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長細拓樸下CDMA無線感測網路之效能評估

Performance Evaluation of CDMA-based Wireless Sensor Networks with Long-Thin Topologies

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本論文係徐名蔚君（學號 R98922118）在國立臺灣大學資訊工程學系完成之碩士學位論文，於民國 101 年 7 月 6 日承下列考試委員審查通過及口試及格，特此證明

口試委員：

（指導教授）

系 主 任

致謝

經過了兩年時間，終於完成了論文，心中五味雜陳，一是即將邁向人生的另一個階段而感到高興，一是即將離開待了七年的台大校園而感到些許悲傷。

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中文摘要

無線感測網路(Wireless Sensor Network)是由眾多的無線感測節點與數個閘道器所組成的無線網路系統。感測節點收集環境中的資料後將其送到閘道器，再由閘道器轉送到伺服器做進一步的處理分析。無線感測網路最初是由美軍發展用於戰場上，後來此項技術繼續發展及應用在不同的用途上，如科學調查、溫濕度監控、火災預報等。

我們觀察到有許多跟安全相關的無線感測網路應用，例如偵測橋樑上的異常振動或張力、礦坑內的易燃氣體濃度等等，其網路拓樸由一些長細狀的分支所組成，呈現"長細拓樸"(long-thin topology)狀。在一般的運作下，感測網路只需定期取得感測節點收集的資料以偵測異常狀況。然而，若發生事故，需要傳送大量資料時，感測網路則需要進入不同的運作模式，例如在礦坑內發生爆炸，感測節點使用更快的速率傳輸則能更快速決定受困礦工之位置，且無線感測網路能被用於傳送受困礦工的聲音和影像以幫助救災行動。

在緊急狀況運作下，無線感測網路需要較大的吞吐量，但目前常見應用在無線感測網路之媒體存取控制協定(MAC protocol)通常為分時多重存取(Time Division Multiple Access)或載波感測多重存取(Carrier Sense Multiple Access)協定，其受到在接收節點的接收範圍內只能有單一傳輸節點做傳輸的限制，整體的吞吐量因此大幅減少。在一般運作下的協定設計目標通常是優化能源消耗的情況下，前面的限制並不構成問題。然而，原有的協定很明顯並不適用於緊急狀況的需求。

分碼多重存取(Code Division Multiple Access)的運作是將原始訊息以偽雜訊碼(Pseudo-noise code)展開成寬頻訊號。此系統除去了前述的限制，並允許多個感測節點在接收節點的接受範圍內同時傳送訊號，因此在使用分碼多重存取之下整體的吞吐量應能得到相當程度的改善。在這篇論文中，我們研究如何設計應用在長細拓樸下的雙模式無線感測網路系統之分碼多重存取協定。此系統在一般運

作模式下使用分時多重存取或載波感測多重存取協定,而在轉換到緊急模式時則使用分碼多重存取協定。

我們研究了單鍊(Single-Chain)拓樸及多鍊(Multi-Chain)拓樸。對於單鍊拓樸,我們提出一個實作簡單的啟發式功率分配方法,其所需的開銷少且在吞吐量的表現上較最大功率配置方法好。對於多鍊(Multi-Chain)拓樸，我們提出一個啟發式的排程原則,能增加同個時槽內同時傳輸到閘道器的傳輸數量並得到顯著提升的吞吐量。模擬結果顯示在長細拓樸下使用分碼多重存取協定較分時多重存取得到了約略兩倍的吞吐量。

關鍵詞：分碼多重存取、分時多重存取、無線感測網路、長細拓樸、功率調控、排程

Abstract

Wireless Sensor Networks (WSNs) are a type of wireless network systems which consist of a large number of wireless sensor nodes and a few gateways. Sensor nodes gather information about the environments and then forward it to the gateways, which in turn relay the information to a server for further processing and analysis. WSNs are initially developed for battlefield purposes by the U.S. military. In the past ten years, the technology continues to develop and begins to serve different purposes, such as scientific investigation, temperature and humidity control, fire forecasting, etc.

We observed that for a number of safety-related WSN applications, e.g., abnormal vibration or tension detection on the bridge, flammable gas density monitoring within the mine pit, the network topology consists of a few long and thin branches, or exhibits a "long-thin topology." During the regular operation, the network only needs to obtain the sensor reading periodically, so that anomaly can be detected. However, if an accident happens, the network instead needs to enter a different operation mode where a much larger amount of data needs to be transferred. For example, when a gas explosion occurs in the mine pit, the sensor nodes transmit at a much faster rate, so that the positions of the trapped miners can be quickly

determined, and the WSN can be used to relay voice and video transmissions from the miners to assist the rescue operation.

During the emergency operation, the WSNs require a large amount of throughput, but the common MAC protocols used in WSNs, usually a variant of the Time Division Multiple Access (TDMA) protocol or the Carrier Sense Multiple Access (CSMA) protocol, have the constraint that only one node can transmit within the receiving range of a node. The throughput is therefore greatly reduced. As the design objective for protocol during the regular operation is often optimized to reduce energy consumption, this does not pose a problem. However, the original protocol is obviously not feasible for the emergency purposes.

The operation of Code Division Multiple Access (CDMA) spreads the original message into a wideband signal by modulating it with a pseudo-noise (PN) code. The scheme removes the aforementioned constraint, and allows multiple nodes to transmit simultaneously within the receiving range of a node. As a result, with a CDMA-based protocol, the throughput could be significantly improved.

