC protocol with performance evaluation. Finally, Chapter 7 concludes the thesis.

Chapter 2

Wireless Sensor Networks And Applications

2.1 Introduction to Wireless Sensor Network (WSN)

A wireless sensor network (WSN) is a wireless network consisting of spatially distributed autonomous devices that use sensors to monitor physical or environmental conditions [8, 9]. These autonomous devices (nodes), in association with other devices like routers, gateway etc., forms a typical Wireless Sensor Network system. The basic components of wireless sensor nodes are shown in figure 2.1.

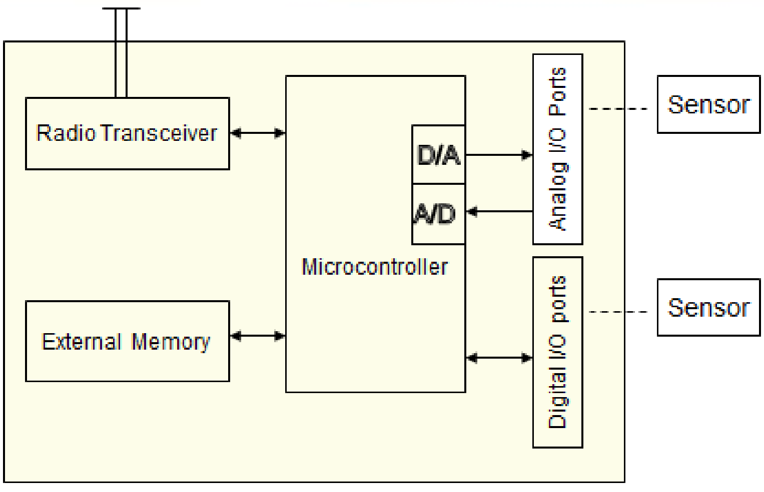

Fig. 2.1. Basic Components of Wireless Sensor node.

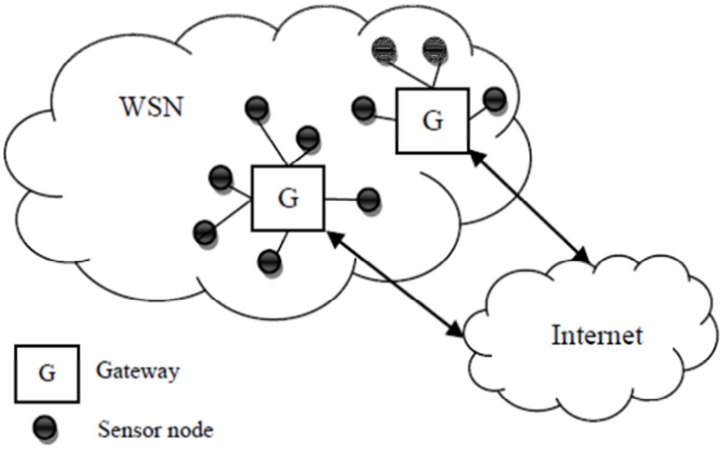

Fig. 2.2. High level view of WSN integrated with Internet.

All nodes belong to a WSN communicate wirelessly to a central gateway directly or indirectly (usually communication is done through multi-hop routing) as shown in figure 2.2. This gateway provides a connection to the existing other network which are deployed and maintained throughout the world where we can collect, process, analyze, and present the measurement data of the WSN.

The comparisons of different wireless technology and WSN in terms of data rate and range/coverage are shown in figure 2.3 and the power consumptions is shown in figure 2.4 .

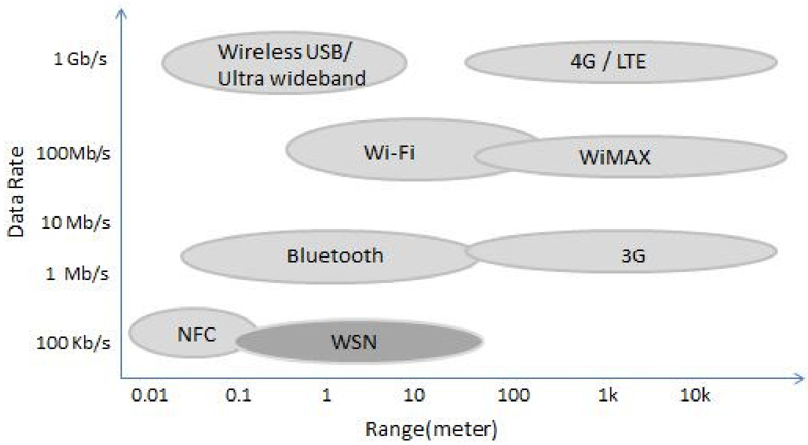

Fig. 2.3. Comparisons of different wireless technology.

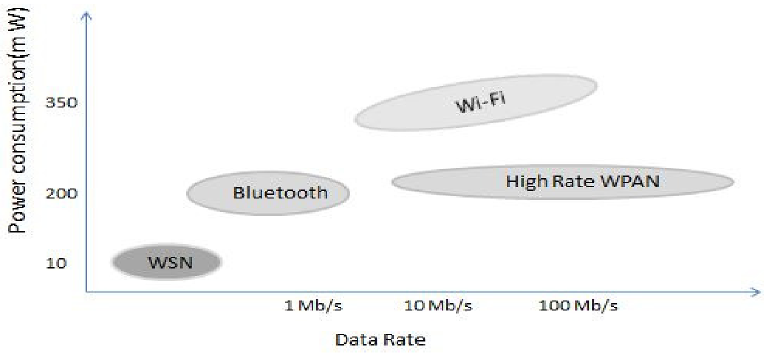

Fig. 2.4. Comparisons of power consumption for different wireless technology in typical automation application.

2.2 Applications of WSN

Embedded monitoring covers a large area of applications, including those in which power or infrastructure limitations make a wired solution costly, challenging, and even impractical [9]. Wireless sensor networks can be used with the wired systems in order to build a complete wired and wireless measurement and control system. Some of the important applications of the WSN are described below:

Applications in disaster: WSNs has very good role in the communication in the disaster situation. Wildfire detection can be cited as an example of disaster situation. Sensor nodes are capable of convening message with its location by which the location of fire can be detected [9]. The sensor maybe deployed from an airplane. The purpose of the deployment is to get a temperature data of the object area. With this temperature map the region of higher temperature area can be determined and that information can be retrieved through the internet. Same type of application is to control of incidents in industry or factories. In this type of application, it is required that the sensor nodes should be very cheap because the number of deployment of the sensor nodes is very large in order to serve the purpose. On the other hand the lifetime requirements of the sensor nodes for these type of application are not usually very high.

Environment control and biodiversity mapping: Another important application of the WSNs can be used to manage the environment. WSNs can be used to collect the number of plant and animal species that exist in a target region. It is one kind of biodiversity information preservation or retrival. The main advantages of WSNs here are the long-term, unattended, wire free operation of sensors close to the objects that have to be observed; since sensors can be made small enough to be unobtrusive, they only negligibly disturb the observed animals and plants [9]. In this type of application, a large number of sensors are required and the lifetime of the sensor nodes should be high.

Intelligent buildings: Energy efficiency is one of the most important criteria of recognized as an intelligent buildings [10]. Besides ensuring energy efficiency and comfort, stress levels of different parts of buildings can be monitored from the remote of a building by sensor nodes. Besides, fire incidence detection is another application of sensor network in an intelligent building.

Machine surveillance and preventive maintenance: Sensor nodes can detect vibration patterns of machinery, and can identify the need for maintenance. Sensor nodes can also detect the leaking chemicals in a chemical plant. The advantages of WSNs in using this type of applications are the cable free operations which incur a maintenance problem in itself.

Precision agriculture: Precision in agriculture can be ensured by using sensors into the fields. Pest control, livestock breeding, etc can also be benefitted by the use of sensor networks.

Medicine and health care: The WSN can be used in health care applications. Some of the applications of WSNs in the health care arena are already successfully realized. These applications are very beneficial. Possible and realized applications range from postoperative and intensive care, where sensors are directly attached to patients, to the long-term surveillance of (typically elderly) patients and to automatic drug administration by embedding sensors into drug packaging, raising alarms when applied to the wrong patient etc.

2.3 WSN System Architecture and hardware of a sensor node

In general, the sensor nodes are deployed in order to acquire measurements data such as temperature, voltage etc. The nodes are part of a wireless network administered by the gateway, which governs network aspects such as client authentication and data security. Sensor nodes send the measurement data to the gateway and gateway sends it over a wired connection, typically Ethernet, to a host controller [9]. The application's requirements play an important role during choosing the hardware components for a wireless sensor node. The size, costs, and energy consumption of the nodes etc., are often chosen according to the types of applications. The trade-offs between features and costs are always crucial. In some extreme cases, an entire sensor node should be smaller than 1 cc, weigh (considerably) less than 100 g, be substantially cheaper than US$1, and dissipate less than 100 μW [9]. In realistic applications, convenience, simple power supply, and cost are very important parameters that are considered [20]. In fact, there is not a single standard available for sensor nodes. It is because a single standard necessarily will not be able to support all application types. However, a basic sensor node comprises with the five following components:

Controller: The function of the controller is to process all the relevant data, and it is capable of executing arbitrary code.

Memory: Small memory is used to store programs and intermediate data. For program and data separate type of memory is used.

Sensors and actuators: Every node must have the devices which will observe or control physical parameters of the environment.

Communication: Every node must have a device for sending and receiving information over a wireless channel.

Power supply: Usually no tethered power supply is available for sensor nodes. Batteries are required to provide energy. Sometimes, some form of recharging by obtaining energy from the environment is available as well (e.g. solar cells) [9].

Each of these components has to perform their task with the constraint of consuming very less energy. In general, for energy preservation both the communication device and the controller should be turned off, when they have nothing to do. A preprogrammed timer can be used by the controller to wake up again. Instead, when a given event is occurred, the sensors can be programmed to raise an interrupt and wake up.

2.4 Power and Network Standard

A sensor node contains several components including the radio, battery, microcontroller, analog circuit, and sensor interface. In battery-powered systems, it is always a desired goal to serve the purpose with less power consumption. As we know, power consumption becomes higher if we want to ensure higher data rates and more frequent radio use. So, some tradeoffs are allowed in order to save power for the energy constrained sensor nodes (to have a long lifetime of the nodes). Due to the low power consumption constrained most often WSN systems are based on ZigBee or IEEE 802.15.4 protocols. The IEEE 802.15.4 protocol defines the lower two layer of the OSI reference model i.e. Physical and Medium Access Control layers, providing communication in the 868 to 915 MHz and 2.4 GHz ISM bands, and data rates up to 250 kb/s. ZigBee uses the 802.15.4 standard and it also provide security, reliability through mesh networking topologies, and interoperability with other devices and standards [9]. In addition to long-life requirements, the size, weight, etc parameter of the batteries are also need to be considered. The low cost and wide availability of carbon zinc and alkaline batteries are used widely for the sensor nodes. Energy harvesting techniques are also considering now a days for wireless sensor networks. Use solar cells or the capability of collecting heat from the environment, can reduce the need for battery power.

2.5 Networking Topologies

Several network topologies can be used in order to ensure the coordination between the WSN gateway, end nodes, and router nodes. In the star topology, each node maintains a single and direct communication path with the gateway. This topology is simple and easy to construct but it restricts the overall distance that the network can achieve. To increase the coverage of the network, a cluster, or tree, topology can be used together of it. With this combined architecture, each node will maintains a single communication path to the gateway but simultaneously each node can also use other nodes to route its data along that path. There are few drawbacks of this topology. For example when a router node goes down for some external reason or run out of energy, the nodes that are dependent on that particular router node will fail to communicate with the gateway. The mesh network topology uses redundant communication paths which increases the system reliability as well as more faults tolerant. In a mesh network, nodes maintain multiple communication paths back to the gateway, so that if one router node goes down, the network automatically reroutes the data through a different path. The mesh topology, while very reliable, does suffer from an increase in network latency because data must make multiple hops before arriving at the gateway [9].

Chapter 3

MAC protocols

Medium Access Control (MAC) protocols regulate the access of a number of nodes to a shared communication medium [9]. There are a large number of protocols have been proposed in this areas. The protocols vary because of the types of media they used. And the protocols also differ according to their optimization goal i.e., the optimization of different performance parameter. Though in OSI reference model the Medium access control is included within the DLL (Data Link Layer), but the functionalities of the MAC and the functionalities of the remaining parts of the DLL are distinctive. The MAC protocol determines whether in a particular point of time a node can access the shared medium or not in order to transmit a packet (either data packet, or control packet). On the other hand the error control and flow control are the two major functions of the remaining part of the Data Link Layer.

In this chapter, we will first briefly describe the Wireless MAC protocol in general and then we will elaborate the specific design goal for designing the MAC protocol of WSNs. We will also cover the different classes of MAC protocols that are already proposed.

3.1 Fundamentals of Wireless MAC protocols

MAC protocols are an important research area to the researchers for last few decades. A lot of MAC protocols have been proposed in order to optimize different design goal by the researchers. Some of the proposed protocols and surveys cover MAC protocols for wireless network in general [21-28]. One thing need to mention here that, energy savings was not the prime concern in the earlier research on the MAC protocol design. But for the designing of the MAC protocol of Wireless sensor networks it becomes the prime concern because of the energy constrained sensor nodes.

Design Constraints for the MAC protocol of Wireless Network: The most important performance requirements for MAC protocols are throughput, efficiency, stability fairness low access delay and minimum transmission delay as well as the low overhead [9]. Low access delay means time between arrival of a packet to a node and first attempt to transmit the packet by the node. Transmission delay is defined as the time between packet arrival and successful delivery. The pre packet overhead, collisions of packets, exchange of extra control packets can be considered as the overhead in MAC protocol. If the MAC protocol allows more than one nodes to send the packet simultaneously then the collision can be happened. For the collisions the receiver cannot receive a packet correctly. So a retransmission of the packet becomes necessary. In case of time-bounded applications it is necessary to ensure guarantees on data reception time. Besides, lower bound of data rate and priority is also needed to be assigned for important packets over unimportant packets.

