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# Medium Reservation Based MAC for Delay-Sensitive Wireless Sensor Network

Graduate School of Chosun University

Department of Information and Communication Engineering

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Advisor: Prof. Jae-Young Pyun

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Graduate School of Chosun University

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# Master's Degree Thesis
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# ABSTRACT

## Medium Reservation Based MAC protocol for Delay-Sensitive Wireless Sensor Network

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In many sensor network scenarios, battery-powered nodes must operate for years, which necessitate the need for advanced power management of the radio. Power management is usually performed in the Media Access Control (MAC) layer of the software communication stack by putting nodes into sleep, while waking up periodically for very short amounts of time only. Both energy efficiency and low latency are the most demanding features for MAC of wireless sensor network.

In this thesis, a new MAC protocol satisfying with both high energy efficiency and low transmission latency at the same time over wireless sensor network, named as medium reservation preamble based MAC (MRPM) is proposed. The proposed MRPM is a synchronized duty cycle MAC protocol. Unlike other synchronized duty cycle MACs, MRPM does

not have separate time frames for SYNC and data traffics. Both traffics are integrated in a short listen period. In MRPM, the channel contention is excluded from listen period and transferred to new period called contention period. That is, the contention period precedes the listen period, and only transmitters wake up in this contention period and contend for medium reservation. Introduction of contention period makes duty cycle adaptive because only transmitters use them and non-transmitters bypass them. Both exclusion of contention from listen period and integrating of SYNC and data into a single period enable MRPM to achieve listen period of very short length, which make MRPM highly energy efficient. Moreover, MRPM uses carrier sensing information for advanced adaptive listening which makes packets travel multiple hops away in a single sleep/listen cycle. MRPM was compared with S-MAC and TEEM protocols through ns-2 simulation. The simulation results verify that MRPM has features of high energy efficient and low latency, which is suitable for delay-sensitive wireless sensor network applications.

# 요약

## 전송지연에 민감한 무선센서네트워크에서 매체 예약 기반의 MAC 방식

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많은 센서네트워크 시나리오에서 배터리로 동작되는 노드들은 여러해 동안 동작이 되어야 함으로 전파의 방사에 대한 전력관리는 필수 적이다. 전력관리는 보통 노드가 대부분의 시간에 sleep 모드에 빠져 있고 주기적으로 매루 짧은 시간동안에만 깨어 있는 방법으로 소프트웨어 통신 스텍의 Media Access Control (MAC) layer 에서 수행되어 진다. 에너지 효율과 낮은 지연은 MAC 무선 센서 네트워크를 위해 가장 많이 요구되는 기능이다.

이번 논문에서,나는 medium reservation preamble based MAC (MRPM)라 이름 붙여진 무선 센서 네트워크를 위한 높은 에너지 효율과 낮은 전송 지연을 동시에 만족시키는 새로운 MAC 프로토콜을 제안한다. 제안된 MRPM 은 동기화된 duty cycle MAC 프로토콜이다. 다른 동기화된 duty cycle MAC 프로토콜과는 다르게 MRPM 은 SYNC 와 data traffics 을 위한 별도의 타임 프레임이 없다. 두 트래픽들은 짧은 listen 구간에 통합이 된다. MRPM 에서, 채널 경합은 listen 구간에선 하지 않고 contention 구간라 불리우는 새로운 시간대에서 전송이 된다. 즉, 경합 구간은 listen 구간 앞에 위치하며 오직 transmitters 는 경합구간에서만 깨어나고 전송매체 점유를

위한 다툼을 한다. 경합 구간의 소개는 duty cycle adaptive 를 만들었다. 왜냐하면 오직 transmitters 만 경합구간을 사용하며 그 이외의 전송하지 않는 기기는 경합 구간을 피해가기 때문이다. Listen 구간를 채널 경합구간에서 제외하는 것과 SYNC 와 데이터를 하나의 구간에 통합하는 것은 MRPM 이 매우 짧은 길이의 listen 구간를 가지게 함으로써 MRPM 은 높은 에너지 효율을 갖게 되었다. 게다가, MRPM 은 패킷들의 다중 홉 전송이 하나의  sleep/listen cycle 동안에 가능하게 하는 진보된 적응적 listening 을 위한 반송파 감지 정보를 사용한다. MRPM 는 ns-2 시뮬레이터를 이용하여 S-MAC 프로토콜과 비교되었다. 이 시뮬레이션 결과로 MRPM 은 높은 에너지 효율과 낮은 지연을 가지는 것은 확인 했으며, 이것은 지연에 민감한 무선 센서 네트워크 응용 프로그램에 적합함을 알 수 있다.

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# Acronyms

| | |
|---|---|
| VLSI: | Very-large-scale integration |
| MEMS: | Micro-Electro-Mechanical Systems |
| WSN: | Wireless Sensor Network |
| CW: | Contention Window |
| MAC: | Medium Access Control |
| CSMA: | Carrier Sense Multiple Access |
| CSMA/CA: | Carrier Sense Multiple Access with Collision Avoidance |
| ER-MAC: | Energy and Rate based-Media Access Control |
| TRAMA: | Traffic-Adaptive Medium Access protocol |
| S-MAC: | Sensor MAC |
| T-MAC: | Timeout MAC |
| DSMAC: | Delay Sensitive MAC |
| TEEM: | Traffic Aware MAC |
| LE-MAC: | Low Energy MAC |
| MRPM: | Medium Reservation Preamble MAC |
| SYNC: | Synchronization |
| MRP: | Medium Reservation Preamble |
| RTS: | Request to Send |
| CTS: | Clear to Send |
| ACK: | Acknowledgement |
| AAL: | Advanced Adaptive Listening |
| NS-2: | Network Simulator-2 |
| NOAH: | NO Ad-Hoc Routing Agent |
| CW: | Contention Window |

| | |
|---|---|
| IEEE: | Institute of Electrical and Electronics Engineers |
| TDMA: | Time Division Multiple Access |

# I. Introduction

## A. Wireless Sensor Networks

Technological advances in VLSI, MEMS, and wireless communication have ushered in a new age of miniature, low cost, low-energy, micro-sensors. A wireless sensor network is a collection of a large number of sensor nodes for monitoring conditions at different locations, such as temperature, sound, vibration, pressure, motion, or pollutants that are deployed in an ad-hoc manner and communicate by using a short-range radio channel [9]. Wireless sensor networks are designed and deployed with a specific application in mind since their efficiency is application dependent. The nodes in sensor networks have limited battery power and it is not feasible or possible to recharge or replace the batteries once deployed. Therefore power consumption should be minimized so that overall network lifetime will be increased. Communication is a major consumer of energy [2]. Therefore, designing energy efficient communication protocols is important in wireless sensor networks. This chapter gives an overview of wireless sensor networks in general such as their application areas, architecture, and characteristics. Also, it shows how these networks are different from normal wireless networks. Additionally, it explains how energy consumption can be reduced in wireless sensor networks by designing low-duty cycle MAC protocols. The sources of energy consumption during the operation of MAC protocols are identified and explained. At the end of the chapter, the contributions and organization of this thesis are described.

## 1. Typical Applications of Wireless Sensor Networks

There are a variety of possible applications for wireless sensor networks, such as environmental monitoring, traffic monitoring, security, and military applications [9].

Recent technological advances in VLSI, MEMS, and wireless communication have enabled the development of wireless sensor networks to be more feasible. In the near future, they might be widely used in shopping malls or parking garages to provide security, in homes to monitor and control home appliances, in factories to monitor and control products, and in highways or traffic lights to monitor vehicle traffic [13]. Considerable works have been done in home automation and some organizations are also providing their works commercially [12]. There are many possible applications in irrigation and agriculture [14].

## 2. Typical Architecture of Wireless Sensor Node

A wireless sensor node usually consists of the following components as shown in Fig. 1.1:

- Embedded microprocessor or microcontroller
- Radio transceiver
- Small memory
- Small battery
- Sensing hardware.

The functions of these components are computing, communication, and sensing, where communication is the dominant part in energy consumption.

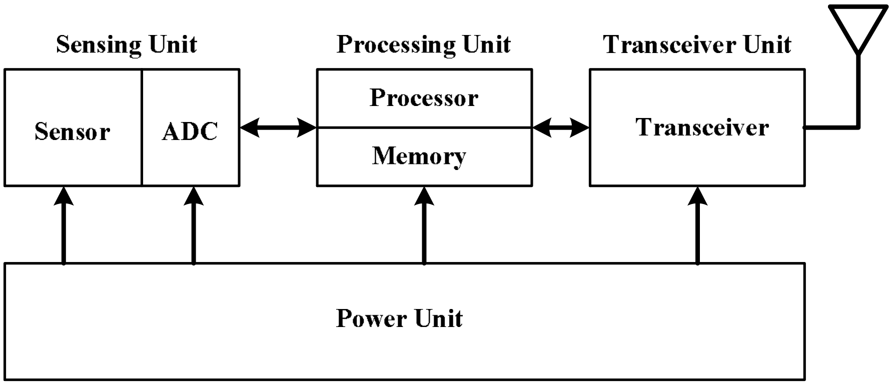


**Figure 1.1: Architecture of a typical wireless sensor node.**

## 3. Characteristics of Wireless Sensor Networks

Wireless sensor networks and the behavior of their applications as well as the generated traffic characteristics are different from other traditional wireless networks [15]. Therefore, existing protocols cannot be used for sensor networks since they have different design criteria. Sensor networks have to be power efficient and scalable, whereas throughput, latency and fairness are the main points in normal wireless networks that are designed for voice or data in order to provide high Quality of Service (QoS) [16]. Wireless sensor networks require low power consumption even at the cost of lower throughput and higher delay. A tradeoff can be made between power consumption and others constraints that are not important for wireless sensor networks such as throughput, delay, and fairness. In fact, most applications of wireless sensor networks can tolerate some delay since network response time is typically orders of magnitude faster than the event that a sensor node might be detecting [17]. Moreover, fairness between the nodes to access the network is not important in sensor networks, as it is in other wireless networks that are designed for data or voice. In wireless sensor networks, all nodes cooperate for a single common task. Therefore, the performance of the application is more important than the individual node performance.