In this thesis, we investigate how to design a CDMA-based protocol for a dual-mode WSN system with long-thin topologies. The system would use a TDMA- or CSMA-based protocol during its regular operation and the CDMA-based protocol when switching to the emergency mode. Two most commonly used long-thing

topologies, single-chain and multi-chain topologies, are studied in this thesis. For single-chain topologies, we propose an easy-to-implement heuristic power allocation scheme, which has low overhead and outperforms the full power allocation scheme in terms of throughput. For multi-chain topologies, we propose a heuristic scheduling principle, which can increase the number of simultaneous transmissions to the gateway in the same time slot and produces significantly higher throughput. Evaluation results suggest that the use of the CDMA-based protocol in WSNs with long-thin topologies approximately doubles the throughput compared to that of TDMA-based protocol.

Keywords: CDMA, TDMA, wireless sensor networks, long-thin topologies, power control, scheduling

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Chapter 1 Introduction

Wireless Sensor Networks (WSNs) are a type of wireless network systems which consists of many wireless sensor nodes and several gateways. It was first developed to collect battlefield information by the U.S. military, and then continued to be developed and applied for many other purposes, such as scientific investigation, temperature and humidity sensing and control, fire prediction, and security monitoring. Figure 1-1 is an example of traditional WSNs. Each sensor in the WSN collects and sends its sensing data to its up-stream node. All sensing data will eventually be transmitted to the gateway, and the gateway relays them to the remote server or storage device.

Since wireless sensor networks usually consist of many wireless sensor nodes and are often set up remotely at areas inconvenient to reach, maintenance involving humans is difficult to be performed. It is therefore desirable that sensor nodes are low-cost and its on-board battery can last for several years. Since wireless sensor nodes are low-cost and small-size, they are usually energy-constrained. Hence, in wireless sensor networks transmission data rates are often limited; otherwise, high energy consumption will reduce the life time of sensor nodes. As a result, lowering the energy consumption of the system is the design objective for most wireless sensor networks.

Many specific scenarios are suitable for utilizing wireless sensor networks

Examples include monitoring systems on the bridge, in the tunnel, and in the mine. The appearances or the interior structure of these locations are long, thin, and with few branches. Figure 1-2 shows a bridge with a deployed WSN. A wireless sensor node is attached to every cable on the bridge and monitors the temperature, the humidity, and the natural vibration of the cable. If abnormal vibration of a cable is detected, the bridge administration can examine and repair the cable in time to prevent cable fractures. Figure 1-3 shows the interior map of a mine before a gas explosion. One can see that most paths in the mine are long and thin. If WSNs could be deployed and utilized to monitor the gas in the mine, the gas explosion could be prevented. As shown in these examples, safety sensor network systems with long-thin topologies are a common and important case. These safety systems, when in urgent or critical situations, often need to report a much larger amount of sensor data to assist in the disaster recovery process, where the objective of the network should be maximizing the effective end-to-end throughput instead of minimizing the energy consumption as during the regular operation.

Media Access Control (MAC) protocol plays an important role in wireless sensor networks. There are three major types of MAC protocols which are often used in wireless sensor networks: Carrier Sense Multiple Access (CSMA), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA). Most MAC protocols for WSNs are designed to maximize the network lifetime and would result in poor throughput in these urgent situations, including the most commonly used TDMA-based and CSMA-based MAC protocols. If TDMA is used as the media access protocol for wireless sensor networks, the transmission time durations of adjacent wireless sensor nodes cannot overlap; otherwise, the receiving nodes experience collisions, i.e., signals sent by different nodes would interfere with each other, received signals would be seriously distorted, and the signal-to-interference-and-noise ratio (SINR) would be greatly reduced. In addition, the node density of the area close to the gateway is usually higher, and therefore, in this case, the average waiting time for nodes in this area would be longer and becomes the bottleneck of the entire network, which leads to lower overall network throughput. Clearly, these are not desirable designs for long-thin WSNs. CSMA-based MAC protocols also have similar designs to TDMA-based MAC protocols and thus have the same limitations. The main difference is that CSMA-based protocols use contention-based approaches to deal with the interference other than scheduling approaches. The most intolerable drawback of CSMA is the unbounded delay since nodes could wait an unbounded time interval as collisions happen [15]. Thus, CSMA is not a good MAC protocol choice with time-sensitive applications.

When CDMA is used as the MAC protocol for wireless sensor networks, the original message is modulated into a broadband signal with a pseudo-noise (PN) code. With the characteristic of PN codes, interference between signals spreaded by different PN codes would be greatly reduced, and, as a result, the adjacent sensor nodes can simultaneously transmit signals, increasing the overall throughput substantially. In addition, due to the modulated PN code, transmitted signals in CDMA systems would appear similar to noises, and, therefore, has the benefits of hiding the information. The transmitted information cannot be easily decoded by unauthorized third parties.