The properties of the underlying physical layer greatly influence the operation and performance of MAC protocols. Since WSN use a wireless medium, all the well-known problems of the wireless transmission are need to be considered and dealt with during the designing of MAC protocol of WSN. Error-rate and delay are sometimes increase due to physical phenomena like change of rate of fading, increased value of the path loss, attenuation and manmade noise [9]. As the distance between the transmitting and receiving nodes increases the received power decreases (path loss). On the other hand, all transceiver need minimum signal strength to demodulate the received signals successfully. As a result, with a given transmit power the maximum range becomes limited that a sensor node can cover the distance ie communicate. If two nodes are not within their communication radius they cannot communicate with each other. This results the consequences of the hidden terminal as well as exposed terminal problems [21]. Usually in the class of Carrier Sense multiple Access (CSMA) protocols faces the hidden terminal problem. In CSMA, a node after sensing the medium, if the medium is found free the node starts to transmit a packet. If the medium is seen to be busy the node doesn't transmit the packet, rather it defers its packet to avoid collision. If CSMA is used without any refining, in a hidden terminal scenario there is a possibility of collision. Similarly, in the simple CSMA due to the exposed terminal scenario experience with the needless waiting. The hidden terminal and exposed terminal problems can be handled with the Busy-Tone solution [21] and the RTS/CTS handshake used in the IEEE 802.11 WLAN standard [22]. The unique solutions were initially proposed in the paper[23] and [24].

In case of wired media the transmitter can easily detect a collision at the receiving side instantly and accordingly the transmitter stop transmission. This technique is recognized as collision detection (CD). Collision detection (CD) concept is used in the CSMA/CD protocol. With the uses of CSMA/CD the throughput efficiency is increased significantly. This collision detection is possible because of the minimum fading in the wired medium, and due to the low attenuation there exist in similar signal to noise ratios at both the transmitting and receiving side. If the transmitter again reads the channel during transmission time and detects a collision, transmitter can easily recognize that a collision has occurred at the receiver end too. And if there is no collision at the transmitter side it means that there has been no collision at the receiver side as well at the time of transmission of packet. But in case of a wireless medium it is not possible to know the situation in the receiver side from the transmitting side. In addition, as the working mode of a wireless transceivers is usually half-duplex , at any specific time both transmit and the receive are not active simultaneously, rather only one is active at a time. For the said reason collision detection protocols are not good choice for the wireless media [9].Another difficulty arises when WSN shares its spectrum with other systems. It is because there is no frequency band exclusively assigned to the WSN. And as we know because of license free operations, many wireless systems use the ISM bands. ISM band 2.4 GHz for example. It can be noted that 2.4 GHz band is used by IEEE 802.11/IEEE802.11b WLANs [25, 26], Bluetooth [27] and the IEEE 802.15.4 WPAN and others as well. Therefore the important issue of coexistence of these systems comes up [28, 29, 30].Finally the expected traffic load pattern is another key design issue of designing of MAC protocols. The traffic for the WSN can be periodic. If reason behind the deployment of a WSN is to monitor a physical phenomena for long period of time, a very low traffic and periodic traffic are the generated traffic by the WSNs. On the other hand, the deployment goal of the WSN can be to wait for the occurrence of an important event. And upon the occurrence of the event the job of the WSN is to report as much data as possible. So in this scenario, the network is almost idle for a long time and then is to take the challenge of facing with a huge number of packets that are to be transmitted promptly. Obviously in this case a high throughput and data rate is desirable. Wildfire observation [31] can be a good example for this class of application.

3.2. Important Classes of MAC protocols

Many Medium Access Control protocols for wireless networks are proposed for the few decades. The protocol can be categorized into the following categories [32]:

3.2.1. Fixed Assignment protocols

Fixed assignment protocols cover protocols where the resources are distributed to the nodes and the nodes holds these allocated resources for long time. Since the resources are allocated exclusively to the nodes, there is no chance of collisions. Long term means that the assignment is for duration of minutes, hours or even longer. In general, it is very difficult to handle the problem of scalability in these classes of protocols. It is because, if the topology is changed (topology can be changed because of dying of nodes or due to the deployment of new nodes, due to mobility or changes in the load pattern) some sort of signaling mechanisms are needed to reallocate the assignment of resources to nodes.

TDMA, FDMA, CDMA, and SDMA are examples of these catagory of protocols. The Time Division Multiple Access (TDMA) scheme [33] divides the communication time into fixed length frames and each frame is again subdivided into fixed number of time slots. These time slots are assigned to nodes exclusively. With this dedicated time slot the nodes can transmit data or control packets periodically in every frame. The success of the TDMA protocol is dependent on the synchronization between the nodes. If the synchronization is not ensured overlapping of signal in the adjacent time slots is occurred. In Frequency Division Multiple Access (FDMA) the available frequency band is divisioned into a number of sub-channels. The participating nodes are assigned with these sub-channels, and they use these sub-channels exclusively in order to transmit signals. Frequency synchronization, relatively narrow band filters, and the ability of a receiver to tune to the channel used by a transmitter are some requirements of the FDMA scheme. For these reason usually an FDMA transceiver is more complex than a TDMA transceiver. In Code Division Multiple Access (CDMA) scheme [34-35] the nodes spread their signals over a much larger bandwidth than needed, using different codes to separate their transmissions. The receiver must have the knowledge about the code used by the transmitter in order to decode the signal. All parallel transmissions that uses other codes are treated by the receiver as a noise. Finally, since the Space Division Multiple Access uses the technique of the spatial separation between the nodes, the SDMA is able to separate their transmissions as well. SDMA requires array of antennas and refined signal processing techniques [36] and thus it cannot be considered as candidate mechanism for the WSN.

3.2.2 Demand Assignment Protocols

In these classes of protocols, the resources are given to the nodes is not made for long-term, and the length of time period allocation is generally is equal or proportionate to the duration of a data burst. The demand assignment protocol can be broadly classified into two; centralized protocol and distributed protocol. The examples of centralized protocols are HIPERLAN/2 protocol [37-39], MASCARA protocol [40], polling schemes [41-43]. In centralized scheme, the central nodes perform the duty of the allocation of the resources among the other nodes. When nodes send request for the bandwidth requirements to the central node, the central node has discretion of accepting or rejecting the requests. If the allocation of bandwidth is successful, an acknowledgement is sent back to the requesting nodes which also contain the description of the given resources. For example in case of TDMA the description of allocated resources may be the number of positions of the assigned time slots in the TDMA frame and the duration of the allocation. After the successful allocation the node can use these resources exclusively. There are two mechanisms to manage the submission of request from nodes to the central station. One way is use random access protocol on an exclusive signaling channel for the request submission by the nodes. And in the second option, the central station polls the nodes defined within its territory. Besides, the nodes also piggyback demand on to data packets transmitted in their dedicated slots. This piggybacking is definitely a very good technique of avoiding transmission of separate request packet. Now one of the drawbacks of this scheme (in consideration of energy constrained nodes) is that, the central nodes need to be switched on all the time to perform proper resource allocation for other nodes. Since for performing numerious activities the central node should be always awake, and thus it needs a lot of energy. So, this class of protocols can be good choice only if a sufficient number of energy-unconstrained nodes are present and the duties of the central nodes can easily be moved to these energy-unconstrained nodes. IEEE 802.15.4 protocol [44] is a good example of this category. If there are no such unconstrained nodes present in the network, a good technique is to rotate the duties of the central station among all nodes. LEACH [45] protocol successfully used this concept of rotation of central node. There is a lot of distributed demand assignment protocols proposed. One typical example can be IEEE 802.4 Token-Bus [46] where the initiation of transmission of a node is done after the reception of a special frame of token. The token frame designed to rotate among the nodes in within the network that are organized in a logical ring on top of a broadcast medium. In this mechanism, with the change of the topology special ring management procedures are needed. Topology can be changed due to include and exclude nodes from the ring. Correcting failure like lost tokens is also need to be handled. Token passing protocols cannot be successfully used in the wireless media [47], because of the problem of maintaining of the logical ring where there is possibility of frequent channel errors [48]. In addition, a node must be switched on most of the time in order to receive the token and to maintain the unbroken ring. It is because token circulation times are not fixed. So, this protocol is not a very good choice for the network composed of much energy constrained nodes. Another challenge of this protocol is to maintain a logical ring if there is a case of frequent topology changes. In fact, it involves considerable signaling traffic for the token frames and others required information.

3.2.3 Random Access Protocol

In this category of protocols there is no central control of the nodes and they operate in a distributed fashion. One of the basic and important mentionable random access protocols are ALOHA and slotted ALOHA protocol [49]. In ALOHA, in case of transmitting a new packet, the node is allowed to transmit the packet instantly. There is no provision of the consideration of the consultation with other nodes and thus the protocol is very susceptible for collisions at the receiver end. In order to clarify about the collision the receiver sends an immediate feedback for a successful packet reception. If no acknowledgement is received the transmitter interprets it as a signal of a collision. After having decided that the sent packet suffered from the collision the transmitter retransmits it after a random time (back off time). After the back off time, it initiates its subsequent trial. In case of lighter traffic the drawback of ALOHA protocol is transmission delays. And in case of higher traffic/loads, the protocol suffers from higher collisions and subsided throughput. This also results increased transmission delays [9]. In case of slotted ALOHA, the total communication time is divided into slots and a node is allowed to transmit a packet only at the starting point of a slot. A slot is large enough to accommodate a maximum-length packet. So, in slotted ALOHA only those nodes that start their packet transmission in the same slot can destroy other node's transmission (packet). If any node failed to transmit at the beginning of a slot it must wait for the beginning of the next slot. This way the slotted ALOHA reduces the probability of collisions and achieves much improved throughput compared to basic/original ALOHA. In CSMA protocols [50], a transmitting node cares for the ongoing transmissions. If a node has a packet to transmit, it first listen the medium; which is termed as carrier sensing. If the node observes that the medium is idle, it starts transmission. On the other hand if the medium is found busy, the node doesn't start its transmission, rather it defers its transmission for an amount of time. The waiting time can be determined by several ways. There are some variants of CSMA protocols. For example, in case of non-persistent CSMA, the node draws a random time, at the end of this time interval the node again sense the medium. In case of p-persistent CSMA, a node initiates communication in each slot with the p probability. So with the $1 - p$ probability of the node postpone its transmission for the subsequent slot i.e., the node defer its transmission. If some other node starts to transmit in the meantime, the node defers again and repeats the whole procedure. If value of the probability, p is very small the probability of collisions also becomes very small or unlikely, but it results high access delays. As the value of p increases the collision also becomes more likely. In the back-off procedure performed Distributed Coordination Function (DCF) of IEEE 802.11 standard protocol, if a node wants to transmit a fresh packet, it takes a value randomly within the current contention window. After that the node starts a timer with this value which is decremented at the end of every slot. If other sensor node initiates its transmission by this time, the timer is suspended and resumed after the subsequent frame finishes. As soon as the value of the timer reaches to zero, the node starts transmission. Though the CSMA protocols are also suffer from the collisions, the throughput efficiency of CSMA protocols is better than ALOHA protocols. It is because the node interested to transmit packet always sense the medium before transmission and they care for the ongoing packets.

Chapter 4

Related Works

4.1 MAC protocols for wireless sensor networks

The requirements and design objective for the Medium Access Control protocols of WSNs are not same as the other wireless networks. We will discuss the design constraints in brief here.

Balance of requirements: In order to conserve energy, the tradeoff of design goal of WSNs is dissimilar from other wireless networks. As we know many of the well established MAC protocols (ALOHA, CSMA etc) do not have any option of dealing with the energy efficiency parameter. Other than energy efficiency, performance parameters like fairness, throughput, or delay requirements are less important consideration in designing the MAC protocol of the WSNs. Fairness is not very important in case of many application, because in the WSNs the nodes do not compete for the bandwidth between each other, rather they cooperate each other to achieve a common goal. In order to achieve the goal of energy efficiency the transmission delay is allowed in WSNs. Throughput is generally not an important issue for most of the application of WSNs. On the other hand, since the sensor network very often experience with the topology changes, scalability and robustness are important issues for the case of MAC protocols of WSNs.

Energy consumption within the function of the MAC layer: As we know in case of sensor network, a nodes transceiver consumes a significant amount of energy compared to the other operations. At a particular time a transceiver of the sensor node may be at the transmitting state, or receiving state, or idling state, or sleeping state. Among the four state transmitting is most costly, receive costs is little less than the transmitting costs, idle listening is very expensive and nearly equal to the receiving operation. Sleeping state consume negligible energy. However at sleeping state the node work as a "deaf" node. Applying these lessons to the operations of a MAC protocol for wireless sensor networks, several design goals [5] are identified:

Collisions: For collisions both the transmitting (source node) and the receiving (destination) nodes suffer from the expenditure of the useless transmit and receive costs respectively. Hence, the one of the important design goal of the MAC protocol of WSNs is collisions avoidance. But in some applications the traffic is very low all the time. In that case, there is no need to give much attention about collision in designing of the MAC protocol of WSNs.

Overhearing: Since the source node broadcast a packet in order to send it to a particular node in WSNs, so all the nodes that are within the transmission range of the source nodes hear the packet. After receiving the packet if a node see that the packet is not destined for the node, the node just drop it. This overhearing consumes a significant amount of energy. But it should also be kept in mind that, overhearing is sometimes expectable though. Usually for collecting neighborhood information overhearing is desirable.

Protocol Overhead: Packet headers and packet trailers, control frames like Request-

To-Send (RTS) and Clear-To-Send (CTS) packets, request packets in demand assignment protocols, are some examples of the protocol overhead. The overhead should be as minimum as possible in order to conserve energy.

Idle listening: When a node is a state of capable of receiving a packet but there is no such packet which is destined for that node, this state of the node is defined as the idle listening state for the node. During this idle state a node consumes mentionable amount of energy. If the protocol can intelligently predict this state, the node can switch off its transceiver and goes to sleep in order to save energy. Though the turn on and turn off also consumes energy but it is less than the state of idle listening. The protocol founded upon TDMA can offer solution to this idle listening problem inherently. In TDMA, a node is allowed to transmit a packet or receive a packet only in the particular time slot that is allocated for the node. So, a node can shut down its transceiver in all time slots other than its transmitting/receiving slot. But using the TDMA protocol alone has disadvantages like lack of flexibility, difficulty in the achieving scalability, and also in achieving synchronization.

Most of the MAC protocols proposed for wireless sensor networks addresses one or more of these problems in order to enhance the energy efficiency. We know, each sensor node is equipped with limited resources i.e., low processing power, small memory, or low powered battery. So, it is important to avoid the computationally costly operations like complex scheduling algorithms. Again, it should be noted that tight time synchronization could be costly for WSNs because it will need recurrent resynchronization among the neighboring nodes, which will definitely consume large amount of energy.

