SCL: A Cross-Layer Protocol for Wireless Sensor Networks

by

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Abstract

Wireless Sensor Networks are a new class of distributed systems that are used to collect information from the physical area they inhabit. They usually consist of a large number of low-power wireless sensor nodes or motes with limited computation power and memory for sensing of the environment. Energy efficiency and real-time response are important features in the design of sensor networks.

Many communication protocols at different layers have been proposed to reduce the energy consumption of wireless sensor networks. In this thesis, the main objective is to present a method to improve the performance of wireless sensor networks in terms of throughput and latency. We use a hybrid access protocol based on a clustering routing scheme, named SCL (Sigma Cross-Layer) protocol. The main idea is to use a hybrid access protocol to deal with the intra-cluster communications after partitioning the whole network into several clusters. The access scheme incorporates both contention-based (e.g., CSMA) and contention-free (e.g., TDMA) medium access schemes. TDMA is used when the networks are under high traffic load or congestion, and CSMA is used during the clusters' setup phase as well as low contention scenarios.

In summary, the results provided by NS-2 simulations showed the proposed scheme, compared to other scheme which uses TDMA stand-alone, improves the throughput and reduces the latency of sensor networks.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

SNs	Sensor Networks
WSNs	Wireless Sensor Networks
MANET	Mobile Ad hoc Network
CH	Cluster Head
LLC	Logic Link Control
MAC	Medium Access Control
OSI	Open System Interconnection
TCP	Transport Control Protocol
IP	Internet Protocol
FDMA	Frequency-Division Multiple Access
TDMA	Time-Division Multiple Access
CDMA	Code-Division Multiple Access
CSMA	Carrier-Sense Multiple Access
CSMA/CD	Carrier-Sense Multiple Access with Collision Detection
CSMA/CA	Carrier-Sense Multiple Access with Collision Avoidance
LEACH	Low-Energy Adaptive Clustering Hierarchy
LEACH-C	Low-Energy Adaptive Clustering Hierarchy-Centralized
LAN	Local Area Network

CHAPTER 1

Introduction

1.1 Overview

Wireless Sensor Networks (WSNs) are relatively new members of the wireless network family. Typically, they consist of large number of tiny densely distributed small sensor nodes deployed in an ad hoc manner, to sense and transmit some specific physical characteristics of the environment to a Sink node [1]. In a sensor network, there are basically four components: (a) an assembly of distributed or localized sensor nodes equipped with a small microprocessor, small radio communication module, a limited energy source; (b) an interconnection network (usually, but not always, wireless-based); (c) a central point (Sink/Base Station) for information gathering; and (d) a set of computing resources at the sink or beyond it to handle data correlation, status querying, event trending, and data mining [2]. Figure 1.1 shows an example of a sensor network.

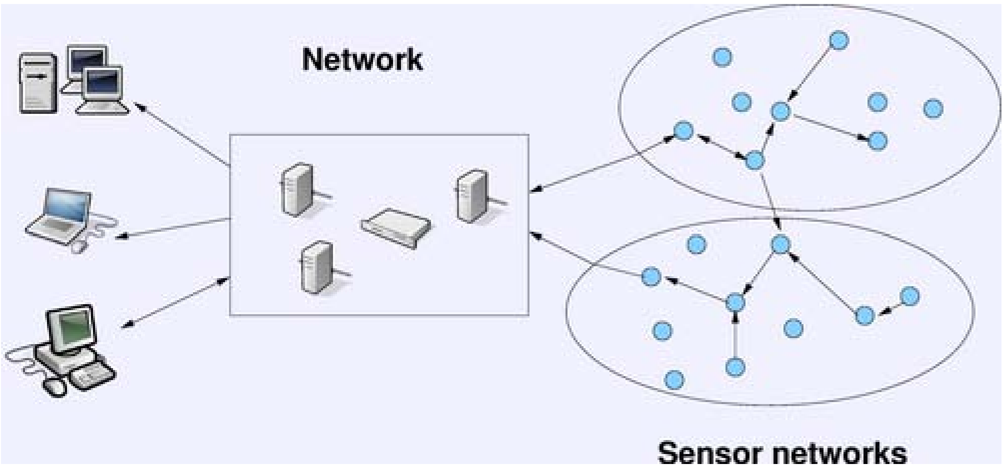


Figure 1.1: A wireless sensor network

As the convergence of the communications, Internet, and information technologies coupled with recent engineering advances, the new generation of sensors and actuators are becoming cheaper. Also with the popularity of cellular phones, PDAs, GPS devices, and intelligent electronics in the post-PC era, they are more distributed, mobile and pervasive in our daily life.

For these developments in the areas of sensor materials, design and concepts, now it is possible to construct a small size embedded system with the equivalent capability of a 90's PC [3]. So from such point of view, after the emergence of WSNs, the latest tendency of Moore's Law begins toward the miniaturization and ubiquity of computing devices.

1.2 Applications of Wireless Sensor Networks

Wireless Sensor Networks are a new group of distributed systems that are an integral part of the real-world they inhabit. Distinguishing from most computers, which work primarily with data created by humans, Sensor Networks (SNs) report the state of the environment around them. So as newer sensor technologies evolve, more and more SNs are used in our daily life [4]. Examples of potential applications of sensor networks include military sensing, physical security, traffic surveillance, air traffic control, industrial and manufacturing automation, process control, video surveillance, distributed robotics, inventory management, environment monitoring, weather sensing, and building and structures monitoring. Reference [5] provides a survey of sensor networks and their applications.

1.2.1 Military Applications

As with many new technologies, army services are the first clients of wireless sensor networks, in another word, without the supports from military and air defense, most of them could not be developed. Nowadays, wireless sensor networks can be treated as an aggregation of military command, communications, control, intelligence, reconnaissance, surveillance, and deployed in places where wired systems sometimes cannot be deployed sometimes. Generally, they can be used in the areas like enemy tracking, reconnaissance of opposing forces and terrain, battlefield surveillance [6], nuclear, biological and chemical attack detection and reconnaissance, battle damage assessment or target classification [7].

1.2.2 Environmental Applications

Besides military applications, another major class of possible applications for WSNs is to provide scientists some specific characteristics of the monitoring area. Example applications include tracking the movement of animals, insects and birds; monitoring atmospheric conditions for weather forecasting; macro-instrumentation for large-scale Earth monitoring and planetary exploration; chemical/biological detection; biological, Earth and environmental monitoring in marine, and soil contexts.

Smart dust motes, tiny and low-cost sensors developed by a UC-Berkeley researcher, show potential in the above application contexts. The battery-powered matchbox-sized wireless networks operating on TinyOS are designed to sense a number of factors [8].

Other applications include industrial monitoring and control, location awareness, mobile wireless low-rate networks for precision location [9], and medical/healthcare monitoring, etc.

1.3 Sensor Network Architectures

As described before, a WSN consists of a group of dispersed sensors (motes) that cover a geographic area in terms of some measured parameters. Reference [10] distinguishes WSNs from some classical wireless networks, such as Mobile Ad hoc Networks (MANETs) [11].

Although they are similar, for example, both classes of networks involve multi-hop communications. However, sensor networks have different characteristics, which result in different design and engineering challenges:

1. Typically, the communication in WSNs is from multiple data sources to one specific data recipient or sink, rather than peer-to-peer communication as in MANETs.
2. Since the source data being collected by different nodes is based on a common event, there is potentially a degree of redundancy in the data, which is not generally the case in MANETs.
3. In most cases, sensor nodes are relatively static at their positions. This means the dynamics in the two types of networks are different.
4. The number of sensor nodes in WSNs may be several orders of magnitude higher than the number of nodes in a MANET.
5. Specially, there is a critical resource constraint in WSNs, such as energy, bandwidth and computational power, while this is not always the case in MANETs. Most of the time, it is not possible for users to replace or recharge the sensors.

Furthermore, one of the main aspects of sensor networks needs to be considered is that they tend to be very application-specific. Just as mentioned in the application section, for different services, the technical details and standards may be different. For these reasons, the plethora of protocols that has been proposed for MANETs may not be suitable for WSNs. Thus alternative methods are needed and a layered method like the one used in OSI imposes a large penalty, and implementations more geared toward the particular application is desirable.

Research on routing protocols for WSNs can be generally classified into two categories: multi-hop routing protocols and cellular/clustering approaches [12], as shown in Figure 1.2 (a) (b).

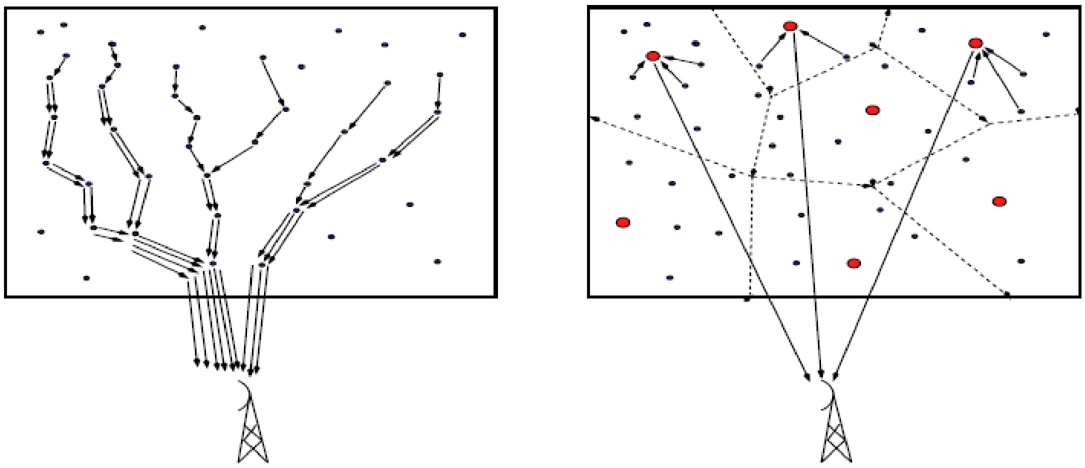


Figure 1.2: Sensor network architectures. (a) Multi-hop routing. (b) Cluster-based routing

Generally, in a sensor network, there are three kinds of nodes, source node, relay node and destination node. Once events occur in the monitored environment, the source node collects the information and then transmits the data packet; Relay node is the one which does not do collection by itself, it just receives the data from the source nodes, and then transmits the meaningful ones to the next node. Destination node acts as a data sink, which receives all the data from the network.

In multi-hop routing, common approaches are based on distance vector and link state. Packets are routed by having each node choose the shortest path to a given destination and storing this information in a routing table. But the disadvantages of this are that the periodic messages needed to maintain valid routes may not only result in network congestion, they may also run out of the limited energy supply of a portable node.

Clustering approach is another method of wireless communication [17]. In this case, each node sends its data to the central cluster-head it belongs to, then the head acts as a relay node to forward the data to the sink end. Clustering enables bandwidth reuse and can thus increase system capacity. By using a clustering approach, better resource allocation can be achieved. In addition, the hierarchical structure obtained using clustering can help to overcome some of the problems with network scalability. Clustering protocols have been investigated in the context of routing protocols [13], [14], or independent of routing [15], [16]. In this thesis, we use a general clustering approach for routing scheme.

1.4 Thesis Outline

In summary, our study focuses on the channel utilization performance in a sensor network: throughput of the network, and latency to gather events information. These factors are modeled using a cross-layer approach, which combines clustering routing with hybrid MAC scheme. The remainder of the thesis is organized as follows: Chapter 2 provides a review of some related work in MAC protocols, and then introduces the model in our research. Chapter 3 describes the cross-layer design for WSNs and presents the simulation results. Finally, Chapter 4 provides conclusions of the thesis and suggests some future work.