In this thesis, we propose that the system uses a CDMA-based MAC protocol when it switches to the emergency mode in these situations. It allows simultaneous transmissions within the receiving range of a node, and could therefore result in higher throughput. We develop a simple heuristic power allocation scheme to be used in single-chain topologies. The developed scheme does not need the knowledge of the path losses between nodes, and is therefore practical to be implemented. We also propose a scheduling principle which can be used in the CDMA networks with multi-chain topologies under the assumption that the gateway can receive different packets spreaded with different PN codes transmitted in the same time slot. The idea is to schedule more chains (nodes) transmitting to the gateway in the same time slot to decrease the duty cycle, and to schedule adjacent chains to transmit in the same time slot to avoid the interference caused by interleaved transmissions and receptions. The error performance is then analyzed and compared to TDMA-based wireless sensor networks with the same topology.

The rest of this thesis is organized as follows. Chapter 2 talks about some researches related to this thesis. Chapter 3 introduces the system model of the proposed system, also including channel configurations, topologies, and evaluation metrics, etc. Chapter 4 talks about the evaluation result of CDMA and TDMA network with the single-chain and multi-chain topologies. Chapter 5 is the conclusion of this thesis, and we propose some future works could be researched based on this thesis.

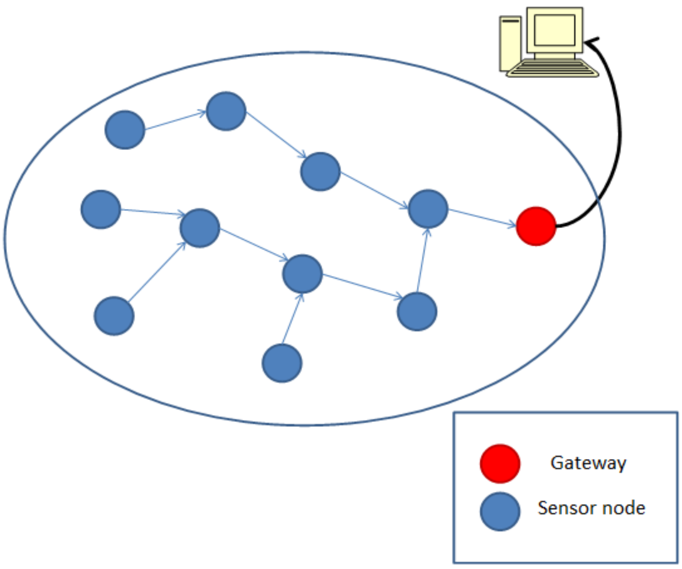

Figure 1-1 A typical wireless sensor network

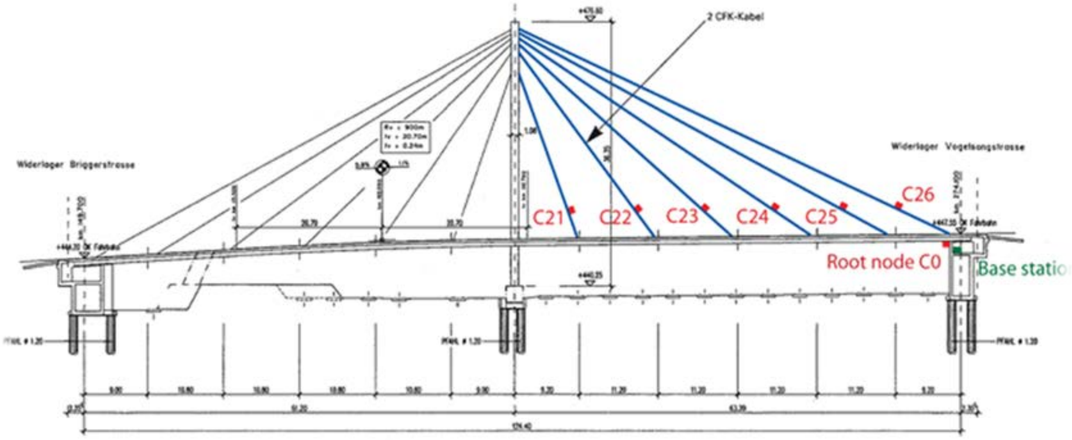

Figure 1-2 A bridge with a WSN to monitor the natural vibration of steel cables on the bridge [1]

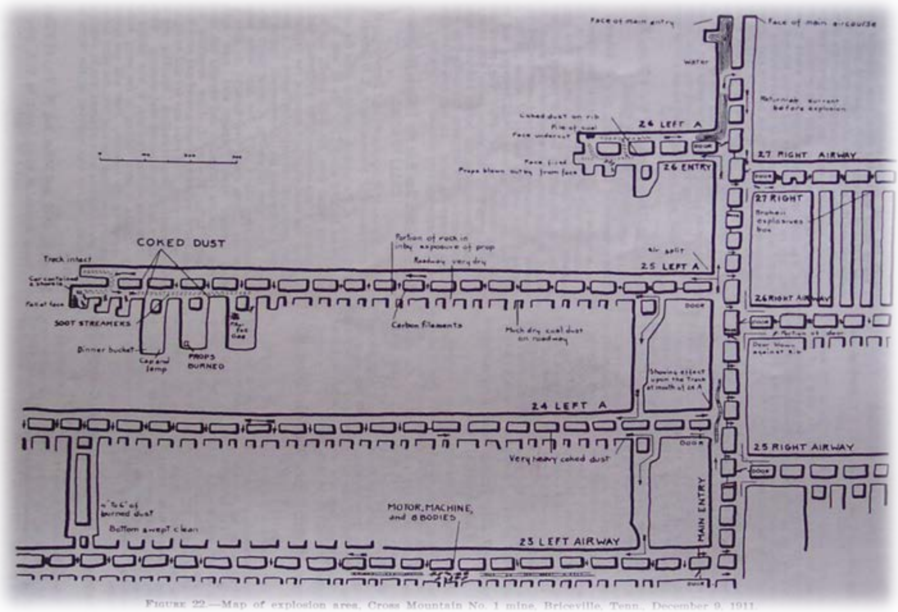

Figure 1-3 A map of the interior of a mine [2]

Chapter 2 Related Works

In this section, we present several researches related to long-thin wireless sensor networks and CDMA.