4.2. Low duty cycle protocols and wakeup concepts

The idea behind the Low duty cycle protocols is to minimize the idle state time for the sensor nodes. In an ideal scenario, a sensor node will sleep all the time, except the time it wishes to transmit a packet or there is packet from the other node destined to that node. With the implementation of wakeup radio concept this ideal state goal can be achieved. But due to some difficulties the system is not practically implementable till now. By using periodic wakeup scheme a lot of MAC protocols have been proposed for WSNs. In most of the protocols of this class, nodes spend the majority portion of their time in the sleep mode and wake up periodically to transmit packet to other nodes or to receive packets from other nodes. And the communication time is fragmented into cycles which consists of sleep period and listen period (or active period). The node's duty cycle is the ratio of the active period to the total time slot period. If a small duty cycle is chosen, the node will be in sleep mode most of the time, and it will conserve more energy by avoiding idle listening. Since the nodes will be in listen mode for small amount of time, the traffic bound for a particular node from neighboring nodes concentrates on a small time window and as long as traffic load increases competition among the neighboring nodes will also increases. In addition to that because of the lengthy sleep period per-hop latency will also increase. In the multi-hop network, due to the increased per-hop latencies, finally end-to-end latencies will be larger. On the other hand, if the sleep period is chosen too short, then the idle listening will not be minimized. Moreover, there will be a turn off and startup radio cost for the transceiver which will outweigh the benefits of the goal of the low duty cycle mechanism.

Wakeup radio concepts: With the goal of energy efficiency under the low duty cycle concept, the advantageous situation can be, if the receiving node is in the state of receiving mode at the time of sending node sends packet to it; the node is in the transmitting state when it transmits a packet, and when there is no packet to transmit or receive the node is in the sleeping mode. The idle listening or the state should be avoided by sleeping. In order to achieve this goal the wakeup radio concept use a simple, receiver which will be active all the time but consume trivial power and it has the capability of triggering the main receiver when it is necessary. The protocol proposed in [51], the authors take necessary assumption that there are several parallel data channels exist which are separated by Frequency Division Multiple Accesses (FDMA) or by Code Division Multiple Access (CDMA) schemes. When a node has a data to transmit, it picks one of the channels randomly and start carrier sensing. If the channel is found busy, the node picks another channel randomly and starts the carrier-sensing as before. If again the channel is found busy it repeats the operating and after a defined number of failures of getting the channel, the node backs off for a random time and starts again. When the node find that the channel is idle, the node first sends a wakeup signal to the intended receiver. The wakeup signal contains two information, the receiver identification and the channel that would be used for data transmission. After getting the wakeup signal the receiver becomes in listen mood from the sleep mode and its data transceiver, tunes to the appropriate channel. When the transmission is finished, the receiver again switches to sleep mode. With this scheme a node (energy consuming data transceiver of the node) sleep all the time if there is no data intended for it. Only the low-power wakeup transceiver is switched on for all the time. So, significant amount of energy is saved. Again as the traffic load increases the participating nodes also to be in the listen mode for longer time, meaning the scheme is inherently traffic adaptive. On the other hand, the periodic wakeup schemes cannot adjust its operation according to the change of the traffic load automatically.

4.3 IEEE 802.11 and Bluetooth

The Bluetooth system is designed with an objective to serve for a Wireless Personal Area Network (WPAN). The connections between devices were the prime objective. It also has been widely used for prototyping WSNs series of applications [53]. The PHY is based on a FHSS scheme (hopping frequency of 1.6 kHz). The nodes are considered to be organized as piconets. One node performs the role of a master and up to seven active slave nodes are allowed. The hopping sequence is chosen by the master node and the slaves follow the sequence. In addition to the active slave, several passive slave nodes may exist in a piconet. There are several drawbacks of Bluetooth. Always there should be a master node, and the master node spends significant amount of energy on polling its slaves. Again the number of active slaves per piconet is limited which is not applicable for dense wireless sensor networks. Because in the case of dense WSN, a huge number of master nodes would be needed thus very significant amount of energy will be wasted for the polling purpose. In IEEE 802.11 protocol (and its variants), node should be always in the listen or active mode. It is because the receiver node doesn't know when a packet will be transmitted by another node and the packet is destined or bound for it. Secondly, overhearing of Request-To-Send (RTS) and Clear-To-Send (CTS) packets is required in order to adjust the NAV timers accurately. Though the IEEE 802.11 has some power-saving functionality [54], the protocol is proposed in order to ensure high bitrates rather than ensuring low energy consumption. In fact, the consumed energy by the available transceivers is higher and not suitable or acceptable for low bit rate sensor network applications. In addition to that, IEEE 802.11 provide fare share on the common channel for the competing users but this goal doesn't match with the ideal design principles of wireless sensor networks.

4.4 The IEEE 802.15.4 MAC protocol and Related Works

The IEEE 802.15.4 standard specifies only the lowest part of OSI communication model: PHY layer and MAC sub-layer which is overviewed in figure 4.1.

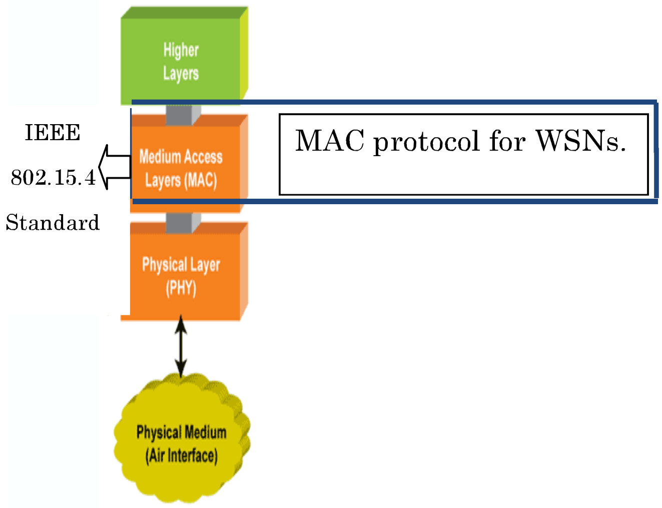

Figure 4.1.Structure of IEEE 802.15.4 protocol stack

With 802.15.4, IEEE had a goal in mind for low-cost, low-power and short-range wireless communications. This standardization process continued and went through an enhancement process. As a result, newer versions like IEEE 802.15.4b, 802.15.4a, 802.15.4c and 802.15.4d were released subsequently. On the other hand ZigBee is a standard from the ZigBee alliance. ZigBee uses the services offered by IEEE 802.15.4 and adds network construction, security, application services etc. The targeted applications for IEEE 802.15.4 are in the area of wireless sensor networks, home automation, home networking, connecting devices to a PC, home security, and so on. Most of these applications require only low or medium bitrates, allow reasonable average delays, and need low energy consumption.

In the seven-layer OSI model the physical layer or layer 1 is the first (lowest) layer. The data transmission service is provided by the physical layer (PHY). Another function of physical layer is to work as the interface to the physical layer management entity, which offers access to every layer management function and maintains a database of information on related personal area networks. Thus, the PHY manages the physical RF transceiver and performs channel selection and energy and signal management functions. It operates on one of three possible unlicensed frequency bands [84]: 868.0–868.6 MHz; 902–928 MHz; and 2400–2483.5 MHz.

The original version of the standard (proposed in 2003) specifies two physical layers: one working in the 868/915 MHz bands which support data transfer rates of 20 kbit/s and 40 kbit/s, and other in the 2450 MHz band which can support data transfer rate of 250 kbit/s. This proposal was based on direct sequence spread spectrum (DSSS) techniques. In the year 2006 the revision of the original proposal was done. The revised proposal improves the maximum data rates of the 868/915 MHz bands, bringing them up to support 100 and 250 kbit/s[84]. Besides depending on the modulation method used, the revised proposal define four physical layers. Among them 3 physical layer preserve the direct sequence spread spectrum approach: in the 868/915 MHz bands, using either binary or offset quadrature phase shift keying ; in the 2450 MHz band, using the latter. An alternative, optional 868/915 MHz layer is defined using a combination of binary keying and amplitude shift keying dynamic switching between supported 868/915 MHz PHYs becomes possible.

The IEEE 802.15.4a was released expanding the four PHYs available in the earlier

2006 version to six, including one PHY using Direct Sequence ultra-wideband (UWB) and another using chirp spread spectrum (CSS) in August 2007. These three ranges of frequencies are allocated by the UWB PHY. The ranges are: 1) below 1 GHz, 2) between 3 GHz and 5 GHz, and 3) between 6 GHz and 10 GHz. The CSS PHY is allocated spectrum in the 2450 MHz ISM band.

Beyond these three bands, the IEEE 802.15.4c study group considered the newly opened 314–316 MHz, 430–434 MHz, and 779–787 MHz bands in China. And the IEEE 802.15.4 d Task Group amended 802.15.4-2006 to support the new 950–956 MHz band in Japan. The group released their amendments of the standard in April 2009 [84].

The medium access control (MAC) ensures the transmission of MAC frames through the use of the physical layer or physical channel. The Media Access Control (MAC) is a part of the data link layer specified in the seven-layer OSI model (layer 2). It provides addressing and channel access control mechanisms. Besides the data service, it offers a management interface and itself manages access to the physical channel and network beaconing. It also controls frame validation, guarantees time slots and handles node associations. Finally, it offers hook points for secure services [84].

The IEEE802.15 Task group 4e made an effort to amend the to amend the MAC existing standard defined in 2006 i.e. 802.15.4-2006. The proposed amendments adopts channel hopping strategy. These features help in improving support for the industrial markets increases, robustness against external interference and persistent multi-path fading. The IEEE 802.15.4e was approved by the IEEE Standards Association Board on February 6, 2012.

Though IEEE 802.15.4 standard and its amendments specify the lowest part of OSI communication model: PHY layer and MAC sub-layer; but unlike 802.11 WLAN cards where MAC is usually included as part of the chipset, In WSNs the MAC designer has absolute control on the design of MAC layer. And during the design of MAC protocol of WSNs the issue that the designers always keep in mind is the energy efficiency. Other attributes are fairness, latency, delivery ratio, and bandwidth [4]. Idle listening is the major source of energy wastage for wireless sensor networks [5]. Therefore, in sensor network, nodes do not wake-up all the time rather prefer energy preservation by going to sleep time to time as explained in figure 4.2.

After the sleep scheduling, nodes could operate in a low duty cycle which can significantly save energy and extend the network lifetime at the expense of increased communication latency and synchronization overhead. In [6], different sleep scheduling schemes are analyzed and a scheduling methods that can decrease the end to end delay is proposed. But this method does not provide an interference free scheduling. One obvious approach is TDMA MAC which can inherently support low duty cycle operation. Besides TDMA has natural advantage of contention and collisions free transmission [4]. To be interference free, a straightforward approach can be to assign each communication link a slot, and thus the number of slot is equal to the number of communication links of the network. However, this scheme requires much more slots than necessary, which enhance delay and reduces the channel utilization. Moreover, minimizing the number of slot assignment for producing an interference free link scheduling is a NP complete problem [7]. On the other hand performance of broadcast scheduling is worse than link scheduling in WSNs, in terms of energy conservation. In fact TDMA has long been dismissed as an unfeasible solution for wireless ad hoc networks for its lack of scalability and adaptability to varying environments. However, it provides a good energy efficient and collision free communication. Recently several techniques [55, 56] have been proposed for TDMA in sensor networks. But these techniques are not successful to deal with the fundamental problems that stand-alone TDMA method suffers from.

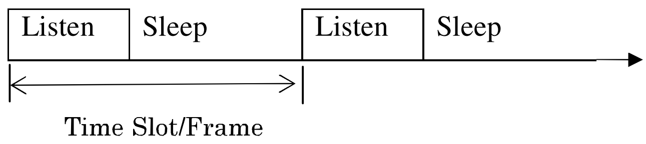

Figure. 4.2. Periodic listen and sleep of a sensor node

For sensor network, S-MAC [5] is one of the pioneering works in contention based MAC protocol. In S-MAC nodes operates in low duty cycle and energy efficiency is achieved by periodic sleeping. Nodes form virtual clusters, based on common sleep schedules, to reduce control overhead and enable traffic adaptive wake-up. S-MAC uses three novel techniques to reduce energy consumption and support self-configuration. To reduce energy consumption in listening to an idle channel, nodes periodically sleep. Neighboring nodes form *virtual clusters* to auto-synchronize on sleep schedules. Motivated by PAMAS [85], S-MAC adopted the concept of setting the radio to sleep during transmissions of other nodes. However, unlike PAMAS, S-MAC only uses in-channel signaling. Besides S-MAC applies the novel technique of message passing in order to subside contention latency for sensor-network applications that require store-and-forward processing as data move through the network.

T-MAC [57] protocol enhance the energy efficiency of Sensor MAC protocol by incorporating duty cycle adaptively. T-MAC also reduces the idle state of sensor node by burst messages transmission. T-MAC introduces the concept of an adaptive duty cycle. This allows T-MAC protocol to adjust the duty cycle ie active part of a slot dynamically. As a result the amount of energy wasted on idle listening is reduced. In the evaluation part of the T-MAC protocol it can be seen that the protocol can successfully handle load variations in time and location.

In AMAC [58] each node can adjust duration of the active period depending on traffic. According to the authors, AMAC is adaptive in terms of guard band assignment mechanism, and sleep or wakeup technique. The work focuses on specific application to monitor human body. In the assumption authors assume the sensor nodes which continuously scan body for updated information. If the current value is with-in a defined limit/range, the sensor nodes do not initiate transmission or access the channel. However, if the sensed value cross the threshold value (either below or above) the sensor nodes switch on their transceiver in order to access wireless channel. Besides, authors also use TDMA approach in their proposed AMAC as an access channel mechanism. Moreover, the synchronization scheme that used for avoiding collisions is precisely defined in the AMAC.