## 4. Energy consumption in the MAC protocols for wireless sensor network

MAC protocols are needed to control access to a shared medium by defining how and when nodes may access the medium. The energy consumption in MAC protocols mainly happens when the node is just listening and waiting for a packet to arrive. Traffic in wireless sensor networks is very low and is triggered by sensing events which would make it bursty [15]. Therefore, wireless sensor networks have a low message rate. Also, packets in wireless sensor networks are relatively short; it takes only about 5 ms to transmit a single packet. For example when the packets inter-arrival time is 5 secs, i.e., they arrive every 5 secs on average, then the nodes spend about 4.955 secs waiting for a packet. Therefore, most of the time (about 99%) is wasted simply waiting for a packet to arrive. These features of sensor networks can be exploited to reduce energy consumption by introducing a listen sleep duty cycle [1]. This would save energy significantly since the radio is the major source of energy consumption, and the best way to conserve energy is through the MAC protocol, because it controls the activity of the radio directly.

There are four main sources of energy consumption where energy might be wasted in the sensor node because of the operation of MAC protocols [1]. These sources of energy wastage are:

**Idle listening**: Most of the energy is consumed when a node is in idle mode listening and waiting for messages to arrive.

**Collision and retransmission**: When there is a collision, more energy will be consumed because the corrupted data has to be retransmitted.
**Overhearing**: Most of the time, nodes are wasting energy by receiving packets that are not intended for them. Overhearing might consume a lot of energy in the node, especially if the traffic is heavy in the network.
**Control packet overhead**: The overhead of the control packets, such as synchronization, is another source of energy consumption.

All of these factors influence the design of MAC protocols in order to make it efficient in consuming energy. However, energy consumption can be reduced significantly by letting nodes in the network go to sleep when they are idle, because about 50-100% of energy is wasted when a node is idle [1]. [15] shows that the ratio of power consumption of idle : receiving : transmitting is 1 : 1.05 : 1.4 and because the nodes are in an idle state for a long time, idle listening is an important factor in node power consumption.

## B. Research Objectives

Unlike other wireless networks, it is generally difficult or impractical to charge/replace exhausted batteries in a wireless sensor network. That is why the primary objective in wireless sensor networks design is maximizing node/network lifetime, leaving the other performance metrics as secondary objectives. Since the communication of sensor nodes will be more energy consuming than their computation, it is a primary concern to minimize communication while achieving the desired network operation. Energy efficiency requirement of WSN motivated the duty cycling in which, sensor nodes periodically alternate between being active and sleeping.

However, the medium-access decision within a dense network composed of nodes with low duty-cycles is a challenging problem that must be solved in an energy-efficient manner. Furthermore, due to duty cycling, delay is introduced which is another factor that must be handled in efficient manner. In emergency messages, there should be very minimum delay. For dissemination of safety information, low latency should be guaranteed.

The major objective of this carried research is to study the limitations and issues in WSN MAC protocols and to suggest some techniques and algorithms which could improve the performance in terms of energy efficiency and latency.

## C. Thesis Contribution

In this thesis, a new energy-efficient MAC protocol for wireless sensor networks is proposed. The protocol is called medium reservation preamble based MAC (MRPM). It was designed to reduce energy consumption which is a primary design factor in wireless sensor networks. The proposed MRPM protocol takes the advantages of being highly energy efficient protocol along with low latency. This thesis surveys MAC protocols used for wireless sensor networks. Important MAC protocols that are proposed in the literature and designed for wireless sensor networks to reduce energy consumption are identified and explained in this thesis. The main contributions of the thesis are as follows:

**New Protocol**: A new MAC protocol called MRPM is designed for wireless sensor networks with two main features: low duty cycle and low latency. Sensor nodes in MRPM have a very short listening time which would reduce the energy that is required to communicate with other nodes by switching off the radio for as long as possible. Also, the latency is minimized by exploiting the carrier sending ability of the node which can be realized from multiple hops away.

**Design Procedure**: A design procedure is given in order to find the important parameters in MRPM. For a given application with its specifications and requirements, an engineer can follow the steps in this procedure to find the important timing parameters and also the appropriate number of phases in MRPM.

**Network simulation**: A network simulation was written in NS-2 simulator to test the performance of MRPM and compare it with other MAC protocols.

## D. Thesis Organization

The remainder of this thesis is organized in modular chapters. Chapter II presents the past works and motivation of the work. Chapter III shows the main features and algorithms for the proposed MRPM protocol. Chapter IV demonstrates the energy efficiency and low data delivery latency achieved by MRPM through simulation results. This thesis is concluded in the last chapter with the wrapping text for summary of this research.

# II. MAC protocols for WSN

## A. Overview of MAC Protocols designed for WSN

MAC protocols play an essential role in determining the channel efficiency by resolving the contention between nodes to access a shared channel. This problem is known as the contention or multiple access problem. MAC protocols for wireless sensor networks must create a network infrastructure to establish communication links for data transfer among thousands of densely and randomly scattered sensors. All the features of wireless sensor networks described in the previous chapter emphasize the need for MAC protocols that are designed specifically for wireless sensor networks.

### 1. Types of MAC protocols for WSN

MAC protocols can be classified into two types depending on the way the access is being controlled: reservation-based and contention-based [16]. Each of these access methods has its own advantages and disadvantages. In reservation-based MAC protocols, the channel is reserved for the nodes for a certain amount of time. This could be done by dividing time into frames and each frame is also divided into slots for allocation to nodes in the network as shown in Fig. 2.1. This technique is called Time Division Multiple-Access (TDMA). Reservation-based MAC protocols are deterministic by using schedules and reservation to determine which node has access to the medium at any time. Reservation-based MAC protocols have many disadvantages that make them difficult to

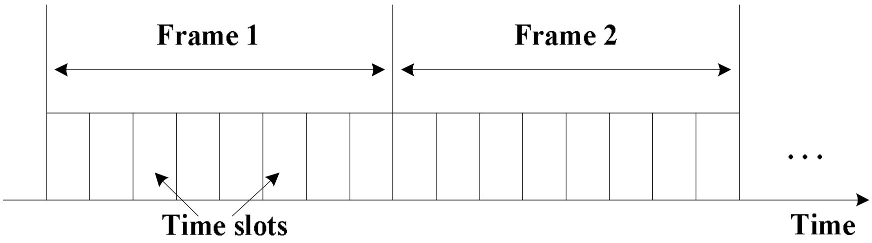


**Figure 2.1: TDMA frames and time slots.**

implement for wireless sensor networks [17]. These disadvantages include:

**Requires coordination**: Reservation-based MAC protocols need coordination to allocate and maintain the reservation slots. For example in TDMA, allocating time slots to the nodes requires frequent control and synchronization overhead.

**Exact timing is critical**: Synchronization is important in reservation-based MAC because the reservation slots are very small, which could cause a problem due to clock drift. Therefore, strict global clock synchronization is critical in reservation-based MAC protocols.

**Not scalable**: Reservation-based MAC protocols are not scalable which is an important design requirement for sensor networks as more nodes could be added to the network, or the nodes might die over time due to failure or low battery. However, reservation based MAC protocols have limited slots to accommodate all the nodes.

However, reservation-based MAC protocols are collision-free since each node is assigned a specific slot that is reserved specifically for a node to use for communication. It is also easy to let nodes sleep in reservation-based MAC protocols when they do not need to use their slots, which results in a very low duty cycle because nodes are only required to wake up during their reserved slots for transmitting or receiving. Also, when nodes turn off their radio during reservation slots for others, they are not affected by others' traffic.

Therefore, reservation-based MAC protocols reduce the energy consumption from most of the major sources of energy waste, i.e., idle listening, collision, and overhearing.

On the other hand, nodes in contention-based MAC protocols determine if they can access the medium by sensing the shared channel and competing to get access to it instead of defining schedules for access. Carrier Sense Multiple Access (CSMA) is the most commonly used technique for this type of protocol. A node first senses the channel and if it is free, it transmits; otherwise it tries to access the channel later on. A collision occurs when two or more nodes try to access the medium at the same time. Nodes that suffer a collision employ a binary exponential back-off mechanism to minimize the probability of another collision.

Contention-based MAC protocols are easy to implement and configure. However, carrier sense in wireless sensor networks is expensive and consumes a lot of energy. Reducing energy consumed by listening to the network channel is accomplished through controlling wake/sleep periods of the sensor nodes.