As mentioned in Chapter 1, our objective is to design a sensor network system with dual modes. The traditional TDMA-based energy-saving mode is used during the regular operation, and a CDMA-based high-speed mode is used in emergency situations. In CDMA high-speed mode, each node aggregates its own sensor data to the packet it receives from its down-stream neighbor and transmits to its up-stream neighbor in its transmitting time slots.

With this one-by-one transmission procedure, one of our goals is to find a pipelined aggregated convergecast [6] scheduling scheme to schedule all transmission with less time slots in CDMA WSNs with long-thin topologies. Several researches [6, 11, 12, 13] have discussed aggregated convergecast in TDMA networks; it can be modeled as a graph coloring problem since each receiver in TDMA networks can only successfully receive the packet from one transmitter at a time. Incel et al. have been shown that the lower bound of the length of TDMA pipelined aggregated schedule is $\Omega(\Delta T)$, where ΔT is the maximum node degree in the network [6]. Conceptually, this lower bound gives an upper limit to the effective throughput which can be achieved by a TDMA network.

The authors of [6] also designed a heuristic algorithm which constructs a degree-constrained routing tree to decrease the number of aggregated time slots. However, it is not guaranteed the algorithm can find a solution. In the extreme case, if there are many chains connecting to the gateway, this algorithm would not find a solution since the number of nodes within the receiving range of the gateway is too large thus the number of interfering links could not be eliminated to a given value of node degree.

Radunovic and Boudec [3] performed a theoretical analysis to derive the optimal scheduling and power control in networks with ring topologies and infinite line topologies in terms of transmission rate with a physical interference model. They found that a node transmitting with maximum power in active mode with the optimal scheduling can be represented as a combination of periodic and symmetric (and rotational) links in networks with infinite line (and ring) topologies. The result matches with researches based on protocol (graph-based) interference model. Similarly, Baccelli et al. [7] give a theoretical analysis to the scheduling scheme of the infinite line topologies. They discuss some performance metric maximizations such as the optimum duty cycle of scheduling under a given SINR threshold, i.e., the ratio of times of each link transmitting to the number of total time slots. As both [3] and [7] use the simplified assumption that the number of nodes in the line network is infinite, all links, as a result, can use the same transmission power using the symmetric property of the network. As the assumption is not realistic in these researched, the results are not applicable in a real-world WSN. In this thesis, we evaluate WSNs with single-chain and multiple-chain topologies with a limited number of nodes. We assume that the gateway can receive data from multiple transmitters at each time slot. Our goal is to find scheduling principles that take advantage of the simplified topologies and can achieve higher throughput than that of a TDMA-based system.

Power control is an important aspect for CDMA-related researches. With the spreading code technique, the lack of spatial-temporal separation in CDMA networks could still result in considerable interference to receivers. The use of a power control scheme to deal with the interference and ensure the signal quality is a common technique used in CDMA networks. There are many different power control schemes proposed by researchers. An objective function common-used [4, 8, 9, 14] for the power control scheme is to minimize the total power of all transmitting nodes under the constraint that the SINR of every link is no less than a pre-specified threshold β in a time slot. This is appropriate for WSNs since sensor nodes are usually energy-constrained. However, the scheme only ensures the one-hop signal quality. When applying the scheme to the chain topology, the number of hops to reach the end node is so large that the route packet error rate (PER) to the gateway is too poor. In addition, it is essential to obtain the knowledge of accurate pairwise link gains in order to use this approach. However, in practice to obtain the information it takes a great amount of overhead. In an environment with rapid small-scale fading, the link gains change so frequently and rapidly that tracking them becomes impractical. In this thesis, we aim to design a power allocation scheme that is suitable for CDMA WSNs with single-chain topologies based on the aforementioned objective function. With our scheme, each link can achieve the maximum SINR instead of just over a SINR threshold, and, in turn, lower the route PER and increase the overall system throughput without the need of having the knowledge of pairwise link gains.

Last, we introduce some researches about CDMA-based WSN in brief. LEACH [16] is a clustering scheme MAC protocol which combines TDMA and CDMA techniques. Cluster heads schedule the nodes in their corresponding cluster. Nodes in the same cluster use the same PN code to spreading the original data to the cluster head, and nodes in different clusters use different PN code to reduce inter-cluster interference. Since all the transmission links in the same cluster still cannot overlap, the scheme would not match the high throughput demand in urgent situations. [17] and [18] use CDMA-based MAC protocols which are combined with frequency division techniques to further reduce MAI. PN code assignment and frequency division can both be modeled as two-hop vertex coloring problems. In [18], receiver-based frequency division scheme, i.e., nodes with a common neighbor cannot use the same frequency, and transmitter-receiver pair based code assignment scheme, i.e., adjacent links in the logical topology cannot use the same PN code, are proposed. In [17], the authors proposed a broadcast scheme where each node uses a different PN code but a common frequency to transmit broadcast packets in order to reduce expensive frequency division cost while broadcasting. Thus they employed one receiver for unicasting and the other one for broadcasting in a sensor node. In the general case networks, the frequency division approaches could reduce the MAI significantly, but with the natural feature where the number of neighbors of nodes in the chain networks is usually not large, applying both power control and frequency division in the sensor nodes seems unnecessary.

