A BIT-MAP-ASSISTED ENERGY-EFFICIENT MAC SCHEME FOR WIRELESS SENSOR NETWORKS

By

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The low-energy characteristics of Wireless Sensor Networks pose a great design challenge for MAC protocol design. The cluster-based scheme is a promising solution. Recent studies have proposed different cluster-based MAC protocols. We propose an intra-cluster communication bit-map-assisted (BMA) MAC protocol. BMA is intended for event-driven applications. The scheduling of BMA can change dynamically according to the unpredictable variations of sensor networks. In terms of energy efficiency, BMA reduces energy consumption due to idle listening and collisions. In this study, we develop two different analytic energy models for BMA, conventional Time Division Multiple Access (TDMA) and energy efficient TDMA (E-TDMA) when used as intra-cluster MAC schemes. Simulation experiments are constructed to validate the analytic models. Both analytic and simulation results show that in terms of energy efficiency, BMA performance heavily depends on the sensor node traffic offer load, the number of sensor nodes within a

cluster, the data packet size and, in some cases, the number of sessions per round. BMA is superior for the cases of low and medium traffic loads, relatively few sensor nodes per cluster, and relatively large data packet sizes. In addition, BMA outperforms the TDMA-based MAC schemes in terms of average packet latency.

DEDICATION

To my parents.

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WSN	Wireless Sensor Network
MAC	Medium Access Control
CSMA	Carrier Sense Multiple Access
BMA	Bit-Map-Assisted MAC protocol
TDMA	Time Division Multiple Access
E-TDMA	Energy-efficient TDMA

CHAPTER I

INTRODUCTION

Wireless Sensor Networks (WSN) typically consist of base stations and a number of wireless sensors. Each sensor is a unit with wireless networking capability that can collect and process data independently. Sensors are used to monitor activities of objects in a specific field and transmit the information to a base station.

Inexpensive sensors networked together have a wide variety of applications. One potential and significant application is homeland security. As another example, soil moisture measurements provide vital input data for a wide range of applications including weather and climate modeling, soil erosion management, geo-technical engineering, and optimization of farmland irrigation. For the U.S. Department of Energy, soil moisture measurements also are used to determine ground water movement and concentration for tracking and modeling contaminant plumes and leaks from waste tanks, landfills, and contaminated structures as well as nuclear testing and waste storage sites. DARPA and other military organizations are extremely interested in large-scale ad hoc networks that can be deployed with minimum amounts of installation (e.g., operational within minutes after being dropped from an airplane).

Medium Access Control (MAC) is used to avoid collisions by keeping two or more interfering nodes from accessing the medium at the same moment, which is essential to the successful operation of shared-medium networks. The unique characteristics of WSNs require an energy-efficient MAC that is quite different from traditional ones developed for wireless voice and data communication networks. The design of a MAC protocol for WSNs must consider the following factors:

- **Energy Efficiency:** Sensors have a limited energy supply and are usually deployed in a hostile environment. Recharging is almost impossible during the operation. Therefore, long-term applications require energy-efficient solutions.
- **Scalability:** Large-scale WSNs usually consist of tens of thousands of sensor nodes at least two orders of magnitude more sensors per router than conventional wireless networks. Highly localized and distributed solutions are required.
- **Dynamic and Autonomous Network Operation:** Sensors are often deployed and arranged in environments that are inaccessible to humans (e.g., dropped from an airplane into remote mountainous regions). The topology of a WSN changes frequently due to failures of the sensor nodes. Therefore, the protocols and algorithms should possess a self-organizing ability.

1.1 Problem Statement and Motivation

Four of the major performance evaluation metrics of MAC protocols are:

- Power conservation.
- Average end-to-end delay.
- Throughput.
- Control overhead.

For a WSN, operating at extremely low power is a critical design constraint.

Although many solutions have been proposed for conventional wireless networks: cellular networks [38], mobile ad hoc network (MANET) [10], and short-range wireless local area networks [1, 2], they are not quite suitable for the unique characteristics of a large-scale WSN.

Recent literature has proposed several solutions to MAC protocols for WSNs. The solution in [36] employs a “super frame” time scheduling. Power Aware Clustered TDMA (PACT) [27] combines an energy-efficient TDMA-based time schedule with passive clustering to reduce the overall energy consumption in large-scale WSNs. Sensor-MAC (S-MAC) is another recent MAC scheme, which was developed specifically for WSNs [50]. It is a hybrid of contention and reservation based schemes aimed at reducing the energy wastes caused by collisions, control packet overheads, and idle listening. The Aloha with Preamble Sampling scheme combines the classical contention-based Aloha protocol with the preamble sampling technique [11].

Use of Time Division Multiple Access (TDMA)-based MAC schemes is viewed as a natural choice for sensor networks because radios can be turned off during idle times in order to conserve energy [19, 27, 36]. In addition, clustering is a promising distributed technique used in large-scale WSNs. Clustering solutions are often combined with TDMA-based schemes to reduce the cost of idle listening [19, 27].

However, TDMA-based solutions usually perform well under high traffic load conditions. A high traffic load means all nodes always have data to transmit, which is not natural behavior for event-driven applications. With conventional TDMA, when a node has no data to send, it still has to turn on the radio during its scheduled slots. Under this condition, the node operates in Idle mode, which is an energy-consuming operation.

The Energy-efficient TDMA (E-TDMA) extends the conventional TDMA to reduce the energy consumption due to idle listening: when a node has no data to transmit, it keeps its radio off during its allocated time slots. However, the cluster head[1] has to keep on the radio during all the time slots. When there is no incoming packet during an idle time slot, the cluster head operates in the Idle mode and wastes energy.

In addition, changing the time slot allocations and frame lengths dynamically according to the unpredictable variations of sensor networks is usually hard for TDMA-based schemes.

The main purpose of this research is to address the following issues:

1. Develop a new energy-efficient intra-cluster communication MAC scheme for large-scale cluster-based WSNs, which

    - reduces the energy consumption due to idle listening by the cluster head,

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[1] See Section 2.2.3.1.

  - has low complexity, and
  - adapts to the unpredictable variations of sensor networks.

2. Develop energy models to evaluate the performances of the proposed MAC scheme, TDMA and E-TDMA.

3. Validate the analytic energy models with simulations.

1.2 Summary of Main Contributions

The main contributions of this work are as follows:

1. Proposal of an intra-cluster communication bit-map-assisted (BMA) MAC protocol for large-scale cluster-based WSNs. The characteristics of BMA are:
   - BMA is intended for event-driven applications, where sensor nodes transmit data to the cluster head only if significant events are observed.
   - BMA is energy-efficient, which reduces energy consumption due to idle listening and collisions.
   - The scheduling of BMA can change dynamically according to the unpredictable variations of sensor networks.

2. Provision of two different energy and packet latency analytical models for BMA, conventional TDMA, and energy efficient TDMA (E-TDMA) when used as intra-cluster MAC schemes.

3. Construction of simulation models and validated the analytic energy models with simulation measurements.

4. The results show that

    - In terms of average packet latency, BMA is superior than TDMA-based MAC schemes.
    - In terms of energy efficiency, BMA performance heavily depends on the sensor node traffic offer load (parameter p), the number of sensor nodes within a cluster (parameter N), the data packet size and, in some cases, the number of sessions per round (parameter k).
    - In terms of energy efficiency, BMA is superior for the cases of low and medium traffic loads, relatively few sensor nodes per cluster, and relatively large data packet sizes.
    - The performance of BMA improves as the data packet size increases.
    - In terms of energy consumption, E-TDMA always performs better than TDMA.

1.3 Organization

The remainder of the thesis is structured as follows.

Chapter II presents the background information and related work about Wireless Sensor Networks. It introduces the sensor node architecture, the energy constraint, the radio model, and the attributed-based naming architecture. For the related work, we describes the protocol stack for WSNs, followed by MAC protocols and routing protocols designed for WSNs. For MAC protocols, we introduce the TDMA-based schemes, a "super frame" TDMA and Power Aware Clustered TDMA (PACT), and non-TDMA-based schemes, Sensor-MAC (S-MAC) and the Aloha with Preamble Sampling scheme. For routing protocols, we discuss the conventional Routing Protocols, Low-Energy Adaptive Clustering Hierarchy (LEACH) and Threshold Sensitive Energy Efficient Sensor Network (TEEN).

Chapter III discribes the cluster-based MAC schemes and analytic performance evaluation. We present the proposed Bit-Map-Assisted (BMA) MAC solution in detail. We also describe the conventional TDMA and energy-efficient TDMA schemes. We also show the two different analytical models developed for BMA, TDMA and Energy-efficient TDMA (E-TDMA) schemes as intra-cluster MAC schemes. We provide the numerical evaluation results.

In Chapter IV, we present the simulation results. A description of the simulation model is followed by experiment results.

Finally, the paper concludes with Chapter V, which also discusses future work.

CHAPTER II

BACKGROUND AND RELATED WORK

2.1 Wireless Sensor Networks

A Wireless Sensor Network (WSN) provides a low-cost and multifunctional means [4] to link communications and computer networks to the physical world. It consists of base stations and a number of wireless sensors. Each sensor is a unit with wireless networking capability that can collect and process data independently. Sensors are used to monitor activities of objects in a specific field and transmit the information to the base station. An overview of a WSN is shown in Figure 2.1.

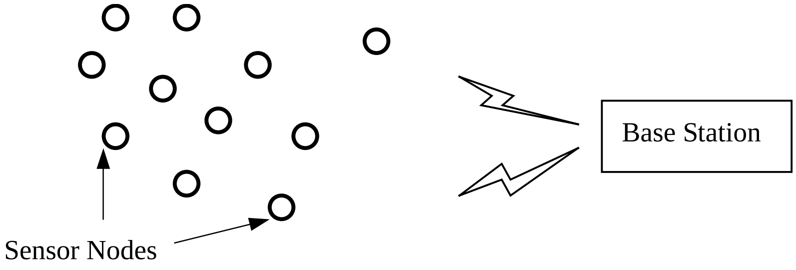

Figure 2.1 An Overview of a WSN

2.1.1 Node Architecture

Figure 2.2 provides a general overview of a typical architecture for a wireless sensor node. A sensor node can be divided into four basic modules: transducer, processor, communications and power [17, 46]. The transducer module contains the physical sensing device and an analog-to-digital converter (ADC). The sampled data is then passed to the processor, where it is stored in memory. Some applications require streaming of raw data, in which case the processor requirements are minimal. Other applications require periodic sampling of the data, which is also a modest load on the processor.

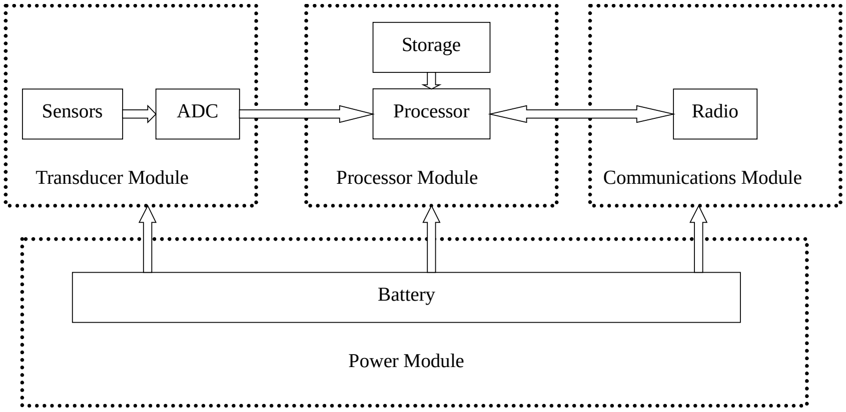

Figure 2.2 Node Architecture

More sophisticated applications require preprocessing of the data to extract important information so that transmission bandwidth can be preserved by simply transmitting the essential information (e.g., alerting the operator of a critical event). Local processing capability is also important for applications in which the sensor supports bidirectional communication. In these cases, users can query the sensor for status, a history of previous samples of data and short-term and long-term statistics.

The communication module consists of a short-range radio transceiver. The power module is used to house the battery and provides energy to the other modules. The functions of all four modules partially depend on the role of the sensor node. A sensor node can operate in one of the three roles: data collector, cluster head, or data relay. If a node is a data collector, the transducer module directly passes the sampled data to the communication module for transmission. A cluster-head node gathers the sensed data from the cluster members and performs data processing to aggregate multiple signals into one signal. If a node works as a relay, it receives the data from nearby nodes and transmits the data to other nodes or the base station.

2.1.2 Energy Constraint

The design of each system component can be optimized to minimize energy consumption. Energy consumption occurs in three aspects: sensing, communication, and data processing. Algorithmic modifications can often result in significant energy savings. Usually the communication of data consumes much more energy than sensing and data processing. Therefore, highly localized and distributed solutions for different levels of communication protocols are required.