Table 2.1 compares some attributes of reservation-based and contention-based MAC protocols. It can be seen from the table that contention-based MAC protocols have some drawbacks in the attributes related to the sources of energy consumption, as contention based protocols consume more power than reservation-based protocols. Therefore, many researchers are trying to define contention-based MAC protocols that overcome these sources of energy inefficiency.

**Table 2.1: Comparison between reservation-based and contention-based MACs.**

| Attribute | Reservation-based | Contention-based |
|---|---|---|
| Idle listening | Small | Varies |
| Collision | Free | Exists |
| Overhearing | Low | High |
| Control overhead | High | Low |
| Synchronization | Critical | Not critical |
| Peer-to-peer communication | No | Yes |
| QOS support | Guaranteed or statistical | Statistical |

Several researchers have proposed different MAC protocols for wireless sensor networks that are either reservation-based or contention-based.

## B. Reservation-Based MAC Protocols

The following subsections give some examples of reservation-based MAC protocols that have been popular in the literature for wireless sensor networks.

### 1. TRAMA

Traffic-adaptive medium access protocol (TRAMA) [18] is a reservation-based MAC protocol that reduces energy consumption by being collision free and by making the nodes switch to sleep mode when they are idle. TRAMA uses a distributed election scheme based on information about the traffic at each node to determine which node can transmit at a particular time slot. The schedules in TRAMA are dynamic and adaptive based on current traffic patterns. Therefore, the schedules are influenced by the traffic information in order to make the protocol more adaptive to the application being used. It tries to avoid wasting slots when nodes do not have packets to send by not assigning them time slots, and also to switch nodes to sleep mode when they are not selected to transmit and they are not the intended receiver of traffic using real time traffic information.

Therefore, the main goal of TRAMA is to significantly save energy by reducing energy consumption from two important sources: collision and idle listening. Thus, TRAMA tries to make no idle node an intended receiver and no receiver suffer collisions. The performance of TRAMA is comparable with contention-based MAC protocols such as IEEE 802.11 [11] and S-MAC [1] that will be discussed in the next section. Its results show that the energy saving of TRAMA is comparable with S-MAC.

### 1. ER-MAC

Energy and rate based MAC (ER-MAC) [19] is another reservation-based MAC protocol designed for wireless sensor networks that use the TDMA technique. ER-MAC periodically switches nodes to sleep in order to save energy. However, unlike other protocols that treat all the nodes equally and to minimize energy consumption at a single given node, ER-MAC selects nodes to sleep based on their criticality, which is a measure of the lifetime of the node. The criticality of a sensor node is an attribute that is based on energy and traffic rates. For example, a node is defined as critical if it has more data to send than other nodes. Then, this node is critical and is assigned more time slots to send its data packets. Also, if a node has lower battery life than other nodes, then this node is critical and will be assigned more time to sleep. Making weaker nodes that are critical sleep longer balances energy consumption and also increases the efficiency of the protocol. Therefore, the duty cycle is based on the criticality of the nodes. A distributed algorithm is used to find the critical nodes. Then, these nodes are assigned appropriate time slots for transmitting or receiving. Those nodes that are not critical are assigned fewer time slots. Simulation results show that ER-MAC has good performance especially when the traffic load is high.

## C. Contention-Based MAC Protocols

The following subsections explain some of the contention-based MAC protocols that are used for wireless sensor networks.

### 1. IEEE 802.11

The IEEE 802.11 [11] is an international standard of physical and MAC layer specifications for wireless networks. It uses CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) protocol. It is a simple and reliable MAC protocol that is widely used in many traditional ad hoc wireless networks. However, it is not suitable for sensor networks because throughput, latency, and fairness were the primary design criteria, not power consumption. However, because of its simplicity and reliability, many researchers are trying to modify and develop the IEEE 802.11 so that it is applicable for wireless sensor networks.

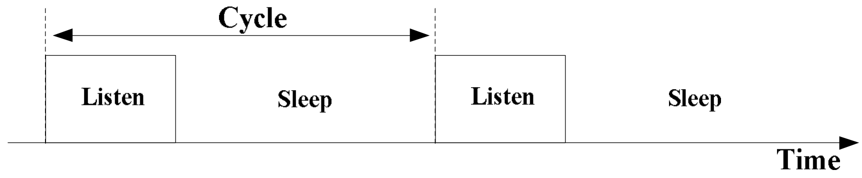


**Figure 2.2: Sleep/listen cycle of S-MAC.**

## 2. S-MAC

Sensor MAC (S-MAC) [1] is a contention-based approach that modified the IEEE 802.11 standard to be suitable for sensor networks. As shown in Fig. 2.2, S-MAC divides time into cycles and each cycle consists of listen and sleep periods. The ratio of the listen period to the cycle length is called the duty cycle. Communication occurs only in the listen period. Packets that are generated during the sleep period are buffered for the next frame cycle. This increases the latency because the sender has to wait for the active period. In S-MAC, nodes try to form one cluster by following the same listen sleep schedule, i.e., by listening and sleeping at the same time. Since nodes can only communicate in listen period, neighboring nodes must be synchronized together. The listen period of S-MAC is further divided into SYNC, RTS, and CTS periods as shown in Fig. 2.3. Each SMAC node periodically exchanges its schedule by broadcasting a SYNC packet to its neighbors at SYNC period. The period of sending a SYNC packet is called synchronization period [9]. In S-MAC, RTS and CTS control packets are used for data communication similar to IEEE 802.11. RTS and CTS packets are transmitted at their respective periods in the listen period. The successful exchange of RTS/CTS packets between two nodes implies that they should stay awake in the whole sleep period for the completion of their data communication. Again, all other nodes that are not involved in data communication can enter a

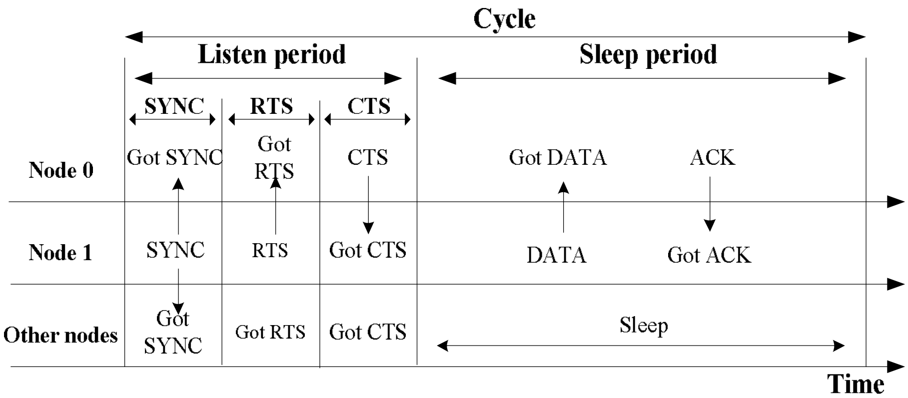


**Figure 2.3: Basic working mechanism of S-MAC.**

sleep mode. Fig. 2.3 shows the data communication between node 0 and node 1 in S-MAC. The nodes overhearing RTS or CTS wake up for a short time when the ongoing communication finishes. This adaptive listening can forward the data to 2 hops in one sleep/listen cycle, reducing the latency to some extent. SMAC has a fixed long listen period. The problem is that, even when nodes have no data or SYNC packet to send, the nodes still have to be awake in listen time, draining their energies.

### 3. TEEM

A traffic aware energy efficient MAC (TEEM) [4] is the modified version of S-MAC. But, unlike S-MAC, in TEEM, the listen period consists of only two parts, $SYNC_{data}$ and $SYNC_{nodata}$, and the time interval of the listen period is also shorter compared to S-MAC as shown in Fig. 2.4. The $SYNC_{data}$ contains data packets, whereas the $SYNC_{nodata}$ contains SYNC packets. Both packets are used for synchronization. Each node will listen in $SYNC_{data}$, whether a node has data to transfer or not. Nodes having data will contend for medium in this period. If there is no

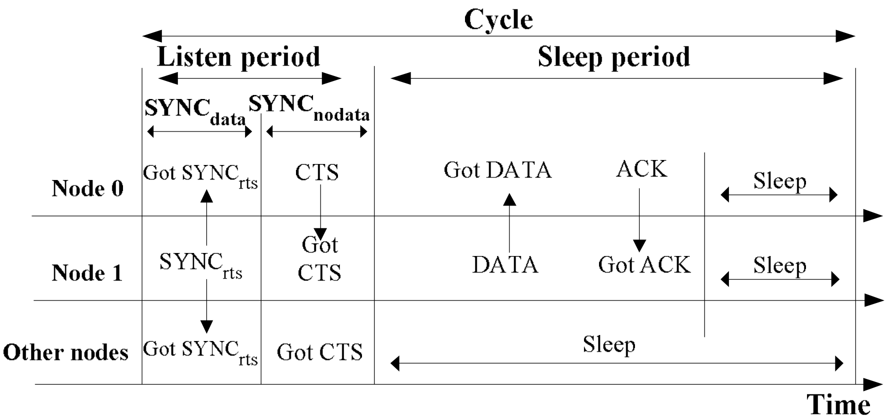


**Figure 2.4: Basic working mechanism of TEEM.**

communication in this period, then node having SYNC packet contend for medium in the $SYNC_{nodata}$ period and the winner sends the SYNC packet. Instead of using a separate RTS and SYNC separately, TEEM combines the RTS packet with a SYNC packet and sends it in $SYNC_{data}$ period. This combination is called $SYNC_{rts}$. Since the data traffic is transferred in the very first period of listen time, nodes that are not involved in current communication can go to sleep immediately. Furthermore, nodes that are involved in communication can go to sleep as soon as communication between them is finished as depicted in Fig. 2.4. These procedures make TEEM's listen period adaptive and much more energy efficient than S-MAC.