In [59] the performance analysis of optimized medium access control for wireless sensor network is done. B-MAC [60] is the default MAC for Mica2. B-MAC allows an application to implement its own MAC through a well-defined interface. In B-MAC, a flexible interface is proposed to obtain low power operation and effective collision avoidance. To achieve low power operation, B-MAC introduces an adaptive preamble sampling scheme which can lessen the wakeup period of an idle sensor node and thus by minimize idle listening time energy can be saved. An analytical model of of B-MAC protocol is proposed and describe by the authors. Authors provide a comparisons of B-MAC performance with respect to IEEE 802.11 based protocol and

S-MAC. Authors claim that due to the inherent flexibility of B-MAC's, it is capable of offering better packet delivery rates, throughput, latency, and energy consumption than S-MAC.

Z-MAC [61] dynamically adjusts the behavior of MAC between CSMA and TDMA depending on the level of contention in the network. The protocol uses the knowledge of topology and loosely synchronized clocks as hints to improve MAC performance under high contention. Z-MAC uses DRAND [62], a distributed implementation of RAND [63] to assign slot to every node in the network. Z-MAC achieves high channel utilization and low latency if there is low traffic load hence lower chance of contention for channel. It has the capability of reducing collision with low cost. Besides, during high traffic high channel utilization is possible by using Z-MAC. The worst case performance of Z-MAC is similar to CSMA.

TH-MAC [64] is a traffic pattern aware hybrid MAC protocol inspired from Z-MAC. It uses A-DRAND as slot assignment algorithm. A-DRAND is an improved version of DRAND for clustered wireless sensor networks where cluster heads require more slots to relay packets. In [65] a hybrid MAC protocol BAZ-MAC is proposed for Ad Hoc networks. The protocol uses a bandwidth aware slot allotment technique during the set-up phase; slots are assigned to the nodes according to their bandwidth requirements. In WiseMAC [66] a sender can minimize the length of the preamble by exploiting the knowledge of the sampling schedules of its neighbors during communication and thus reducing the preamble transmission overhead.

Chapter 5

Proposed MAC layer protocols for Wireless Sensor Networks

5.1 Protocol Design Principle and Its Energy Consumption Standpoint

In this section, we clarify diverse design choices for communication protocol from the energy consumption standpoint which motivate the design choices for the IH-MAC. We investigate four important design considerations to achieve energy efficiency in IH-MAC.

5.1.1 Application specific design

It is known that, considering the most promising and practical applications of WSN, IETF ROLL identified the four potential applications of WSN namely industrial, urban, building, and home applications [3]. However, because of the wide range of application targeted, these requirements sometimes contradict each other, e.g. data delivery reliability is more important than energy efficiency in a refinery monitoring WSN, while it is the opposite in an urban –wide air quality monitoring WSN. So, it is evident that any particular protocol can't serve the best for applications of different (sometimes opposite) requirements. Besides, due to the wide range of applications, without application specific design the quality of services cannot be easily ensured. Again, the nature of the most of the applications of WSN are such that only the sink nodes need to communicate with the outside world and the remaining nodes perform merely two duties; sensing data and forwarding packets of the neighbour towards the sink. So, these natures of sensor nodes which are quite different from the other kind of network; can be exploited to achieve optimum network gain. Ideally, the deployed sensor network must be able to perform the best for achieving the objective for which it has been deployed. Considering the above discussion, it is clear that application specific protocol which is optimized for that particular application of WSN can be a good design principle rather than the protocol targeting to cover a wide range of applications.

5.1.2 Cross layer architecture

The most of the communication protocols that are already proposed for WSN are individually developed and optimized for different layers of classical layered protocol. But during designing a protocol for a particular layer (i.,e., Transport, Network, MAC, or Physical layer) designer´s objective is to maximize the performance in terms of the metrics related to that particular layer, which do not necessarily ensure the optimization of the overall network performance. On the other hand by violating the layered architecture optimum performance can be achieved. So, realizing the nature and objective of sensor network within the limitation of resources we advocate for cross layer adaptation in the protocol design of WSN. Overall network performance gain can be achieved by the concept of cross layer approach which avoids the extra overhead as well as exploits actively the dependence between the protocols layers [39, 76]. Moreover, in the traditional layered architecture there is a little scope of finding the tuneable solutions.

5.1.3 Cluster based design

Cluster-based protocols are based on hierarchical network organization. Sensor nodes are grouped into clusters, with a cluster head elected for each cluster. Cluster members transmit their sensed or aggregated or relayed data to the cluster head. Cluster head takes the responsibility to communicate with the sink node. Using clusters has the benefit of limiting the area for flooding data to the cluster instead of the whole network, with positive consequences over scalability, lifetime and energy efficiency [77, 78]. Moreover, because nodes physically close usually sense similar events, data can be efficiently aggregated at the cluster head to obtain more precise data with avoiding redundancy.

On the other hand the benefits of the cluster-based solutions must be balanced against the signalling cost for cluster formation, cluster head selection and cluster maintenance [3]. Clustering is based entirely on smooth coordination between nodes. Since motes are interconnected by lossy links, ensuring a consistent state is complex. State inconsistency and race conditions can cause network instabilities, turning real-world deployments into a very challenging task. For these reasons, no clustering protocol has been standardized or used in commercial WSN products [3]. Furthermore works such as [79] conclude that clustering doesn't increase the throughput of the network if all the nodes are homogeneous. And the work [80] proves that clustered networks do not necessarily outperform non-clustered WSNs.

5.1.4 Deliberation of the Energy model of the targeted hardware

Before initiating the design of communication protocol of WSNs, it is important to consider the accurate and thorough energy model of the different components of the targeted hardware. These components include the start-up energy for the transceiver, the static (distance-independent) power drawn by the transmitter and receiver, power amplifier inefficiencies, coding energy, and protocol over-head [81]. For example, start-up energy for the transceiver must be considered before formulating sleep scheduling algorithm for sensor nodes. For sensor networks that transmit with short packet sizes occasionally, if static broadcast scheduling algorithm is used, even the start-up energy will defeat the energy consumption for transmission.

Transmission power adjustment is a very good technique for minimizing energy consumption of sensor nodes. This idea is based on power control protocol for wireless ad-hoc network [69, 72, 82, 83]. In the literature, we find that usually there are four ways to use the transmission power for efficient communication. The first solution is to use a single transmission power in the whole network to reduce energy consumption which is referred as network level solution in [83]. The other options can be using a single transmission power for all neighbors, using different transmission power for different neighbors or using different transmission power for different packet. Though it is true that by using different transmission power level on the basis of the dynamics of the link quality is apparently the best option for energy savings but for making a good tradeoff between performance metrics as well as with consideration to computational complexity and additional overhead, the fixed transmission power for pairwise neighbors is the optimum design choice.

5.2 Intelligent Hybrid MAC (IH-MAC) protocol

In this section, we present Intelligent Hybrid MAC (IH-MAC) [72], a novel low power with quality of service guaranteed medium access control protocol for wireless sensor networks (WSNs). IH-MAC achieves high energy efficiency under wide range of traffic load. It ensures shorter latency to critical and delay-sensitive packets. IH-MAC protocol achieves high channel utilization during high traffic load without compromising energy efficiency. IH-MAC does it by using the strength of CSMA and TDMA approach with intelligence. The novel idea behind the IH-MAC is that, it uses both the broadcast scheduling and link scheduling. Depending on the network loads, the IH-MAC protocol dynamically switches from broadcast scheduling to link scheduling and vice- versa in order to achieve better efficiency. The scheduling is done in IH-MAC with a novel decentralized approach where the nodes locally use the clock arithmetic to find the time slot, allocated for it. Furthermore, IH-MAC uses Request-To-Send (RTS), Clear–To-send (CTS) handshakes with methods for adapting the transmit power to the minimum level necessary to reach the intended neighbor. Thus, IH-MAC reduces energy consumption by suitably varying the transmit power. IH-MAC also uses the concept of parallel transmission which further reduces delay. The analytical and simulation results corroborate the theoretical idea, and show the efficiency of our proposed protocol.

5.2.1 Terminology

We first define the terminology used for our proposal. A *Timeslot* or *Slot* or a *Frame* is defined as the periodic interval, which consists of an active period and a sleep period. A *duty cycle* is the proportion or ratio of active period to the entire cycle time (frame length). A *rendezvous-slot* is defined as a time slot explicitly dedicated to a pair of nodes to communicate with each other. During *rendezvous,* a node forms a channel for transmission and reception with one of its neighbor. The term channel here refers to a time period or slot as opposed to frequency or code.

IH-MAC classifies packets according to their importance (i.e. delay requirements) and stored the packets into the appropriate queue. The source node knows the degree of importance of the sensed data and accordingly the application layer sets the priority. Application layer does it by appending 1 extra bit at the end of the data packet. Figure 5.1 shows the format of each data packet. The mechanism of IH-MAC is based on dividing the communication time into fixed length slots or frames. The contents of each slot are shown in Figure 5.2. Each slot begins with a SYNC period. The purpose of the SYNC packet is to maintain synchronization between the nodes within the same virtual cluster. The next part of the active period of the frame is reservation slot which is used for the data slot reservation. And the last part is used for data and ACK transmission by sensor nodes.

Header	Data	Extra 1 bit

(Used for priority)

Fig. 5.1. The format of Data Packet

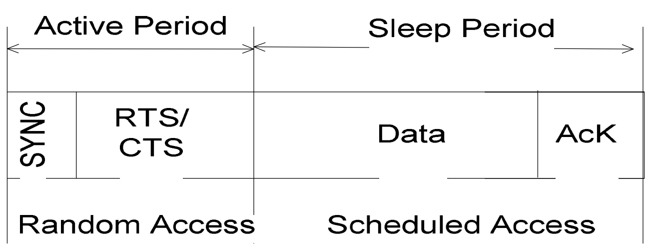

Figure 5.2. Contents of a slot or frame for the proposed IH-MAC protocol.

5.2.2 Neighbor Discovery, Clustering and Synchronization Stage

Frame synchronization is done by virtual clustering, as described in the S-MAC protocol [5]. When a node comes to life, it starts by waiting and listening. If it hears nothing for a certain period, it chooses a frame schedule and transmits a SYNC packet. The SYNC packet contains the time until the next frame starts. If the node during start up hears a SYNC packet from another node, it follows the schedule in that SYNC packet and transmits its own SYNC accordingly. Nodes retransmit their SYNC once in a while. When a node has a schedule but it hears SYNC with a different schedule from another node, it adopts both schedules. Adopting both schedules ensures the successful communication between the nodes of different schedule. The described synchronization scheme, which is called virtual clustering [5], urges nodes to form clusters with the same schedule. So, all the nodes in the networks need not to follow the same schedule.

During this virtual cluster creation, each node creates the one hop neighbor list and with using these a node can easily constitutes the two hop neighbor list. After that each node is given an id such that within a two hop neighbor the id is unique.

5.2.3 Slot Assignment

Each slot in IH-MAC consists of a fixed length SYNC period, a fixed length data period (For RTS/CTS) and a sleep period that depends on the duty cycle. The duty cycle should be chosen in such a way that the sleep period of a slot is large enough to transmit a data packet along with ACK. All nodes are allowed to transmit in any slot, but the owner of the slot will get the priority. Priority can be ensured by choosing contention window size which is elaborately described later in this chapter. The owner calculation can be performed by each sensor node locally by simple clock arithmetic.

For example, if there are 8 neighbor nodes (every node is 1 or 2-hop neighbor to each other), the node 1 will be the owner of the Slot 1, 9, 17……etc. The procedure is explained in figure 5.4 where T1, T2…, T10 represent the slot sequences and S1, S2…., S8 represent the sensor nodes. So according to the clock arithmetic (modulo 8) in figure 5.3, the sensor node S1 is the owner of slot T1 and T9.

S1	S2	S3	S4	S5	S6	S7	S8	S1	S2
T1	T2	T3	T4	T5	T6	T7	T8	T9	T10

Figure 5.3.Owner selection of each slot for 8 sensor nodes.

S1	S2	S3	S4	S5	S6	S7	S8	S1	S2
T9	T10	T11	T12	T13	T14	T15	T16	T17	T18

Figure 5.4.Rendezvous slot selection for 8 sensor nodes by using modulo 16

Now, each node can make some of its owned slot as a rendezvous slot with which it can send message to its neighbor exclusively. The rendezvous slots can be also calculated by clock arithmetic, as modulo m. The value of m is set according to the system requirements, i.e. network load, delay, message buffer size etc. m will be always multiple of node id. For instance, let node 1 wants to create a rendezvous slot. By using modulo16, the rendezvous slots of node 1 will be a subset of [1, 17…etc.]. The procedure is explained with the figure 5.4 where T9, T10…, T18 represent the slot sequences and S1, S2…., S8 represents the sensor nodes. If we use modulo 16, node S1 can make slot T17 as its rendezvous slot. Here it is noticeable that, though node S1 is owner of both slots T9 and T17 but S1 cannot make T9 as its rendezvous slot. It is because 9 is not a subset of [1, 17 …etc.].

For the sake of scalability the value that we use in modulo operation i.e., m will be always larger than the number of two hop neighbor nodes in a virtual cluster. So when a new node wants to join in the network, at least there will be some slots which are not using as rendezvous and it will be used for the scalability.

5.2.4 State Machine Description

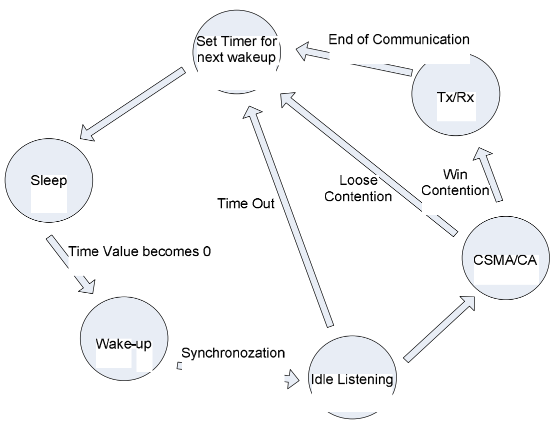

Fig. 5.5.State diagram (Moore machine description) of sensor nodes working in IH-MAC

The state machine of the IH-MAC protocol is shown in the figure 5.5. During the sleep state the node make its radio off and initiate a timer with a duration which is predetermined according to the duty cycle of the protocol with consideration of the existence of rendezvous communication between any pair of nodes. When the timer expires, the node goes to wake-up state. It turns its radio on and goes to listening mode to the data channel and its goes to idle listening state. If the node have any data to send or receive it goes in the CSMA/CA state otherwise after time out it goes to sleep state again. If the sender node wins the contention both the sender and the intended receiver go to the Transmission /Reception state and go to sleep state after successful communication. Nodes that fail contention go to sleep state.