A simple energy consumption model for the communication module is proposed in [47]. This model can be used to simulate the energy dissipated by a sensor node when it transmits and receives data. To transmit a k-bit packet over a distance d, the energy cost is described as:

$$E_{Tx}(k,d) = kE_{elec} + \varepsilon_{amp} k d^2, \tag{2.1}$$

and to receive a k-bit packet, the radio consumes

$$E_{Rx}(k) = kE_{elec}. \tag{2.2}$$

where E_{elec} (J/b) represents the energy dissipated by the electronics to transmit or receive a 1-bit of data, and ε_{amp} (J/b/m^2) represents the energy expended by the power amplifier at the transmitter for achieving an acceptable bit energy to noise power spectral density ratio (E_b/N_0) at the receiver.

2.1.3 Radio Mode

The radio of a sensor node can operate in four different modes: Transmit, Receive, Idle, and Sleep [30]. An important measurement in [39] demonstrates that idle listening dissipates very high energy, almost equal to 50-100% of the energy consumed in the Receive mode [31]. Therefore, the radio might be scheduled to turn off completely instead of changing to the Idle mode when it is not transmitting or receiving any signals.

The major sources of energy waste are idle listening, collision, overhearing, and control packet overhead [50]. A collision occurs when a transmitted packet is destroyed and retransmission is required. Overhearing refers to the condition that a node receives a packet sent to others. The control packet overhead is the energy consumed in transmitting the control packet.

2.1.4 Attribute-based Naming Architecture

In many cases, WSNs are required to be data-centric. Applications are interested in the data collected from a group of sensors rather than the status of any individual sensor. In these cases, it is unlikely for the application to ask the question: “What is the humidity at sensor 130.18.64.74?” Rather, it might ask questions such as: “What is the average humidity in the northwest quadrant?” or “Which area has humidity higher than 50? ”

To adapt to the data-centric characteristic of sensor network applications, WSNs use an attribute-based naming architecture instead of explicit addresses or identifiers [12, 15]. Data is named by one or more attributes. For example, the data generated by a sensor node may have the name [type=humidity, id=54, timestamp=01/01/2002/20:15:28, location=60N/120W, humidity=60]. It means a node located at 60N/120W detected a humidity value of 60 at time 01/01/2002/20:15:28.

Based on these attributes, a sink node inquires about humidity information by broadcasting an interest. An interest is a description of the task, which generally defines a range of attribute values. For example, the interest, “Which area has humidity higher than 50?” limits the query to the range higher than 50. Network nodes propagate interests and build up a path for data that matches the query. Whenever a node receives an interest, it checks whether its local data matches the query. If the data does, the node will send its local information; otherwise the node will decline the interest. In the example, the node transmits the data [type=humidity, id=54, timestamp=01/01/2002/20:15:28, location=60N/120W, humidity=60] along the reverse path to the sink when the query, “Which area has humidity higher than 50?” arrives. The attribute-based naming scheme transfers addressing and routing from the network layer to the application, which is highly efficient and application specific.

2.2 Related Work

The design of each system component can be optimized to minimize energy consumption. Algorithm design [5, 7, 20, 33, 43, 46, 51] can result in significant energy consumption reduction.

Protocol design for WSNs has received far more attention than other design issues. Protocol design attempts to improve energy efficiency by accepting a trade-off on other aspects of network performance, such as bandwidth efficiency and quality of service (QoS) [35]. Energy-aware networking protocols, rather than the optimization of hardware, can provide the largest energy savings [28].

Although there are many solutions proposed for conventional wireless networks, they are not quite suitable for the unique characteristics of WSNs. There are three basic types of wireless networks: cellular networks, mobile ad hoc networks, and short-range wireless local area networks. A cellular network (CNET) [38] includes both stationary nodes, referred to as base stations, and mobile nodes containing the sensors. CNETs are ideal for applications placing a premium on high mobility, high QoS and bandwidth efficiency. Energy consumption is not crucial because the mobile nodes are battery powered, and the base stations are not energy-constrained (typically powered from line voltage). Battery technology has progressed to the point where an acceptable tradeoff between size, weight, energy, and battery lifetime has been achieved.

A second network model, known as a mobile ad hoc network (MANET) [10], consists of hundreds of fully mobile nodes, which are deployed over ranges typically not exceeding hundreds of meters. The mobile nodes in MANET are portable battery-operated units with a limited lifetime, so the energy source issue is not a critical design constraint. The primary goal in MANET is to provide users with high mobility, maximum throughput and minimum end-to-end delay. Such networks are often deployed for transient applications with limited lifetimes. Battery life is not as critical as ease of installation and operation.

The third type of WSN is a short-range wireless local area network (SNET). These have recently gained large amounts of media attention. Bluetooth [2] and HomeRF [1] are examples of this technology that have been developed for home or office networking applications. Bluetooth is also being considered for automotive applications as well as ubiquitous networking applications for academic environments. They both provide low mobility and much shorter radio range. Energy consumption is also not crucial because the mobile nodes are typically powered using rechargeable batteries, and the base stations are powered from line voltage readily accessible in office or home environments.

For WSNs, operation at extremely low power is the critical design constraint. New wireless network techniques are anticipated to satisfy the specific energy constraints and application requirements of WSNs.

2.2.1 Protocol Stack

The protocol stack for a WSN consists of the physical layer, data link layer, network layer, transport layer, and application layer. The physical layer is concerned with transmitting raw bits over a wireless channel. It is responsible for modulation, transmission and receiving schemes. The main task of the data link layer is to control access to the shared channel. A key design issue of the network layer is determining how to route the data packets from the source to the destination. The transport layer is required when a WSN is accessed through the internet or other external network. The application layer contains different application software.

2.2.2 MAC Protocols for WSNs

Medium Access Control (MAC) attempts to prevent collisions by keeping two or more interfering nodes from accessing the medium at the same moment, which is essential to the successful operation of shared-medium networks. As we mentioned in the previous section, the unique characteristics of WSNs require an energy-efficient MAC that is quite different from traditional ones developed for wireless voice and data communication networks.

Four of the major performance metrics of MAC layer are:

- Power conservation.
- Average end-to-end delay.

- Throughput.
- Control overhead.

MAC schemes for wireless networks are usually classified into two categories, contention-based and contention-free. Contention-based schemes are widely applied to ad hoc wireless networks because of simplicity and a lack of synchronization requirements. Such an example is the IEEE 802.11 wireless LAN standard, which is designed for minimum delay and maximum throughput. Traditional contention-based schemes require sensor nodes to keep their radios on to receive possible incoming messages. Therefore, such schemes are not energy-efficient due to idle listening.

Contention-free schemes, known as reservation-based or scheduling-based schemes, try to detect the neighboring radios of each node before allocating collision-free channels to a link. TDMA is an example of a contention-free scheme.

2.2.2.1 TDMA-Based MAC Protocols

Use of TDMA is viewed as a natural choice for sensor networks because radios can be turned off during idle times in order to conserve energy [19, 27, 36]. However, changing the time slot allocations and frame lengths dynamically according to the unpredictable variations of sensor networks is usually hard for TDMA schemes. A cluster-based method, LEACH [19], applies TDMA within a cluster.

The solution in [36] employs a “super frame” time scheduling. A super frame is similar to a TDMA frame, which is comprised of a TDMA sub-frame, a BOOTUP sub-frame and an unused sub-frame assigned on demand. Sensor nodes enter in the BOOTUP mode immediately after being powered on and then search for new nodes to build links. During the TDMA period, sensors transmit local data and control signals to destination nodes. The unused period is assigned to specific applications to build a short-time local network. The structure of the super frame may change from epoch to epoch and different sub-frames of the super frame can be assigned to various transactions. However, the algorithm performs well only under specific conditions such as non-hierarchical architecture and no mobility. In addition, it is not bandwidth efficient.

Power Aware Clustered TDMA (PACT) [27] combines an energy-efficient TDMA-based time schedule with passive clustering to reduce the overall energy consumption in large-scale WSNs, as shown in Figure 2.3.

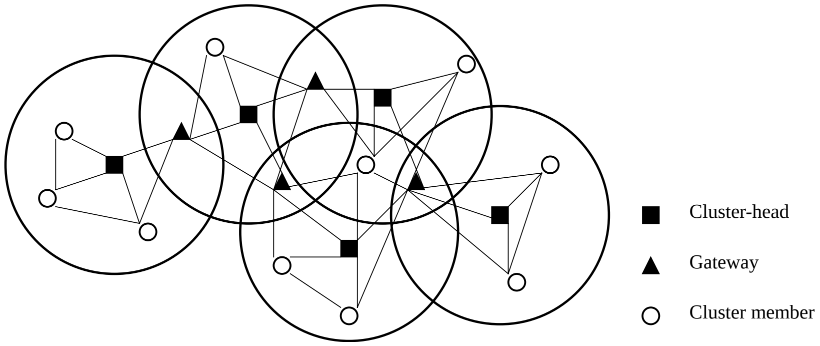

Figure 2.3 Passive clustering is used in PACT to reduce the overall energy consumption

In the time domain, PACT divides each TDMA frame into a control slot and a data slot. Each node turns on its radio during the control slot of a TDMA frame. Since the destination addresses of the node are included in the control packet, other nodes are scheduled to power down during the inactive period. Nodes pick up collision-free transmission slots according to the data slot assignment status specified in control packets. Cluster heads and gateways have priority for slot selection over normal nodes.

In the space domain, PACT applies the passive clustering structure to further reduce the overall communication cost. The passive clustering builds up clusters passively by referring to the status information received from neighbors. There are three kinds of clustering status for a node: cluster-head, gateway, and cluster member. PACT rotates cluster-heads and gateways according to the battery energy levels of nodes. Each node keeps the neighboring cluster-head IDs. The algorithm selects the node with the highest number of distinct cluster-heads as the gateway.

2.2.2.2 Other MAC Protocols

Sensor-MAC (S-MAC) is another recent MAC scheme, which was developed specifically for WSNs [50]. It is a hybrid of contention and reservation based schemes aimed at reducing the energy wastes caused by collisions, control packet overheads, and idle listening. To avoid energy waste due to idle listening, nodes are scheduled to periodically sleep. Furthermore, in-channel signaling puts a node to sleep during the transmission period of other nodes, which avoids overhearing and collision.

In addition, S-MAC uses message passing to reduce control overhead and message-level latency. A message is defined as a unit of data that a sensor can process. The message transmitted by the node is usually long and consists of some small fragments due to the attribute-based naming architecture of WSNs. If a long message is transmitted as a single packet and a few bits are lost during transmission, the whole message has to be retransmitted, which results in a high cost. The principle of message passing is dividing a long message into small fragments and transmit them one by one. Message passing can decrease energy dissipation by avoiding overhearing and reducing control overhead. Compared to IEEE 802.11, S-MAC delivers a six-fold improvement in energy efficiency. However, S-MAC is not suitable for time-critical data monitoring applications. Nodes are periodically turned off to avoid idle listening, so time-critical data cannot be processed immediately.

The Aloha with Preamble Sampling scheme combines the classical contention-based Aloha protocol with the preamble sampling technique [11]. Conventional Aloha is not an energy efficient scheme because the receiver must stay on continuously. Preamble sampling is an energy efficient scheme that is used in traditional paging systems. By combining preamble sampling with Aloha, the resulting scheme greatly saves energy by eliminating idle listening.

This is accomplished by prefixing a preamble of length T_p into each packet. The receiver is periodically turned on every T_p seconds for channel listening. If a preamble is detected, the receiver stays on to receive the rest of the packet. The drawback of this scheme is that it functions well only under low transmission rates and is not scalable.

When compared to the conventional Aloha, the cost of this scheme in achieving higher energy efficiency is higher delay and lower throughput.

2.2.3 Routing Protocols for WSNs

2.2.3.1 Conventional Routing Protocols

There are several conventional routing protocols for wireless networks: direct communication with the base station, multi-hop routing and static clustering.

In the direct communication with the base station scheme, the sensor nodes communicate with the base station directly without routing. Each sensor has to transmit the information to the base station over a long distance, which requires a great amount of power. Thus the effective lifetime of the network is short. Direct communication is feasible only when all sensors in the network are close to the base station. However, this is not the case with large-scale WSNs.

In multi-hop routing, the data is transmitted to the base station through other intermediate nodes. The communication of the sensed data needs to be transmitted and received several times.

The Minimum Transmission Energy (MTE) routing is categorized as a multi-hop routing scheme. The MTE routing chooses intermediate nodes to minimize the transmit amplifier energy. This scheme might not be globally energy efficient because transmitting and receiving information both require energy. Furthermore, the power consumption for receiving is often higher than that for transmitting over small distances [30]. [18] shows that

MTE routing requires more energy than direct communication with the base station when the receiving energy is the same as the transmitting energy. In addition, a major drawback of this scheme is that the sensors near the base station exhaust their energy quickly causing the lifetime of the whole system to be short.

In static clustering the entire network is divided into non-overlapping clusters, as shown in Figure 2.4.