### 4. LE-MAC

The basic working principle of Latency and Energy aware MAC (LE-MAC) [5] is same as that of S-MAC. The difference is the approach of using carrier sensing signals for reducing sleep delay in multi-hop transmission. LE-MAC exploits the cross-layer information obtained by the interaction of MAC and the network layer. When nodes that are in routing path between source and sink become aware of the traffic based on the carrier signal, they wakeup once more during the sleep period for transmitting data such that they are likely be the next candidate nodes in the current multi-hop data transmission. This technique allows nodes to forward data to few more hops away than SMAC at the cost of some energy required for adaptive listening [1][5].

## D. Motivation

The S-MAC, TEEM, and other synchronized duty cycle MAC protocols periodically send SYNC packets for synchronization of listen period among the neighboring nodes. Thus, to deal with SYNC and data traffics, these protocols have separate time frames on their listen period, which make the listen period quite long. The shorter the listen period is, the longer the network life is. Furthermore, these protocols use CSMA/CA based random access method for channel access. Therefore, the backoff duration (contention duration) is also included in the listen period (in both SYNC and DATA periods) as shown in Fig. 2.5, which further lengthens the listen period. Due to the backoff duration of listen period, large energy consumption can be inevitable. In a typical synchronized

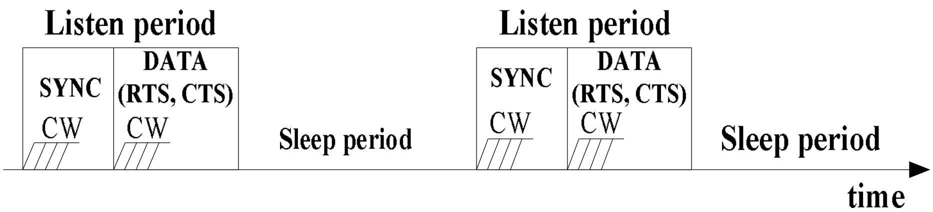


**Figure 2.5: Inclusion of contention windows in SYNC and DATA periods of typical synchronized duty cycle MAC.**

duty cycle MAC such as in S-MAC, the length of the listen period $\boldsymbol{L_p}$ is given by

$$L_p = t_{sync} + t_{data} \qquad (1)$$

where $\boldsymbol{t_{sync}}$ and $\boldsymbol{t_{data}}$ represent the time duration of SYNC and data period, respectively.

$$t_{sync} = \sigma \times CW_{sync}^{max} + Tx_{sync} \qquad (2)$$

$$t_{data} = \sigma \times CW_{data}^{max} + Tx_{data} \qquad (3)$$

Thus, the duration of SYNC and data periods are given by equation (2) and (3), where $\boldsymbol{\sigma}$ represents slot time, $\boldsymbol{CW_{sync}^{max}}$ and $\boldsymbol{CW_{data}^{max}}$ represent the maximum contention windows (CWs) for SYNC and data. $\boldsymbol{Tx_{sync}}$ represents time required to transmit SYNC packet and $\boldsymbol{Tx_{data}}$ represent time required to transmit RTS and CTS packets. Since the length of SYNC, RTS, and CTS are of only some bytes, the most dominant parameter that occupies the most of the time of the listen period is contention window. Listen period can be made much shorter if contention windows are excluded from it. Also, because of inclusion of contention duration in listen period, nodes have to listen for long time in every cycle regardless of traffic. Since contention is done only by the transmitters, non-transmitters can go to sleep during channel contention. The above-mentioned problems motivated to have a separate period (contention period) for transmitters contending for medium reservation. Furthermore, introduction of contention period also makes listen time adaptive because contention period is only used by nodes when they have data and in other time they are bypassed. Taking above points into consideration, a new MAC protocol called medium reservation preamble based MAC (MRPM) [6][7] is proposed, which is expected to be efficient than these conventional synchronized duty cycle MAC protocols. With the energy efficiency feature, MRPM also has low data delivery latency by adopting the physical carrier sensing and adjusting nodes duty cycle dynamically [5]. The proposed MRPM is suitable candidate for delay sensitive WSN applications.

# III. Proposed MRPM Design

Inspired by S-MAC, MRPM is a synchronized duty cycle MAC protocol and inherits basic working mechanism of S-MAC. But, unlike S-MAC, in MRPM, each cycle is divided into three periods, i.e., contention, listen, and sleep as shown in Fig. 3.1. In the contention period, nodes contend for the medium. Only the transmitters wake up in contention period, whereas all neighbors wake up at the listen period. Nodes with SYNC and data traffics compete for channel during the contention period, and the winner gets the chance to use the listen period. The basic concept of MRPM is to make nodes listen for very short time. If the node hears transmission within this listen period, it remains awake, otherwise goes to sleep.

## A. Contention Period

MRPM excludes the contention from listen period and transfers it to a new period called contention period as shown in Fig. 3.1. The length of contention period, $C_p$ is given by

$$C_p = t_{difs} + \sigma \times CW_{sync}^{max} + \sigma \times CW_{data}^{max} + Tx_{mrp} + t_{guard} \qquad (4)$$

where $t_{difs}$ is the distributed inter-frame space and $t_{guard}$ is the guard time for preventing small synchronization errors. $Tx_{mrp}$ represents the time required to transmit MRP packet, which will be explained in detail in next section. MRPM takes the contention windows of SYNC and data

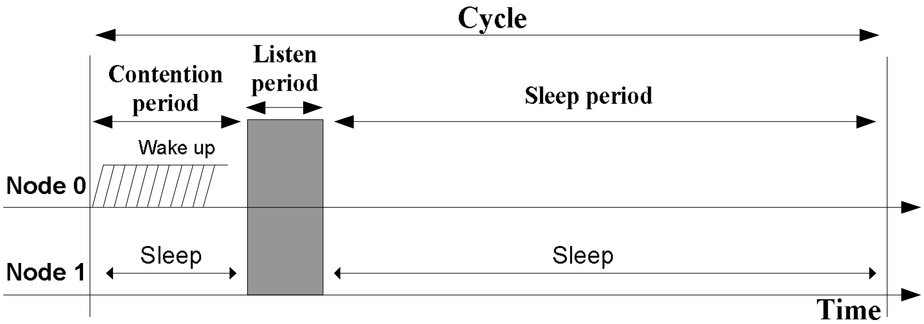


**Figure 3.1: Sleep listen cycle in MRPM.**

periods and moves it to contention period. This transfer of contention to new period drastically reduces the duration of listen period. As shown in Fig. 3.1, only the nodes that have packets to transfer wake up at contention period. In this example, node 0 has packets and node 1 has no packets. Nodes that have nothing to transmit are still sleeping at this period. This nature of MRPM makes its duty cycle adaptive, and makes it highly energy efficient. As mentioned earlier, MRPM integrates SYNC and data traffics in short listen period. Thus, during the contention period, nodes with SYNC or data traffics contend for channel access using CSMA/CA protocol as in IEEE 802.11, and the winner uses the listen period [11]. To give priority to the data traffic, the contention windows for data and SYNC traffics are respectively assigned as shown in equations (5) and (6). Here, $random[0 - CW]$ generates random number between 0 and CW, and $SYNCRO_{period}$ is the synchronization period (period of sending SYNC packet). As can seen from the equations, if both traffics compete, data is always the winner. Furthermore, if the nodes with SYNC packets are unable to get medium even after trying for more than two synchronization period, the left hand side of the equation (5) is use to assign the $CW_{sync}$. This will eventually give node a chance to transmit its SYNC packet.

$$CW_{data} = random[0 - CW_{data}^{max}] \tag{5}$$

$$CW_{sync} = \begin{cases} random[0 - CW_{sync}^{max}] + CW_{data}^{max} \\ if, N_{Fail}^{access} < 2 \times SYNCRO_{period} \\ random[0 - CW_{data}^{max}] \qquad else, \end{cases} \tag{6}$$

To reduce the number of SYNC traffic, SYNC information is also transferred during data traffic. In MRPM, SYNC and RTS packets are combined and newly generated packet, called $SYNC_{rts}$ is used in place of RTS as in TEEM [4]. Fig. 3.2 shows the packet structure of $SYNC_{rts}$. With this new packet, nodes don't need to send SYNC packets *w*hen they also have data packets. This single packet can be used for synchronization as well as RTS packet. This method obviously reduces the SYNC traffic, which in turn reduces the channel contention, and also saves energy from the reduced communication.