Chapter 3 System Model

3.1. DS-CDMA Signal Representation

Direct-Spread CDMA (DS-CDMA) is a type of CDMA techniques which uses spread spectrum modulation to convert data signal to higher-rate "chip" bit sequences by phase-modulating the original data bit sequences with a PN code. We assume that the WSN in the emergency mode, utilizing a CDMA-based protocol, uses DS-CDMA to transmit the packets.

The considered DS-CDMA model is shown in Figure 4 [5]. There are K nodes in the network. The data signal of the k-th node $b_k(t)$ can be modeled by a sequence of unit-amplitude, positive or negative, rectangular pulse of duration T, given by

$$b_k(t) = \sum_{l=-\infty}^{\infty} b_{k,l}\, p_T(t - lT), \tag{3.1}$$

where $b_{k,l} \in \{1, -1\}$ and $p_\tau(t) = \begin{cases} 1, & 0 \le t < \tau \\ 0, & \text{otherwise} \end{cases}$. $b_{k,l}$ is the l-th bit of $b_k(t)$, and $p_\tau(t)$ is an indicator function to indicate if $0 \le t < \tau$.

The PN code sequence $a_k(t)$, which consists of a periodic, repetitive sequence of unit-amplitude, positive or negative, rectangular pulse of duration T_c, is assigned to the k-th nodes as its transmission PN code. It is given by

$$a_k(t) = \sum_{l=-\infty}^{\infty} a_j^{(k)}\, p_{T_c}(t - lT_c), \tag{3.2}$$

where $a_j^{(k)} \in \{1, -1\}$, and $p_\tau(t) = \begin{cases} 1, & 0 \le t < \tau \\ 0, & \text{otherwise} \end{cases}$. $a_0^{(k)}$, $a_1^{(k)}$,..., and $a_{N-1}^{(k)}$ form a complete PN code sequence with a length of $\frac{T}{T_c} = N$. Each bit of $a_k(t)$ has duration a duration of T_c.

The data signal $b_k(t)$ is then converted to the transmitted signal $S_k(t)$ with the Binary Phase Shift Keying (BPSK) modulation, given by

$$S_k(t) = \sqrt{2P_k} a_k(t) b_k(t) \cos(\omega_c t + \theta_k), \tag{3.3}$$

where ω_c is the carrier frequency, θ_k is the initial phase of the carrier, and P_k is the transmission power of the k-th node. We assume that the DS-CDMA system is asynchronous, i.e., the phases of the carriers of the transmissions from different nodes are not correlated. Since there are K transmitting nodes in the system, the received signal $r(t)$ can be given by

$$r(t) = n(t) + \sum_{k=1}^{K} \sqrt{2P_k'} a_k(t - \tau_k) b_k(t - \tau_k) \cos(\omega_c t + \emptyset_k), \tag{3.4}$$

where P_k' is the signal power of the k-th node measured at a certain receiving node, τ_k is the propagation delay of the signal of the k-th node, $n(t)$ is the Additive White Gaussian Noise (AWGN) with 2-sided power spectral density $N_0/2$, ω_c is the carrier frequency, θ_k is the initial phase of the carrier, and $\emptyset_k = \theta_k - \omega_c \tau_k$. After the decoding operation, the corresponding receiving node of the signal of the k-th node gets the corresponding data bit $\hat{b}_k$; however, b_k and $\hat{b}_k$ can be different since the interference, noise, and the channel quality cause errors.

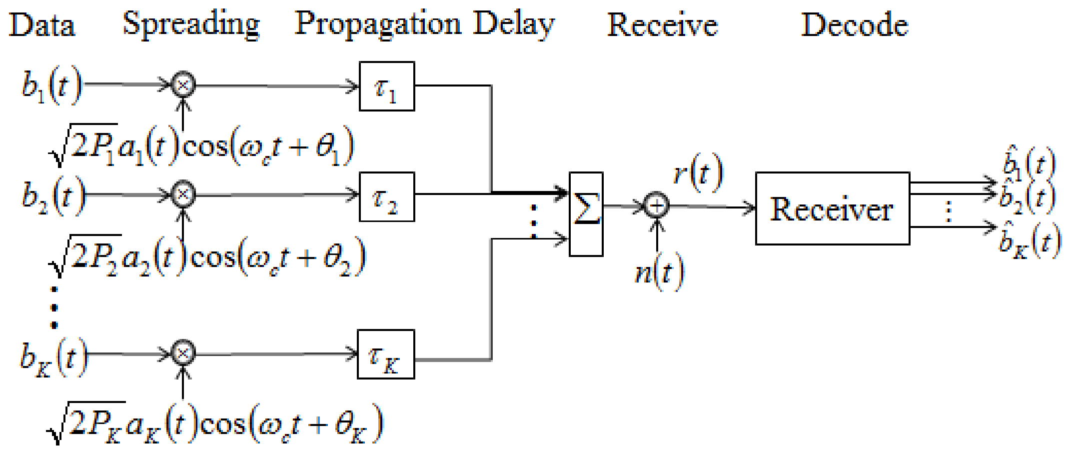

Figure 3-1 The DS-CDMA system model used in our analysis

3.2. Topology

There are two types of nodes in the WSN that we consider. Regular sensor nodes (SN) are responsible for collecting sensor information, such as temperature, pressure, humidity, etc. The other type of the nodes is the gateway node, which is responsible for aggregating the data from regular sensor nodes and relaying the data to the remote server or the storage device via pre-deployed wired communications. In the scenario we consider, we assume that there is only one gateway node in this network.