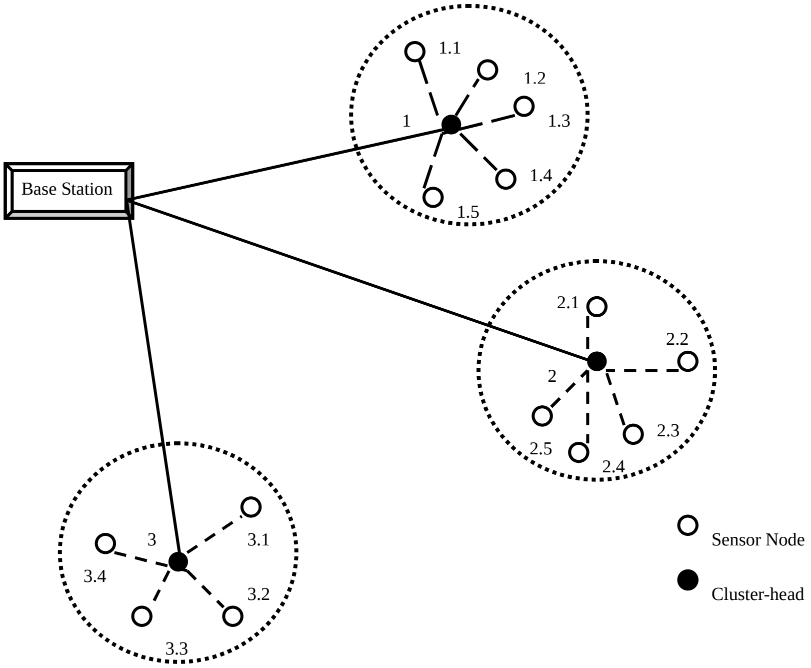

Figure 2.4 Static Clustering

Each cluster has a cluster-head. Instead of transmitting the data to the base station directly, the sensors send their data to the cluster-head. The cluster-head relays the data to the global base station. The clusters and cluster heads are unchangeable during the lifetime of the network. The scheme greatly reduces the energy dissipation of the system because only cluster head nodes need to transmit data over a long distance. In addition, the scheme can make the trade-off between computations and communication costs. If the communication cost is high, the data can be refined and aggregated on the cluster head before transmitting to the base station. If computation is expensive, the data can be transmitted to the base station with little processing.

However, the cluster head nodes experience heavier energy dissipation and deplete energy quickly. If the cluster head node is out of energy, the other nodes within the cluster cannot transmit data to the base station any more.

2.2.3.2 LEACH

Low-Energy Adaptive Clustering Hierarchy (LEACH) randomly rotates the cluster head to distribute the energy consumption evenly among all sensors in the network [18].

The operation of LEACH is separated into rounds. Each round consists of a set-up phase and a steady-state phase. When the set-up phase begins, each node must make a decision about whether to be a cluster head based on a simple algorithm. The new cluster-head then broadcasts the advertisement message to the other nodes to claim as a cluster-head by using a non-persistent CSMA MAC protocol. Each non-cluster-head node chooses the cluster in which communications with the cluster-head require the minimum amount of energy. Once the clusters are built, the system enters into a steady-state phase.

During the steady-state phase, each cluster member sends its data to the cluster head during its allocated transmission slot. The radio of the non-cluster head node is turned off except during its transmission slot. The cluster head sends the aggregated and compressed data to the base station. This process is repeated every time the round time interval expires. LEACH applies direct-sequence spread spectrum technique to reduce inter-cluster interference. All nodes within a cluster communicate with the cluster head using a unique spreading code.

2.2.3.3 TEEN

Threshold Sensitive Energy Efficient Sensor Network (TEEN) [22] is a hierarchical clustering technique where each cluster head forwards the data to an upper-level cluster head, called the super cluster-head. All the super cluster heads at the same level form an upper level cluster with an upper super cluster head and so on until the top level of the network. A hierarchical clustering structure is finally formed. The cluster formation at each level is same as that in the LEACH protocol. Because the application of super-cluster-heads shortens the transmission distance from cluster heads to the base station, TEEN is a more energy efficient scheme for large-scale WSNs than LEACH.

In addition, TEEN uses hard (HT) and soft threshold (ST) to further reduce energy consumption. Hard threshold is an absolute threshold value. When the sensed physical attribute value is above the hard threshold, the node sends the updated data and stores the information in an internal unit, which is called the sensed value (SV). If the sensed value of the next time detection is beyond the hard threshold, the node sends the data to the cluster head only when the difference between the value and SV is equal to or bigger than the soft threshold. Thus the soft threshold gives the leeway to the hard threshold, and further limits the needed communications between the sensors and the cluster head. TEEN is suitable for time-critical sensing applications because the value of a sensed physical attribute can be processed almost immediately. However, the nodes might always keep silent if the thresholds are not reached.

The formation of clusters does not require centralized control from the base station. Localized coordination realizes scalability for the large-scale dynamic WSNs. Due to the two features, energy-efficient and scalable, the cluster-based scheme is a promising solution for WSNs.

CHAPTER III

CLUSTER-BASED MAC SCHEMES AND ANALYTIC PERFORMANCE EVALUATION

3.1 Bit-Map-Assisted (BMA) MAC

This thesis proposes a new cluster-based MAC scheme, Bit-Map-Assisted (BMA). The main objective in designing the Bit-Map-Assisted (BMA) MAC protocol was to reduce the energy wastes due to idle listening and collisions while maintaining a good low-latency performance.

The operation of BMA is divided into rounds, as in LEACH [19]. Each round consists of a cluster set-up phase and a steady-state phase. A complete round is depicted in Figure 3.1.

3.1.1 Cluster Set-Up Phase

We assume a similar cluster formation algorithm as done in LEACH [19]. During the set-up phase, each node must decide whether it could become a cluster-head, based on its energy level. Elected cluster-heads broadcast an advertisement message to all other nodes claiming to be the new cluster-heads by using non-persistent CSMA. Next, each non-cluster-head node joins the cluster in which communications with the cluster-head

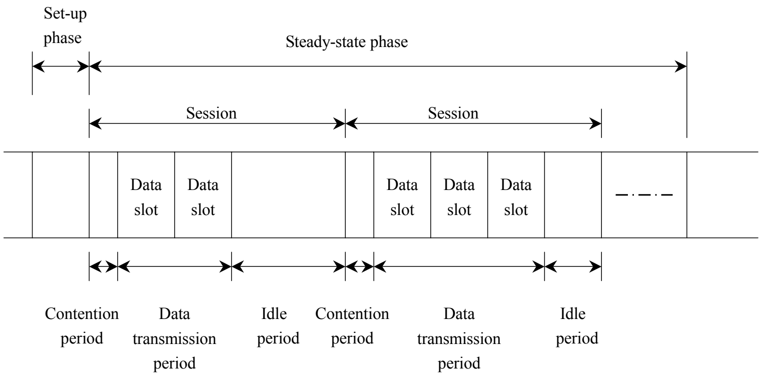

Figure 3.1 Illustration of a single round for BMA

requires the minimum amount of energy. Once the clusters are built, the system enters into the steady-state phase.

3.1.2 Steady-State Phase

The steady-state phase is divided into k sessions. The duration of each session is fixed. Each session consists of a contention period, a data transmission period and an idle period. Assuming that there are N non-cluster-head nodes within a cluster, then the contention period consists of exactly N slots. Since each source node does not always have data to send, the data transmission period is variable. However, in each session, the data transmission period plus the idle periods is fixed to a constant (implementation) value. In this paper, we assume that all the data slots have the same size. Hence, the number of data slots in each session depends on the amount of data needed to be sent.

During each contention period, all nodes keep their radios on. The contention period follows a TDMA-like schedule: each node is assigned a specific slot and transmits a 1-bit control message during its scheduled slot if it has data to transmit; otherwise, its scheduled slot remains empty. A node with data to transmit is called a source node.

After the contention period is completed, the cluster-head knows all the nodes that have data to transmit. The cluster-head sets up and broadcasts a transmission schedule for the source nodes. After that, the system enters into the data transmission period, as shown in Figure 3.1. If none of the non-cluster-head nodes have data to send, the system proceeds directly to an idle period, which lasts until the next session. All source and non-source nodes have their radios turned off during the idle periods.

During the data transmission period, each source node turns on its radio and sends its data to the cluster-head over its allocated slot-time, and keeps its radio off at all other times. All non-source nodes have their radios off during the data transmission period.

When a session finishes, the next session begins with a contention period and the same procedure is repeated. The cluster-head collects the data from all the source nodes and forwards the aggregated and compressed data to the base station. After a predefined time, the system begins the next round and the whole process is repeated.

3.2 Conventional TDMA and Energy-Efficient TDMA

With the conventional TDMA and energy-efficient TDMA (E-TDMA) schemes, the operations are divided into rounds. Each round consists of a cluster set-up phase and a steady-state phase. A complete round is depicted in Figure 3.2.

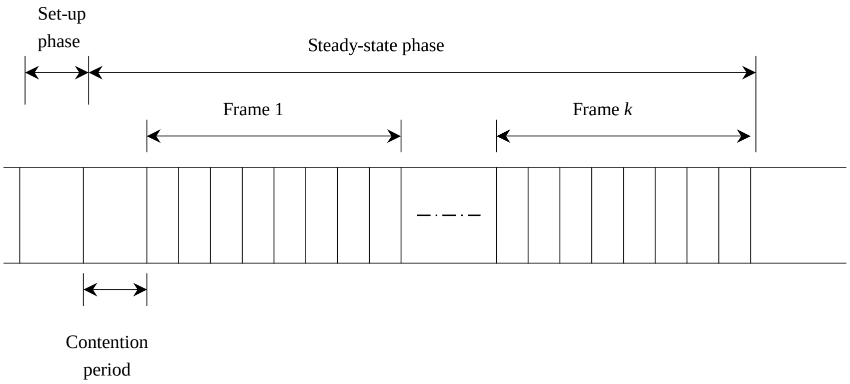

Figure 3.2 Illustration of a single round for TDMA

3.2.1 Cluster Set-Up Phase

During the set-up phase, each node must decide whether it could become a cluster-head based on its energy level. Elected cluster-heads broadcast an advertisement message to all other nodes claiming to be the new cluster-heads. Next, each non-cluster-head node joins the cluster in which communications with the cluster-head requires the minimum amount of energy. Once the clusters are built, the system enters into the steady-state phase.

3.2.2 Steady-State Phase

The steady-state phase is divided into a contention period and k frames. The duration of each frame is fixed. During the contention period, all nodes keep their radios on. The cluster-head builds a TDMA schedule and broadcasts it to all nodes within the cluster.

There is one data slot allocated to each node in each frame. A node with data to transmit is called a source node. Each source node turns on its radio and sends its data to the cluster-head over its allocated slot-time, and keeps its radio off at all other times.

With the basic TDMA scheme, a node always turns on its radio during its assigned time slot regardless whether it has data to transmit or not. If it has no data to send, the node operates in *idle* mode, which is a high energy-consuming operation. E-TDMA extends the basic TDMA in order to reduce the energy consumption due to idle listening: when a node has no data to transmit, it keeps its radio off during its allocated time slots.

When a frame finishes, the next frame begins and the same procedure is repeated. The cluster-head collects the data from all the source nodes and forwards the aggregated and compressed data to the base station. After a predefined time, the system begins the next round and the whole process is repeated.

3.3 Analytic Performance Evaluation

We assume that a clustered network has already been formed and there are N non-cluster-head nodes within a cluster. A round consists of k sessions/frames. There are n_i source nodes in the i^{th} session/frame. The event whether a node has data to transmit or not can be viewed as a Bernoulli trial. The possibility that a node has data to transmit is p. Therefore, n_i is a Binomial random variable, and

$$E[n_i] = Np = n \qquad i = 1, 2, \ldots, k. \tag{3.1}$$

Since the number of source nodes is independent from session/frame to session/frame, the expectation of the total number of source nodes in a round is:

$$E\left[\sum_{i=1}^{k} n_i\right] = \sum_{i=1}^{k} E[n_i] = kn. \tag{3.2}$$

We provide two different energy models for evaluating performances of BMA, conventional TDMA, and energy-efficient TDMA (E-TDMA).

3.3.1 Energy Model I

Energy model I describes the energy consumption as the multiplication of the power consumtion and the operation time. The power consumption during the transmit mode, the receive mode, and the idle mode, are denoted by P_t, P_r, and P_i, respectively. When a source node spends T seconds transmitting a packet, the radio dissipates

$$E_{Tx}(T) = P_t T, \tag{3.3}$$

and to spend T seconds receiving a packet, the radio consumes

$$E_{Rx}(T) = P_r T. \tag{3.4}$$

The energy dissipated by the radio during an idle listening period of T seconds is expressed as

$$E_I(T) = P_i T. \tag{3.5}$$

For the following theoretical analysis, the time required to transmit/receive a data packet is described as T_d seconds, the time required to transmit/receive a control packet is T_c seconds, and the time required for the cluster-head to transmit a control packet for BMA is T_{ch}.