5.2.5 Identifying the Maximal Set of Communication Link Supporting Collision Free Transmission Simultaneously Assignment

Within two hop neighbors simultaneously more than one transmission is possible without collision. The idea can be explained by the following scenario as explained through Figure 5.6. We use the similar approach of parallel transmission used in [22]. But we incorporate the concept of transmission power adjustment of sensor nodes in order to find the superset of mutually collision free transmission link which further support more transmission simultaneously. In Figure 5, we take four sensor nodes which are within three hops neighbors and belong to the same virtual cluster to explain the situation. We use the IEEE 802.11 [67] scheme as well.

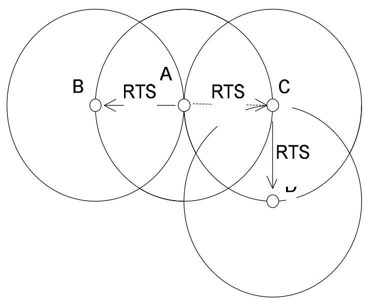

Fig. 5.6. The idea of Parallel transmission using four nodes.

Let us consider that node A wants to send a message to node B. First of all A will send a RTS packet to the sensor node B. But node C will overhear the RTS packet because the node C is within the transmission range of node A. By overhearing the RTS the node C concludes with the decision that the transmission medium is busy. Now let us consider at the same time node C has a data to send to D. In the conventional method, since node C knows that the transmission medium is busy it will not send any message to initiate any transmission. But we can see from the figure that the communication (RTS) from node C to node D will not affect the previous communication *i.e.*, communication (RTS) from node A to node B. Since collision happens at the receiving end, and node B and node C are not within the same transmission range, transmission of C by no means will interfere with the reception of node B. Similarly if node B sends a RTS to node A, node A will reply with a CTS. This CTS will be overheard by C. But C need not to stop its transmission and it can send or receive during this time without any collision. By using the transmission power adjustment as described in following Section we can maximize the set of communication links which can transmit data simultaneously.

5.2.6 Transmission

Each node will sleep for some time and then periodically wakes up to see whether any other node wants to talk to it. During sleeping, the node turns off its radio, and sets a timer to awake later. If a node wants to send data to another node it will check whether the node itself is the owner of the slot. The node will also check the status of the data, whether it is high priority (or critical) data or not. The node which has any critical (i.e. low latency requirement data) will get the priority for transmission. If there is no such data, then the protocol will consider the ownership of the slot. The node who is the owner of the slot will get priority. If there is more than one owner of the slot then the contention will be taken place between the owners. It should be mentioned here that using modulo might result in multiple owners of a slot, since different node IDs can map to the same slot number. In case of such situation owners will compete among each other for getting access of the medium. Now if the intended node is not owner of the slot, it will contend with other nodes (non-owner nodes) to get the slot. Broadcast packets are sent without Request-To-Send (RTS) and Clear-To-Send (CTS). Unicast packets will follow the sequence of RTS, CTS, Data, and Acknowledgement (ACK). This scheme is well recognized and used, for example in the IEEE 802.11 standard [68].

Which couple of nodes are allowed to communicate simultaneously, it can be found in the neighbors list table. So, by obeying the status of the mutually exclusiveness of the two link in the neighboring list, only those sensor nodes who has an intention to communicate will contend for successful agreement of data transfer. It should be mentioned that, since the RTS message contains the link information (both sender and the receiver) after seeing the first RTS, the number of candidate node for desiring the access to the medium will be considerable decreased to meet the parallel transmission requirements.

In order to allow more than one pair of nodes to communicate in one duty cycle there is a need for modification of the mechanism of virtual carrier sense that controlled by the Network Allocator Vector (NAV) timer which is used to prevent collision. In IEEE 802.11 and S-MAC protocols, the NAV timer used to block a node from sending and receiving whenever it overheard a packet transmission from other nodes. We modify the scheme in a way that after overhearing the transmission from other node the NAV timer will not directly block a node from sending or receiving rather it will judge the possibility of parallel transmission before doing so and will work accordingly.

Now, if messages for a particular node queued in its buffer cross threshold value the node will make some of its owned slots as rendezvous slots. The node will first broadcast the declaration of its making rendezvous slot. The declaration message contains how many slots will be used as rendezvous slot, and between whom the rendezvous will be done. So, remaining neighboring nodes can calculate locally about the slot so that they need not to wake up during those slots. For each rendezvous slot since all the neighbors of both sender and receiver will be in sleep mode, there will be no hidden or exposed terminal problem. So, on those cycles no RTS-CTS are required. Only Data–Ack will work. Part of the energy saving scheme of IH-MAC is pictorially represented in the timing diagram of Figure 6.

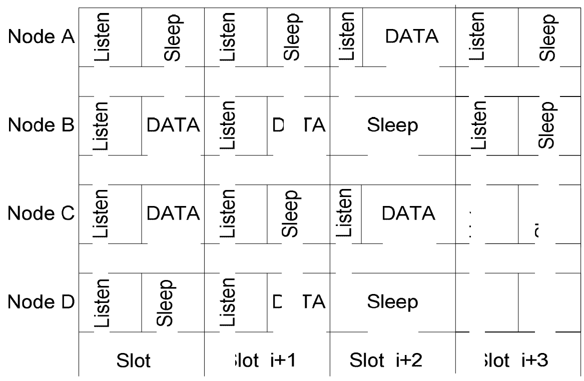

Fig. 5.7.Timing diagram of sensor nodes working in IH-MAC

Consider a simple case scenario of four sensor nodes A, B, C, and D where each node is within transmission range of others and they follow same schedule. In Fig. 5.7 we consider four consecutive slots namely, i, i+1, i+2 and i+3. Each slot is further divided into two parts, the first one is listen part which is used for SYNC, RTS and CTS, and the next portion is sleep part, which is used for data transmission between two nodes. The proportion of listen and sleep interval depends on the duty cycle of the operation of sensor nodes. We take some arbitrary transmission to clarify the different consequences of working principle of IH-MAC. Now, during slot i, let data transmission occur between node B and C. But node A and D also need to wake up to see whether there is any data for them. But subsequently they go to sleep because either there is no data to receive or send by them or they lose in contention. Similar situation occurs in slot i+1 where transmission is occurred between node B and D. In slot i+2, node A and C created rendezvous between them. So, on that slot node B and D will not wake up rather they will sleep the whole slot. Therefore, during this period node B and D save energy by operating with zero duty cycle, lingering their sleep time as well as by avoiding transition from sleep to active state. And node A and C will save energy by avoiding RTS and CTS and contention for getting the slot. Another power savings feature of IH-MAC is by adjusting transmission power, which is explained in the following section.

5.2.7 Transmission Power Adjustment

The power adjustment features of IH-MAC allow the sensor nodes to suitably vary the transmission power to reduce energy consumption. This idea is based on power control protocol for wireless ad-hoc network proposed in [69]. IH-MAC transmits the RTS and CTS packets with maximum power P_{max}. When receiver node receives an RTS packet, it responds with a CTS packet at usual maximum power level P_{max}. When the source node receives this CTS packet, it calculates $P_{desired}$ based on the received power level P_r and transmitted power level P_{max} as

$$P_{desired} = \frac{P_{max}}{P_r} \times Rx_{thres} \times c$$

Where Rx_{thres} is the minimum necessary signal strength and c is a constant. The source node uses power level $P_{desired}$ to transmit data packet. Similarly, receiver uses the signal power of received RTS packet to determine the power level to be used $P_{desired}$, for the ACK packet. This method assumes the attenuation between sender and receiver nodes to be the same in both directions. It also assumes the noise level at nodes to be below a certain predefined threshold value.

Since IH-MAC allows data transmission between only one pair of nodes in a slot and all the neighbors of both sender and receiver sleep during transmission, it overcomes the shortcomings of said technique, like increased collision and degradation of network throughput.

5.2.8 Contention window size for critical traffic and owner's priority

IH-MAC protocol ensures three levels of priority i.e., highest priority for critical traffic (generated by either owner or non-owner of a slot), medium priority for normal traffic generated by owner of a slot and the lowest priority for normal traffic generated by non-owner of a slot. The protocol does it by using different contention window size for critical traffic, owners' traffic and non-owners' traffic. When a node acquires a data to transmit, it first checks whether the data is a critical data or not. If it is a critical data, the node takes a random backoff within affixed time period, T_c . When the backoff timer expires, the node runs CCA and if the channel is found clear, the node transmits data. If the channel is busy then it waits until the channel becomes free and repeats the above process. Now, if the data is not a critical data then it checks whether the node itself is an owner of the time slot or not. If it is an owner then the node waits for T_c and then performs a random back-off within a contention window $[T_c, T_o]$. When the backoff timer expires, the node runs CCA and if the channel is clear it starts transmission. If the channel is busy then the node waits until the channel becomes clear and repeats the above process. On the other hand, having a noncritical data, a non-owner node waits for , T_0 and then performs a random backoff within a contention window $[T_o,\ T_{no}]$ and follow the same procedure as described for the other two cases above. It should be noted here that when a slot is already declared as rendezvous slot for that slot without waiting for contention window the node can initiate transmission as like as a TDMA link scheduling.

5.2.9 Energy Consumption Analytical Model

An analytical model for the energy consumption of nodes for IH-MAC is explained in this section. For simplicity we consider the case where a sensor node is either in broadcast scheduling mode or in a link scheduling mode. Let d be the duty cycle and t_{SIM} be the simulation time and t_{TX} , t_{RX}, t_{OH} , t_{IDLE} , t_{SLEEP} , t_{TRANS} are denoted as the time spent for transmitting, receiving, overhearing, idle listening, sleep, and radio transitions during sleep to wakeup state of a sensor node, respectively. So, t_{SIM} can be expressed as

$$t_{SIM} = t_{TX} + t_{RX} + t_{OH} + t_{IDLE} + t_{SLEEP} + t_{TRANS} \quad (IV.1)$$

and

$$t_{SIM} = t_{SLOT} \times N \qquad (IV.2)$$

Here, N is total numberof slots during time t_{SIM}

Again, $t_{SIM} = t_W + t_R (IV.3)$

Where, t_W and t_R represent time period while IH-MAC operates in broadcast scheduling mode and link scheduling mode respectively.

Let n_H, n_{TX}, n_{RX}, n_{OH} , represents the total number of times that a node hears, transmits, receives, and overhears duringt_{SIM} . A sensor node consumes energy by transmitting (e_{TX}), receiving (e_{RX}), overhearing (e_{OH}), and idle listening (e_{IDLE}) during the awake state. And during the sleep state very less energy is consumed.

During transition (e_{TRANS}) from sleep state to active state energy is also consumed. Since our IH-MAC protocol operate both in broadcast scheduling and link scheduling (Rendezvous) and we have used power adjustment technique, so transmitting energy is further divided into two category, without rendezvous, $e_{TX(W)}$and with rendezvous, $e_{TX(R)}$. Similarly, receiving energy can be divided into $e_{RX(W)}$and $e_{RX(R)}$. Now energy consumption during t_{SIM} can be expressed by

$$e = n_{TX(W)} \times e_{TX(W)} + n_{TX(R)} \times e_{TX(R)} + n_{RX(W)} \times e_{RX(W)} + n_{RX(R)} \times e_{RX(R)} + t_{OH} \times e_{OH} + t_{IDLE} \times e_{IDLE} + t_{SLEEP} \times e_{SLEEP} + t_{TRANS} \times e_{TRANS} (IV.4)$$

Since IH-MAC has the probation of adjusting transmission power we use maximum transmission power as$E_{TX(max)}$and right transmission power as, $E_{TX(right)}$.

When a sensor node transmits a packet, it sends SYNC, RTS, DATA and it receives CTS and ACK. So, for transmitting a packet energy consumed by a transmitting node is

$$e_{TX(W)} = E_{TX(max)} \times t_{SYNC-RTS} + E_{TX(right)} \times t_{DATA} + E + E_{RX} \times t_{ACK} (IV.5)$$

$$e_{TX(R)} = E_{TX(right)} \times t_{SYNC} + E_{TX(right)} \times t_{DATA} + E_{RX} \times t_{ACK} (IV.6)$$

Where $t_{SYNC-RTS}$, t_{DATA}, t_{CTS} and $t_{ACK}$are required time to send SYNC-RTS, DATA, and to receive CTS and ACK, respectively. Now, when a sensor node receives a packet, it receives SYNC, RTS, DATA and it sends CTS and ACK. So, for receiving a packet energy consumed by receiving node is

$$e_{RX(W)} = E_{RX} \times t_{SYNC-RTS} + E \qquad + E_{TX(max)} \times \quad t_{CTS} + E_{TX(right)} \times \ t_{ACK} (IV.7)$$

$$e_{RX(R)} = E_{RX} \times t_{SYNC} + E_{RX} \times t_{DATA} + E_{TX(right)} \times \quad t_{ACK} \quad (IV.8)$$

Now, let the sensor nodes Poisson arrival rate of transmitting packet is $\mu_{TX}$and sensor nodes Poisson arrival rate of receiving packet is μ_{RX}during time t_{SIM} . So, the number of times the sensor node transmits and receives packet during t_{SIM} is

$$n_{TX(W)} = \mu_{TX} \times t_{SIM\ (W)} (IV.09)$$

$$n_{TX(R)} = \mu_{TX} \times t_{SIM\ (R)} (IV.10)$$

Similarly,

$$n_{RX(W)} = \mu_{RX} \times t_{SIM\ (W)} (IV.11)$$

$$n_{RX(R)} = \mu_{RX} \times t_{SIM\ (R)} (IV.12)$$

The overhearing of packets and idle listening occur during listen interval. So,

$$t_{OH} = n_{OH(SYNC-RTS)} \times t_{SYNC-RTS} + \quad n_{OH(CTS)} \times t_{CTS} (IV.13)$$

and $n_{OH} = n_H - n_{RX} (IV.14)$

$$t_{IDLE} = d \times t_W - n_{TX(W)} \times (t_{SYNC-RTS} + t_{CTS})$$

$$-n_{RX(W)} \times (t_{SYNC-RTS} + t_{CTS}) - t_{OH} (IV.15)$$

The transition from sleep mode to active mode will occur in every slot. So,

$$t_{TRANS} = N \times t_{SA} \ (IV.16)$$

Where t_{SA} represents the time required for switching radio from sleep mode to active mode. So, the energy consumption of a sensor node can be computed analytically using the equation (IV.4)

Now, we also develop energy consumption analytical model of S-MAC, one of the fundamental MAC protocol for sensor network, to compare with IH-MAC. In fact S-MAC protocol is the most popular general purpose MAC protocol specially designed for wireless sensor network. For S-MAC the total simulation time, t_{SIM} can be expressed as

$$t_{SIM} = t_{TX} + t_{RX} + t_{OH} + t_{IDLE} + t_{SLEEP} + t_{TRANS} \quad (IV.17)$$

And

$$t_{SIM} = t_{SLOT} \times N \quad (IV.18)$$

S-MAC protocol operates like broadcast scheduling and no power adjustment technique is used. Therefore energy consumption during t_{SIM} can be expressed as

$$e = n_{TX} \times e_{TX} + n_{RX} \times e_{RX} + t_{OH} \times e_{OH} + t_{IDLE} \times e_{IDLE} + t_{SLEEP} \times e_{SLEEP} + t_{TRANS} e_{TRANS} \quad (IV.19)$$

When a node transmits a packet, it sends SYNC, RTS, DATA and it receives CTS and ACK. So, for transmitting a packet energy consumed by transmitting node is

$$e_{TX} = E_{TX} \times (t_{SYNC-RTS} + t_{DATA}) + E_{RX} \times (t_{CTS} + t_{ACK}) \quad (IV.20)$$

Now, when a node receives a packet, it receives SYNC, RTS, DATA, and sends CTS and ACK.So, for receiving packet energy consumed by a receiving node is

$$e_{RX} = E_{RX} \times (t_{SYNC-RTS} + t_{DATA}) + E_{TX} \times (t_{CTS} + t_{ACK}) \quad (IV.21)$$

Let, sensor nodes Poisson arrival rate of transmitting packet and receiving packet during the time t_{SIM} are same as before.