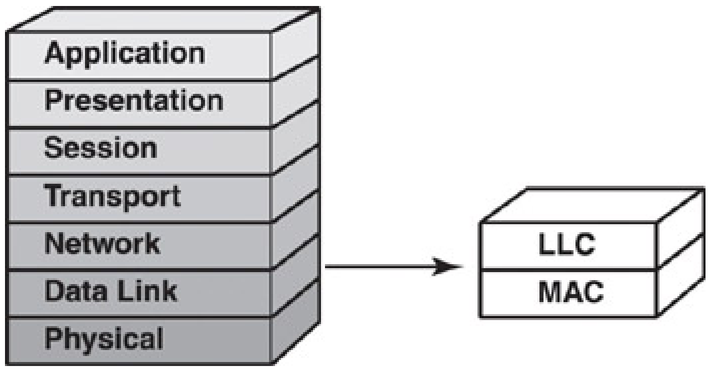
CHAPTER 2

Medium Access Control Protocols in Wireless Sensor Networks

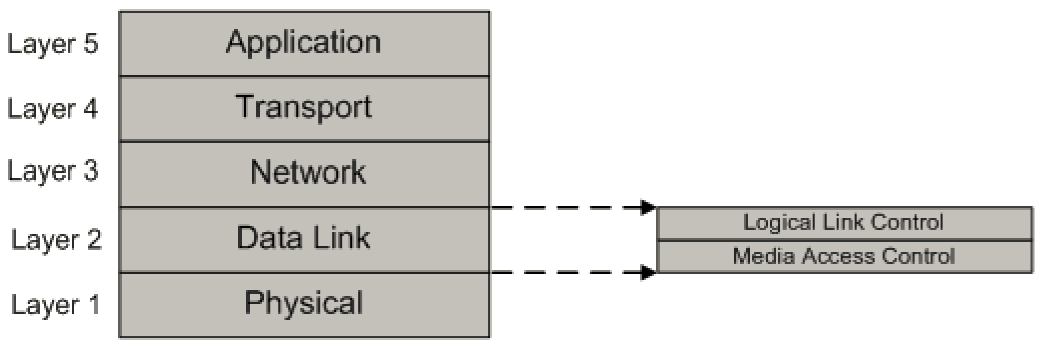
2.1 Overview

Wireless Sensor Networks (WSNs) usually consist of a large number of low-cost, low-power, multi-functional wireless devices deployed over a geographical area in an ad hoc fashion. Unlike communication in wired networks, however, communication in wireless networks is achieved in the form of electromagnetic signal transmission through the air. This common transmission medium must therefore be shared by all sensor network nodes in a fair manner. To achieve this goal, a medium access control protocol is the major determining factor in WSN performance. A number of access control protocols have been proposed for WSNs [23], [24], [25].

Communications among wireless sensor nodes are typically achieved by means of a unique channel acquisition, and it is the characteristic of this channel that only a single node can occupy it for transmission at any time. For shared access of the channel, a Medium Access Control (MAC) protocol needs to be established among these sensor nodes for coordination. From the perspective of the Open System Interconnection (OSI) and TCP/IP reference model, the Data Link Layer (DLL) is made up of two sub-layers: MAC sub-layer and Logical Link Control (LLC) sub-layer (shown in Figure 2.1(a) and (b)), and the MAC protocol functionalities are provided by the lower sub-layer of the DLL. The subdivision of DLL into two parts is necessary to accommodate the logic required to manage access to a shared access communications medium. Furthermore, the presence of the LLC allows support for several MAC options, depending on the structure and topology of the network, the characteristics of the communication channel, and the quality of service requirements of the supported application.



(a)



(b)

Figure 2.1: Sub-layers of the Data Link Layer (a) in OSI Model, (b) in TCP/IP Model

2.2 Representative MAC Protocols

The MAC sub-layer acts as an interface between the LLC sub-layer and the network's physical layer. It provides addressing and channel access control mechanisms that make it possible for several nodes to communicate within a multiple access network that incorporates a shared medium [18]. Although many schemes for medium access have been proposed for

MANETs [19], [20], [21], the design of an efficient MAC scheme for the new realm of sensor networks is still an open research issue.

The choice of the MAC method is the major determining factor in the performance of WSNs. Three major strategies have been proposed to solve the shared medium access problem, and they attempts to strike a balance between achieving the highest-quality resource allocation decision and the overhead necessary to reach this decision by various mechanisms: channel partitioning, random access, and demand assignment.

a. In channel partitioning strategies, the channel is divided into smaller pieces using several techniques, and then each node is allocated a predetermined fixed amount of the channel resources. Each node uses its allocated resources exclusively without competing with the others. Typically, such techniques include frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA).

b. Compared with channel partitioning, whose assignment is static, regardless of whether or not the node has data to transmit, in random access, the link is not divided, No predictable or scheduled time is assigned for any node to transmit. All the back-logged nodes must contend to access the transmission medium. Then collisions occur when more than one node attempt to transmit simultaneously. So to handle this situation, the protocols must include a mechanism to detect collisions and a scheme to schedule colliding packets for subsequent retransmissions. The well-known protocols with such strategies include ALOHA [45], carrier-sense multiple access (CSMA) [46], carrier-sense multiple access with collision detection (CSMA/CD) [47], carrier-sense multiple access with collision avoidance (CSMA/CA) [48].

c. The main objective of demand assignment protocols is to improve channel utilization by allocating the capacity of the channel to contending nodes in an optimum or near-optimum fashion [3]. The protocols typically require a network control mechanism to arbitrate access to the channel between contending nodes. Furthermore, a logical control channel, other than the data channel, may be required for contending nodes to dynamically request access to the communication medium. Generally, demand assignment protocols can be further classified into two branches, centralized and distributed. Polling schemes are the representative of centralized control, while token ring and reservation-based schemes use distributed control [2].

2.3 MAC Protocols for WSNs

In WSNs, the main task of a sensor node is to detect events, perform quick local data processing, and then transmit the data to a specific sink. Power consumption can hence be divided into three domains: sensing, data processing, and communication. Several factors contribute to energy waste, including excessive overhead, idle listening, packet collisions, and overhearing. Among these factors, the retransmission of colliding packets is a significant source of energy waste. A large number of these collisions may lead to severe performance degradation of the MAC layer protocols.

For networks, MAC layer protocols play a key function in determining channel utilization, network delay, and more important, power consumption. The main objective of most MAC layer protocols is to reduce energy waste caused by collisions, idle listening, overhearing, and excessive overhead to prolong the network lifetime. According to the definition of lifetime in [22], the network lifetime is the time interval over which the network can operate effectively.

It can also be referred as the moment when the number of live nodes drops below $(1-\beta)N$ where $0 \le \beta < 1$ and N stands for the total number of nodes in the network [23].

These protocols can be typically categorized into two main groups: contention-based and schedule-based MAC protocols. Using contention-based protocols, a single radio channel is shared by all nodes and is allocated on-demand. However, simultaneous attempts to access the shared communications channel will result in collision. The main function of contention-based MAC protocols is to minimize, rather than completely avoid, the occurrence of collisions. For the other kind, schedule-based protocols are a class of deterministic MAC protocols in which access to the channel is based on a schedule. The channel access is limited to exactly one sensor node at a given time. This is achieved based on pre-allocation of resources to individual sensor nodes. An example of such a scheme is TDMA.

2.3.1 Schedule-Based Protocols

In typical schedule-based MAC protocols for WSNs, the contentions between nodes can be avoided by making a schedule that regulates access to resources. Usually, the resources include time, frequency band, or a CDMA code. And most of the schedule-based protocols for WSNs use a variant of a TDMA scheme whereby the channel is divided into time slots, as depicted in Figure 2.2. A set of N slot contiguous in time domain, where N is a system parameter, form a logical frame which repeats cyclically over time. In each frame, each node is assigned a set of specific slots.

Based on the assigned schedule, a sensor alternates between two modes of operation: active mode and sleep mode. In the active mode, the sensor wakes up and transmits or receives data frames using its assigned time slots within a logical frame. Otherwise, they switch their transceivers off to move themselves into sleep mode for energy conservation. In contrast with contention protocols, TDMA protocols have an expected advantage of energy conservation, because they reduce the duty cycle of the radio, also, there is no overhead and collisions introduced owing to contention.

Nowadays, many variations of TDMA protocol have been proposed for medium access control in WSNs [24], [25], [26].

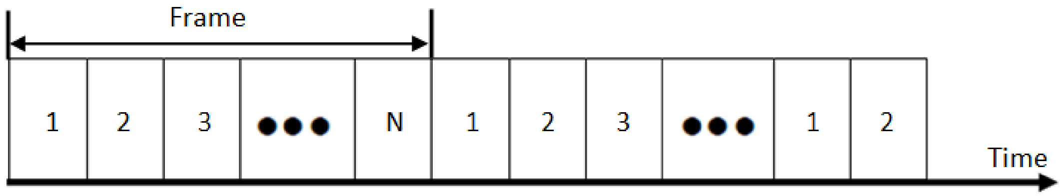


Figure 2.2: TDMA MAC protocol for WSNs

2.3.2 Contention-Based Protocols

Traditional contention-based protocols, unlike the schedule-based ones, require no coordination among the nodes accessing the channel. Nodes that have information to transmit must try to obtain bandwidth while minimizing collisions with other nodes' transmissions. When collision occurs, the colliding nodes back off for a random duration of time before attempting to access the channel again. These MAC protocols are more efficient than the other MAC protocols when nodes have bursty data. However, because they suffer from possible collisions of the data, as all nodes are contending for the resources, these protocols are considered not so well suited for WSN environments.

Carrier-Sense Multiple Access (CSMA) is one such contention-based approach. Using CSMA, when a node has data to send, it first listens to the channel to try to determine if any other node is currently using the channel. Due to the simplicity, flexibility, and robustness, CSMA is used popularly in wireless networks. However, the work in [27] has shown that using this MAC, more energy could be consumed when nodes are in idle mode mainly due to the idle listening.

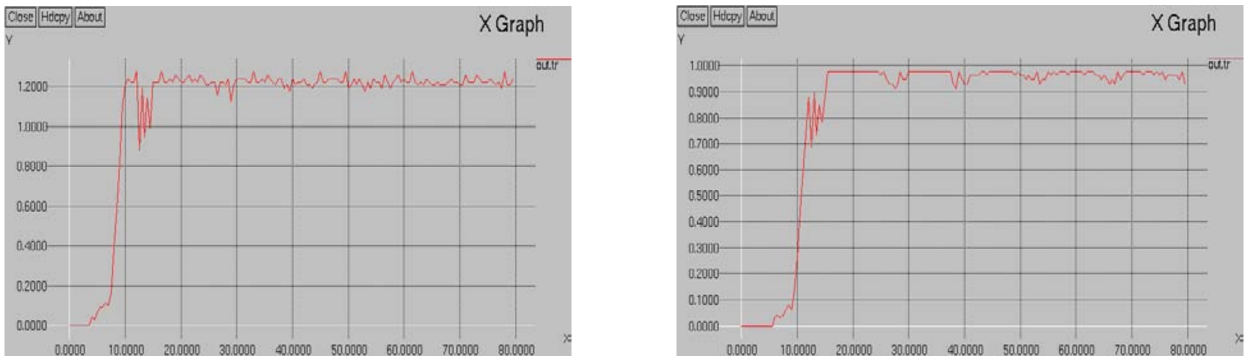
In sensor networks, the applications such as surveillance or monitoring should be vigilant for long period of time, but largely inactive until some events are detected. This means most of the time, WSN is event-driven, the traffic load in a WSN should varies at different time and occasions, so the need to treat the varying contention level should be considered in the design of scalable and stable MAC protocols for WSNs.