3.3.1.1 BMA

All nodes keep their radios on during the whole contention period. Each source node transmits a control packet during its scheduled slot, and remains idle for $(N-1)$ slots. After receiving the transmission schedule from the cluster-head, each source node sends its data packet to the cluster-head over its scheduled time slot. Therefore, the energy consumption by each source node during a single session is:

$$E_{sn} = P_t T_c + (N-1) P_i T_c + P_r T_{ch} + P_t T_d. \tag{3.6}$$

Each non-source node stays idle during the contention period and keeps its radio off during the data transmission periods. Thus, over a single session, it consumes the following energy:

$$E_{in} = N P_i T_c + P_r T_{ch}. \tag{3.7}$$

During the contention period of the i^{th} session, the cluster-head node receives n_i control packets and stays idle for $(N-n_i)$ contention slots. During the following transmission period, it receives n_i data packets. Hence, the energy dissipated in the cluster-head node during a single session is

$$E_{ch} = n_i (P_r T_c + P_r T_d) + (N-n_i) P_i T_c + P_t T_{ch}. \tag{3.8}$$

Therefore the total system energy consumed in each cluster during the i^{th} session is:

$$E_{si} = n_i E_{sn} + (N - n_i) E_{in} + E_{ch}. \tag{3.9}$$

Each round consists of k sessions, thus the total system energy dissipated during each round is:

$$E_{round} = \sum_{i=1}^{k} E_{si}. \tag{3.10}$$

The average system energy consumed during each round is therefore

$$E = E\left[E_{round}\right] = E\left[\sum_{i=1}^{k} E_{si}\right] = k\left[n E_{sn} + (N - n) E_{in} + E_{ch}\right]. \tag{3.11}$$

We define the average packet latency (delay) as the average time required for a packet to be generated by a source node and received by the cluster-head. For BMA, the average packet latency is

$$L = \frac{N T_c + T_{ch} + n T_d}{n}. \tag{3.12}$$

3.3.1.2 TDMA

During the contention period, the communication between the cluster-head and all other nodes is accomplished by using non-persistent CSMA. Suppose α is the throughput of non-persistent CSMA when there are N attempts per packet time. Each node transmits a control packet, and remains idle for the time $(N-1)\frac{T_c}{\alpha}$. Hence, the energy consumption by each node during the contention period is

$$E_n = \frac{P_t T_c}{\alpha} + (N - 1)\frac{P_i T_c}{\alpha} + P_r T_c. \tag{3.13}$$

The cluster-head node receives N control packets and dissipates the energy

$$E_{ch} = NP_rT_c + P_tT_c. \tag{3.14}$$

Therefore, the total system contention energy dissipation is

$$\begin{aligned} E_c &= NE_n + E_{ch} \\ &= N\left[\frac{P_tT_c}{\alpha} + (N-1)\frac{P_iT_c}{\alpha} + P_rT_c\right] + NP_rT_c + P_tT_c. \end{aligned} \tag{3.15}$$

During the i^{th} frame, the energy dissipated in a source node is equal to

$$E_{sn} = P_tT_d. \tag{3.16}$$

A non-source node turns and leaves on its radio during its scheduled time slot, and therefore, P_iT_d Joules of energy are wasted:

$$E_{in} = P_iT_d. \tag{3.17}$$

Also, during the i^{th} frame, the cluster-head consumes the following energy

$$E_{ch} = n_iP_rT_d + (N - n_i)P_iT_d. \tag{3.18}$$

Hence, the system energy dissipated during the i^{th} frame is

$$\begin{aligned} E_{fi} &= n_iE_{sn} + (N - n_i)E_{in} + E_{ch} \\ &= n_iP_tT_d + (N - n_i)P_iT_d + n_iP_rT_d + (N - n_i)P_iT_d. \end{aligned} \tag{3.19}$$

The total system energy dissipated during each round is computed as

$$E_{round} = E_c + \sum_{i=1}^{k} E_{fi}. \tag{3.20}$$

The average system energy consumed during each round is hence

$$\begin{aligned} E &= E\left[E_{round}\right] \\ &= \left(\frac{N}{\alpha}+1\right)P_tT_c + \frac{N(N-1)}{\alpha}P_iT_c \\ &+ 2NP_rT_c + k\left[nP_tT_d + 2(N-n)P_iT_d + nP_rT_d\right]. \end{aligned} \tag{3.21}$$

The average packet latency is

$$L = \frac{\left(\frac{N}{\alpha}+1\right)T_c + kNT_d}{kn}. \tag{3.22}$$

3.3.1.3 E-TDMA

The total system contention energy dissipation is same as that of TDMA.

$$E_c = N\left[\frac{P_tT_c}{\alpha} + (N-1)\frac{P_iT_c}{\alpha} + P_rT_c\right] + NP_rT_c + P_tT_c. \tag{3.23}$$

In E-TDMA, during the i^{th} frame, the energy dissipated in a source node is equal to

$$E_{sn} = P_tT_d. \tag{3.24}$$

A node with no data to send keeps its radio off during its allocated time slots. Therefore,

$$E_{in} = 0. \tag{3.25}$$

Also, during the i^{th} frame, the cluster-head consumes the following energy

$$E_{ch} = n_iP_rT_d + (N-n_i)P_iT_d. \tag{3.26}$$

Hence, the system energy dissipated during the i^{th} frame is

$$\begin{aligned} E_{fi} &= n_iE_{sn} + (N-n_i)E_{in} + E_{ch} \\ &= n_iP_tT_d + n_iP_rT_d + (N-n_i)P_iT_d. \end{aligned} \tag{3.27}$$

The total system energy dissipated during each round is computed as

$$E_{round} = E_c + \sum_{i=1}^{k} E_{fi}. \tag{3.28}$$

Thus, the average system energy dissipated in each round is:

$$\begin{aligned} E &= E\left[E_{round}\right] \\ &= \left(\frac{N}{\alpha} + 1\right) P_t T_c + \frac{N(N-1)}{\alpha} P_i T_c \\ &+ 2NP_r T_c + k\left[nP_t T_d + (N-n)P_i T_d + nP_r T_d\right]. \end{aligned} \tag{3.29}$$

The average packet latency is as given in TDMA.

3.3.1.4 Analytic Results

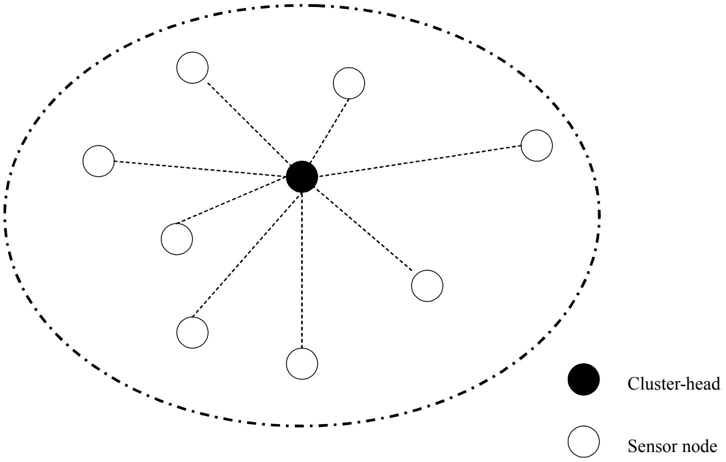

Figure 3.3 Ilustration of a single cluster with N nodes and 1 cluster-head

We compare the performance of BMA, TDMA and E-TDMA as intra-cluster MAC schemes in terms of energy and average packet latency. The comparison does not consider the possibility of bit-errors in the contention period. Figure 3.3 depicts the topology used in our evaluation: a cluster with N sensor nodes and one cluster-head node.

There are two types of representative sensor nodes: Rockwell's WINS node and MEDUSA node [30]. The former represents a high-end sensor node, and the latter is an experimental sensor node. We use the WINS energy node model: the radio transceiver uses 462 mW for transmitting, 346 mW for receiving, and 330 mW for idle listening. The data rate is 24 kbps. Unless noted, we assume a data packet size of 250 bytes and a control packet size of 18 bytes. For TDMA and E-TDMA, we set α to 0.815 [21].

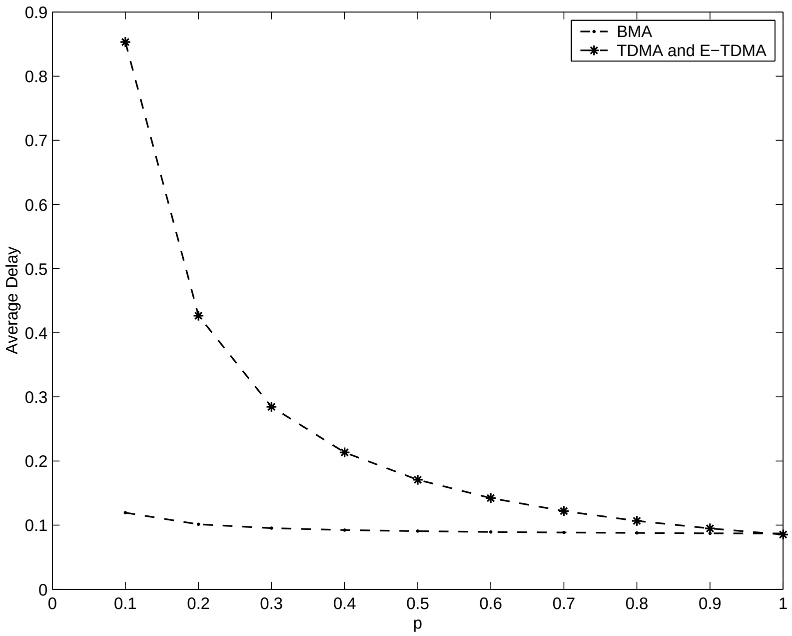

Figure 3.4 Average packet latency vs. p for the case of $N = 10$ and $k = 4$

We compare the three techniques in terms of the average packet latency in Figure 3.4. For large p, all three schemes have similar low average packet latencies. However, as p goes to zero, the average packet latency for both TDMA and E-TDMA grows exponentially, whereas for BMA, it stays relative low.

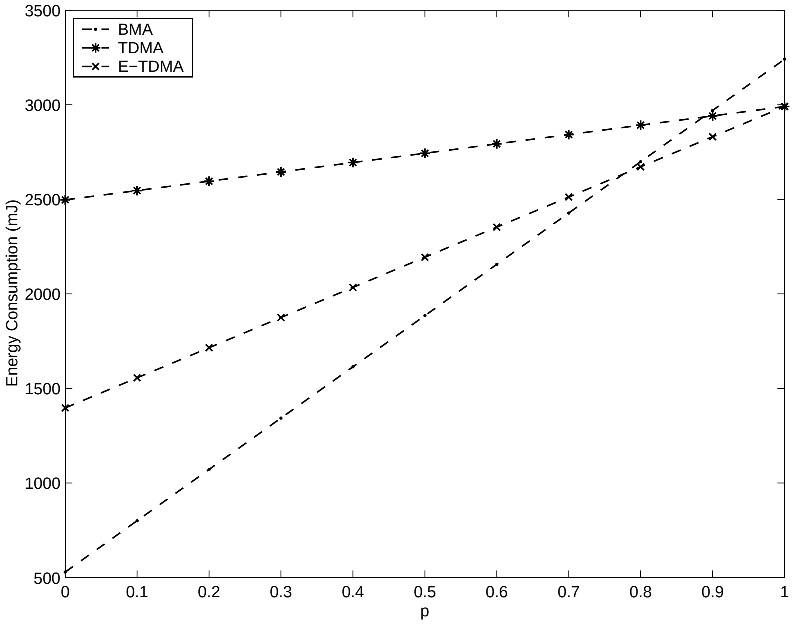

Figure 3.5 Average total cluster energy consumption vs. p ($N = 10$ and $k = 4$)

Figure 3.5 provides a comparison of the three intra-cluster MAC techniques in terms of the average total cluster energy consumption per round as a function of p for the case of $N = 10$ and $k = 4$. When p is less than about 0.75, BMA performs better than both TDMA and E-TDMA. The main energy conservation comes from avoiding idle listening. When p is above 0.75, the idle period is small and thus the energy cost from the contention periods outweighs the energy saving from the idle periods. Note that as p increases, the average idle period decreases. Thus, for p above 0.75, both TDMA schemes perform better. Note that for p less than 1, E-TDMA outperforms TDMA. The energy savings by E-TDMA relative to TDMA grow as p approaches zero.

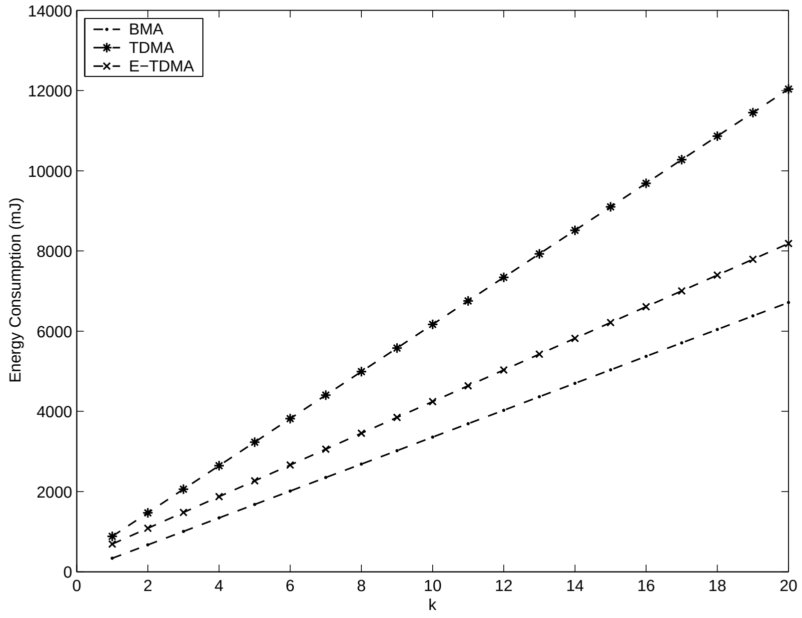

Figure 3.6 Average total cluster energy consumption vs. k ($N = 10$ and $p = 0.3$)

Figure 3.6 compares the three intra-cluster MAC schemes in terms of average total cluster energy consumption versus the number of sessions/frames per round for the case of $N = 10$ and $p = 0.3$. Clearly, for $k = 1$ to 20 sessions/frames/round, BMA is a much more energy conservative scheme than E-TDMA. Note that this is not true for all cases. This is illustrated in Figure 3.7. That is, BMA performs better than E-TDMA for N and p relative small.