First, we consider long-thin sensor networks with a “straight-line” topology, or a “chain” of nodes, as shown in Figure 3-2. The first node is the gateway, which relays collected sensor information to a remote server, and all other nodes are regular sensor nodes. Data collected by each sensor node are aggregated with the packet it has received from its down-stream neighboring node and forwarded to its up-stream neighboring node. The gateway node would eventually receive the packet containing the sensor information from all nodes in the chain.

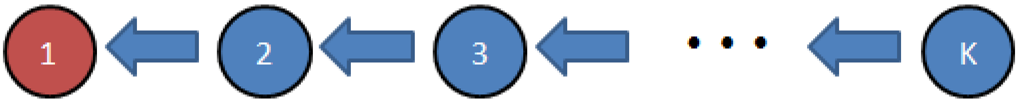

Figure 3-2 A straight-line, or chain topology

The straight-line topology, or the single-chain topology, is the elementary component of any long-thin topology. In this thesis we consider two long-thin topologies which are formed by straight-line topologies. The first case is simply the original straight-line topology. The second case is the multi-chain topology, which represents a network with multiple branches connecting to a merge point, such as the mine pit shown in Figure 1-3. It is a rotational combination of multiple straight-line topologies. The angle between any adjacent chains is a constant, and the gateway is at the center. Figure 3-3 shows an example of the multi-chain topology- a four chain network; the angle between any two adjacent chains is 90 degrees.

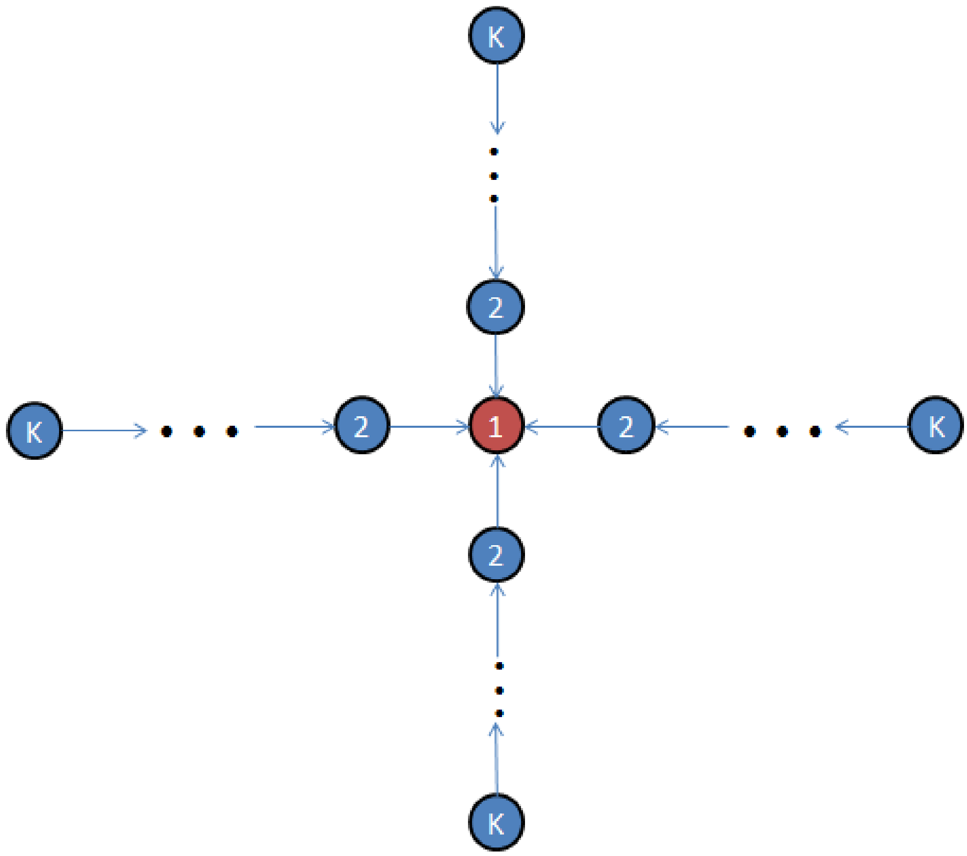

Figure 3-3 An example of the multi-chain topology- a four-chain network

3.3. Scheduling

Based on the description in Subsection 3.2, we will now present the scheduling model for both WSNs during its regular operation, utilizing a TDMA-based MAC protocol (referred as TDMA network in subsequent text), and WSNs in the emergency mode, utilizing a CDMA-based MAC protocol (referred as CDMA network in subsequent text), with the considered topologies. The scheduling model for the TDMA networks are derived so that the performance of the TDMA-based networks can later be analyzed and compared with that of the CDMA networks

First, we derive the transmitting schedule for the single-chain topology, as shown in Figure 3-4 and Figure 3-5. The small circles represent nodes and the big circles represent the effective transmission range of a node. One node can only successfully send data to nodes within its effective transmission range.