So, the number of times the node transmits and receives packet during t_{SIM} is

$$n_{TX} = \mu_{TX} \times t_{SIM} \qquad (IV.22)$$

Similarly,

$$n_{RX} = \mu_{RX} \times t_{SIM} \qquad (IV.23)$$

The overhearing of packets and idle listening occur during listen interval. So,

$$t_{OH} = n_{OH(SYNC-RTS)} \times t_{SYNC-RTS} + n_{OH(CTS)} \times t_{CTS} \qquad (IV.24)$$

and

$$n_{OH} = n_H - n_{RX} \qquad (IV.25)$$

$$t_{IDLE} = d \times t_{SIM} - n_{TX} \times (t_{SYNC-RTS} + t_{CTS})$$

$$-n_{RX} \times (t_{SYNC-RTS} + t_{CTS}) - t_{OH} \qquad (IV.26)$$

The transition from sleep to active mode will occur in every slot. So,

$$t_{TRANS} = N \times t_{SA} \qquad (IV.27)$$

So, the energy consumption of a sensor node of S-MAC can be computed analytically using equation (IV.19). For simplicity we avoid considering the collision both for S-MAC and IH-MAC in our analytical model.

Now, if we compare equation (IV.5) & (IV.6) with the equation (IV.20) we see that the consumed power for a packet transmission for the source node is less in IH-MAC than S-MAC. Similarly, if we compare equation (IV.7) & (IV.8) with equation (IV.21) we see that the consumed power for a packet reception for the destination node is less in IH-MAC than S-MAC. Finally if we put these value in equation (IV.4) and (IV.19) we can conclude that the IH-MAC is more energy efficient than S-MAC.

5.2.10 Result and discussion

We use Castalia [70] in our simulations. Castalia is a simulator for Wireless Sensor Networks (WSN), Body Area Networks (BAN) and generally networks of low-power embedded devices. It is based on the OMNeT++ [71] platform.

In the simulation setup, we take 100 nodes distributed in a uniformly random way on a 100m $\times$100 m area grid. The nodes are static and the radio range is chosen so that all the non-edge nodes have eight neighbors. The sink node is chosen on the bottom right corner of the network grid. The duty cycle is chosen 15 percent. The results are averaged over several simulation runs. The parameters used for simulation are listed in Table 5.1.

We compare the performance of our proposed IH-MAC protocol with the standard S-MAC protocol, T-MAC protocol and Q-MAC protocol. We took S-MAC and T-MAC protocol because they are widely accepted Medium Access Control protocol for Wireless Sensor Network and the reason behind taking the Q-MAC is that Q-MAC protocol considers the traffic with different priority like our proposed IH-MAC protocol. The Q-MAC (MAC with Quality of Service) protocol minimizes the energy consumption in multi-hop wireless sensor networks (WSNs) and provides Quality of Service (QoS) by differentiating network services based on priority levels. To compare IH-MAC with the said protocols (S-MAC, T-MAC and Q-MAC) the performance metrics that we used in the evaluation are Energy consumption, and Average Packet Latency.

Table 5.1 Parameters used for simulating the IH-MAC protocols

Parameter Name	value
Channel bandwidth	20 kbps
Data packet length	20 bytes
Transmission power	36 mW
Receive power	14.4 mW
Idle power	14.4 mW
Sleep state	15 μW
Frame length	1 sec
Threshold value for the buffer size (for IH-MAC)	5 packet
Duty cycle	15 %

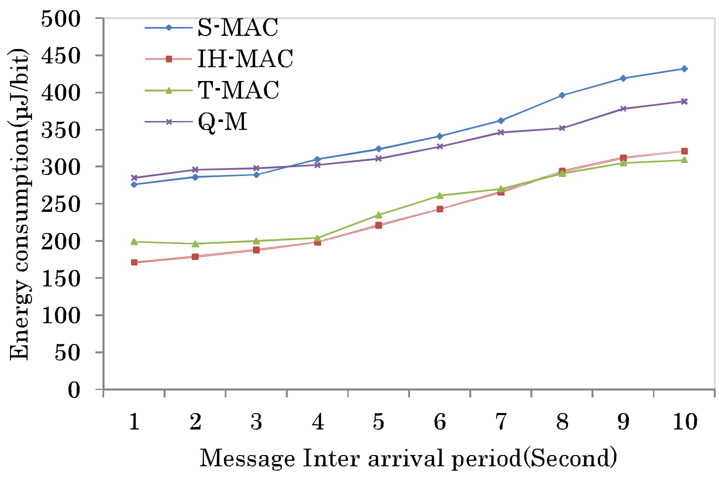

Fig. 5.8 Average Energy consumption under different traffic load (non-prioritized traffic).

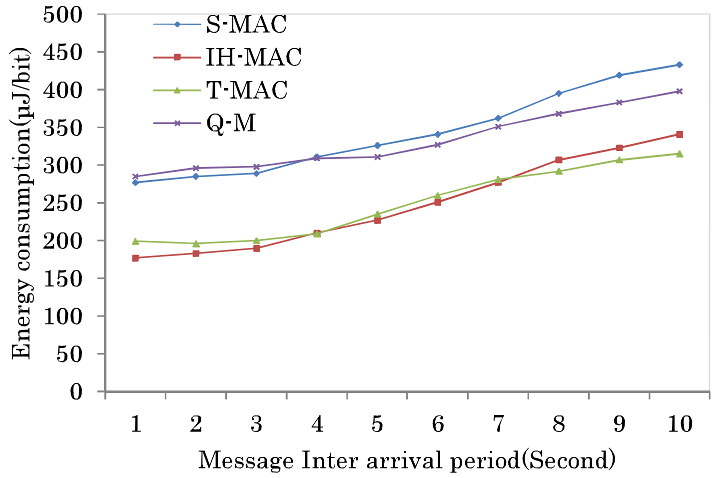

Fig. 5.9 Average Energy consumption under different traffic load (prioritized traffic).

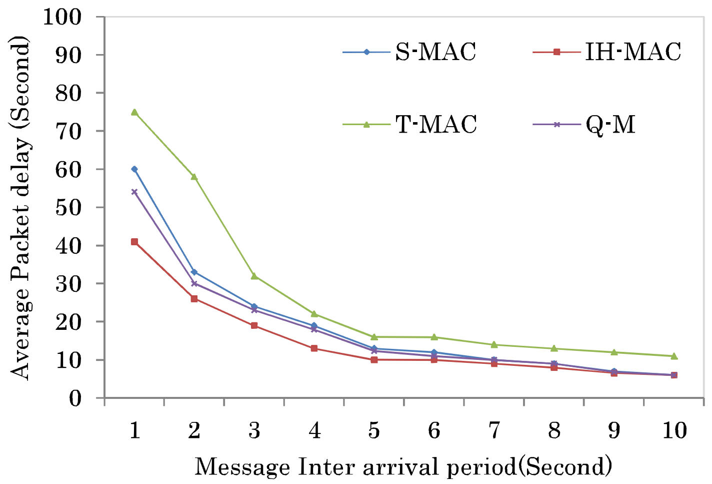

Fig. 5.10 Average packet latency under different traffic load (non-prioritized traffic).

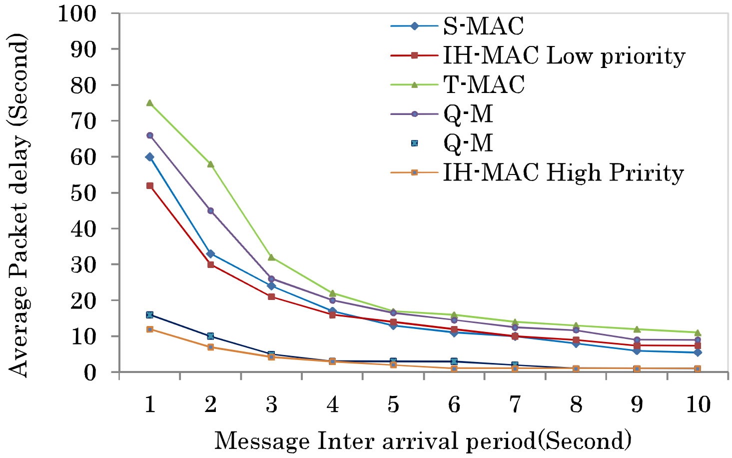

Fig. 5.11. Average packet latency under different traffic load (prioritized-traffic).

Energy consumption of sensor nodes for IH-MAC, S-MAC, T-MAC and Q-MAC [75] are shown in figure 5.8. We vary the packet generation interval from 1 to 10 seconds. We see that energy consumption per bit of IH-MAC is less than the energy consumption of S-MAC and Q- MAC for both the heavy and light traffic. The reason behind consumption of less energy is the use of adjusted transmission power in our proposed IH-MAC which is explained in previous section. And during heavy traffic the performance of IH-MAC protocol in terms of energy conservation is more evident. It is because during heavy traffic IH-MAC protocol makes some rendezvous slots. Energy consumption in rendezvous slot is less than the energy consumption of a slot of S-MAC. And with comparison of T-MAC, IH-MAC performs better with the heavy traffic. But as the traffic declines IH-MAC cannot create frequent rendezvous slot, as well as the scope of parallel transmission also decreases, hence its energy efficiency deteriorates. When the messages inter arrival period increases, i.e., the traffic becomes light, the performance of T-MAC is slightly better than our proposed IH-MAC. It is because T-MAC trades off latency for energy savings. About the prioritized traffic, as figure

5.9 shows, the energy consumption is not much effected with the introduction of differential traffic (traffic with different priority). It should be noted that when we use the term of non-prioritized traffic, it means that all the traffic has the equal priority. And in case of prioritized traffic we use (consider) the 5 % of the total traffic with critical or high priority and it is generated randomly.

Average packet latency of sensor nodes for IH-MAC, S-MAC, T-MAC and Q-MAC for non-prioritized traffic is shown in figure 5.10. We see that, IH-MAC achieve better delay performance compared to other three protocol. It is because of using parallel transmission. And link scheduling feature of IH-MAC further minimizes control signal during transmission. Besides, when the protocol works in link scheduling it also avoid the contention phase which minimizes the overall delay. Again as the messages inter arrival rate increase (the network is running with a light traffic) the delay performance of IH-MAC deteriorates and become almost similar to other three protocols.

Average packet latency of sensor nodes for IH-MAC, S-MAC, T-MAC and Q-MAC for prioritized traffic is shown in figure 5.11. We use the 5 % of the total traffic as the critical traffic of high priority. So though the packet generation is high (message inter arrival rate is low) the number of priority traffic is not high. On the other hand, IH-MAC protocol gives the service to the priority traffic by using small contention window size compared to the normal traffic (traffic with less priority). And for using the parallel transmission the delay will be further minimized. Another most important achievement of our proposed IH-MAC protocol that needed to be mentioned that in the figure 5.11 we can notice that, though the IH-MAC is serving the high priority traffic with the lowest minimum delay, still the normal traffic are not experiencing high delay. Where in case of Q-MAC protocol the normal traffic experience a greater delay in order to achieve the lower delay for traffic with high priority.

5.3. Conclusion

This chapter presents IH-MAC; a novel energy efficient hybrid based medium access control protocol for wireless sensor networks. There are three novel contributions in the proposal of IH-MAC. Firstly, our proposed IH-MAC protocol introduces the use of the concept of link scheduling and broadcast scheduling together. To the best of our knowledge, in a single protocol, IH-MAC is the pioneer which exploits these two concepts (pairwise TDMA and broadcast TDMA) together to obtain optimum resource utilization. Secondly, we successfully identified (and achieved) the possibility of enhancement of the scope of parallel transmission by transmitting a signal (wireless) with the appropriate power (adjusted power). The third novel contribution is the introducing the idea and realization of a decentralized TDMA. We successfully showed that without any centralized scheduling how TDMA can run smoothly (we use clock arithmetic here).

We believe these novel ideas will significantly contribute not only in the area of protocol design of WSNs but also the protocol design of any wireless Ad-hoc network.