2.4 Hybrid MAC Protocols for WSNs

2.4.1 Comparison between CSMA and TDMA

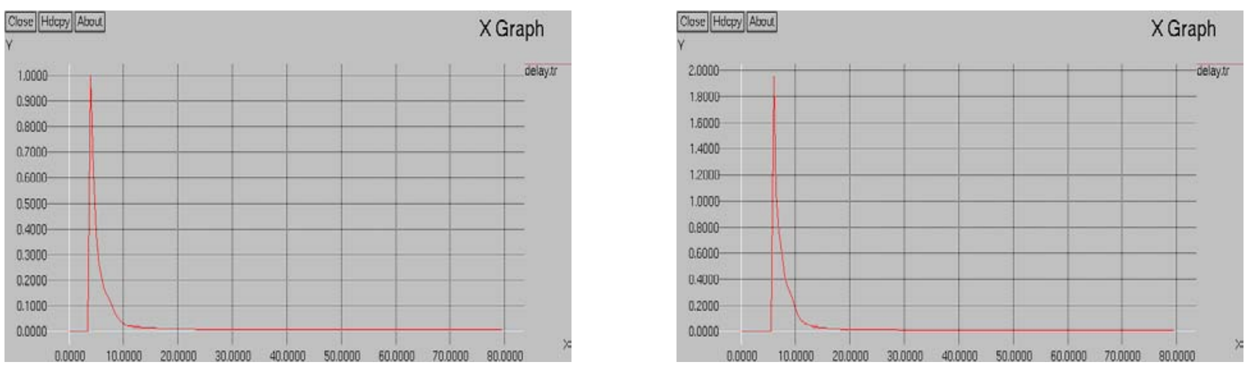
As discussed above, there exists mainly two kinds of MAC protocols, one is contention-based and the other is schedule-based. CSMA and TDMA are the representatives for them respectively. In general, schedule-based protocols can provide good energy efficiency, but they are not flexible to the changes in node density or traffic load. Meanwhile, due to the simplicity, flexibility, and robustness, CSMA is used popularly in wireless networks. However, there are also many disadvantages for it, when more than two conflicting nodes transmit at the same time, the signal fidelity at the destinations may degrade significantly. Furthermore there exists a problem, called the hidden terminal problem, in CSMA. It may cause serious throughput degradation particularly in high-data-rate sensor application. Although RTS/CTS (Request to Send / Clean to Send) [51] can alleviate the hidden terminal problem, it incurs a high overhead in the network [49].

So both CSMA and TDMA have their pros and cons in networks. In this section, we will compare the performances of CSMA and TDMA with different number of traffic nodes by comparing their throughputs and latencies. All results provided are obtained by simulating on NS-2 [33].



(a) (b)

Figure 2.3: Throughput Comparison with 10 Sending Nodes, (a) CSMA; (b) TDMA

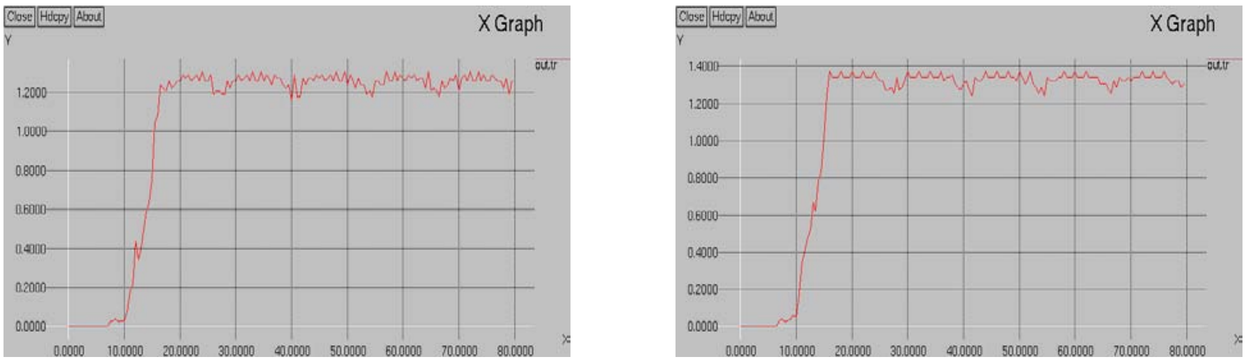


(a) (b)

Figure 2.4: Latency Comparison with 10 Sending Nodes, (a) CSMA; (b) TDMA

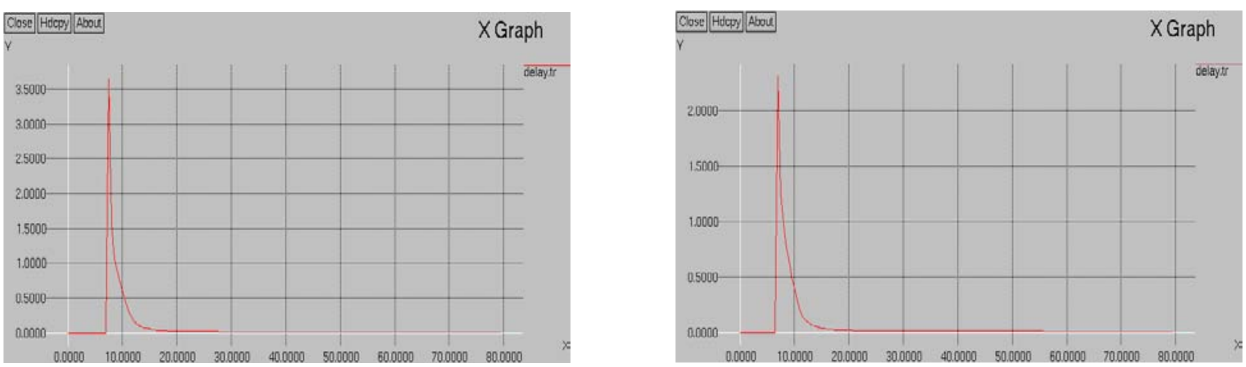
As depicted in Figure 2.3 and Figure 2.4, when the number of traffic nodes is relatively low, (i.e. the traffic load is low), compared with TDMA, CSMA gets better performance metric with higher throughput and lower latency. This is because under low contention, the node in TDMA can only transmits its data during its allocated time slot. While using CSMA, when the traffic load is low, chances of contention are also low, then nodes have more space to compete the available slot to access the channel.

To get a reference for the previous situation, in the following one, we increased the number to 30, which means 30 nodes are transmitting, and 1 Sink node is receiving, after setting these parameters in the simulator, we get the following result figures.



(a) (b)

Figure 2.5: Throughput Comparison with 30 Sending Nodes, (a) CSMA; (b) TDMA



(a) (b)

Figure 2.6: Latency Comparison with 30 Sending Nodes, (a) CSMA; (b) TDMA

Then, from the latter results of Figure 2.5 and 2.6, it is obvious that under high traffic load, because of more collisions incurred by high contention, with scheduled-based MAC protocol, better performance can be achieved.

While, as we mentioned, WSNs are application specific, which means traffic load in WSNs varies with the application. But the need for network to reach relatively high performance should be independent of the time. From this view, a stand-alone MAC scheme for each application is not practical. So combining them together to offset their weakness should be another way for MAC design.

2.4.2 Study of Hybrid MAC Protocols

From comparing the performance of CSMA and TDMA schemes, it can be observed that each of them have merits under some specific cases. Hence by combining them together, a hybrid MAC protocol seems to be an effective way to improve the system's robustness to timing failures, time-varying channel conditions and topology changes. To achieve such purpose, many researchers have focused on hybrid protocols [32].

The sensor-MAC (S-MAC) protocol [23] and timeout-MAC (T-MAC) protocol [28] adopt the strategy to combine CSMA and TDMA together. They also maintain the synchronized time slots, while unlike TDMA, their slots can be much wider than normal TDMA slots. The basic scheme of S-MAC is to put all sensor nodes into a low-duty-cycle mode, listen and sleep periodically. When nodes are listening, they follow a contention rule to compete for accessing the medium, which is similar to the IEEE 802.11 Distributed Coordination Function (DCF) [50]. Because they employ RTS/CTS, synchronization failures in them do not necessarily result in communication failure. As in S-MAC, the nodes in T-MAC also maintain periodic duty cycle to listen for channel activities and transmit data alternating between sleep and wake-up modes. Compared with S-MAC, each node in T-MAC wakes up periodically and all sending nodes are forced to start transmission at the beginning of each active period. Furthermore, the overhead introduced by using RTS/CTS is quite high, whereas in most cases, the data payloads are relatively small in sensor networks.

In [29], the authors explored a seamlessly switching algorithm between TDMA and CSMA called Probabilistic TDMA (PTDMA) for wireless LAN environment, depending on the level of contention. As in TDMA, the real time is slotted, and PTDMA adapts the behavior of MAC between CSMA and TDMA by adjusting the access probability of the number of owners “a” and that of nonowners “b” according to a function $a+(M-1)b=1$, where M is the number of sending nodes.

Zebra MAC (Z-MAC) [30], a relatively new hybrid MAC scheme for sensor networks was proposed by Dr. Rhee and his colleagues in 2008. It combines the strengths of TDMA and CSMA, and the main feature of Z-MAC is its adaptability to the level of contention in the network. When the level is low, it behaves like CSMA, otherwise, like TDMA.

In Z-MAC, a time slot is assigned to each node at the time of deployment by using DRAND [31], a distributed and scalable time slot allocation protocol for WSNs. After such phase, the node assigned to a slot is called an owner of that slot, and the others are nonowners of that slot. Unlike TDMA, a node can transmit during any time slot in Z-MAC. However, owner of that slot has higher priority over the nonowners to access the channel in its slot. And if the owner does not use the channel in its slot, after waiting a period of back-off time, the nonowners can compete for the slot, just like in CSMA. So Z-MAC can dynamically switch its behavior of MAC between CSMA and TDMA according to the level of contention in the network. Furthermore, some enhanced algorithms based on Z-MAC were proposed, like a novel algorithm in [37], which is an improvement of the distributed time slots assignment used in Z-MAC, by incurring the functions of Latin Square Matrix and Collision Avoidance near Intersection of

Grids (CAIG). And in [38], the authors presented ER-MAC, an enhanced hybrid MAC protocol for emergency WSNs with flexibility to adapt to the changes on traffic and topology.

As a relatively good hybrid MAC protocol, in the next section, we will present the performance of Z-MAC by simulating it on NS-2.

2.4.3 Simulation Study of Z-MAC

There are two modes in the simulations: 1. LCL (Low Contention Level), in this mode, any node can compete to transmit in any slot, just like CSMA; 2. HCL (High Contention Level), in such one, only the owners of the current slot and their one-hop neighbors have the right to compete for channel access.

Z-MAC was simulated using NS2, though the results are slightly different from the original ones, the trends reflected from them are the same. In this simulation, the total number of nodes is 104, the topology is a square area with 300 by 300, after using DRAND (Distributed TDMA Scheduling for Sensor Networks), there exists a schedule table for the network to prevent the problem of hidden terminals in every two-hop neighbors, the number of slots is 29, and after setting the system parameters shown in Table 1 in Appendix, the slot size is 0.00138s, the number of sending nodes is increased from 1 to 30.