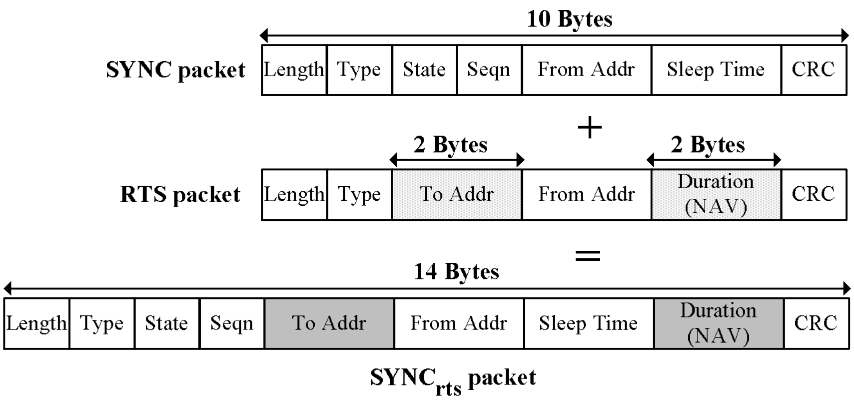


**Figure 3.2: Packet structure of $SYNC_{rts}$ packet.**

## B. Medium Reservation Preamble

In MRPM, nodes have two wakes up points: transmitters wake up early at contention period, whereas other nodes wake up later at listen period as shown in Fig. 3.1. During the contention period, nodes with SYNC and data traffics contend for channel access by using CSMA/CA protocol with their respective $CW$ values ($CW_{data}$ or $CW_{sync}$). Whichever node backoff first, sends a short packet called medium reservation preamble (MRP). MRP is a regular bit pattern of some bytes and does not contain any useful information. Its sole purpose is to make other nodes realize that a certain node has gained the channel. Nodes don't need to decode MRP, thus just realizing transmission in contention period is enough for nodes to give up contention. Since carrier sensing can be done from multiple-hops away, hidden node problem can be avoided here. Since the sender is already decided at contention period, nodes can immediately transmit data at listen period. But, there may be chances that two nodes employ same CWs during the contention period leading to collision of MRP packets. Since data are comparatively larger then control packets, this may lead to waste of energy as well as time. Thus, for efficient design, our protocol employs RTS/CTS mechanism as in S-MAC. If there is collision in MRP, there will be also collision in RTS. But there will be no CTS because of collision in RTS. This will make nodes to backoff for sending new RTS. Eventually, there will be one transmitter. Furthermore, the employment of RTS/CTS enables MRPM for adaptive listening.

## C. Short Listen Period

MRPM is unique in the way that it does not have separate timing for SYNC and data. Nodes wake up for short duration during listen period and both SYNC and data traffics are handled in this short listen period. The listen period is shown in Fig. 3.1, which is represented by the shaded region. The length of listen period ($L_p$) should be at least the duration taken to exchange $SYNC_{rts}$ and CTS packets completely and is given by

$$L_p = Tx_{rts} + t_{sifs} + Tx_{cts} + t_{guard} \qquad (7)$$

where $t_{sifs}$ is short inter-frame space, $Tx_{rts}$ and $Tx_{cts}$ are the transmission time for $SYNC_{rts}$ and CTS packets respectively. Listen period of this much duration is required to make sure that the nodes that are located within the carrier sensing range of the node originating CTS packet don't miss the carrier sensing by early sleeping. Nodes remain awake if they hear transmission within this listen period, otherwise they go to sleep with the end of listen period. In most of the WSN applications, nodes in a neighborhood don't have packets to transmit. Thus, most of the time, the nodes wake up only in listen period for short time and go to sleep immediately. This adaptive nature of MRPM makes much more energy efficient than conventional MAC protocols.

If there is no collision during contention period, there is always one transmitter ready to transmit in listen period. In listen period, the sender transmits after waiting for small guard time to prevent from synchronization error. The overall protocol can be seen with any example. In Fig. 3.3(a), node 0 and 1 want to transmit data. Thus, they wake up early in the contention period and contend for the medium. Here, node 0 finishes backoff first and transmits the MRP. Node 1 hears MRP and gives up contention. After that, nodes enter to listen period. This time, all neighbors wake up. Node 0 transmits $SYNC_{rts}$ packet. Upon receiving $SYNC_{rts}$, node 1 acknowledges with CTS packet. The successful exchange of $SYNC_{rts}$/CTS between two nodes implies that these two nodes should

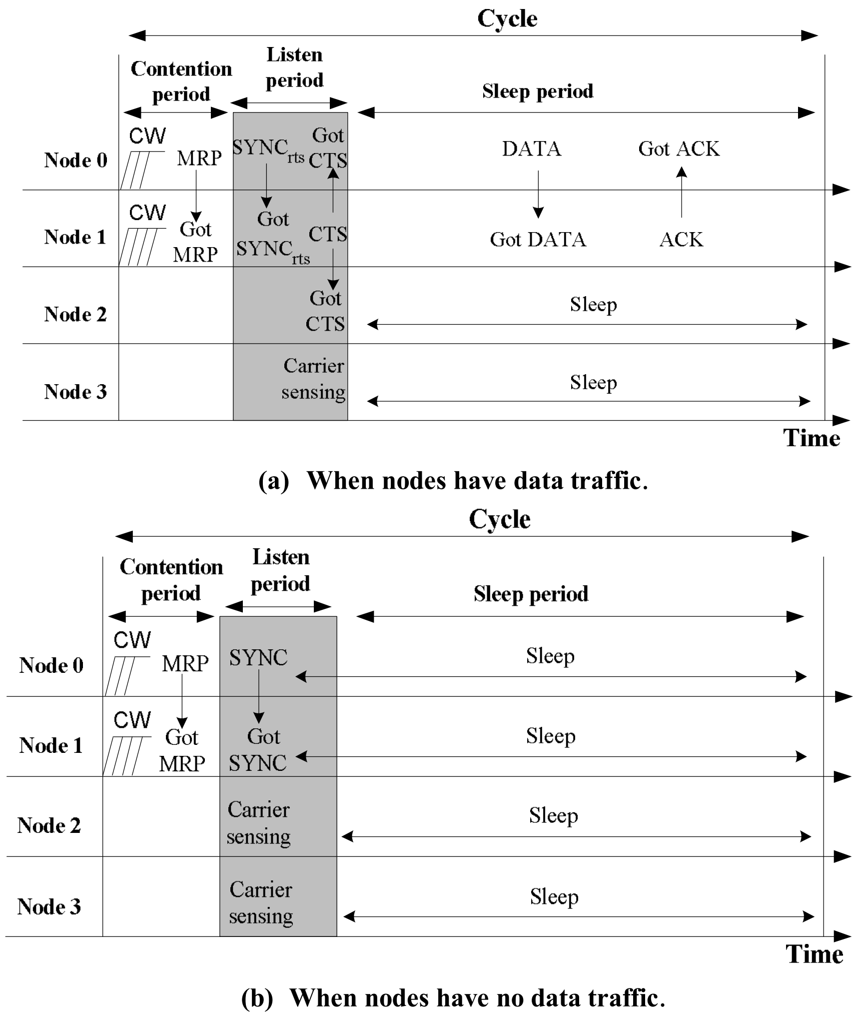


**Figure 3.3: Basic mechanism of the proposed MRPM.**

stay awake until the completion of data communication. All other nodes that are not involved in data communication can go to sleep. Similar to adaptive listening in S-MAC [1], nodes in MRPM overhearing $SYNC_{rts}$/CTS perform adaptive listening. Node 3 can't decode CTS but can sense it because it is within the carrier sensing range of node 1. Here, node 3 performs advanced adaptive listening. Node 3 goes to sleep with completion of its listen period. For synchronization, nodes periodically send their SYNC packet to their neighbors. As mentioned earlier, synchronization is also done with $SYNC_{rts}$ packet. Fig. 3.3(b) shows the exchanging of SYNC packets, which is exactly same as the case of transmitting $SYNC_{rts}$ as explained above. Since SYNC packet is normally received when there is no queued data packet in the neighborhood, nodes immediately go to sleep after exchanging SYNC packet as shown in Fig. 3.3(b). Furthermore, the nodes that can sense the SYNC packet but can't decode it do not perform adaptive listening to avoid unnecessary wakeup.