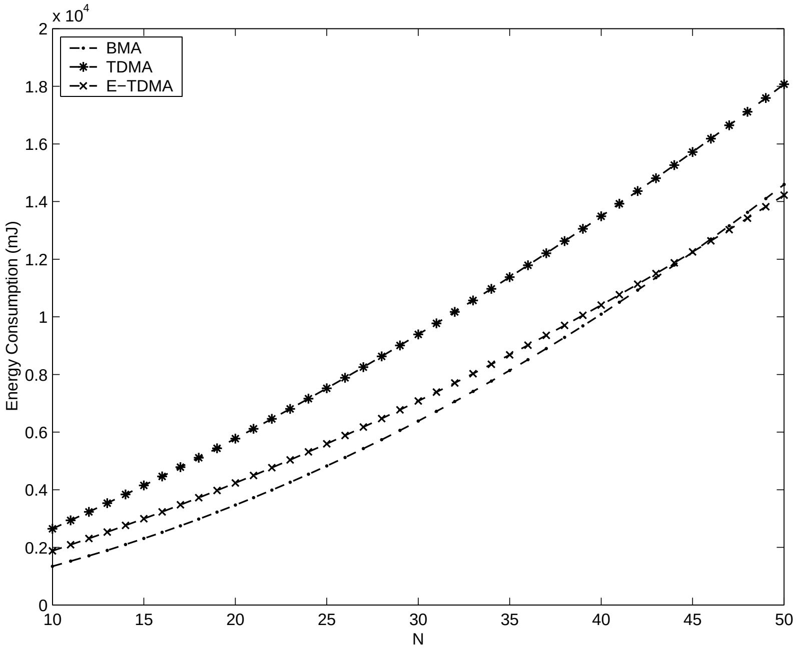

Figure 3.7 Average total cluster energy consumption vs. N ($k = 4$ and $p = 0.3$)

In Figure 3.8, we illustrate the impact of the data packet size on the overall system energy consumption for the case of $N = 10$, $k = 4$ and $p = 0.3$. When N and p are relative small, BMA performs better than the two TDMA scheme for large data packet sizes. This is due to the fact that in the BMA MAC scheme, the energy consumption in the contention periods becomes negligible compared to the total energy required to transmit large data packets (see Figure 3.1). When data packet is less than 40 bytes long, both TDMA and E-TDMA outperform BMA.

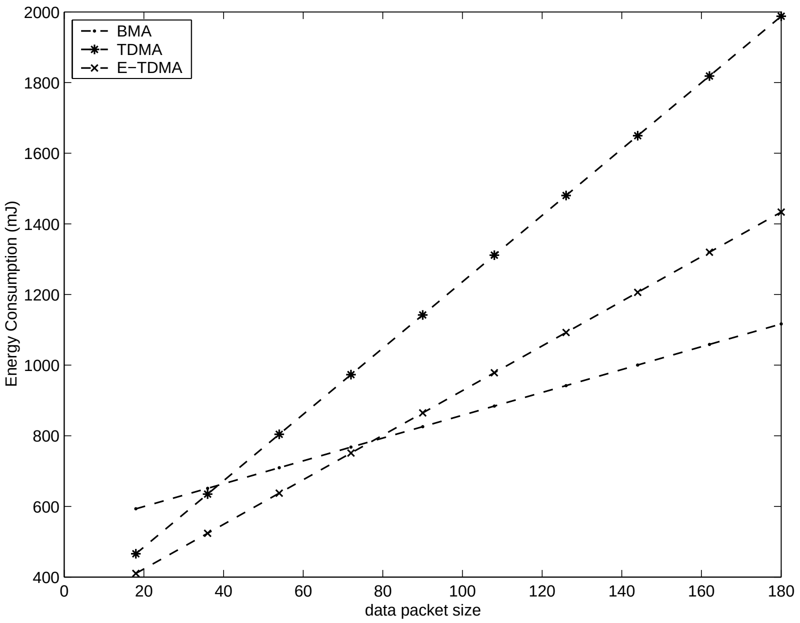

Figure 3.8 Average total cluster energy consumption vs. data packet length

3.3.2 Energy Model II

Model II assumes a simplified radio energy dissipation model, as in [19]. Let E_{elec} (J/b) to represent the energy dissipated by the electronics for transmitting or receiving a 1-bit of data, and ε_{amp} (J/b/m^2) to denote the energy expended by the power amplifier at the transmitter for achieving an acceptable bit energy to noise power spectral density ratio (E_b/N_0) at the receiver. Then, when source node j transmits a k-bit packet over distance d_j, the radio dissipates

$$E_{Tx}(k,d) = kE_{elec} + \varepsilon_{amp}kd^2, \tag{3.30}$$

and to receive a k-bit packet, the radio consumes

$$E_{Rx}(k) = kE_{elec}. \tag{3.31}$$

We express the energy dissipated by the radio during each idle listening period as

$$E_I(k) = \beta E_{Rx}(k). \tag{3.32}$$

As mentioned earlier, during each idle listening mode, the radio dissipates 50% to 100% of the energy dissipated in the receiving mode [31]. Hence, β is the ratio of the energy dissipated in receiving mode to the energy dissipated in idle listening mode.

Let k_c be the normal control packet size, k_d be the data packet size, and d_j be the distance between node j and the cluster-head. We let d_{max} be the maximum distance between nodes and the cluster-head. Note that in BMA, the control packets sent by the source nodes to the cluster-head contain fewer bytes (1-bit control message plus packet header information) than the normal control packets. Hence, for BMA we use k_{c_B} to represent the source to cluster-head control packet size.

We also let T_d to be the time required to transmit/receive a data packet, T_c to be the time required to transmit/receive a normal control packet, and T_{c_B} the time required for a BMA source node to transmit a control packet.

3.3.2.1 BMA

All nodes keep their radios on during the whole contention period. Each source node transmits a control packet during its scheduled slot, and remains idle for $(N - 1)$ slots. After receiving the transmission schedule from the cluster-head, each source node sends its data packet to the cluster-head over its scheduled time slot. Therefore, the energy consumption by the j^{th} source node during a single session is:

$$\begin{aligned} E_{sn}(j) &= E_{Tx}(k_{c_B}, d_j) + (N-1)E_I(k_{c_B}) \\ &+ E_{Rx}(k_c) + E_{Tx}(k_d, d_j). \end{aligned} \tag{3.33}$$

Each non-source node stays idle during the contention period and keeps its radio off during the data transmission periods. Thus, over a single session, it consumes the following energy:

$$E_{in}(j) = NE_I(k_{c_B}) + E_{Rx}(k_c). \tag{3.34}$$

During the contention period of the i^{th} session, the cluster-head node receives n_i control packets and stays idle for $(N-n_i)$ contention slots. During the following transmission period, it receives n_i data packets. Hence, the energy dissipated in the cluster-head node during a single session is

$$\begin{aligned} E_{ch} &= n_i E_{Rx}(k_{c_B}) + n_i E_{Rx}(k_d) \\ &+ (N-n_i)E_I(k_{c_B}) + E_{Tx}(k_c, d_{max}). \end{aligned} \tag{3.35}$$

Therefore the total system energy consumed in each cluster during the i^{th} session is:

$$E_{si} = \sum_{j=1}^{n_i} E_{sn}(j) + \sum_{j=1}^{N-n_i} E_{in}(j) + E_{ch}. \tag{3.36}$$

Each round consists of k sessions, thus the total system energy dissipated during each round is:

$$E_{round} = \sum_{i=1}^{k} E_{si}. \tag{3.37}$$

The average system energy consumed during each round is therefore

$$\begin{aligned} E &= E\left[E_{round}\right] = E\left[\sum_{i=1}^{k} E_{si}\right] = kE\left[E_{si}\right] \\ &= k\left[\sum_{j=1}^{n} E_{sn}(j) + \sum_{j=1}^{N-n} E_{in}(j) + E_{ch}\right]. \end{aligned} \tag{3.38}$$

We define the average packet latency (delay) as the average time required for a packet to be generated by a source node and received by the cluster-head. For BMA, the average packet latency is

$$L = \frac{NT_{c_B} + T_c + nT_d}{n}. \tag{3.39}$$

3.3.2.2 TDMA

During the contention period, the communication between the cluster-head and all other nodes is accomplished by using non-persistent CSMA. Suppose α is the throughput of non-persistent CSMA when there are N attempts per packet time. The energy consumption by the j^{th} node during the contention period is

$$E_n(j) = \frac{1}{\alpha}E_{Tx}(k_c, d_j) + \frac{N-1}{\alpha}E_I(k_c) + E_{Rx}(k_c). \tag{3.40}$$

The cluster-head node receives N control packets and dissipates the energy

$$E_{ch} = NE_{Rx}(k_c) + E_{Tx}(k_c, d_{max}). \tag{3.41}$$

Therefore, the total system contention energy dissipation is expressed as

$$E_c = \sum_{j=1}^{N} E_n(j) + E_{ch}$$

$$\begin{aligned} &= \sum_{j=1}^{N} \frac{1}{\alpha} E_{Tx}(k_c, d_j) + E_{Tx}(k_c, d_{max}) \\ &+ \frac{N(N-1)}{\alpha} E_I(k_c) + 2N E_{Rx}(k_c). \end{aligned} \tag{3.42}$$

During the i^{th} frame, the energy dissipated in source node j is equal to

$$E_{sn}(j) = E_{Tx}(k_d, d_j). \tag{3.43}$$

A non-source node turns and leaves on its radio during its scheduled time slot, and therefore, the energy consumption is

$$E_{in} = E_I(k_d). \tag{3.44}$$

Also, during the i^{th} frame, the cluster-head consumes the following energy

$$E_{chi} = n_i E_{Rx}(k_d) + (N - n_i) E_I(k_d). \tag{3.45}$$

Hence, the system energy dissipated during the i^{th} frame is

$$\begin{aligned} E_{fi} &= \sum_{j=1}^{n_i} E_{sn}(j) + (N - n_i) E_{in} + E_{chi} \\ &= \sum_{j=1}^{n_i} E_{Tx}(k_d, d_j) + 2(N - n_i) E_I(k_d) + n_i E_{Rx}(k_d). \end{aligned} \tag{3.46}$$

The total system energy dissipated during each round is computed as

$$E_{round} = E_c + \sum_{i=1}^{k} E_{fi}. \tag{3.47}$$

The average system energy consumed during each round is hence

$$\begin{aligned} E &= E\left[E_{round}\right] \\ &= E_c + kE\left[E_{fi}\right] \end{aligned}$$

$$\begin{aligned} &= E_c + k\left[\sum_{j=1}^{n} E_{Tx}(k_d, d_j)\right. \\ &+ \left. 2(N-n)E_I(k_d) + nE_{Rx}(k_d)\right]. \end{aligned} \tag{3.48}$$

The average packet latency is

$$L = \frac{\left(\frac{N}{\alpha}+1\right)T_c + kNT_d}{kn}. \tag{3.49}$$

3.3.2.3 E-TDMA

For E-TDMA, the total system contention energy dissipation is same as that of TDMA

$$\begin{aligned} E_c &= \sum_{j=1}^{N} E_n(j) + E_{ch} \\ &= \sum_{j=1}^{N} \frac{1}{\alpha} E_{Tx}(k_c, d_j) + E_{Tx}(k_c, d_{max}) \\ &+ \frac{N(N-1)}{\alpha} E_I(k_c) + 2NE_{Rx}(k_c). \end{aligned} \tag{3.50}$$

During the i^{th} frame, the energy dissipated in source node j is equal to

$$E_{sn}(j) = E_{Tx}(k_d, d_j). \tag{3.51}$$

A node with no data to send keeps its radio off during its allocated time slots, and therefore, the energy consumption is

$$E_{in} = 0. \tag{3.52}$$

Also, during the i^{th} frame, the cluster-head consumes the following energy

$$E_{chi} = n_i E_{Rx}(k_d) + (N - n_i)E_I(k_d). \tag{3.53}$$

Hence, the system energy dissipated during the i^{th} frame is

$$\begin{aligned} E_{fi} &= \sum_{j=1}^{n_i} E_{sn}(j) + (N - n_i)E_{in} + E_{chi} \\ &= \sum_{j=1}^{n_i} E_{Tx}(k_d, d_j) + (N - n_i)E_I(k_d) + n_i E_{Rx}(k_d). \end{aligned} \tag{3.54}$$

The total system energy dissipated during each round is computed as

$$E_{round} = E_c + \sum_{i=1}^{k} E_{fi}. \tag{3.55}$$

Hence, the average system energy dissipated in each round is:

$$\begin{aligned} E &= E\left[E_{round}\right] \\ &= E_c + k \left[\sum_{j=1}^{n} E_{Tx}(k_d, d_j)\right. \\ &+ \left.(N - n)E_I(k_d) + nE_{Rx}(k_d)\right]. \end{aligned} \tag{3.56}$$

The average packet latency is as given in TDMA.