The following figures show the throughputs of simulation results in different ZMAC modes.

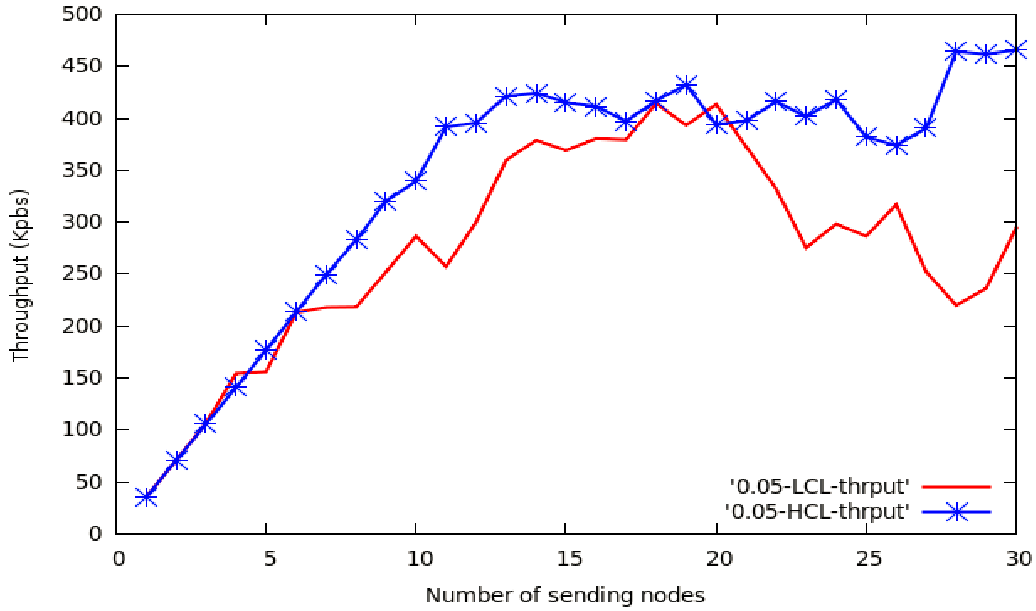


Figure 2.7: Throughputs in Z-MAC simulation

Form Figure 2.7, it can be observed that as the number of source nodes increases, there will be more contention situations, then the performances in the HCL modes are slightly better than the ones under LCL mode, because with more contentions, the MAC will behave like TDMA, then using HCL mode, there are relatively fewer contentions in the network than LCL mode. Under low contention, both modes act as CSMA, so their performances are similar to each other. This result matches the analysis we made for hybrid MAC protocol in the former sections, and verifies the merits by combining contention- and schedule-based protocols together.

However, because of the time slots distribution algorithm used in Z-MAC, there is a maximum amount of slots according to the topology. As in the simulation above, there are totally 104 nodes in the network, while only 29 slots can be assigned to avoid the hidden terminals problem. So from this point of view, Z-MAC is not practical for a large scale event-driven network.

In the following chapter, we will use the idea of the hybrid MAC protocols to improve the measured performance of a sensor network under various traffic conditions, and also, clustering routing method will be introduced to deal with the limited slots problem in Z-MAC. This results in that enhanced system throughput and reduced latency for transmissions. Also, for comparison, we will compare the proposed one with the one which only uses TDMA as MAC protocol.

Chapter 3

Cross-Layer Design for WSN

3.1 Overview

During the past few years, increased interest in the potential use of WSNs in various applications have been witnessed around the world, such as disaster management, border protection and security surveillance. In these applications, the sensor nodes are usually expected to be remotely deployed in large numbers and to operate autonomously in unattended environments. In WSNs, the transmission medium is shared by all nodes within each others' transmission range, and because of limited amount of energy and scarcity of the medium spectrum, choosing appropriate network architecture for routing is deemed to be an important step for sensor networks. Based on [17], the transmission energy for transmitting a k-bit message to a distance d receiver can be computed as:

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d) = \mathrm{E}_{elec} * k + \varepsilon * k * d^{\alpha} \quad (3.1)$$

where $E_{Tx-elec}$ is the transmission electronics energy consumption, E_{Tx-amp} is the transmit amplifier energy consumption, ε is a constant coefficient for this formula, α is a coefficient greater or equal to 2, it is 2 in the free space model. So compared to direct transmission between source nodes and destination sink, using intermediate nodes for relaying should be more efficient in WSNs.

As mentioned in section 1.3, there are two common network architectures adopted in recent research on WSNs, multi-hop and hierarchical (i.e. clustering), while to enable the system to cope with dynamic load and cover a large area of interest without service degradation, cluster-based routing protocols get more spotlight [34], [35]. In this thesis, we will start our research to get better system performance based on using LEACH-C [17], [44], a general centralized clustering application-specific protocol, to be the comparison to our proposed protocol.

Also, to deal with the various traffic patterns during network lifetime and to improve the throughput and reduce latency of the system, it is necessary to implement a hybrid MAC protocol as discussed in Chapter 2 to achieve the goal. The focus of this chapter is to propose a cross-layer design in wireless sensor networks.

3.2 Introduction to LEACH-C

Before we describe the proposed protocol, SCL, a short introduction to the LEACH-C protocol will be provided.

Compared with LEACH, LEACH-C almost uses the same mechanism but with a centralized clustering algorithm, while LEACH is based on a distributed cluster formation algorithm. Though there are advantages to using distributed formation, where each node can make autonomous decisions to place it into clusters, a central control algorithm can produce better clusters by dispersing the cluster-head nodes throughout the network evenly, then the guarantee about the placement and also the number of clusters can be offered, [44] gives these improvements by using LEACH-C.

During the set-up phase of LEACH-C, each node sends information about itself, like the locations and energy level, to the sink. Then it is the sink's mission to determine the clusters formation by running an optimization algorithm, which will result in better network scheme. After this procedure, the sink broadcasts the information about the network formation to each node, which tells them the clusters they belong to and also their TDMA schedule during the current round. Based on the received information, the node gets its TDMA slot for data transmission and goes to sleep until it is time to transmit data to its cluster-head.

Throughout the lifetime of the network, only TDMA acts as the MAC protocol, it is stable, but as analyzed in Chapter 2, it is not efficient for the event-oriented networks, like WSNs. In the following sections, we will describe our proposed protocol, SCL. And in Chapter 4, the performance comparisons between LEACH-C and SCL will show the enhancements by using SCL.

3.3 Simulation Model of SCL

We propose to create a cluster-based MAC protocol that takes advantage of the mechanisms of both CSMA and TDMA protocols. The following assumptions are made in the architecture of the network:

1. All nodes are homogenous, i.e. all have equal capacity in terms of power, computation and communication capability.
2. The nodes in the network are aware of information about themselves, like the node IDs, locations and energy levels.
3. Nodes are stationary.
4. The Sink node has unlimited resource;
5. The number of transmitting nodes is varying, which means the system is event-driven, and traffic load is dynamic.

The purpose of our protocol is to find a balance between contention- and schedule-based protocols in the real world simulation. As the typical cluster-based architecture, the sensor nodes in the network are divided into clusters with one cluster-head in each cluster, and these cluster-heads form the backbone of the sensor network. Therefore, all nodes in one cluster only send data to their own cluster-head. As described in LEACH [17], to reduce the interference between clusters, we use CDMA for the communication between CHs and Sink, while the hybrid MAC protocol is used among nodes within each cluster.

Just as in LEACH, the operation of the protocol is broken into rounds. For each round, it begins with a set-up phase, when the clusters are formed. Then a steady state phase follows, when data is collected by the cluster-heads then transmitted to the sink. The time-line of such operation is depicted in Figure 3.1.

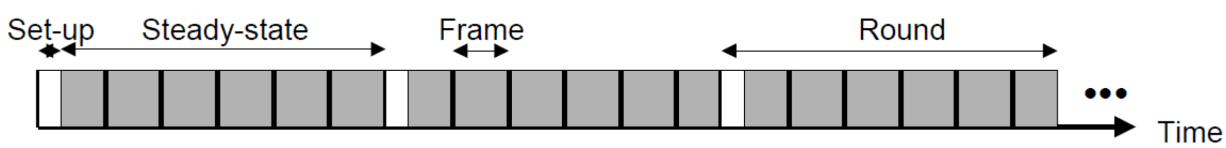


Figure 3.1: Time-line of protocol operation

The following flow chart in Figure 3.2, describes the operation of the proposed protocol in this thesis. A detailed explanation is given bellow, and Figure 3.3 shows the main protocol scheme of the network.

The procedure is described in a flow-graph manner, and then we will introduce the states of the procedure.

3.3.1 Cluster Establishment Procedure

1. Information Advertisement

At the beginning of the procedure, all nodes, which are still alive, send the information about themselves, such as their locations and energy levels to the Sink node in one hop at a specific time, which equals to $id * T_{Info-adv}$, where id is the identity number of the node, and

$T_{Info-adv}$ is a parameter being set as $T_{Info-adv} = \frac{L_{hdr} + l_{interval}}{Bw} * 8$ (8 bits per byte), here L_{hdr} is the length of the header in bytes in each packet, $l_{interval}$ is a constant coefficient to represent an interval, and Bw is the bandwidth of the channel, all the default parameter will be given in the Table 1 in Appendix. After this, they will go to sleep mode and wait for the information from the Sink node.