## D. Adaptive Listening

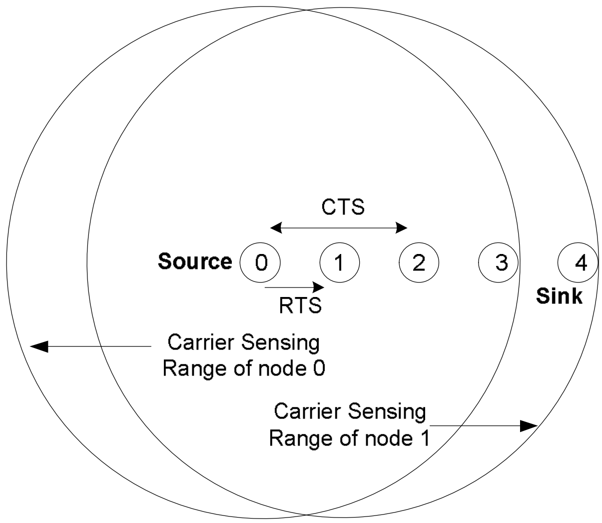


**Figure 3.4: Carrier sensing range of node 0 and node1.**

For the adaptive listening [1], the nodes that overhear $SYNC_{rts}$/CTS packets schedule themselves to wake up in their sleep period after completion of current transmission, such that the data packets can be received in the same cycle. With this technique, packets are transmitted to 2 hops away in single sleep/listen cycle. The adaptive listening in

MRPM is not limited to these 2 hops. The carrier sensing ability of nodes is also taken into account for advanced adaptive listening, which increases the range of adaptive listening [5]. To differentiate with adaptive listening, this new adaptive listening is named as advanced adaptive listening (AAL). The nodes that are unable to decode the $SYNC_{rts}$/CTS are assumed to be at least two hops away from the sender or receiver [1]. Let us see this whole process with an example. In Fig. 3.4, source node 0 wants to transfer data to sink node 4 via the intermediate nodes 1, 2, and 3. The transmission range is of a single hop. The two circles here represent the carrier sensing range of node 0 and node 1 respectively. The working process of adaptive listening is shown in Fig. 3.5. The grey rectangular box in the figure represents contention period, whereas white rectangle represents the listen period. Initially, node 0 transfers the $SYNC_{rts}$ packet and node 1 reply with CTS packet. This CTS packet is overheard by the node 2 which schedules itself for adaptive listening. Since node 3 and 4 are within the carrier sensing range of node 1, they both can sense the CTS. Since a packet is transmitted up to 2 hops by adaptive listening mechanism, nodes 3 and 4 schedule themselves for AAL after $AAL_{dur}$ duration. $AAL_{dur}$ is duration required by a fixed length packet to reach 2 hops away, and is given by

$$AAL_{dur} = 2(Tx_{ack} + Tx_{data}) + C_p + L_p \tag{8}$$

where $Tx_{ack}$ and $Tx_{data}$ represent the durations taken for the transmission of ACK and data packets, and Cp and Lp represent the contention period and listen period respectively. The SIFS and guard time are assumed to be embedded in the packets where necessary in above representation. Data packets are of fixed length. The derivation of equation (8) can be easily explained through Fig. 3.5. To reach the data

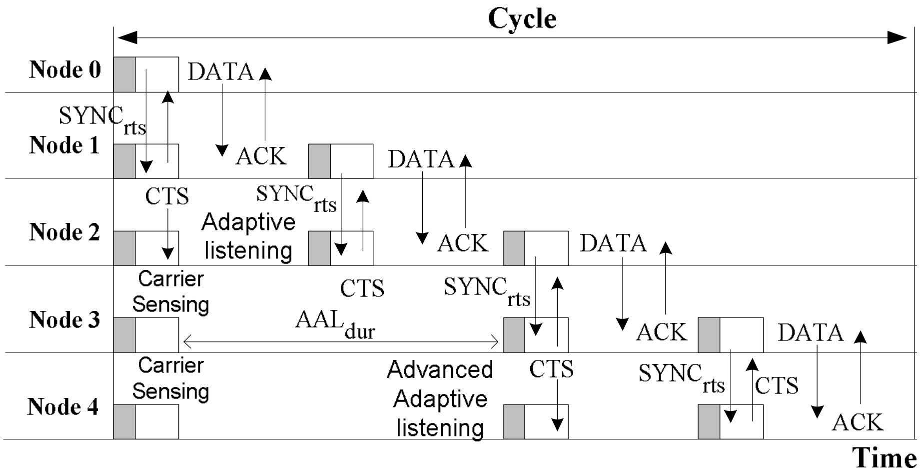


**Figure 3.5: Advanced adaptive listening in MRPM.**

from node 0 to node 2 (2 hops), it requires 2 data packets, 2 ACK packets, 1 contention period, and 1 listen period as shown in the figure. Note that listen period is equal to duration required to exchange $SYNC_{rts}$ and CTS. As we can see in Fig. 3.5, node 3 and 4 perform the AAL after $AAL_{dur}$. Thus, they wake up at same time. Node 4 can overhear the CTS transferred from node 3 to node 2. From CTS, node 4 acknowledges when it should perform adaptive listening. In this way, multiple hops can be achieved in a single sleep/listen cycle with this new approach. With this new enhanced adaptive listening, data can travel to multiple hops away till where the carrier sensing of $SYNC_{rts}$ or CTS can be realized. The AAL may lead to inefficiency in the situations when there are only SYNC packets and no data packets. All the nodes sensing SYNC packets perform adaptive listening unnecessarily wasting energy. Generally, there are less data transmissions in WSN applications. Thus, in order, to prevent this inefficiency of adaptive listening in low traffic load situation, nodes logically divide their listen period into $SYNC_{rts}$ period and CTS period. Nodes don't perform adaptive listening if they sense transmission in $SYNC_{rts}$ period. They only perform adaptive listening, if they sense transmission in CTS period. That means nodes don't perform adaptive listening if they sense either SYNC packet or $SYNC_{rts}$. We believe that nodes in routing path definitely hear or sense the CTS packet if the node would be the next hop after the completion of current transmission. This management considerably removes negative effect on the new advanced adaptive listening. Doubtlessly, there may be many nodes sensing CTS. This will definitely waste network energy proportional to node density. But, since our proposed MRPM has very short listen period, the amount wasted by adaptive listening will not account much.

# IV. Performance Evaluation

MRPM was implemented on the ns-2.32 network simulator [20]. For the performance evaluation, MRPM was compared with S-MAC and TEEM protocols. In the simulation model, the transmission and the CS ranges are of 250m and 550m respectively. For All the protocols, the simulated nodes are configured using the parameters listed in Table 1. The duty cycles of S-MAC and TEEM protocols were set to 10%. The cycle period of MRPM was set same as that of S-MAC. The duty cycle of MRPM was measured as just 1.93% for the same cycle period of S-MAC. The size of MRP used in MRPM was of 10 bytes. Various sets of simulations were performed to test the energy efficiency and end-to-end latency of MRPM. In all the simulations, nodes use NOAH static ad-hoc routing protocol [21]. Also, the source node generates total of 50 messages of 50 bytes. Each message is transferred to sink and simulation ends with the transfer of the last packet. Data flows pass through from source to sink node via the intermediate nodes.

**Table 4.1: Parameters for NS-2 simulation.**

| | |
|---|---|
| **Channel bandwidth** | 20kbps |
| **Reception power** | 14mw |
| **Transmission power** | 36mw |
| **Idle power** | 14mw |
| **Sleep power** | 15μw |
| **Transition power** | 28mw |
| **Transition time** | 2ms |
| **Slot time** | 1ms |

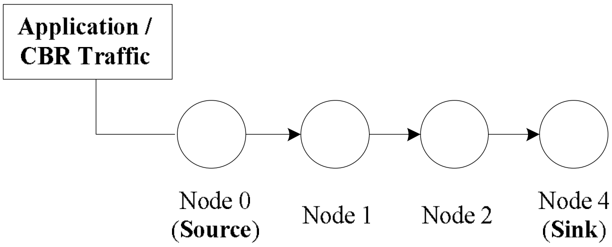

**Figure 4.1: Linear topology**.

In the first set of experiment, a liner topology of 4 nodes (3 hops) with the first node as source and the last node acting as sink was taken as shown in the Fig. 4.1. This set of experiment analyzes the performance of MRPM for the nodes involved in routing under varying traffic load. Here, the message inter-arrival period was varied from 4 to 12 secs. The average energy consumed by nodes involved in routing for all three protocols are shown in Fig. 4.2. The energy efficiency of MRPM with and without AAL was compared against S-MAC and TEEM.