3.3.2.4 Analytic Results

In the evaluation, Model II uses the topology as shown in Figure 3.3. The parameters of the energy consumption model are set as follows: E_{ele} = 50 nJ/bit, ε_{amp} = 10 pJ/bit/m^2, and $\beta = 0.8$. Unless noted, we assume a data packet size of 500 bytes and a normal control packet size of 25 bytes. For BMA, the source to cluster-head control packet size is set 16 bytes. We assume a 1-Mbps transmission rate. For TDMA and E-TDMA, we set α to 0.815 (see [21] for details). We assume the distance between a node and the cluster-head to be a random variable uniformly distributed over the interval $[10, 100]$ meters.

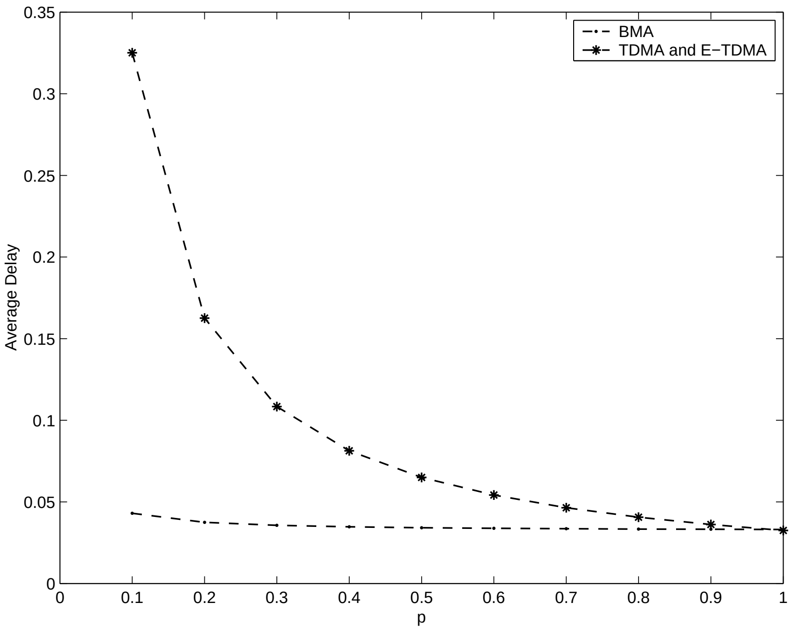

Figure 3.9 Average packet latency vs. p for the case of $N = 20$ and $k = 4$

Figure 3.9 compares the three techniques in terms of the average packet latency. For large p, all three schemes have similar low average packet latencies. However, as p goes to zero, the average packet latency for both TDMA and E-TDMA grows exponentially, whereas for BMA, it stays relative low.

Figure 3.10 provides a comparison of the three intra-cluster MAC techniques in terms of the average total cluster energy consumption per round as a function of p for the case of $N = 20$ and $k = 4$. When p is less than about 0.7, BMA performs better than both TDMA and E-TDMA. The main energy conservation comes from avoiding idle listening. When p is above 0.7, the idle period is small and thus the energy cost from the contention periods outweighs the energy saving from the idle periods. Note that as p increases, the

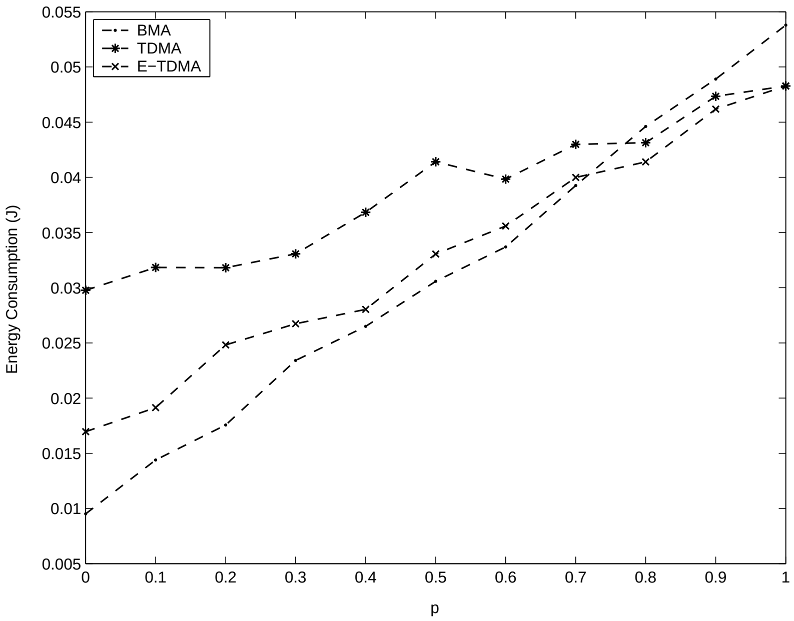

Figure 3.10 Average total cluster energy consumption vs. p ($N = 20$ and $k = 4$)

average idle period decreases. Thus, for p above 0.7, both TDMA schemes perform better. Obviously E-TDMA outperforms TDMA for all values of p. The energy savings by E-TDMA relative to TDMA grow as p approaches zero.

Figure 3.11 compares the three intra-cluster MAC schemes in terms of average total cluster energy consumption versus the number of sessions/frames per round for the case of $N = 20$ and $p = 0.3$. Clearly, for $k = 1$ to 14 sessions/frames per round, BMA is a much more energy conservative scheme than E-TDMA. Note that this is not true for all cases. This is illustrated in Figure 3.12. That is, for the case of $p = 0.3$, $k = 4$, and data packet size of 500 bytes, BMA performs better for $N \leq 37$. However, by comparing Figure 3.12 with Figure 3.13, we observe that as we increase the data packet size, BMA performs better than E-TDMA for much higher values of N.

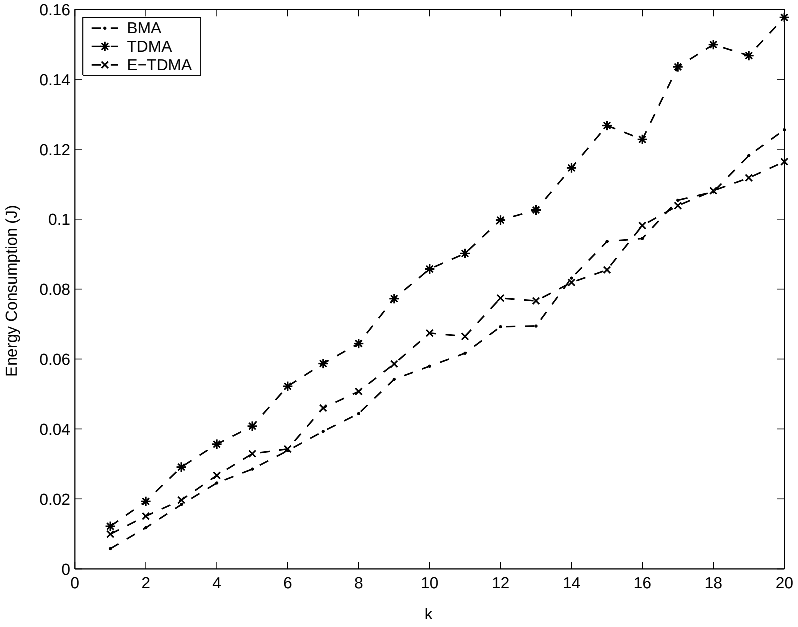

Figure 3.11 Average total cluster energy consumption vs. k ($N = 20$ and $p = 0.3$)

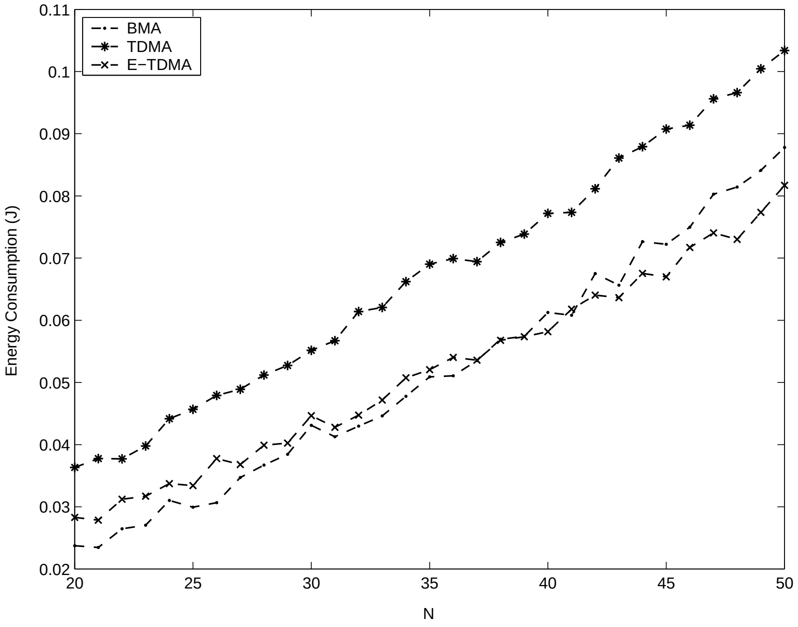

Figure 3.12 Average total cluster energy consumption vs. N (data packet size = 500 bytes)

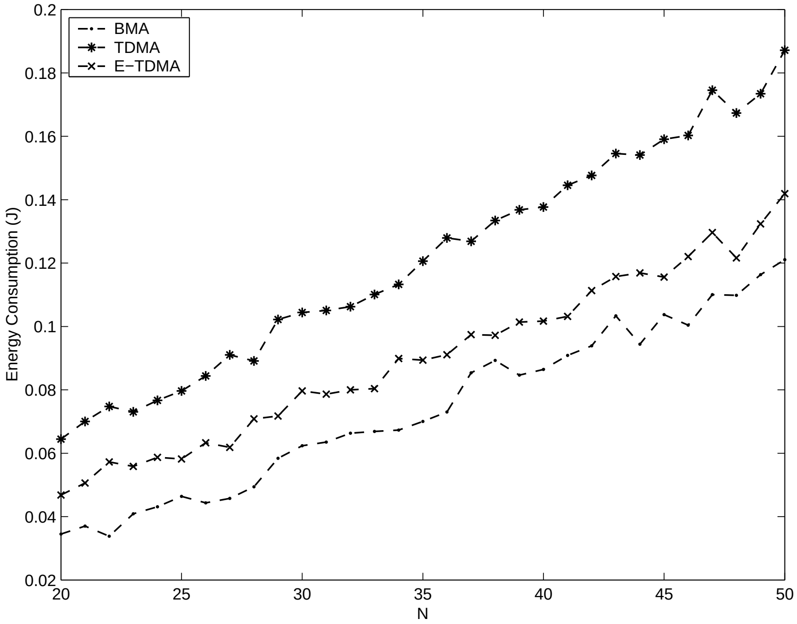

Figure 3.13 Average total cluster energy consumption vs. N (data packet size = 1000 bytes)

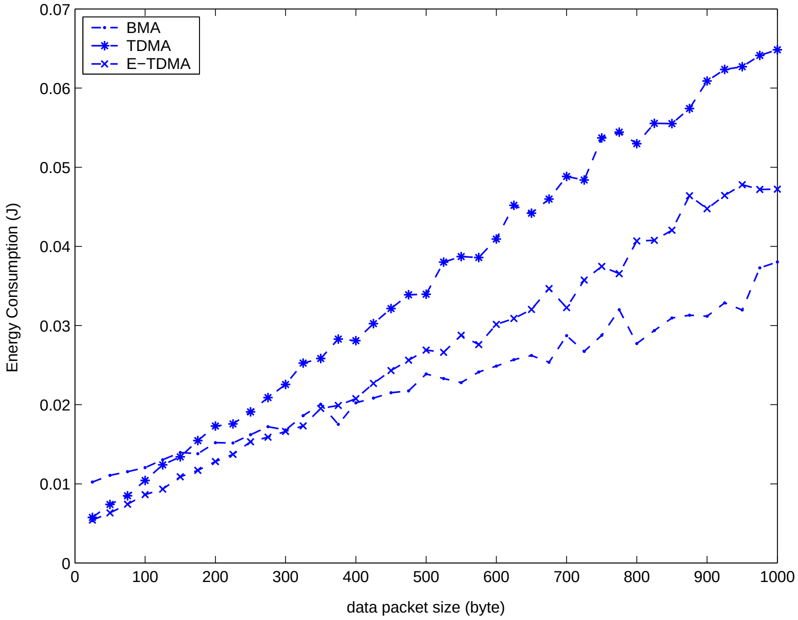

Figure 3.14 Average total cluster energy consumption vs. data packet length

In Figure 3.14, we illustrate the impact of the data packet size on the overall system energy consumption for the case of $N = 20$, $k = 4$ and $p = 0.3$. When N and p are relatively small, BMA performs better than the two TDMA scheme for large data packet sizes. This is due to the fact that in the BMA MAC scheme, the energy consumption in the contention periods becomes negligible compared to the total energy required to transmit large data packets.