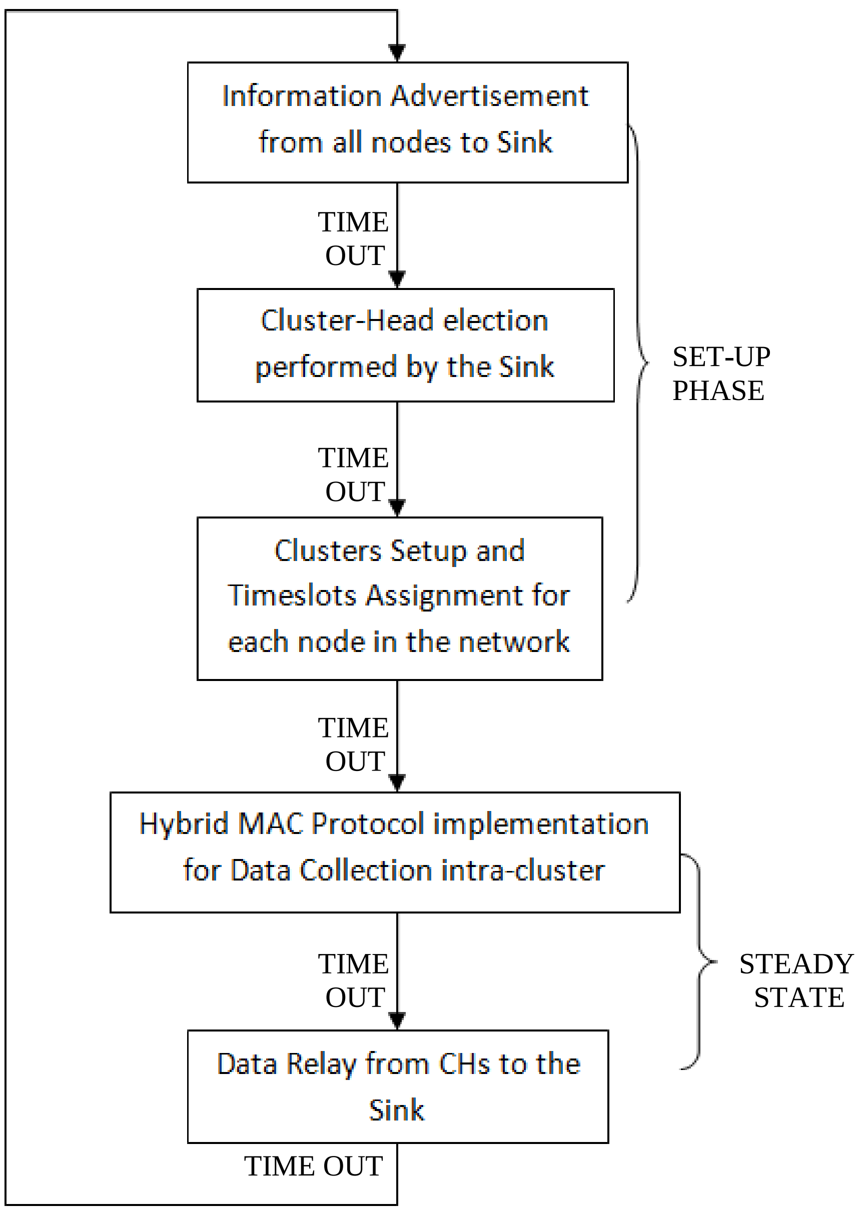


Figure 3.2: Flow-graph of State Transitions

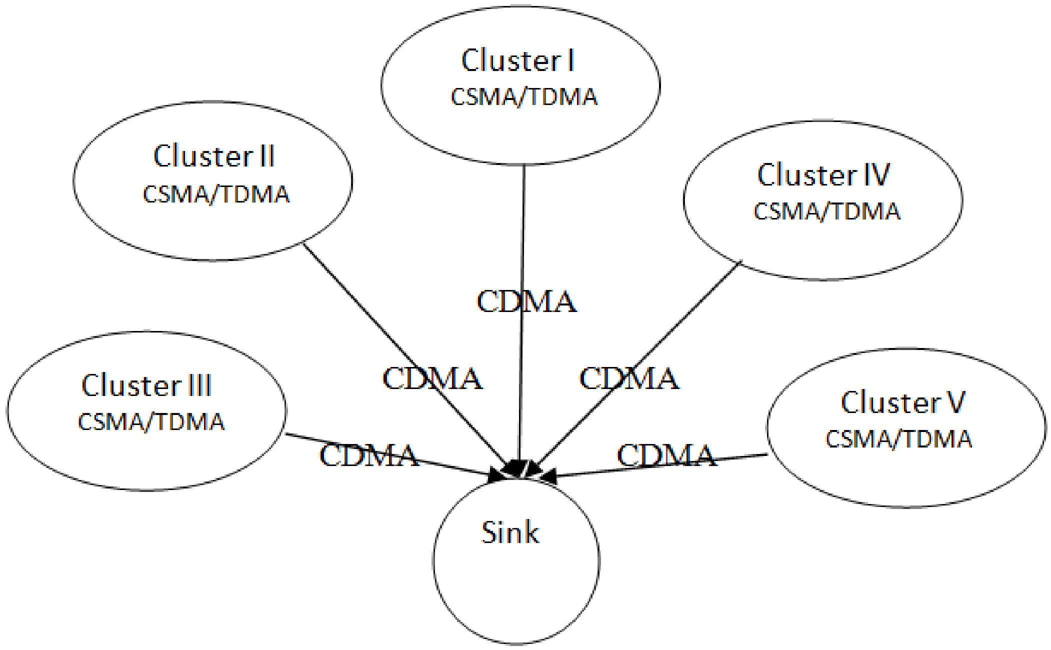


Figure 3.3: Protocol Scheme in the Network

So in this step, a simple TDMA protocol is used based on our assumption that all nodes know this information. Furthermore, there is a timer for each state for avoiding overlapping. For step 1, a timer with duration of $T_{end\_adv} = N * T_{Info-adv}$ is set, N is the total number of nodes in the network except the Sink node, and when it times out, the nodes wake up for receiving the information from the Sink node.

2. Cluster-Head Election

This step is also called the Cluster-Setup phase. The cluster-head needs to perform the functions like collecting data from the sensor nodes in its cluster, and then it does data aggregation before transmission, finally sends the compressed information to the Sink node. So compared with other sensor nodes, it will deplete its energy rather quickly. So choosing an optimal set of cluster-heads from the nodes is an NP-Hard problem [39]. In [40], an approximation algorithm named simulated annealing, which is based on thermodynamic principles, was proposed and can be used to approach the optimal solution to the cluster-head selection problem. According to the prior result reports in [17], [43], in our simulation, we set the number of clusters to be 5 based on the 100 total nodes in the network.

After selecting the optimal cluster-heads and their associated cluster members are determined, by using broadcast, the Sink node transmits this information containing the cluster-heads' IDs back to each node in the network.

3.3.2 TDMA Time Slot Assignment and Hybrid Protocol Utilization Procedure

1. Cluster Setup and Time Slot Assignment

Sleeping for a duration of T_{end_adv} after sending the information, all nodes wake up to receive the information from the Sink node to determine their own roles in the current round, if a node's cluster-head ID is the same as its own ID, then this node will get the cluster-head role in its cluster, otherwise, the node needs to determine the cluster-head it is associated with. Furthermore, its TDMA slot for data transmission is determined by the Sink, and then it goes to sleep until it senses some events happening. At this point, the operation for set-up phase is over, next phase will be the steady state phase. Here, the time frame for the cluster-head and the structure of a time slot needs to be specified before we continue to discuss the procedure. They are shown in Figure 3.4 and 3.5.

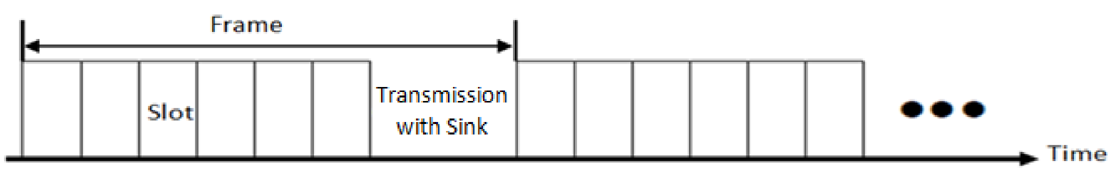


Figure 3.4: Time Frame for the cluster-head

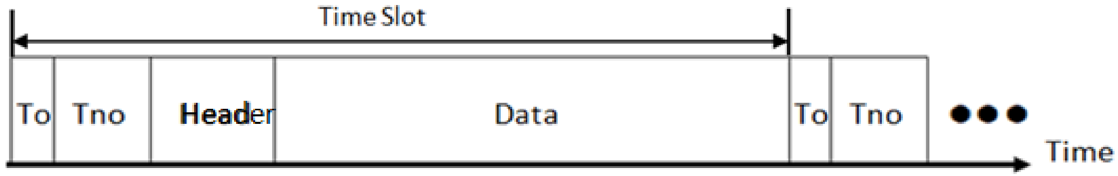


Figure 3.5: Structure of Time Slot for Transmitting Nodes

In each cluster, for the cluster head, the number of time slots in the frame is determined by the number of sensor nodes, which belong to the cluster-head, and after one frame is fulfilled with the data from sensor nodes, cluster-head will do a process named data aggregation then using a dedicated CDMA code to deliver the data to Sink node. And for each sensor node, if the current slot is its own, then it is called the owner of this slot, and the others will be nonowners of this same slot. These concepts are important for the hybrid access protocol described in the next section.

2. Data Collection

As depicted in Figure 3.6, one situation at the end Set-Up phase, there are totally 100 sensor nodes in the simulation scenario, and they are divided into 5 in different colors and symbols, the one with red rectangles are the elected cluster-heads by the Sink node.

Once the clusters are set up, and all nodes get their own TDMA slots, then the data collection simulation begins, in this section, we will use a probabilistic approach to simulate the events. The details about the operation of the hybrid access protocol will be introduced below.

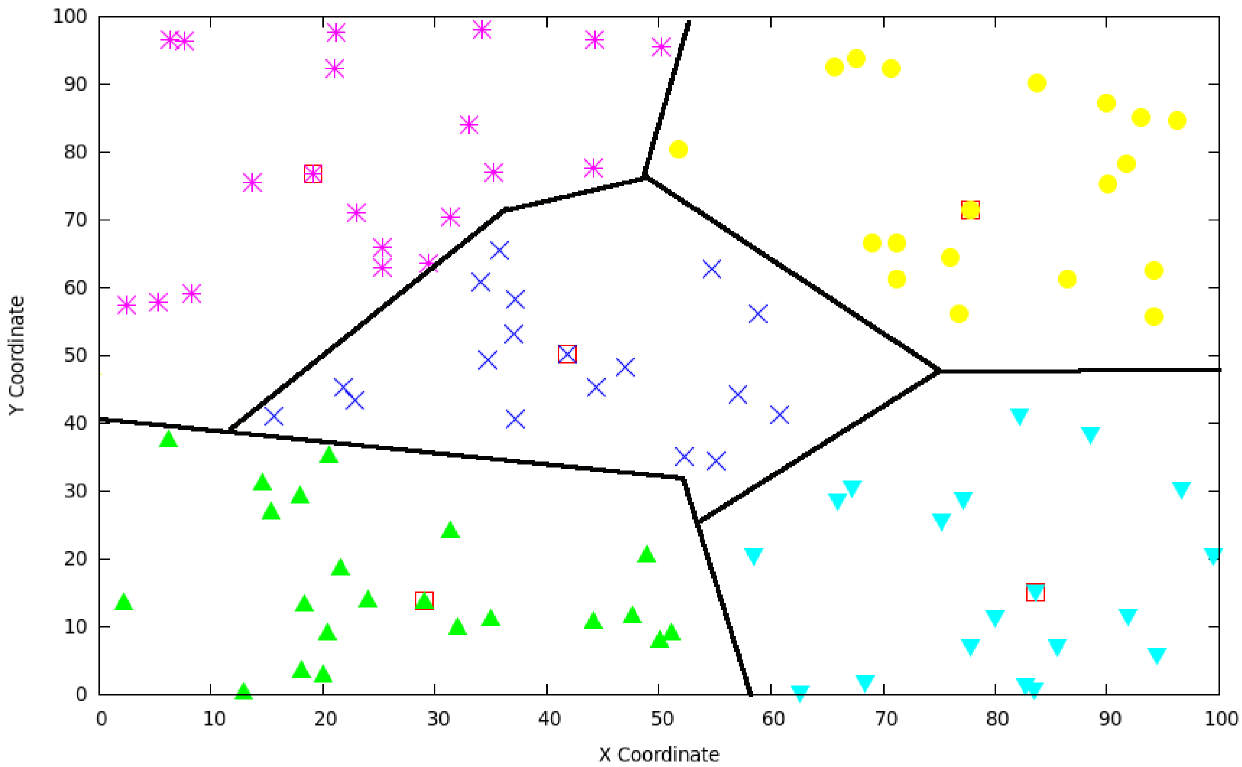


Figure 3.6: Network scheme at the end of Set-Up phase

Since the traffic in the network dynamically changes, a series of simulations with different numbers of sending nodes is used to approach these scenarios. There are totally 100 sensor nodes in the network, which consists of 5 cluster-heads and 95 normal sensor nodes. In the simulation, we vary the number of sending nodes from 10 to 100 increasing by a step of 5 and obtain 19 sets of simulation records. According to these records, we can analyze and compare the performance of different protocols.