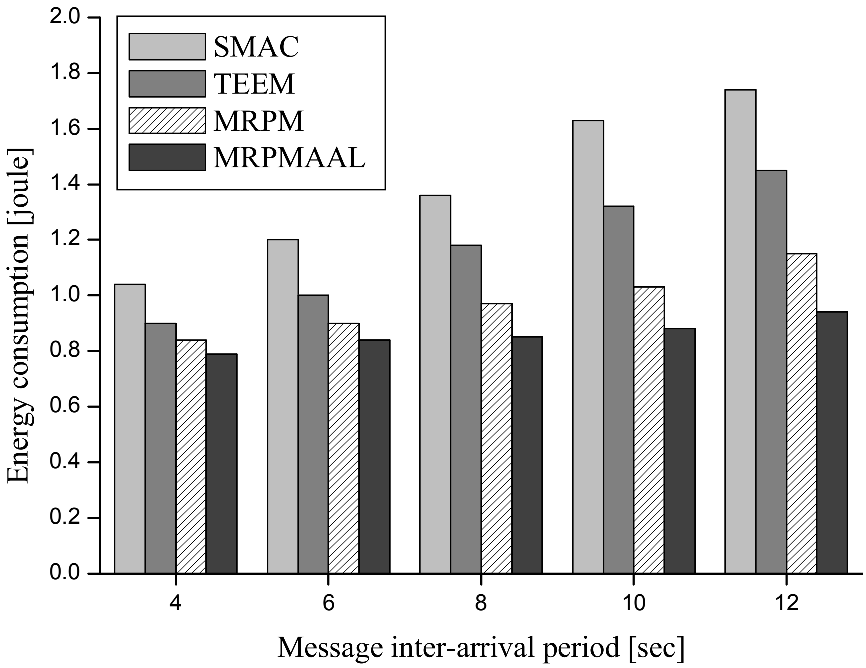

**Figure 4.2: Average energy consumption in linear topology**.

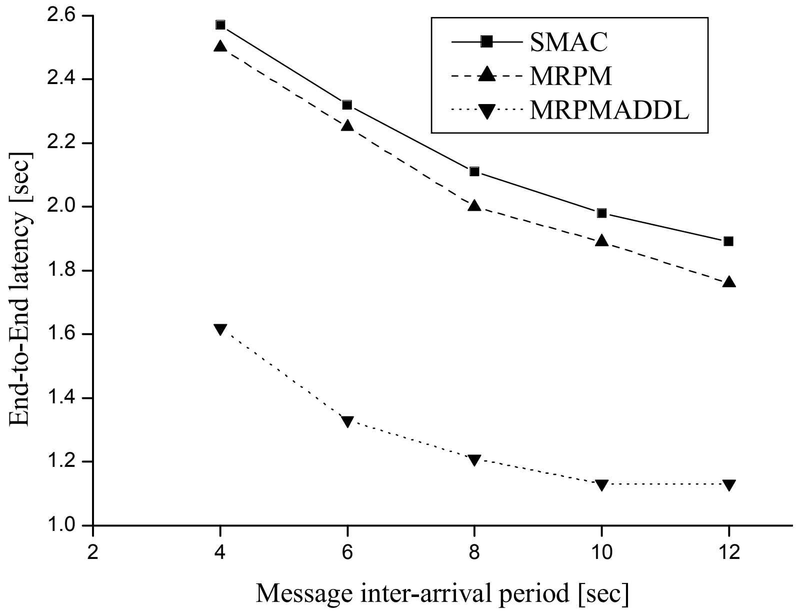


**Figure 4.3: Latency experienced in linear topology.**

The results show that MRPM has highest energy efficiency in either way. It is found that inclusion of AAL in MRPM makes it more energy efficient because with AAL packets travel more hops in a single cycle largely reducing the overall time needed to pass the fixed amount of data through the network. The experimental results show that MRPM with AAL achieves energy efficiency 45% and 35% higher than SMAC and TEEM respectively at message inter-arrival period of 12 secs. The average latency recorded during the simulation for each message inter-arrival period is shown in Fig 4.3. Since the TEEM does not have adaptive listening, its latency is poor as compared to others, thus is not shown in the figure. As expected, the latency of MRPM without AAL is less than that of S-MAC. This is because, firstly, in MRPM, nodes don't have to waste time in SYNC period. Secondly, nodes can transmit immediately as soon as they are in listen period. Finally, in MRPM, $SYNC_{rts}$ packet is used which greatly reduce the network congestion and latency due to the collision of SYNC packets. MRPM with AAL has least

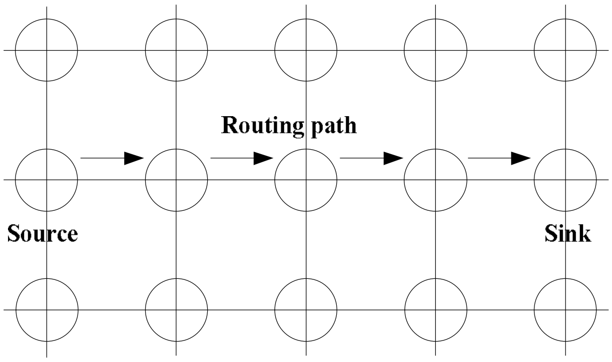


**Figure 4.4: Grid topology**.

latency since MRPM with AAL can transfer packets more hops in single cycle. For the current configuration of simulation, it took single cycle to reach data from source to sink for MRPM, whereas S-MAC took at least 2 cycles. Moreover, at the message inter-arrival period of 4 secs, the latency of MRPM with AAL was 1.6 times better than that of S-MAC.

In the second set of experiment, more realistic grid topology of 15 nodes arranged in 3 rows with 5 nodes in each row was taken as shown in the Fig. 4.4. The nodes are at the distance of 250m from each other. The first and the last nodes of the second row are source and sink. The other nodes, between the source and the sink nodes in the second row, act as intermediate relay nodes and forward data to the sink. Here also, the message inter-arrival period was varied from 4 to 12 secs. As mentioned earlier, MRPM has shorter listen period compared to other two protocols. Also, only the nodes with packets wake up in contention period making the duty cycle adaptive. Thus, the average energy consumption of MRPM is significantly less as compared to S-MAC and TEEM as shown in Fig. 4.5. Further, the changing rate of energy with growing arrival times is much lesser in MRPM. The experimental results show that MRPM achieves energy efficiency of 2.16 time and 1.5 times higher than S-MAC and TEEM respectively at message inter-arrival period of 12 secs. The average latency experienced by all the protocols is shown in Fig. 4.6. The graphs verify that MRPM has lower latency.

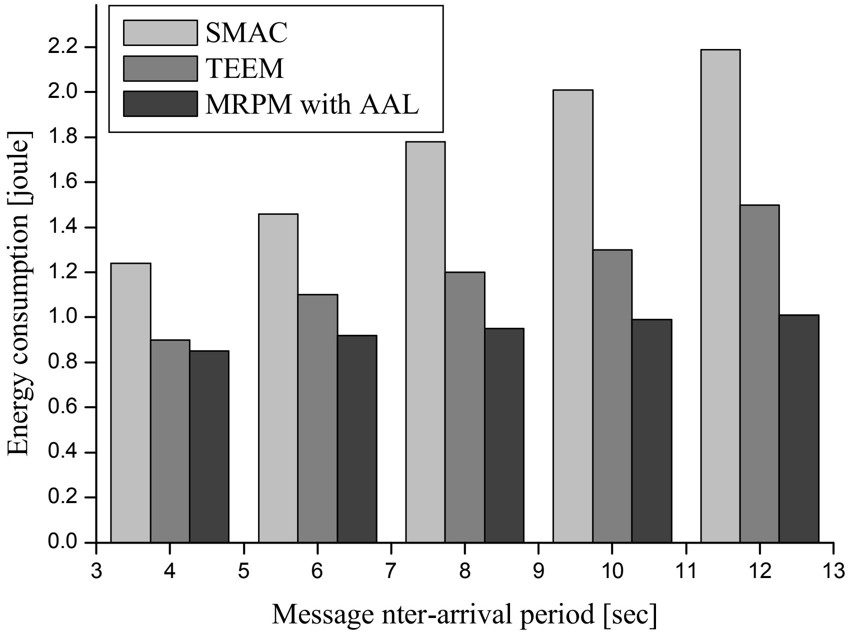


**Figure 4.5: Average energy consumption in grid topology.**

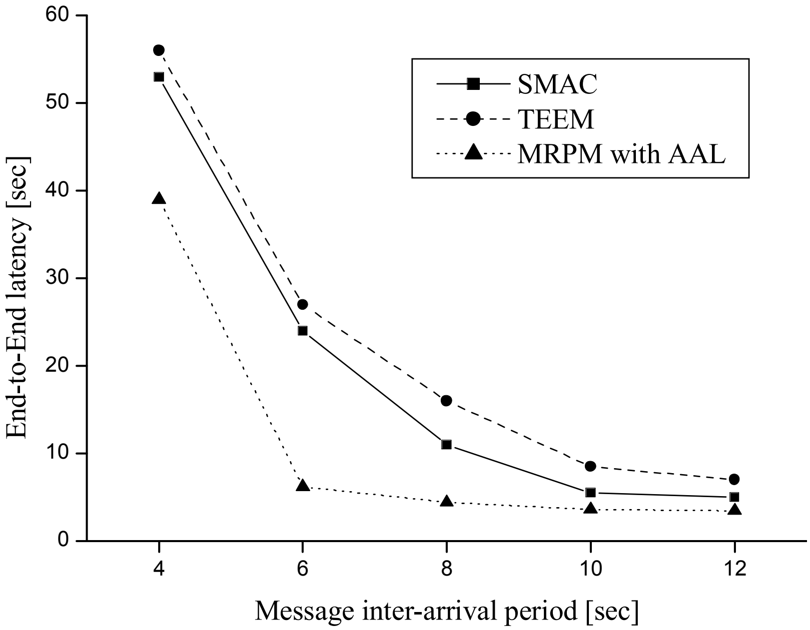


**Figure 4.6: Latency experienced in grid topology.**

For the final set of experiment, a linear topology where first node is source and last node is a sink was taken. The message inter-arrival period was fixed to 10 secs, but the numbers of intermediate nodes between the source and the sink were varied. The distances between any two nodes were set to 250m. For all the protocols, the cycle times were fixed at 1403ms. This set of experiment focus on analyzing the latency under variable hops between the source and the sink. Fig. 4.7 shows the average energies consumed by MRPM and S-MAC protocols. There is a noticeable change in energy consumption under varying number of hops for S-MAC and TEEM. Whereas, in case of MRPM, the energy consumption for transferring 50 packets on varying number of hops between source and sink is almost same. This is because, firstly the MRPM has short listen period. And secondly, in MRPM, packets move more hops in one cycle than in SMAC, which contribute to less energy consumption. The minimum latency recorded during the simulation for all the protocols in this set of experiment is shown in Fig. 4.8. The Fig. 4.8 shows that TEEM protocol has a liner nature of graph. This is because data in TEEM can travel only a single hop in a cycle. Whereas, because of the presence of adaptive listening employed in S-MAC, packets can travel 2 hops in a single cycle. The nature of the graphs in the figure also reveals the traveling of packets to 2 hops in a single cycle. However, in the case of MRPM, its latency is much less than that of S-MAC. Since MRPM also uses physical carrier sensing along with virtual carrier sensing, it achieves the delivery of packets into more hops than in S-MAC till where the transmission can be sensed. In the current set of experiment, data travel one more hop than that of S-MAC in a single cycle. MRPM achieved the latency performance of 1.53 times higher than that of S-MAC when the source and sink are 8 hops away.