3.3.3 Discussion of Results

Comparing Figure 3.4 and Figure 3.9, Figure 3.5 and Figure 3.10, Figure 3.6 and Figure 3.11, Figure 3.7 and Figure 3.12, Figure 3.8 and Figure 3.14, we can see that energy model I and model II show similar results. The results demonstrat that:

1. In terms of average packet latency, BMA is superior. When the possibility p that a node has data to transmit is large, BMA, TDMA and E-TDMA have similar low average packet latencies. As p goes to zero, the average packet latency for both TDMA and E-TDMA grows exponentially, but BMA stays relatively low[1].

2. In terms of energy consumption, BMA is superior for the cases where the possibility p that a node has data to transmit is relatively small. When the possibility p is relatively large, both conventional TDMA and E-TDMA outperform BMA[2].

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[1] See Figure 3.4 and Figure 3.9.

[2] See Figure 3.5 and Figure 3.10.

3. BMA is more energy-efficient than TDMA and E-TDMA for the case of relatively few sessions/frames per round[3].
4. BMA is superior for the case of relatively few sensor nodes per cluster[4].
5. The performance of BMA improves as the data packet size increases[5].

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[3] See Figure 3.6 and Figure 3.11.

[4] See Figure 3.7 and Figure 3.12.

[5] See Figure 3.8 and Figure 3.14.

CHAPTER IV

SIMULATION

We evaluate the performance of BMA, TDMA and E-TDMA through simulation experiments. All experiments are built in the network simulator ns-2 [44]. We assume that a clustered network has already been formed and there are N non-cluster-head nodes within a cluster. The schemes are compared in terms of energy consumption.

4.1 Simulation Model

Figure 4.1 shows the topology used in the experiments: The topology consists of a cluster with N sensor nodes and one cluster head node. There are n source nodes. The source nodes send data to the cluster head directly. The nodes are deployed randomly through the 100 m $\times$ 100 m area [45]. The node location patterns are generated using CMU's movement generator.

The experiments employ UDP agents[1]. The maximum segment size for UDP agents is set to 2000 bytes. An omni-directional antenna and a Two Ray Ground (d^4 power loss) propagation model are used by sensor nodes [45].

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[1] The operation of the UDP agents is similar to the behavior of the packets we considered in analytic models.

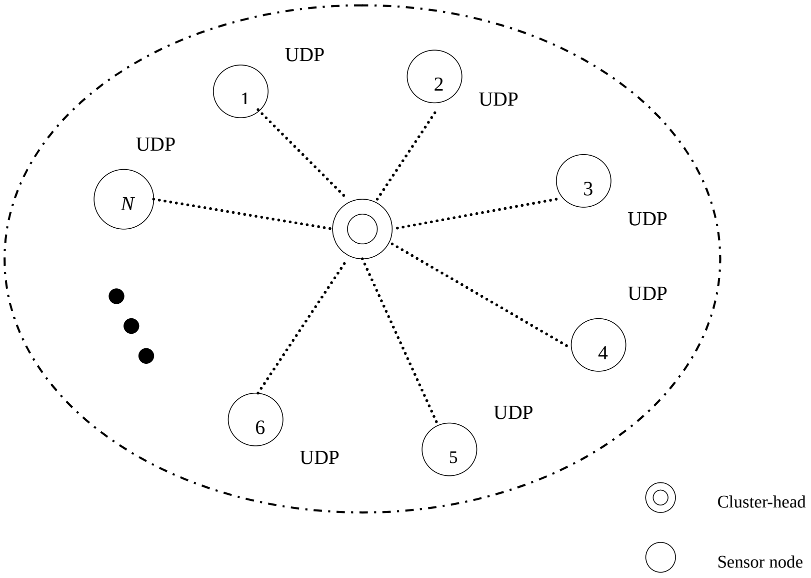

Figure 4.1 Simulation topology

We implement BMA, TDMA and E-TDMA schemes under ns-2, and use the energy model contained in ns-2. Energy model I is implemented as a node attribute in ns-2. The values for the configuration parameters of the energy model are given in Table 4.1. Each node begins with 100 J of energy. The power consumption for transmitting is 462 mW, 346 mW for receiving, and 330 mW for idle listening.

The bandwidth is set to 2 Mbps. The data packet size is 1452 bytes, which includes 1400 bytes payload and 52 bytes header. The control packet size is set to 152 bytes, which consists of 100 bytes payload and 52 bytes header. For BMA, the source to cluster head control packet size is set 72 bytes, which contains 20 bytes palyload and 52 bytes header.

Table 4.1 Parameters for Energy Model

Parameter	Attribute	Values
rxPower	receiving power	0.346 W
txPower	transmitting power	0.462 W
idlePower	idle listening power	0.330 W
initialEnergy	initial energy	100 J

4.2 Simulation Experiment Results

The experiments make the following measurements and calculations:

1. Record the remaining energy of each node when the simulation stops.
2. Record the sleeping time of each node.
3. Calculate the energy consumption of each node.
4. Calculate the total cluster energy consumption.
5. Calculate the average total cluster energy consumption per round.

The energy model under ns-2 counts the sleeping time to the idle time. Therefore, the real energy consumption of a node is described as:

$$\begin{aligned} EnergyConsumption &= InitialEnergy - RemainingEnergy \\ &+ SleepingTime \times idlePower. \end{aligned} \tag{4.1}$$

Figure 4.2 shows the simulation results of the energy consumptions of the three intra-cluster MAC schemes when the number of sessions/frames per round changes from 1 to 10. Figure 4.3 illustrates the analytic results. Comparing Figure 4.2 to Figure 4.3, we can see the simulation results correspond with the analytic results. For the cases of $N = 20$ and $p = 0.3$, BMA performs better than E-TDMA for k relatively small, and E-TDMA is the best choice for k relatively large.

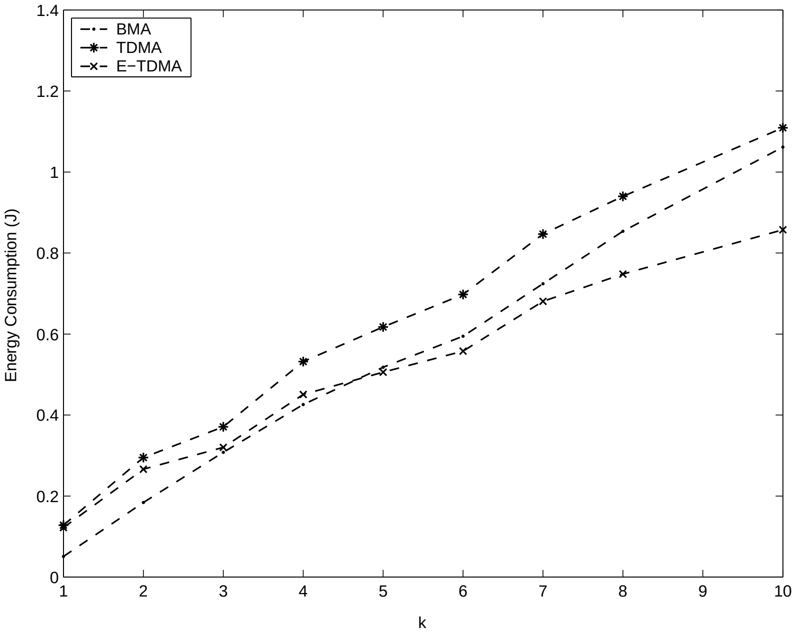

Figure 4.2 Simulation Results. Average total cluster energy consumption vs. k ($N = 20$ and p=0.3)

Figure 4.4 provides the simulation results of the three intra-cluster MAC techniques in terms of the average total cluster energy consumption per round as a function of p for the case of $N = 20$ and $k = 4$. Figure 4.5 illustrates the corresponding analytic results. The

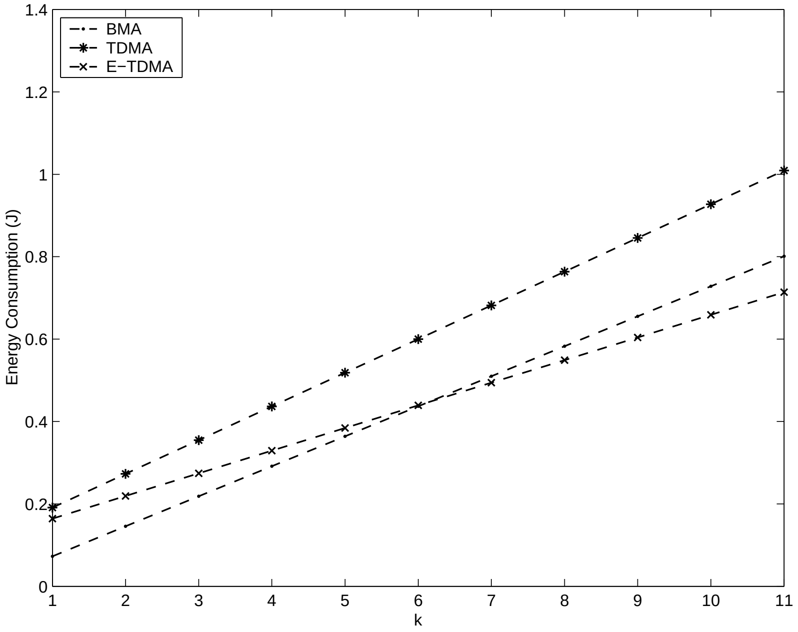

Figure 4.3 Analytic Results. Average total cluster energy consumption vs. k ($N = 20$ and p=0.3)

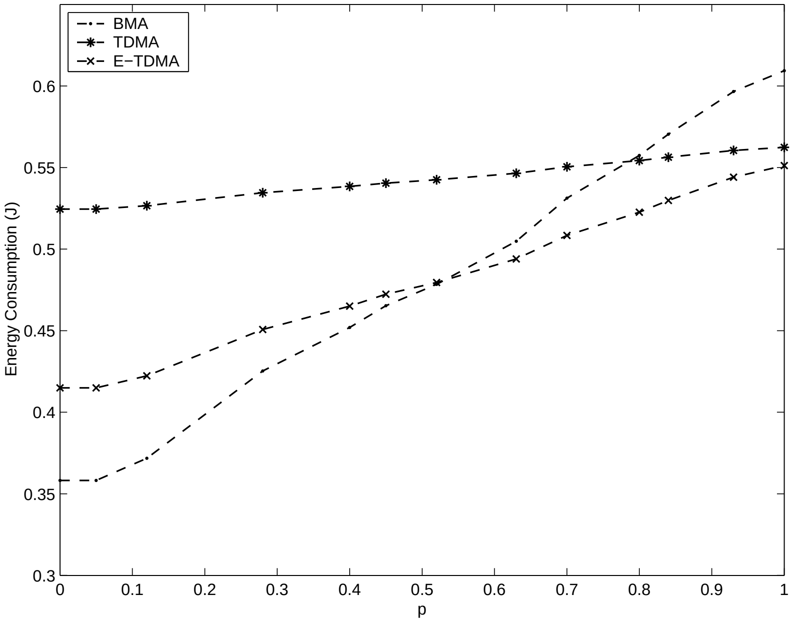

Figure 4.4 Simulation Results. Average total cluster energy consumption vs. p ($N = 20$ and k=4)

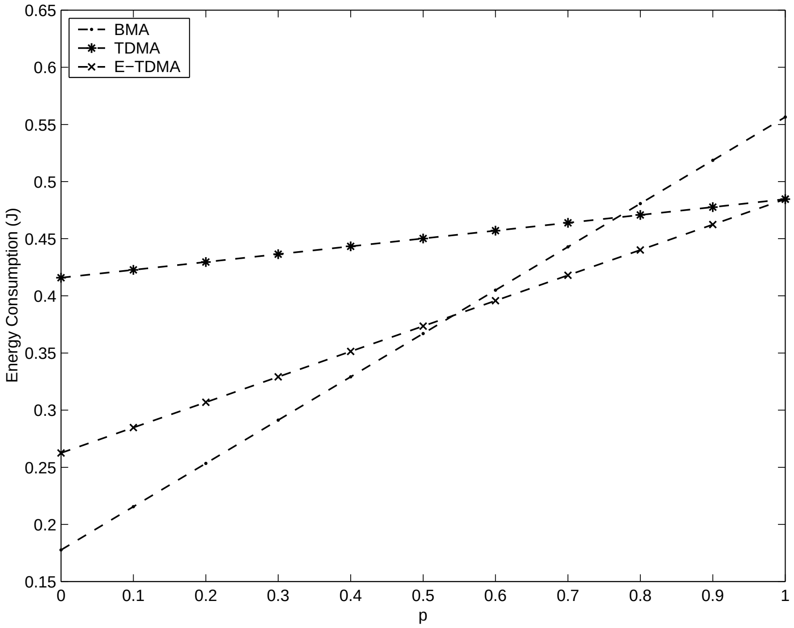

Figure 4.5 Analytic Results. Average total cluster energy consumption vs. p ($N = 20$ and k=4)

simulation results exactly corresponds with the analytic results. When p is less than about 0.5, BMA performs better than both TDMA and E-TDMA. The main energy conservation comes from avoiding idle listening. When p is above 0.5, both TDMA schemes perform better. E-TDMA always outperforms TDMA. The energy savings by E-TDMA relative to TDMA grow as p approaches zero.