Chapter 6

Proposed Energy Efficient MAC with Parallel Transmission (EP-MAC) protocol for WSN

In this chapter we propose EP-MAC, a novel low power medium access control protocol for wireless sensor networks (WSNs). The proposed protocol achieves high energy efficiency and high packet delivery ratio under different traffic load. EP-MAC protocol is basically based on TDMA (Time Division Multiple Access) approach. The power of CSMA is used in order to offset the fundamental problems that the standalone TDMA method suffers from i.e., problem like lack of scalability, adaptability to varying situations etc. Novel idea behind the EP-MAC is that, it uses parallel transmission concept with the TDMA link Scheduling. EP-MAC uses the methods for the transmission power adjustment i,e, uses the minimum level power necessary to reach the intended neighbor within a specified BER target. This reduces energy consumption, as well as further enhances the scope of parallel transmission of the protocol. The simulation studies support the theoretical results, and validate the efficiency of our proposed EP-MAC protocol.

6.1 Frame Structure

The mechanism of EP-MAC is based on dividing the communication time into variable length frames. The frame structure is shown in figure 6.1. Each frame begins with a SYNC period. The purpose of the SYNC packet is to maintain synchronization between the nodes within the same virtual cluster. The next part of the active period of the frame is reservation slot which is used for the data slot reservation. And the last part composed with fixed number of data slots which are used for data and ACK transmission by sensor nodes. The number of data slots will in a frame is not fixed. It depends upon the system requirements for a particular application.

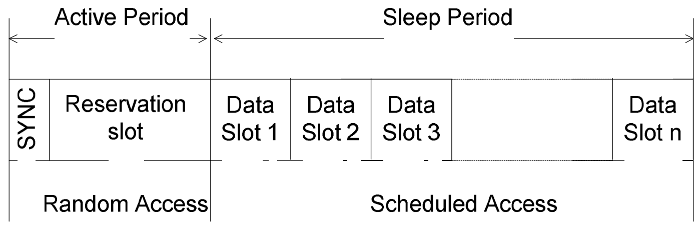

Figure 6.1. Frame structure for the proposed EP-MAC protocol

For example delay bound for the message is not same for all applications. Moreover, the clock drift and synchronization error are deciding factors for number of data slots in a frame. Within the limit, without violating the synchronization condition, if a frame contains more slot then the nodes will save more energy, because the nodes having no data can sleep more time. On the other hand delay may be increased. So, the number of data slots in a frame or the duty cycle should be chosen very carefully in order to fulfill the particular application purpose.

In figure 6.2, we have showed a sample frame scenario of EP-MAC with comparison to S-MAC. We take 4 data slots in a frame. It is noticeable that to handle the effect of clock drift and to minimize the synchronization error we fix the data slot length a little longer than the required period for sending data and receiving acknowledgement.

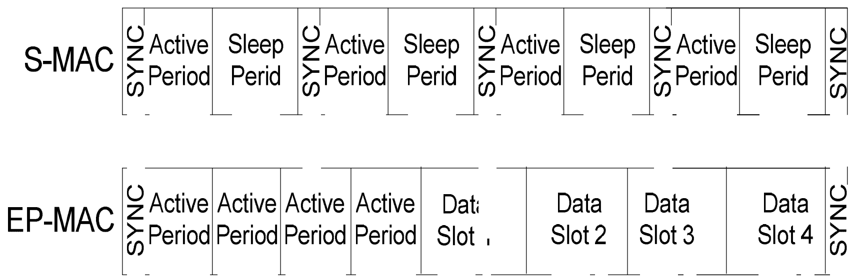

Figure 6.2.Comparison of Frame structure of EP-MAC with S-MAC

6.2 Concept of collision free simultaneous parallel transmission:

Within two hop neighbors simultaneously more than one transmission is possible without collision. The idea can be explained by the following scenario as explained through figure 6.3. We use the similar approach of parallel transmission used in [61]. But we incorporate the concept of transmission power adjustment of sensor nodes in order to find the supper set of mutually collision free transmission link which further support more transmission simultaneously.

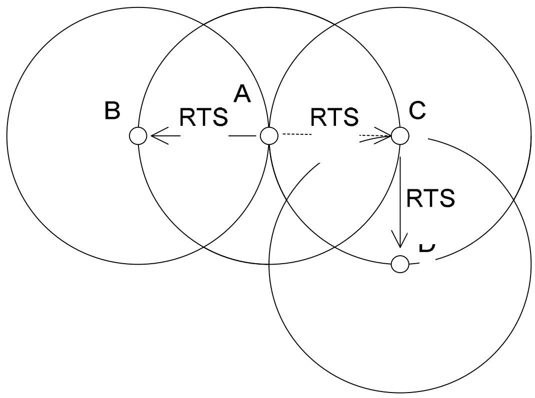

Figure 6.3. The idea of Parallel transmission using four nodes

In figure 6.3, we take four sensor nodes which are within three hops neighbors and belong to the same virtual cluster to explain the situation. We use the IEEE 802.11 [67] scheme as well.

Let us consider that node A wants to send a message to node B. First of all A will send a RTS packet to the sensor node B. But node C will overhear the RTS packet because the node C is within the transmission range of node A. By overhearing the RTS the node C concludes with the decision that the transmission medium is busy. Now let us consider at the same time node C has a data to send to D. In the conventional method, since node C knows that the transmission medium is busy it will not send any message to initiate any transmission. But we can see from the figure that the communication (RTS) from node C to node D will not affect the previous communication i.,e., communication (RTS) from node A to node B. Since collision happens at the receiving end, and node B and node C are not within the same transmission range, transmission of C by no means will interfere with the reception of node B. Similarly if node B sends a RTS to node A, node A will reply with a CTS. This CTS will be overhear by C. But C need not to stop its transmission and it can send or receive during this time without any collision. By using the transmission power adjustment (as described later part of this chapter) we can maximize the set of communication links which can transmit data simultaneously.

6.3 Reservation of Slot and Data Transmission

At the beginning of each frame the nodes belong to the same virtual cluster will be synchronized with each other. After synchronization the reservation slot will be used for transmission agreement purpose between nodes. The node that has data to send will contend with other intended sender in a slotted CSMA/CA fashion. And the reservation will be done using the exchange of RTS/CTS technique used in IEEE 802.11 with slight amendment. The amendment is that the CTS message will be accompanied with the data slot number. And that particular couple of nodes who exchange the RTS, CTS successfully will use that data slot. The first couple of nodes who successfully exchange RTS/CTS will get data slot number 1. Data slot number will be sent by the receiver with the CTS. The transmission which involves one node as sender or receiver of the previous successful pair will get priority for the next slot. Consecutive slot assignment of a node will minimize the on off radio of the node.

Now the next couple of nodes who successfully transfer RTS/CTS will be given either data slot number 1 or slot number 2 depending on the mutual exclusiveness of the two transmission links. In fact the receiver i.e., the node sending CTS will decide the slot number by looking at the sets of links created in the way already described in this chapter. In each data slot more than one communication is possible at a time. Which links can be communicate simultaneously it can be seen in the neighbors list table. So, the second couple will get the same slot as the previous couple or a new slot depending on the status of the mutually exclusiveness state of the two link in the neighboring list. Thus for the ith couple it can get any slot previously chosen by another couple or a new slot. But if one node is in common with in two transmissions either as sender or receiver in that case the transmissions will never be given the same slot at a time.

For bursty traffic of large message more than one consecutive data slot can be assigned to a particular link if during RTS, sender sends a request of it. In that case receiver replies CTS with mentioning i, i+1, i+2… slot. But during huge traffic this consecutive slot allocation to a particular node will be impractical and also it will promote unfairness. So during heavy traffic the ith slot can be given to every frame to that particular couple of node. So that RTS/ CTS exchange will be minimized for that particular couple. When a sensor node successfully exchanges RTS/CTS with other node then they wait for the time to see where one of them can successfully send a RTS or receive a RTS. If so then the node will be given consecutive data slot. If the next successful RTS is directed to other node then the previous couple will go to sleep with an agreement to wake up at the beginning of their designated data slot.

There will be no wastage of the radio/energy due to the multiple on-off. Because the node intended to send multiple data to different nodes usually will do it in the consecutive time slots. The nodes who have failed to reserve any slot during reservation period will go to sleep until the beginning of the next frame. The nodes that successfully reserved slots will perform data transmission during this phase. Since this phase is in fact TDMA, so without any RTS or CTS data will be transmitted between nodes. In this transmission procedure the sensor nodes can save more energy because when a node wake up it has a guaranteed data slot and thus perform transmission. The protocol ensures throughput maximization and best channel utilization because simultaneous transmission facilities among the neighbors are allowed. Another advantage is the bandwidth reuse.

The slot allocation and transmission technique of the EP-MAC protocol is explained in figure 6.4. Consider a simple sensor network consisting of four sensor nodes namely A, B, C, and D and every node run in the same schedule. Now let us consider that, the communication is possible between node A and D (link AD) and node B and C (link BC) simultaneously without any interference.

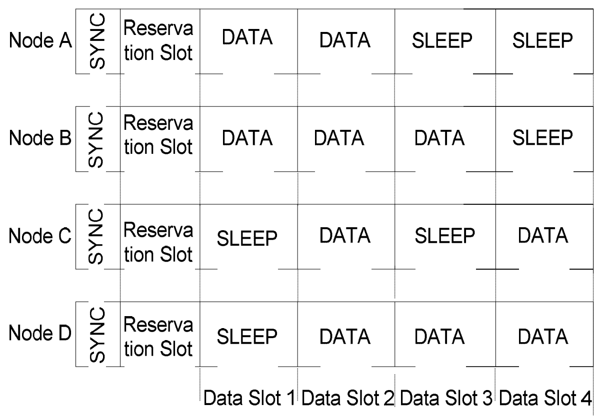

Figure 6.4. Timing diagram of sensor nodes working in EP-MAC

We further consider a frame which consists of an active period or listen period and a sleep period. Active period is further divided into two parts. The first part is used for synchronization and the second part is used for making reservation of data slots by sensor nodes. In this part sensor nodes exchange several RTS and CTS for data slot reservation. The next part of the frame is sleep part, which will be used for data transmission between nodes. The sleep part is subdivided into few data slots. In this example we take four data slots. The ration of listen and sleep period depends on the duty cycle of the operation of sensor nodes. So, as the SYNC period is fixed, with the change of the duty cycle the span of reservation slot and number of data slot will be changed accordingly.

We consider some random transmission between nodes to explain the different scenario of operation of EP-MAC protocol. Let each of the four nodes A, B, C and D have data to send other nodes. And let the node pair AB exchange RTS and CTS with each other as the first successful pair. The next pair is BC and then sequentially AD, BD and CD. According to our proposed algorithm the data slot 1 will be allocated for the communication between AB. Now the next pair who won the contention is BC. Since B already participated in the data slot 1 so there is no scope of parallel transmission in slot 1 for the BC link. Hence data slot 2 will be allocated for transmission between BC. The third pair is AD. For this pair data slot 1 cannot be allocated because node A is already participating in communication of data slot 1. During the data slot 2 communications will take place between node B and node C. But link BC and link AD are simultaneously collision free transmission free link. So, data slot 2 can be assigned to AD also. For the next pair BD, since B is already participating in the previous two data slot so new data slot 3 is allocated to BD. Again, for the next pair CD though during data slot 1 neither C nor D is participating in the communication but data slot 1 cannot be given to CD. Because link AB and link CD s transmission will interfere with each other. So, data slot 4 will be allocated for transmission of CD.

6.4 Transmission power adjustment

The power adjustment features of EP-MAC allow the sensor nodes to suitably vary the transmission power to reduce energy consumption. We use the similar concept of transmission power adjustment that we proposed in IH-MAC.

6.5 Performance Evaluation

We inspect the performance of the proposed IH-MAC and EP-MAC protocol. We compare our proposed IH-MAC and EP-MAC protocol with two other protocols: S-MAC, T-MAC. The performance metrics used in the evaluation of the protocols are the energy consumption, average delay and average delivery ratio.

We compare the performance of our proposed EP-MAC [74] protocol with the T-

MAC [57] , S-MAC [5] and IH-MAC [72] protocol. T-MAC is a popular MAC for WSN as it employs many techniques to keep the energy consumption low (using aggressive duty cycling and synchronization) while trying to keep performance (e.g. packet delivery) high by adapting its duty cycle according to the traffic needs. S-MAC can be seen as the predecessor of T-MAC as it initiated many of the techniques but uses a more rigid duty cycle. One Castalia module (TMAC) offers the functionality of both protocols.

Table 6.1: Default Simulation Parameters for IH-MAC, EP-MAC, T-MAC and S-MAC protocol

Parameter	value
Channel band width	20 kbps
Data packet length	20 bytes
Transmission power	36 mW
Receive power	14.4 mW
Idle power	14.4 mW
Sleep state	15 μW
Frame length (for S-MAC,T-MAC,IH-MAC)	1 sec
Frame length for EP-MAC	4 sec

We investigate the performance of the proposed EP-MAC protocols. In the simulation setup, we take 100 nodes distributed in a 10 m×10 m area grid. The nodes are static and the radio range is chosen so that all the non-edge nodes have eight neighbors. The sink node is chosen on the bottom right corner of the network grid. The duty cycle is chosen 15 percent. The results are averaged over several simulation runs. The performance metrics used in the evaluation of the protocols are the energy consumption, average delay and average delivery ratio. The parameters used for simulation are listed in Table 6.1.

Energy efficiency of sensor nodes for IH-MAC, EP-MAC, T-MAC and S-MAC are shown in figure 6.5. We vary the packet generation interval in order to measure the performance for variable traffic load. We take the packet generation interval from 1 to 10 seconds. We see that energy consumption per bit of IH-MAC is less than the energy consumption of S-MAC when traffic is heavy. It is because during heavy traffic IH-MAC protocol makes some rendezvous slots. Energy consumption in rendezvous slot is less than the energy consumption of a slot of S-MAC. But as traffic declines IH-MAC cannot create frequent rendezvous slot, hence its energy efficiency deteriorates. From the figure 6.5, we see that when message inter arrival period is 1 to 5 second, energy efficiency of IH-MAC is better than the energy efficiency of S-MAC but when the message inter arrival period increases, the performance of IH-MAC and S-MAC become almost equal. In the worst case scenario, while

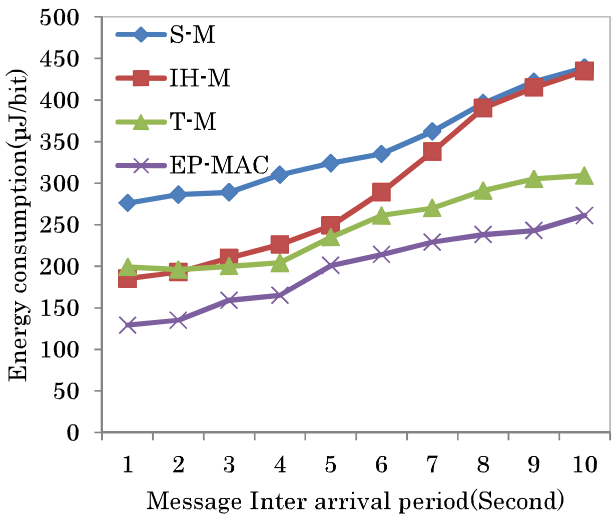

Figure 6.5. Average energy consumption per bit under different traffic load

very light traffic or no traffic at all, the energy consumption of IH-MAC will be at least equal to the S-MAC. For simplicity, we have not considered all features of IH-MAC, like transmission power adjustment. Nevertheless IH-MAC shows its energy efficiency evidently. The energy efficiency of the T-MAC is better than IH-MAC. But T-MAC trade off the energy with the average packet delay. On the other hand, we see that the average energy consumption per node of EP-MAC is less than the energy consumption of other three protocols both for low and high traffic load. It is because proposed EP-MAC protocol avoid redundant control signal (RTS/CTS). Besides, only during the reservation period the protocol works as a CSMA and the remaining time the protocol works like TDMA. During these data transfer phase all the nodes remain sleeping mode except the participation nodes that is the basic difference that helps EP-MAC to conserve more energy.