Now, we assume that $k \le N$ nodes will sense the events from the environment and transmit data in the current round, a probability threshold then generates. Let us define a threshold $P_{th}(k) = k / N$, N is the total number of nodes in the network. Each node chooses a random number uniformly distributed between 0 and 1, if the number is less than or equal to the threshold $P_{th}(k)$, it will send one packet in its own time slot by using a random back-off time uniformly selected within the T_o period as shown in Figure 3.5.

Here we assume that it still has data to send, then as described in the original LEACH-C, it has to wait till its own slot in the next frame, however, k is less than N, which means there are still many other idle slots available, therefore, the channel resource is wasted and long latency will be incurred, especially under low traffic level. And now, we will introduce how our proposed hybrid access protocol works to cope with this drawback.

For the send nodes still need to send data during one round, to simulate such situation, again we use a probability threshold to approach such situation, $P_{rth} = e / k$, e is a constant, here we set it to be 3 to get a low traffic condition. Then doing the random number pick and comparison once more, so besides they transmit at their own slots, some of them can also use slots belonging to other nodes, but with a low priority.

As illustrated in Figure 3.5, following T_o, there is a time period called T_{no} which means the time period for the non-owners of the slot to contend. Every non-owner of this slot has to wait a period of T_o for the owners' transmissions, after that, by assuring the channel is idle, then it picks a random back-off uniformly within T_{no}, during this duration time, it competes for the access to the channel with the other non-owners using CSMA. Then additional idle time slots can be used, and channel resource waste will be reduced. As the number of sending nodes increases, more contention will be incurred, then in a time slot, for the higher priority of the owner, it is unlikely for non-owners to get the channel access, and thus the access control scheme will act more like TDMA.

This is the access method in the proposed one, and in the next chapter, the performance comparison with LEACH-C will be provided by simulating with NS2 under the same conditions.

3.3.3 Data Transmission between Cluster-Heads and Sink Node

Wireless sensor networks are data-centric, because the original data is from the response of the sensed events in the monitored environment. As we know, in sensor networks, there exists a concept of sensing range, which means that once an event happens, the nodes within such range will sense this change, and generate data that will be transmitted. Also because of the characteristic of dense deployment in sensor networks, it is usual that data generated from neighboring sensors is redundant and highly correlated. So a specific process named data aggregation or data compression is needed in such networks [41] to extract the most critical information with less data latency.

The definition of data aggregation is the process of aggregating the correlated data from multiple sensor nodes to ignore the redundant data and provide fused information to the sink. Data aggregation is done at the cluster-heads in our model.

There has been intense research in recent years on data aggregation in WSNs, and we will not describe this topic in detail here. But, we will briefly introduce the one used in LEACH [17] which is called beamforming [42]. Beamforming combines the signals from multiple sensors as follows:

$$y[n] = \sum_{i=1}^{N} \sum_{l=1}^{\mathrm{L}} w_i[l] s_i[n-l] \tag{3.2}$$

where $s_i[n]$ is the signal form the i^{th} sensor, $w_i[n]$ is the weighting filter for the i^{th} signal, N is the total number of data source sensor nodes, and L is the number of taps in the filter.

As mentioned in the previous paragraph, once a cluster-head collects a full frame of data, it extracts the useful information by the data aggregation by using beamforming algorithm, and then transmits the fused information to the Sink node directly. Because the number of sensor nodes in the clusters is different with the others, so for these cluster-heads, it is hard for them to keep synchronization with each other, their transmitting times are also distinct, also, to prevent the clusters from inter-clusters interference, then using CDMA to cope with the transmissions between cluster-heads and Sink node is more convenient and also practical.

After this procedure, at the beginning of the next round, all the nodes need to do the alive check again. If the energy is sufficient enough, the procedures described above will repeat. By using such periodic states, the energy consumption can be evenly dispatched to all the nodes in the network, to prevent some specific nodes from draining their battery quickly.

3.4 Simulation and Results

This section examines the performance of the proposed protocol using NS2.34 under Linux Operating System. The main purpose of this work is to analyze and develop the channel utilization of a clustering approach, and the factors influencing it include throughput, and data latency.

In this simulation, we assume the network is in a 100 x 100 square area, all sensor nodes are uniformly randomly deployed in it, with the Sink node at the origin, and all the default values of the parameters used in the simulations will be given in the table in the Appendix. After setting up the scenario, simulations start following the procedure described in Chapter 3. The following results will show the performance comparisons between LEACH-C and proposed scheme from several points of view to verify the improvement by using the proposed scheme.

3.4.1 Traffic Load Comparisons

In this thesis, we do the comparisons between the original LEACH-C and our proposed scheme. Traffic load, which reflects the number of transmitting nodes and the number of packets transmitted, is varied dynamically during the simulations, as shown in Figure 4.1 and Figure 4.2.

From the two 3-D figures, we can find that during low-contention, the traffic load in LEACH-C is slightly less than the one in the proposed protocol because its fixed transmission method described in the previous chapter.

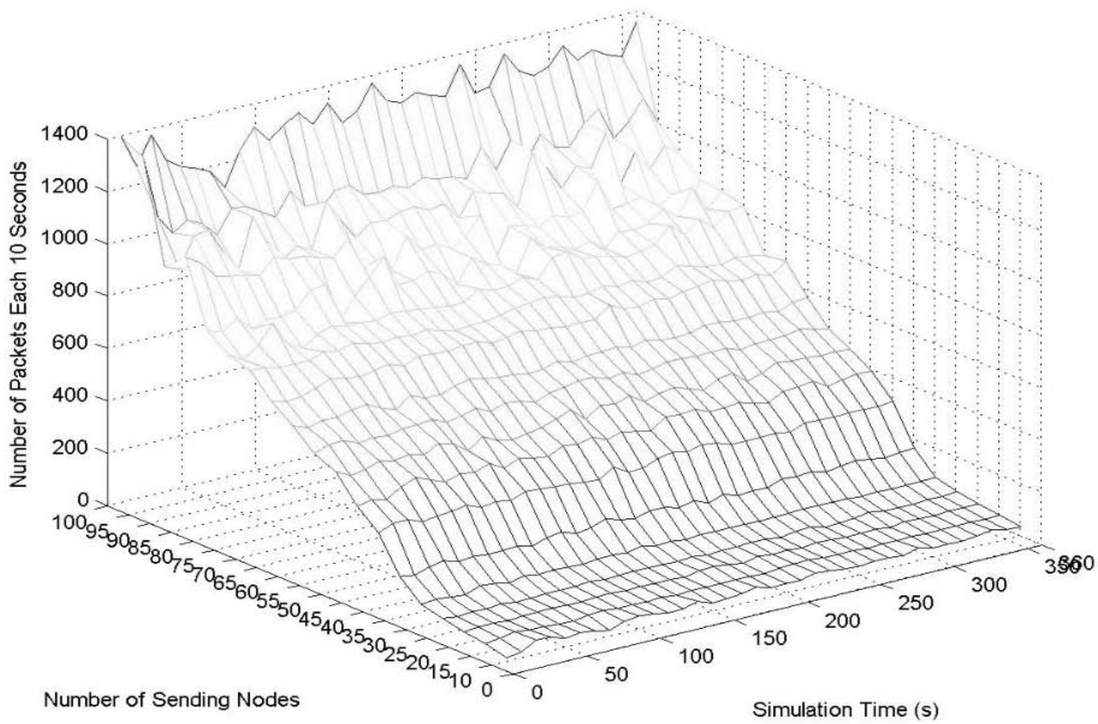


Figure 3.7: Traffic Load of LEACH-C

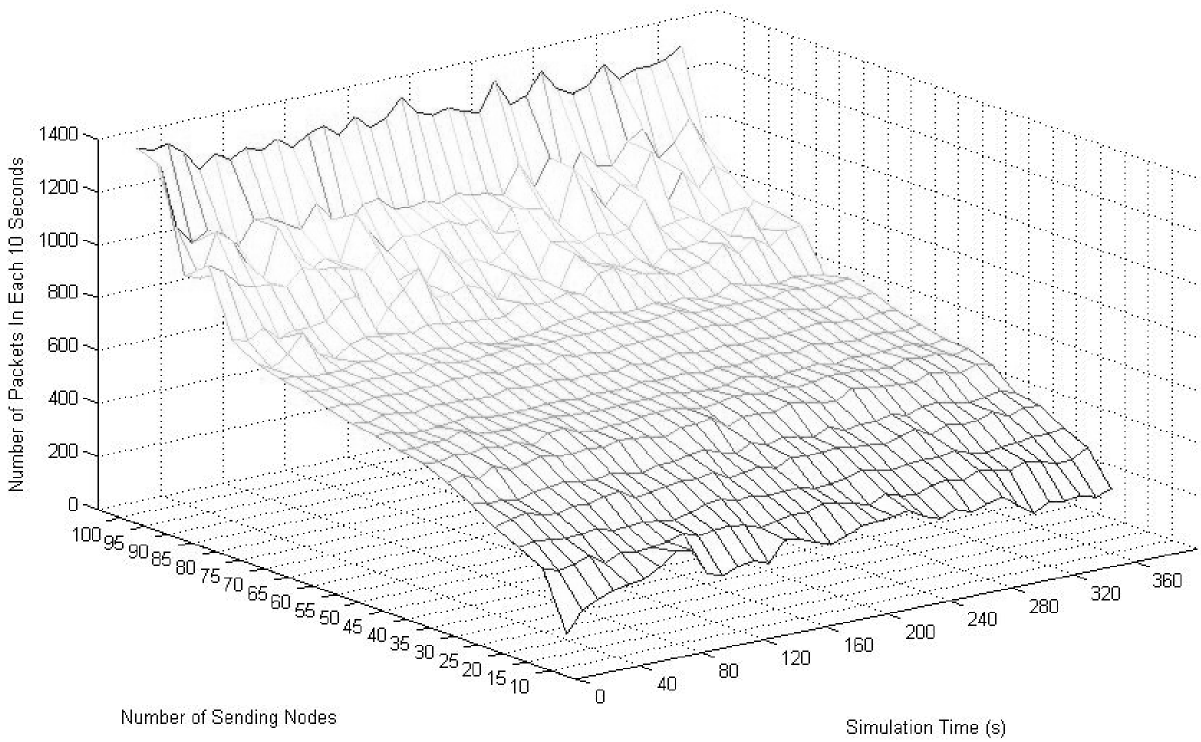


Figure 3.8: Traffic Load of SCL

3.4.2 Throughput and Latency Comparisons

Any network can be measured by two major characteristics: latency and throughput. Throughput is defined as the number of packets transmitted through the network in a given time duration. Here, as shown in Figure 4.3 and 4.4, the average system throughputs and per node throughput are presented. Figure 4.5 indicates the average time taken for transmitting a packet.

Since LEACH-C just uses TDMA protocol for intra-cluster communication, though it avoids unnecessary collisions within the cluster, it also incurs long data latency. This is because a node can only send one packet in each time frame, and it will wait till the next one frame to send another packet. While in the proposed one, unlike TDMA, a node can transmit during any time. From Figure 4.3 and 4.4, we can get the advantage of SCL, where both the average throughputs of system and per sending node throughput are better than those from LEACH-C.