Figure 4.6 provides the simulation results of the three intra-cluster MAC techniques in terms of the average total cluster energy consumption per round as a function of N for the case of $p = 0.3$ and $k = 4$. Figure 4.7 shows the corresponding analytic results, which are validated by the simulation results. When N is relatively small, BMA performs better than both TDMA and E-TDMA; otherwise, E-TDMA performs better.

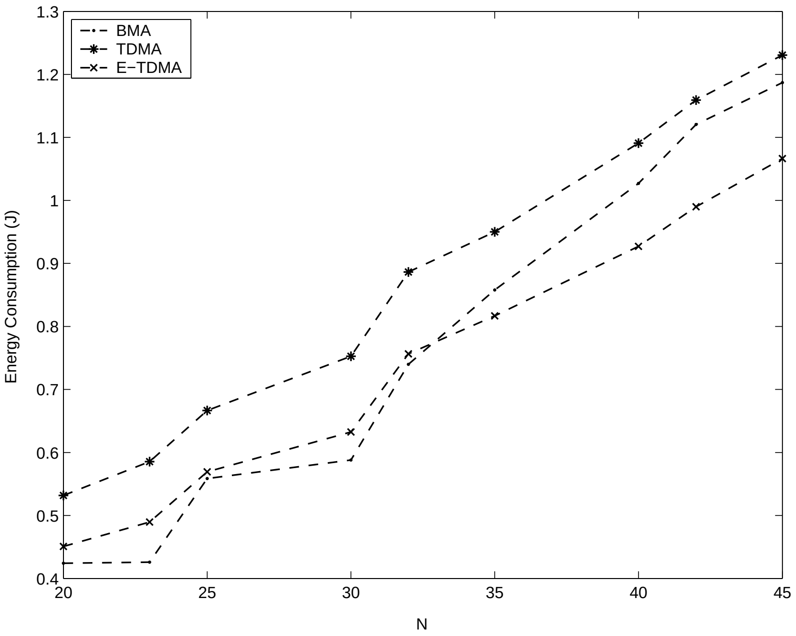

Figure 4.6 Simulation Results. Average total cluster energy consumption vs. N ($p = 0.3$ and k=4)

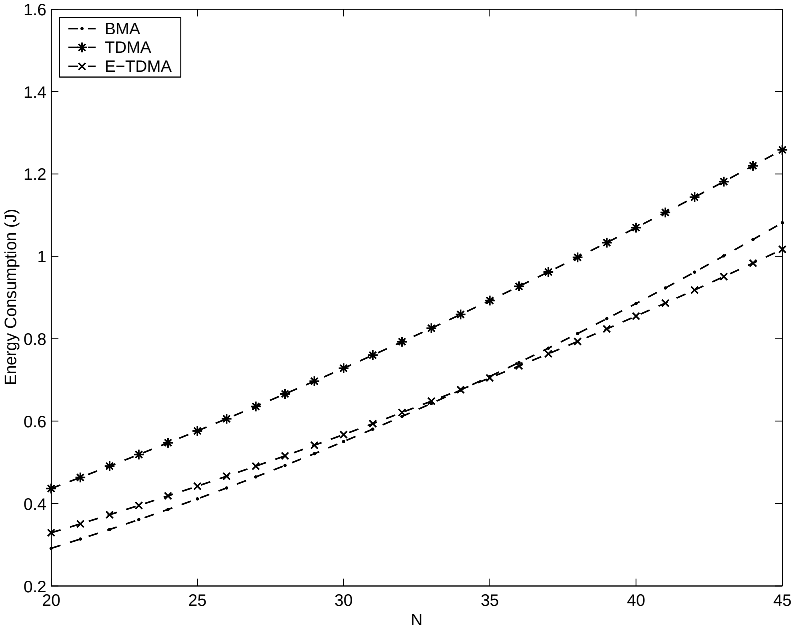

Figure 4.7 Analytic Results. Average total cluster energy consumption vs. N ($p = 0.3$ and k=4)

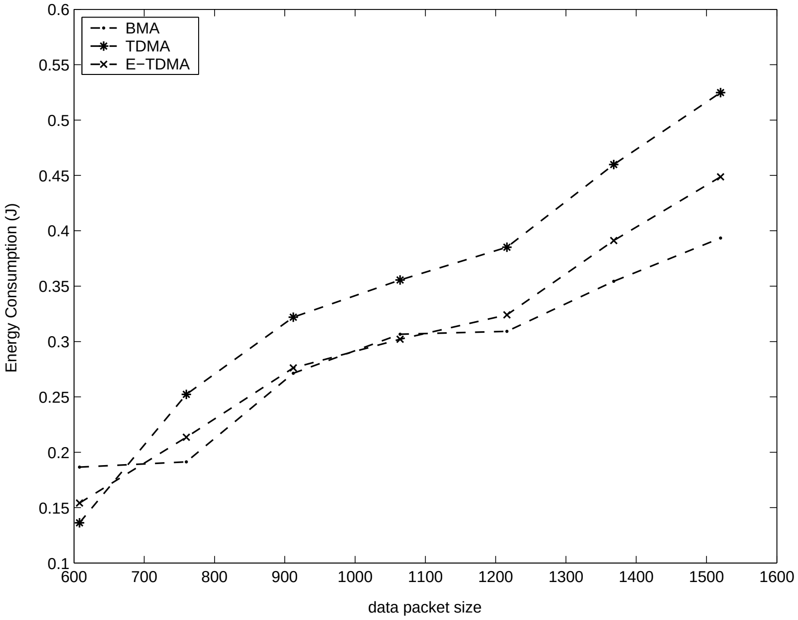

Figure 4.8 Simulation Results. Average total cluster energy consumption vs. data packet size ($N = 20$, $k = 4$ and $p = 0.3$)

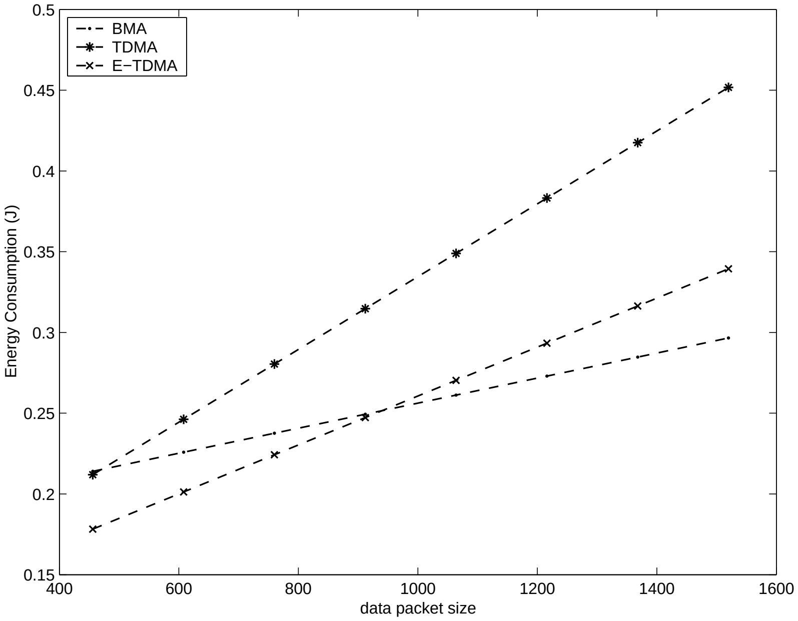

Figure 4.9 Analytic Results. Average total cluster energy consumption vs. data packet size ($N = 20$, $k = 4$ and $p = 0.3$)

The simulation results in Figure 4.8 illustrate the impact of the data packet size on the overall system energy consumption for the case of $N = 20$, $k = 4$ and $p = 0.3$. Figure 4.9 shows the analytic results. Both the simulation results and the theoretical analysis demonstrate that BMA performs better than the two TDMA schemes for the large data packet sizes when the parameters N and p are relatively small. E-TDMA performs best for the case of small data packet sizes.

4.3 Discussion of Results

We constructed simulation experiments to validate the analytic energy models. The simulation results demonstrate that:

1. The simulations validate the analytic energy models successfully.
2. In terms of average packet latency, BMA is superior than TDMA-based MAC schemes.
3. In terms of energy efficiency, BMA is superior for the cases of low and medium traffic loads, relatively few sensor nodes per cluster, and relatively large data packet sizes. The performance of BMA improves as the data packet size increases.
4. In terms of energy efficiency, E-TDMA always outperforms TDMA.

CHAPTER V

CONCLUSIONS AND FUTURE WORK

5.1 Conslusions

In this paper, we propose a simple bit-map-based technique, BMA, which can potentially improve the efficiency of intra-cluster MACs. BMA is intended for event-driven applications, where sensor nodes transmit data to the cluster head only if significant events are observed. Also, we provide two analytic models for the energy and packet latency for BMA, conventional TDMA, and energy efficient TDMA (E-TDMA) when used as intra-cluster MAC schemes.

We compared BMA to conventional TDMA and E-TDMA by applying both theoretical analysis and simulation experiments. The results demonstrated that:

1. In terms of average packet latency, BMA is superior. When the possibility p that a node has data to transmit is large, BMA, TDMA and E-TDMA have similar low average packet latencies. As p goes to zero, the average packet latency for both TDMA and E-TDMA grows exponentially, but BMA stays relatively low.

2. In terms of energy efficiency, BMA performance heavily depends on the sensor node traffic offer load (parameter p), the number of sensor nodes within a cluster

(parameter N), the data packet size and, in some cases, the number of sessions per round (parameter k).

3. Based on the results presented in the paper, we conclude that BMA is superior for the case of low and medium traffic loads, which means the possibility p that a node has data to transmit is relatively small. Under this condition, the main energy conservation comes from avoiding idle listening. When the traffic load is high, which means the possibility p is relatively large, both conventional TDMA and E-TDMA outperform BMA. For this case, the idle period is small and thus the energy cost from the contention periods outweights the energy saving from the idle periods.

4. BMA is superior for the case of relatively few sensor nodes per cluster. The energy saving from the idle periods outweights the energy cost from the contention periods.

5. BMA outperforms TDMA and E-TDMA for the case of relatively few sessions/frames per round. The energy saving from the idle periods outweights the energy cost from the contention periods.

6. The performance of BMA improves as the data packet size increases, because the energy consumption in the contention periods becomes negligible compared to the total energy required to transmit large data packets.

7. In terms of energy consumption, E-TDMA always performs better than TDMA. E-TDMA reduces the energy consumption due to idle listening: when a node has no data to transmit, it keeps its radio off during its allocated time slots.

8. BMA introduces a shorter-time contention period where each node declares its intention to transmit or not in a particular session. This knowledge helps the cluster head to reduce the energy consumption. The cluster head sets up a shorter schedule by excluding all nodes that do not have packets to transmit from the schedule. The cluster head turns off its radio at the end of this schedule. The radio is kept off until the beginning of next session.

For most applications, p, N, k, and the data packet sizes can be controlled. For example, to keep p less than 0.5 and the data packet size large, sensor nodes could aggregate the sensing information from two or more events into one packet.

In addition, BMA and E-TDMA can be combined together to form a dynamically adaptive MAC scheme, where BMA is used in all the rounds that p is perceived to be small (or medium) and E-TDMA is used in all the rounds for which p is perceived to be large.

5.2 Future Work

The possible future works are as follows:

- For this work, the performance evaluation does not consider the possibility of bit-errors in the contention period. A further topic to work on from this thesis would be taking the possibility of bit-errors in the contention period into consideration.

- In order to simplify the problem, we assumed a clustered network had already been formed. A future work could be evaluating the whole operation procedure, including cluster set-up phase.

- There are four main performance parameters of MAC layer: power conservation, average end to end delay, throughput, and control overhead. We only use the power conservation and the average end to end delay parameters to evaluate the proposed scheme. For the future research, the other two performance parameters could be considered.

- In this work, we compare the proposed BMA scheme to TDMA and E-TDMA. This research can be enhanced by comparing the proposed scheme to other MAC protocols, such as S-MAC and IEEE 802.11.

- We have concluded that in terms of energy efficiency, BMA performance heavily depends on the sensor node traffic offer load (parameter p), the number of sensor nodes within a cluster (parameter N), the data packet size (parameter k_d) and, in some cases, the number of sessions per round (parameter k). BMA is superior for the cases of low and medium traffic loads, relatively few sensor nodes per cluster, and relatively large data packet sizes. However, we have not given the optimal values of the parameters p, N, k_d and k. A future research topic could be optimizing the problem

$$0 < \frac{E_{BMA}}{E_{ETDMA}} < 1 \tag{5.1}$$

and finding the optimized relationship between those parameters.

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