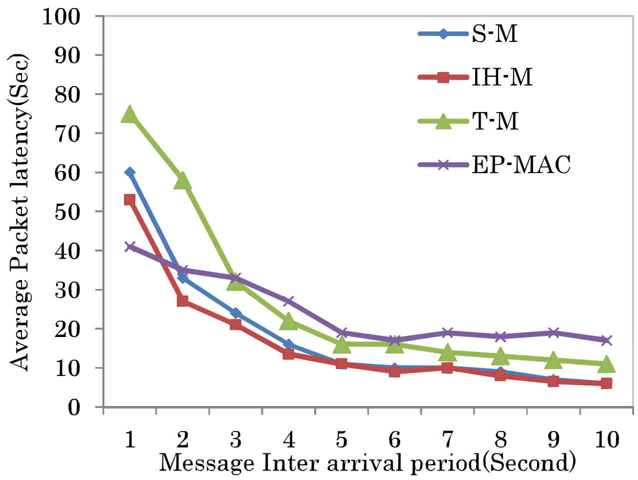

Figure 6.6. Average Packet Latency under different traffic load

Figure 6.6 shows the average packet delay for proposed IH-MAC and EP-MAC and other two protocols T-MAC and S-MAC. For IH-MAC the average packet delay is almost equal to the S-MAC. Though with heavy traffic load IH-MAC performs slightly better than S-MAC because of the creation of rendezvous slot but it is not significantly mentionable. But the delay of the T-MAC protocol is higher than both the S-MAC and the IH-MAC. On the other hand, as the packet inter arrival time increases and reaches to a certain level the average packet delay of EP-MAC become steady. But the delay in EP-MAC is little bit higher than the delay of other three protocols because it trades off latency for energy savings. But the delay performance of EP-MAC is better than the pure TDMA because of using the concept of parallel transmission.

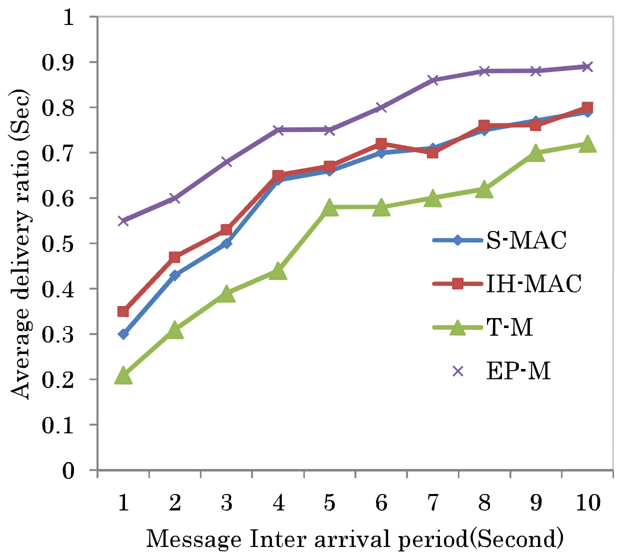

Figure 6.7. Average Packet delivery ratio under different traffic load

Figure 6.7 shows the average packet delivery ratio for the said protocols. Packet delivery ratio of the IH-MAC is better than S-MAC when the packet inter arrival rate is high. It is because of the rendezvous slot creation of the IH-MAC protocol. For any traffic load the throughput of the IH-MAC is better than the T-MAC. In fact T-MAC performs the worst in the performance metric of delivery ratio. It is because T-MAC trade-off it with the energy efficiency. On the other hand, EP-MAC clearly outperforms the T-MAC, S-MAC and IH-MAC in terms of packet delivery ratio for different traffic load. It is because of using the concept of TDMA and parallel transmission together in the EP-MAC protocol. The properties of the S-MAC, T-MAC, Q-MAC, IH-MAC and EP-MAC are summarized in the following table 6.2.

Table 6.2 Comparison of Wireless Sensor Network MAC protocols

Protocols	Energy Efficiency	Latency	QoS support	Control Packet Overhead
S-MAC	Low due to fixed duty cycle	Moderate	No	moderate
T-MAC	High when there is a variation of network load/traffic and low when there is traffic with regular interval.	High latency because it trades off latency to gain energy efficiency	No	moderate
Q-MAC	Low due to fixed duty cycle	Moderate	Limited control and limited flexibility due to fixed scheduling	High
IH-MAC	High irrespective of network load	Moderate	Limited control and limited flexibility due to dynamic scheduling	Low
EP-MAc	High when there is high traffic	Low when there is high traffic	No	Moderate

6.6 Conclusion

The proposed EP-MAC protocol is basically based on the TDMA approach. However, EP-MAC uses the strength of the contention based scheme to offset the drawback of the schedule based approach in medium access control of Wireless Sensor networks to achieve a significant amount of energy savings. In addition, EP-MAC uses the concept of parallel transmission for minimizing the latency and maximizing energy savings. The transmission power adjustment feature of EP-MAC is very promising which further enhances the scope of parallel transmission and contributes to increase the sensor nodes lifetime.

Since all the features of EP-MAC are yet to be implemented, as a future work; we expect more detailed results concerning energy efficiency, throughput and the fairness issue of our proposed EP-MAC protocol. Further, we plan to implement our proposed EP-MAC protocol on hardware mote.

Chapter 7

Conclusion and Scope Of the future work

7.1 Conclusion

This thesis presents two novel medium access control protocol for wireless sensor network. The first one is intelligent hybrid MAC (IH-MA*C*) a novel energy efficient MAC protocol for WSNs. IH-MAC uses the ides to combine the strength of contention based and schedule based approach of medium access control to achieve significant amount of energy savings. To the best of our knowledge, IH-MAC is the first protocol where broadcast scheduling (broadcast TDMA) and link scheduling (pair wise TDMA) works together. Moreover, it introduces the flexibility to the TDMA by allocating the TDMA slot in distributed manner. It also handle the scalability problem efficiently which the TDMA protocol suffer from. The transmission power adjustment feature of IH-MAC is very promising and will certainly contribute to enhance sensor nodes lifetime. The second proposed MAC protocol is Energy efficient MAC with parallel transmission (EP-MAC) designed for wireless sensor networks. EP-MAC protocol is basically based on TDMA approach. But EP-MAC protocol uses the strength of contention based scheme to offset the drawback of schedule based approach in medium access control of Wireless Sensor network to achieve significant amount of energy savings. The most innovative idea of the EP-MAC protocol is using the concept of parallel transmission for minimizing the latency and maximizing energy savings. EP-MAC also uses the transmission power adjustment feature in order to enhance the scope of parallel transmission and contribute to increase sensor nodes lifetime.

7.2 Scope of Future Work

As a future work, there are scopes of implementing the IH-MAC and EP-MAC protocol on mote hardware. Besides, there is a scope of re-designing IH-MAC protocol for applications other than home or building appliance. The energy efficient features of the protocols can be exploited in many other applications of WSNs.

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Appendix A. List of Achievements

Category (subheading)	[Paper/Article] Author(s), "Paper Title", Conference/Journal Title, Issue number and page numbers, Presentation/Publication Date [Work] Author(s), Category, "Title", Role in creating the work (Competition/Art Festival Name, Place of Showing, Date of Award-winning/Publication, Award Type)
Articles in Refereed journals	○ **Arifuzzaman M.**, Matsumoto Mitsuji, Sato Takuro, "An Intelligent Hybrid MAC with Traffic-Differentiation-Based QoS for Wireless Sensor Networks". Sensors Journal, IEEE; Volume: 13, Issue: 6; Page(s): 2391-2399, June 2013 ○ **Arifuzzaman M.**, Matsumoto Mitsuji, "A Hybrid MAC with Dynamic Sleep Scheduling for wireless Sensor Networks". The Journal of Image Electronics Society Volume 42, No. 2, pp197-205 March 2013 ○ **Arifuzzaman, M.**; Matsumoto, M. "An Efficient Medium Access Control Protocol with Parallel Transmission for Wireless Sensor Networks." Journal of Sensor and Actuator Networks.", Vol. 1, Issue. 2, pp111-122 August 2012. **Arifuzzaman M.**, Keping Yu, Sato Takuro, "An Optimum Relay Sensor Placement Technique to Enhance the Connectivity of Wireless Sensor Network ". International Journal of Engineering and Advanced Technology(TM), Volume-4 Issue-2, December 2014. Arifuzzaman. M, Zhenyu Zhou, Kasumi Haruta and Sato Takuro " 早稲田大学における企業ビジネスと標準化教育:ゲーム理論によるクオルコム社 CDMA 標準化戦略解析に関する研究", Accepted in the Journal of Japanese society for engineering education, Vol. 63, No. 3; to be published on May 2015. Arifuzzaman M., Keping Yu, Sato Takuro, "Collaboration between Network Players of Information Centric Network: An Engineering-Economic Analysis". Accepted in the Journal of ICT Standardization, River Publishers; Volume 2 Issue 4; to be published on June 2015.
International Conference Proceedings	**Arifuzzaman, M.**; Keping Yu, Sato, Takuro, "Content Distribution in Information Centric Network: Economic Incentive Analysis in Game Theoretic Approach", ITU Kaleidoscope conference, Saint Petersburg, Russian Federation, 3-5 June 2014.

	Arifuzzaman, M.; Keping, Yu ; Quang. N. Nguyen, Sato, T. " Locating the Content in the Locality: ICN Caching and Routing Strategy Revisited " Accepted at EuCNC'2015; European Conference on Networks and Communications, Paris, France, June 29/July 2, 2015. ○ **Arifuzzaman M.**, M.S. Alam, Matsumoto Mitsuji, " A Hybrid MAC with Intelligent sleep scheduling for Wireless Sensor Networks.", In the Proceedings of the ITU Kaleidoscope Academic Conference, 12-14 December, 2011 , Cape Town, South Africa .**(*Achieved best paper award)** **Arifuzzaman, M**.; Mitsuji, Matsumoto, "An Optimum Relay Sensor Placement Technique to Enhance the Connectivity of Wireless Sensor Network.", in the Proceedings of the Asia-Pacific Microwave Photonics Conference (APMP) April 25-27, 2012 Kyoto.
National Conferences	**Arifuzzaman, M**.; Tam Hoang, Mitsuji, Matsumoto, " TDMA MAC with parallel transmission for Sensor Network by Introducing the concept of Link Scheduling with Broadcast scheduling", Accepted for the Media Computing Conference, IIEEJ,2012, to be held in Tokyo, Japan June 23-24 ,2012. **Arifuzzaman, M**.; M. S. Alam, Mitsuji, Matsumoto, "An Energy Efficient MAC for Sensor Network by Introducing the concept of Link Scheduling with Broadcast scheduling", In the Proceedings of the Media Computing Conference, IIEEJ,2011, June 25-26, Shimane, Japan. **Arifuzzaman, M**.; Mohammad Shah Alam, Chen Jiehui, Mitsuji, Matsumoto, "Algorithm for Connecting a Disconnected Sensor Network with Deploying Additional Sensor Nodes", In the Proceedings of the General Conference, IEICE , 2011, March 14-17 Tokyo city University, Tokyo, Japan.
Presentation at Domestic Academic Meeting held by Study Group	**Arifuzzaman, M**.; Yu Keping, Takuro Sato , "Economic Incentives for major network players in Information Centric Networking: A Game Theoretic Analysis" March 2014 , pp.145-150 , IEICE RCS , Tokyo
Others	Quang. N. Nguyen, **Arifuzzaman. M**, T. Miyamoto, and Sato. Takuro "An Optimum Information Centric Networking Model for the Future Green Network". Accepted in the International Workshop on Smart Grid Communications and Networking Technologies, SmartGridComNet2015, IEEE ISADS 2015 March 25-27, 2015 , Taiwan.

	Keping, Yu; Li Zhu; Zheng Wen ; **Arifuzzaman, M.** ; Zhenyu Zhou; Sato, T. " CCN-AMI: Performance Evaluation of Content-Centric Networking Approach for Advanced Metering Infrastructure in Smart Grid" IEEE Workshop on Applied Measurements for Power Systems, to be held in AACHEN, GERMANY, September 24- 26, 2014. Keping Yu, **Arifuzzaman M.**, Zheng Wen, Li Zhu, Zhenyu Zhou, and Takuro Sato "A Key Management Scheme for Secure Communications of Information Centric Advanced Metering Infrastructure in Smart Grid", IEEE International Conference on Power System Technology (POWERCON), October 20 - 22, 2014, Chengdu, China Keping, Yu; Li, Zhu; Zheng, Wen; **Arifuzzaman, M.;** Zhenyu, Zhou; and Takuro Sato "CCN-SG: Performance Evaluation of Content-Centric Networking Approach for Smart Grid", AsiaSim & JSST, 29-31, Kita-Kyushu, Japan 2014 Na Yu, **Arifuzzaman, M**. Keping Yu, Takuro Sato ; " Study on CCN Based Disaster System", IEICE Tech. Rep., vol. 113, no. 360, pp. 1-6, Dec. 2013, Takamatsu, Kagawa, Japan.