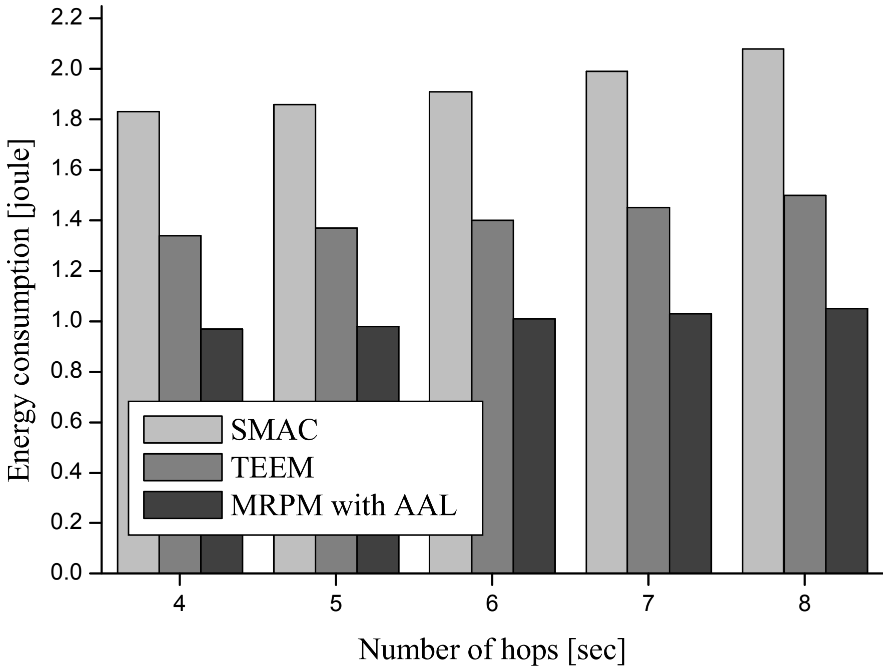


**Figure 4.7: Average energy consumption under variable hops.**

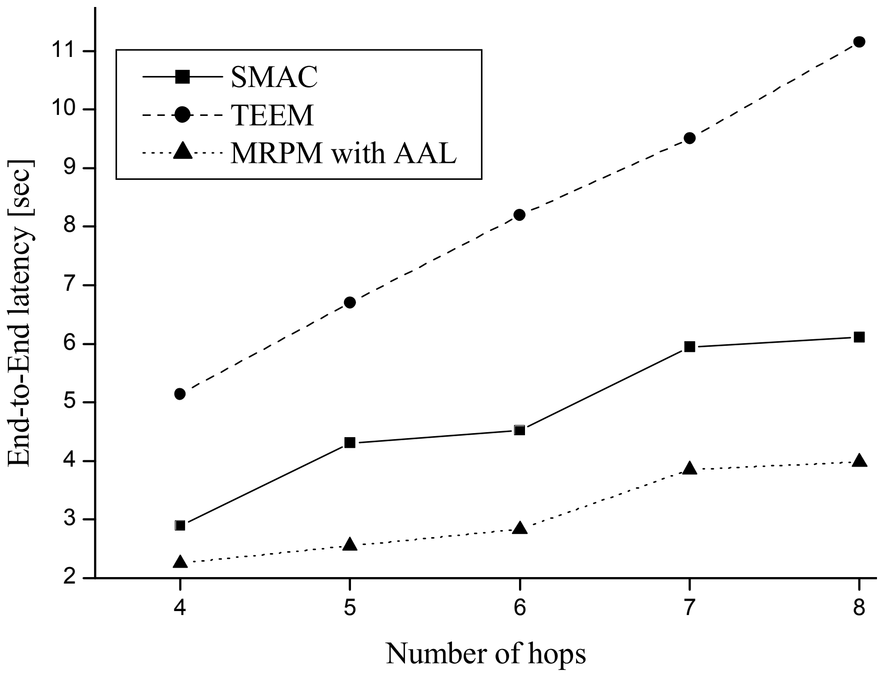


**Figure 4.8: Latency experienced under variable hops.**

# V. Conclusion

Wireless sensor networks are used in a variety of applications which require continuous monitoring and detection of distributed events. They can be used in industrial, medical, consumer, and military applications. Sensor nodes are operated and constrained by battery, energy efficiency is the most important design factor in wireless sensor networks. Energy consumption in a sensor node occurs mainly in three places: sensing, data processing, and communications. In a wireless sensor network, communications is the major consumer of energy. Thus, wireless sensor networks should be efficient in consuming power for communications.

Energy consumption can be optimized by designing energy-efficient MAC protocols since they have a large impact on the efficiency of wireless sensor networks. Designing MAC protocols for wireless sensor networks raises a different set of challenges. There are many MAC protocols that are proposed in the literature designed specifically for wireless sensor networks. This thesis surveys MAC protocols used for wireless sensor networks. Important MAC protocols that are proposed in the literature and designed for wireless sensor networks to reduce energy consumption are identified and explained in this thesis.

An energy-efficient MAC protocol for wireless sensor networks called MRPM is proposed in this thesis. MRPM is highly energy efficient, and also have low latency. In order to achieve these properties, MRPM excludes the contention from the listen period and transfers to a new period called contention period. Exclusion of contention from listen period makes listen period very short. Moreover, the listen period is further shortened by integrating SYNC and data traffics into a single short listen period. These techniques made MRPM possible to achieve listen period of very short time with adaptive duty cycle. Furthermore, MRPM achieves low latency by continuously transmitting data multiple hops away in one listen/sleep cycle by using its AAL. Our simulation results demonstrated that our protocol is highly energy efficient and also has very low latency that can be adapted for delay sensitive WSN applications.

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# List of Publications

**Pranesh Sthapit**, Jae-Young Pyun, “Impact of Duty Cycle in Wireless Sensor Networks,” KIMICS, Korea, Nov. 2008

**Pranesh Sthapit**, Jae-Young Pyun, "Intelligent Network Synchronization for Energy Saving in Low Duty Cycle MAC Protocols," Proc. of 10th IEEE Int'l Symposium on World of Wireless, Mobile and Multimedia Networks (WoWMoM), Greece, Jun. 2009.

**Pranesh Sthapit**, Y. T. Park, and J.-Y. Pyun, “Medium Reservation Preamble based Medium Access Control for Wireless Sensor Network,” Proc. of IEEE Vehicular Technology Conference (VTC), Anchorage, Alaska, Sep. 2009.

**Pranesh Sthapit**, Yong Tae Park, and J.-Y. Pyun, “Medium Reservation based MAC for Delay-Sensitive Wireless Sensor Network,” Proc. of IEEE International Conference on Computer and Information Technology (CIT), Xiamen, China, Oct. 2009.

Yong Tae Park, **Pranesh Sthapit**, Jae-Young Pyun, "Smart Digital Door Lock for the Home Automation," accepted on the proceedings of TENCON2009, Singapore, Nov. 2009.

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# 저작물 이용 허락서

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| 논문 제목 | 한글<br>전송지연에 민감한 무선센서네트워크에서 매체 예약 기반의 MAC 방식 | | | | |
| | 영문<br>Medium Reservation Based MAC for Delay-Sensitive Wireless Sensor Network | | | | |

본인이 저작한 위의 저작물에 대하여 다음과 같은 조건 아래 조선대학교가 저작물을 이용할 수 있도록 허락하고 동의합니다.

\- 다 음 -

1. 저작물의 DB 구축 및 인터넷을 포함한 정보통신망에의 공개를 위한 저작물의 복제, 기억장치에의 저장, 전송 등을 허락함.
2. 위의 목적을 위하여 필요한 범위 내에서의 편집과 형식상의 변경을 허락함. 다만, 저작물의 내용변경은 금지함.
3. 배포・전송된 저작물의 영리적 목적을 위한 복제, 저장, 전송 등은 금지함.
4. 저작물에 대한 이용기간은 5 년으로 하고, 기간종료 3 개월 이내에 별도의 의사 표시가 없을 경우에는 저작물의 이용기간을 계속 연장함.
5. 해당 저작물의 저작권을 타인에게 양도하거나 출판을 허락을 하였을 경우에는 1 개월 이내에 대학에 이를 통보함.
6. 조선대학교는 저작물 이용의 허락 이후 해당 저작물로 인하여 발생하는 타인에 의한 권리 침해에 대하여 일체의 법적 책임을 지지 않음.
7. 소속 대학의 협정기관에 저작물의 제공 및 인터넷 등 정보통신망을 이용한 저작물의 전송・출력을 허락함.

**동의여부 : 동의( ○ ) 반대( )**

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