In Figure 3-4, if Node B is sending a packet to Node A, Node C cannot send a packet to Node B in the same slot since a sensor node cannot transmit and receive at the same time. However, Node D can send a packet to Node C in the same slot. When using CDMA as MAC protocol, we assume that all transmitting nodes use different transmitting PN code, so the correlation between signals from different sources should be small; thus, we can assume that the interference from Node B to Node C is low. For CDMA, a transmitting node must be located at least two hops away from another transmitting node. Therefore, it is sufficient to use two alternating time slots to schedule all transmissions in the single-chain network. In this schedule, a node is in the transmission state in a time slot, and in the reception state in the next time slot. The node and its immediate neighbors are in different states in each time slot.

The scheduling model for TDMA network with the single-chain topology is different and shown in Figure 3-5. If Node B is sending a packet to Node A, Node C cannot send a packet to Node B in the same time slot. The reason is the same as in the CDMA networks. However, Node D cannot send a packet to Node C either, since we assume that there can only exist one transmitting node in the receiving range of a node, in order to prevent collisions. All nodes use the same spreading code in TDMA networks and, therefore, unlike CDMA, collisions usually result in erroneous packet receptions. In summary, a transmitting node must be located at least three hops away from another transmitting node. Therefore, for TDMA, it is required to use three alternating time slots to schedule all transmissions in the single-chain network, and the utilization of links is apparently smaller than that of the CDMA network. The difference in the schedules for these two different types of networks leads to their performance difference in terms of throughput.

With the same principle, we can deduce that the utilization of links with the multi-chain topology is smaller than that of the network with the single-chain topology for TDMA networks; since there can only be one transmitting node in the receiving range of the gateway, the utilization of links is limited by the number of chains connecting to the gateway. In the TDMA network with the single-chain topology, the length of schedule is three time slots (the schedule repeats itself), and for the multi-chain topology it is at least the number of chains (three time slots when the number of chains connecting to the gateway is smaller than three).

To analyze the performance of a TDMA network with the multi-chain topology, we need to derive a simple and feasible schedule in details. In our analysis, we will utilize a heuristic periodical schedule based on a prime number theorem described below:

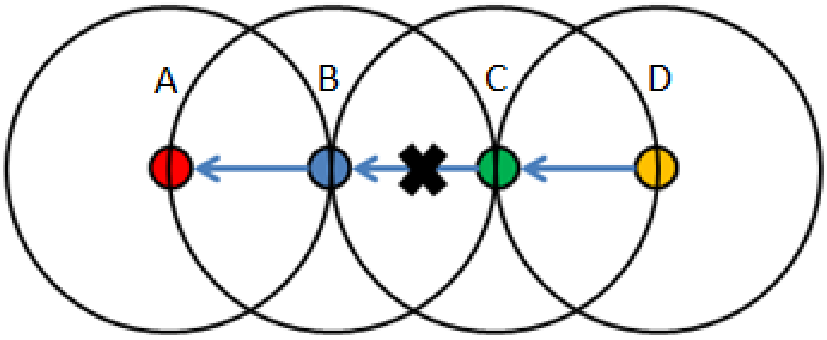

Figure 3-4 The schedule in a CDMA network with the single-chain topology

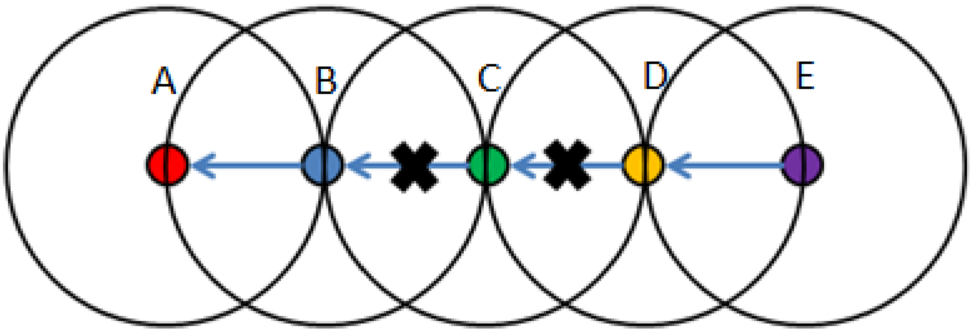

Figure 3-5 The schedule in a TDMA network with the single-chain topology

Theorem 3.1: If $(A, B) = 1$ and $S = \{0, 1, 2, \ldots, B-1\} \rightarrow A \cdot S = S \ (mod\ B)$

Proof: If $A \cdot S \neq S \ (mod\ B)$, then there are at least two elements s_1 and s_2 in S such that $A \cdot s_1 \equiv A \cdot s_2 (mod\ B)$. Arrange the equation, we can find that $A \cdot (s_1 - s_2) \equiv 0 (mod\ B)$. Since $(A, B) = 1$, we can deduce that $(s_1 - s_2) \equiv 0 (mod\ B)$. Therefore, s_1 is equal to s_2. This result leads to a contradiction.