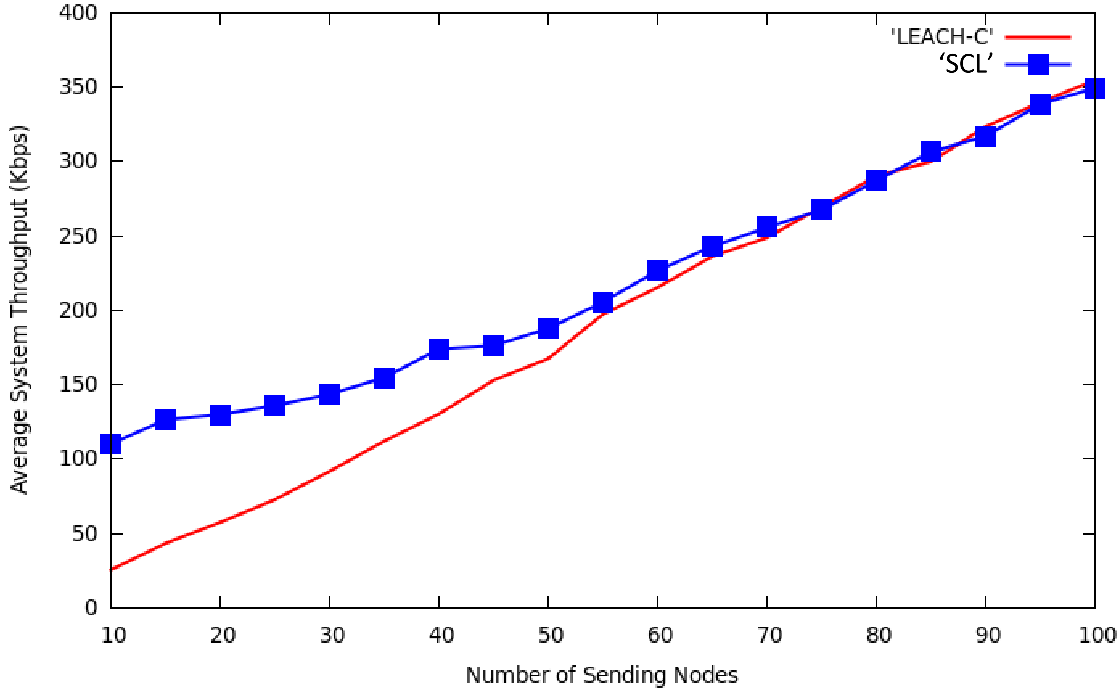


Figure 3.9: Average System Throughput

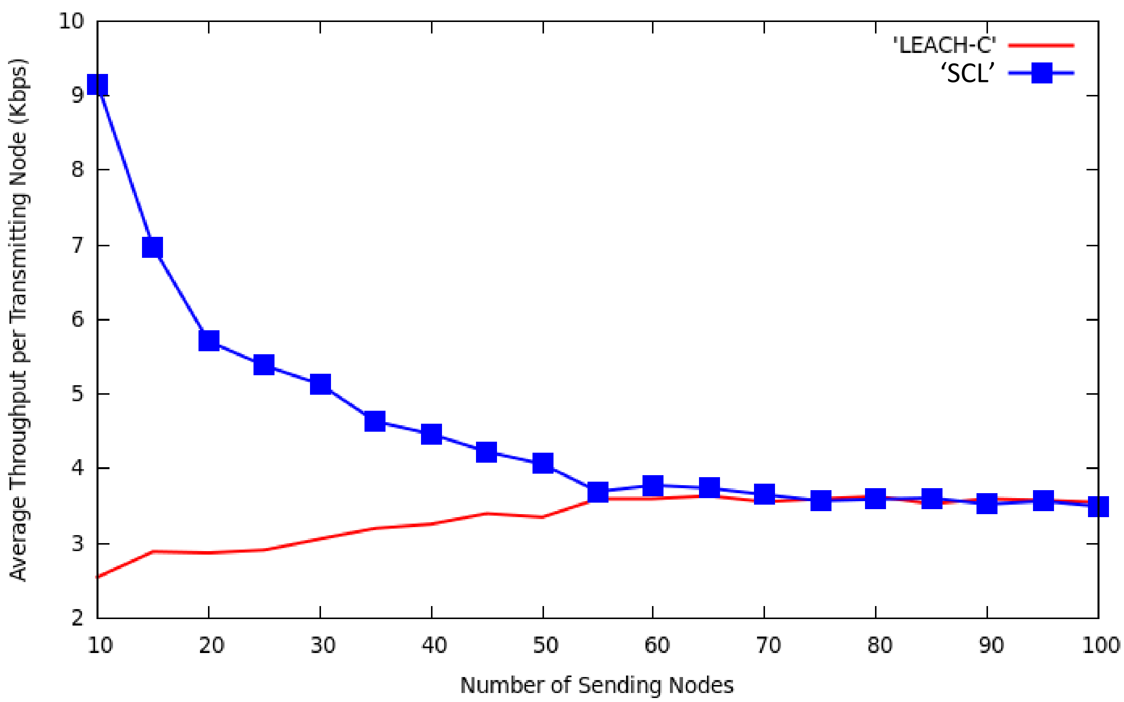


Figure 3.10: Average Throughput per Sending Node

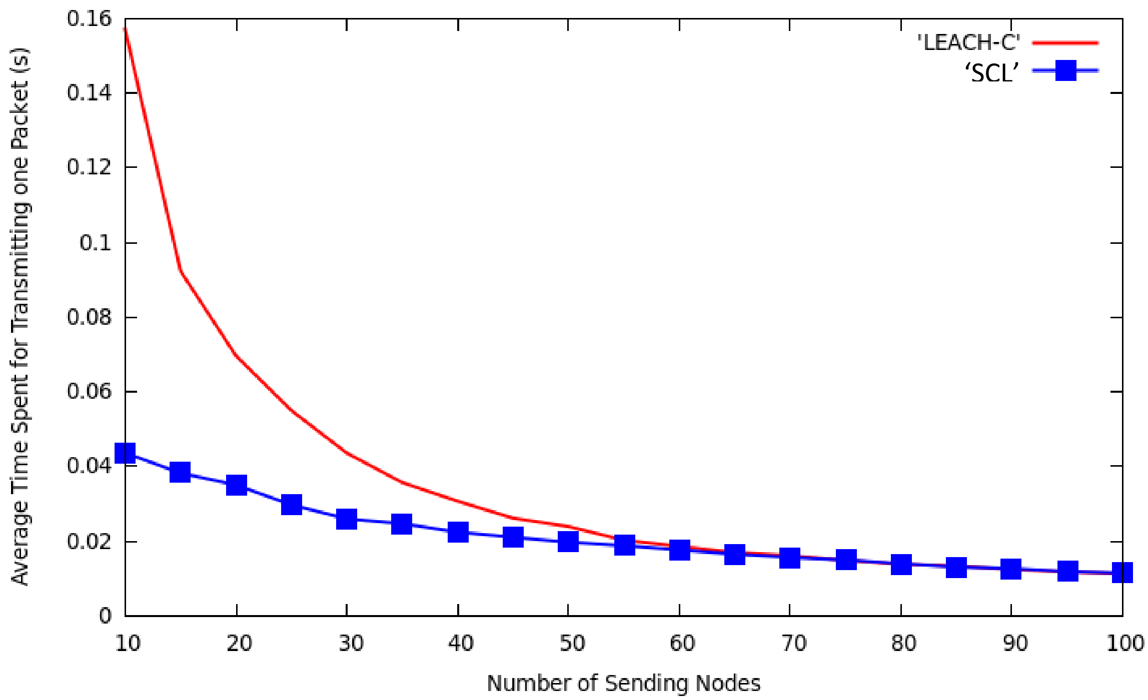


Figure 3.11: Average Time spent for transmitting one Packet

WSN being an application-specific network, data latency is important in many applications where the freshness of data is a significant factor. Data latency can be defined as how much time it takes for a packet of data to get from one designated point to another. As shown in Figure 4.5, the time to transmit a packet is lower than LEACH-C.

3.4.3 Energy Consumption

In these simulations, all the nodes begin with the same energy, 2J. Based on the number of packets sent by the nodes, we can calculate the average energy consumption to send one packet: $2 * N / N_{packet}$, where N is the total number of nodes and N_{packet} is the number of transmitting packets.

From the results in the Figure 4.6 and 4.7, we can see that compared with the original LEACH-C, the nodes in SCL need a little more energy to send one packet, and also, the number of packets received by the sink is slightly less. It is not hard to understand such situation, because by combining CSMA and TDMA, more control overhead will be incurred, like the classic back-off and retransmission mechanism.

Furthermore, by using CSMA for intra-cluster communication, some energy will be consumed during the conflict resolution process. But on the other hand, the total numbers of receiving packets in both schemes are very close. The reason is that as shown in Figure 4.5, LEACH-C spends more time to transmit the same amount of data, which means longer latency and lower channel utilization.

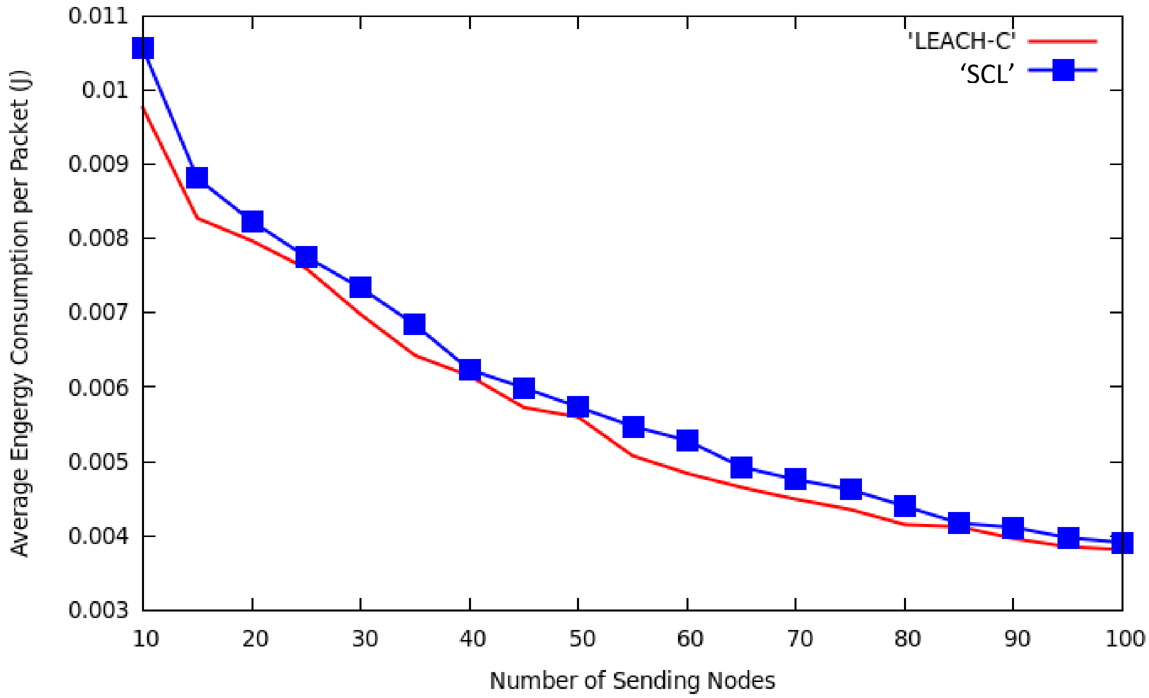


Figure 3.12: Average Energy Consumption per Sending Packet

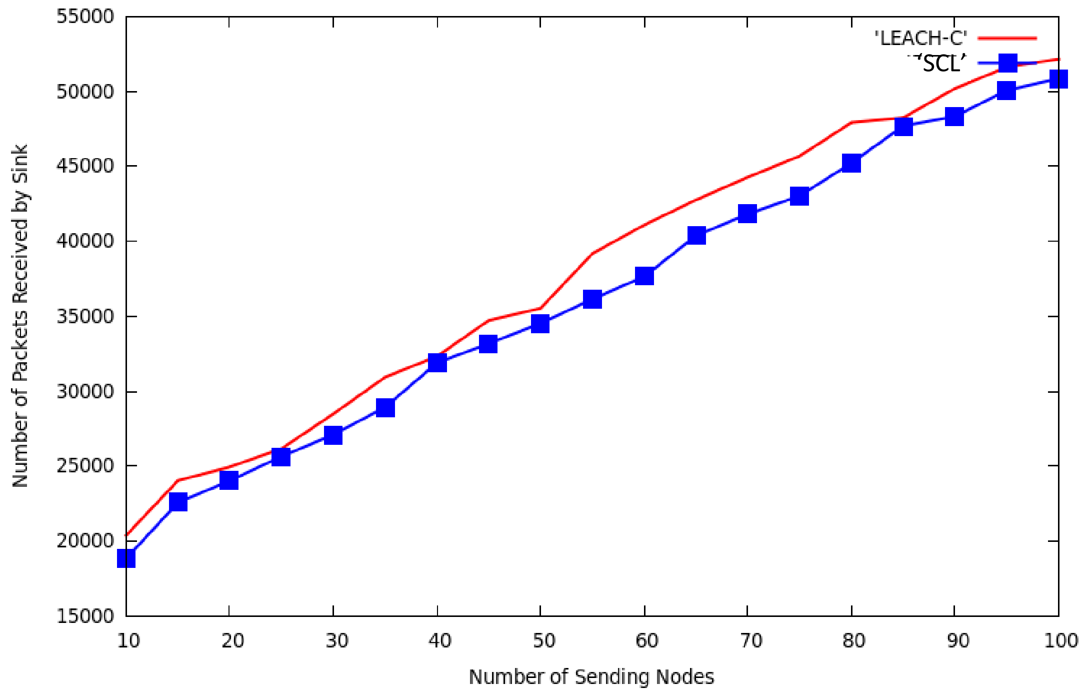


Figure 3.13: Number of Packets Received by Sink

3.4.4 Utilization Comparison

As is well known, when the system is in a low contention environment, compared to CSMA, TDMA provides much lower channel utilization, because by utilizing TDMA, a node cannot transmit at other times but only during its own scheduled time slots. On the other hand, in CSMA, nodes can transmit at any time as long as there is no contention. We will define a term named effective utilization of the channel, as the ratio of data payload to bandwidth of the channel. Because the data received by the Sink node is the resulting fusion of information, the achieved utilization cannot be accurately determined. However, we can say that the utilization is higher than that observed.

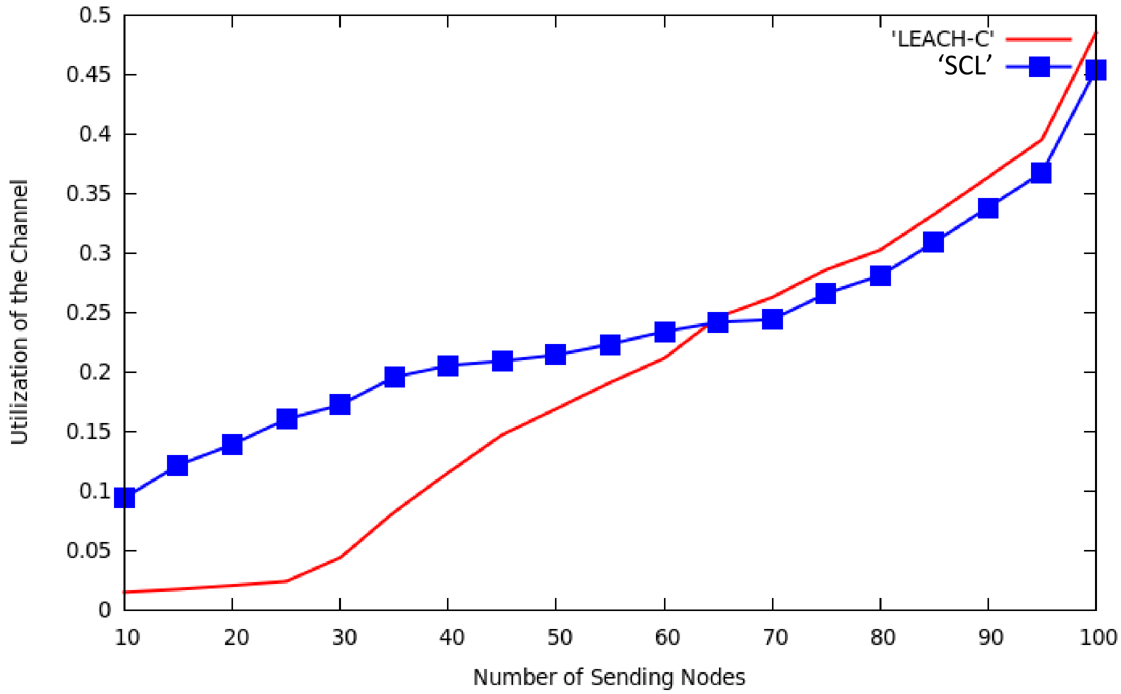


Figure 3.14: Effective Utilization of the Channel

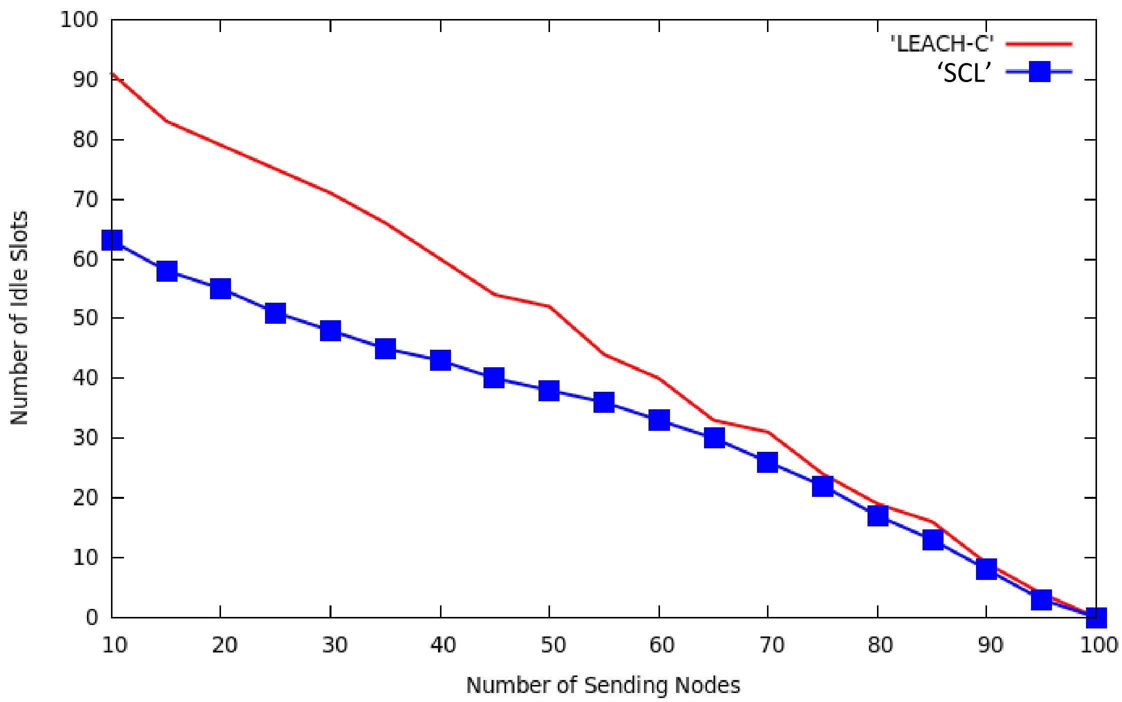


Figure 3.15: Idle Slots Distribution

From the results above, when under low contention, the channel can be used more efficiently and more time slots can be used. While as the number of sending nodes increases, for the utilization, SCL performs slightly below LEACH-C. The reason is that, as observed from Figure 4.3, the throughputs of the two protocols are close to each other when the number of sending nodes beyond a threshold, which is about 65, but in SCL, there is more overhead per packet for contention avoidance. Hence the ratio of the data payload in one packet decreases, decreasing the effective channel utilization correspondingly.

Also, from the distribution of idle slots in the network as shown in Figure 4.9, it can be observed that SCL has about 40% more idle time slots to transmit information under low contention. This also indirectly reflects the property of higher channel utilization by using SCL.

Chapter 4

Conclusion and Future Work

In this thesis, we have described the design of a hybrid access protocol suitable for wireless sensor networks. It combines CSMA and TDMA multiple access schemes and is based on a clustering scheme.

Since both of CSMA and TDMA have their pros and cons, they can be efficiently combined exploiting the benefits of each of them. This is because CSMA is advantageous when the contention is not high, while TDMA can do better in a contention free situation. Also, to compensate the energy consumed by incurring collision, we used the routing scheme from LEACH-C as our routing protocol. As in LEACH-C the network is divided into several disjointed clusters, then using the hybrid access protocol for the intra-cluster communication.

By comparing the measured performance of LEAHC-C and the proposed SCL using the simulation results in Chapter 4, it can be verified that the latter can achieve better performance, such as higher throughput and lower data latency, which are important criteria to measure the network performance.

As expected, the proposed protocol can dynamically switch the behavior of its MAC component between CSMA and TDMA according to the level of contention in the network. Furthermore, we find a threshold for access switch from the simulation results. By setting such threshold, when the number of sending nodes is below it, using hybrid access protocol can get better performance. Otherwise, it is more efficient to use TDMA protocol. Furthermore, the full range of source nodes' amount also compensates the drawback with limited time slots assignment in Z-MAC.

However, SCL achieves a better measured performance of such application-specific networks at the cost of consuming a little more energy in receiving each packet. So in the future, the main work should be to consider the energy efficiency as well, a more efficient CSMA protocol should be used in the hybrid access. Also, by incurring the polling scheme to the network in the future, the cluster head can dynamically allocate the number of time slots in the current cell.

Furthermore, as we know, the trend of wireless networks is to use distributed protocols rather than centralized one. While this means more computing capacity for each node in the network, especially in WSNs. Compared with transmission between nodes and a Sink node, the energy consumption for computation has little advantage currently [35]. So for large scale monitored environments, more researches concern such scheme: pre-allocating several high-energy nodes (e.g., cluster heads) in the network to act as relay nodes, then send the data to the end Sink node with multi-hop routing scheme. Just as provided in this work, the network we adopted can be treated as one cell in such large scale network, so this is a practical scheme not only for small but also large area environment monitoring.

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Appendix

Table 1: Default Settings of System Parameters

NS-2 Simulation Parameters	Default
Header Size	25 Byte
Data Payload Size	500 Byte
Contention Window Size for Owner (T_o)	8
Contention Window Size for Non-owner (T_{no})	32
Beamforming Energy	5e-9 J/bit
Energy for Radio Circuitry	50e-9 J/bit
Initial Energy	2 J
Channel Bandwidth	1 Mbps
Total Number of Sensor Nodes	100