Now we will utilize Theorem 3.1 to derive the schedule. Let B be the number of chains connecting to the gateway, and A be a chosen co-prime number smaller than B. With a schedule of a length of B, it is trivial that the first transmitting node of each chain is among the first B regular nodes. Applying the theorem, the $\left((A \cdot 1)\%B + 1\right)$-th regular node of the first chain, $\left((A \cdot 2)\%B + 1\right)$-th regular node of the second chain,…, and $((A \cdot B)\%B + 1)$-th regular nodes of the B-th chain would be the first transmitting node of each chain in the first time slot in the schedule. The next transmitting node of each chain is B hops away from the first transmitting node in that chain, and so on. The transmitting nodes of each chain in the next time slot are the receiving regular nodes in this time slot. Continuing with this approach, we can construct a simple, periodic, and repetitive schedule for the TDMA network with the multi-chain topology. It also guarantees that the transmission constraints of TDMA are satisfied. The choice of the parameter A could influence the network performance. An example of the schedule in the TDMA network with a multi-chain topology is depicted in Figure 3-6.

On the other hand for CDMA network, we assume that the radio in the gateway is equipped with multiple decoders and can receive packets spreaded with different PN codes (from different nodes) simultaneously. As the constraints of having only one transmitting node in the receiving range of the gateway is lifted, the schedule for a CDMA networks with the multi-chain topology could be shorter than that of a TDMA network. It is obvious that the received SINR of the gateway would decrease compared to that of the single-chain topology if more chains are allowed to transmit at the same time. There is clearly a tradeoff between the signal quality and the length of schedule. To derive the schedule for CDMA networks, we modify the one for TDMA networks to allow more flexibility. The number of nodes transmitting to the gateway and their relative positions would affect the performance, and therefore are made configurable parameters. The optimal values for these parameters will be determined later in Section 4. Figure 3-7 presents an example of the schedule for a CDMA network with eight chains. On the left sub-figure, 4 nodes take turns to transmit signal to the gateway in an interleaving manner. The figure shows that there is a great amount of interference from each transmitting node to its immediate neighboring receiving nodes, which are the ones that are affected the most. On the other hand, if we assign transmitting nodes to every other neighboring chains, one can find that there are still 4 nodes transmitting to the gateway, but the interference is greatly reduced. Our goal is to quantify the amount of performance improvements with the added flexibility in the schedule of the CDMA networks compared to that of the TDMA networks.

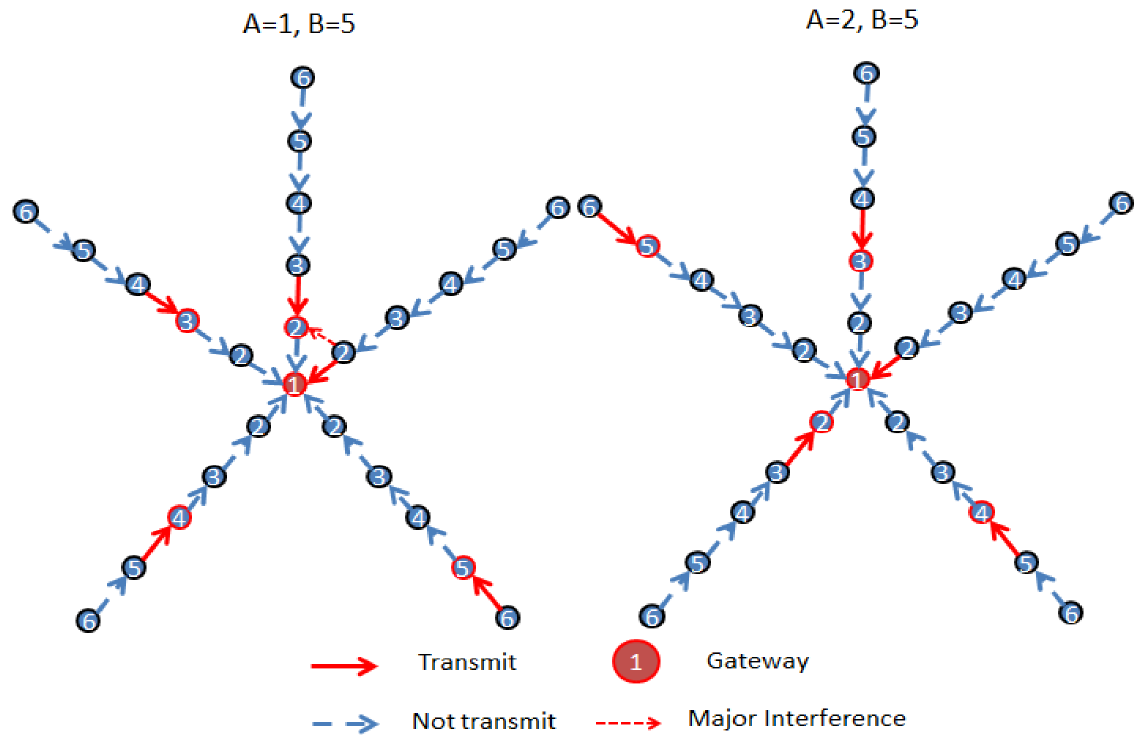

Figure 3-6 The schedule of a TDMA network with the multi-chain topology

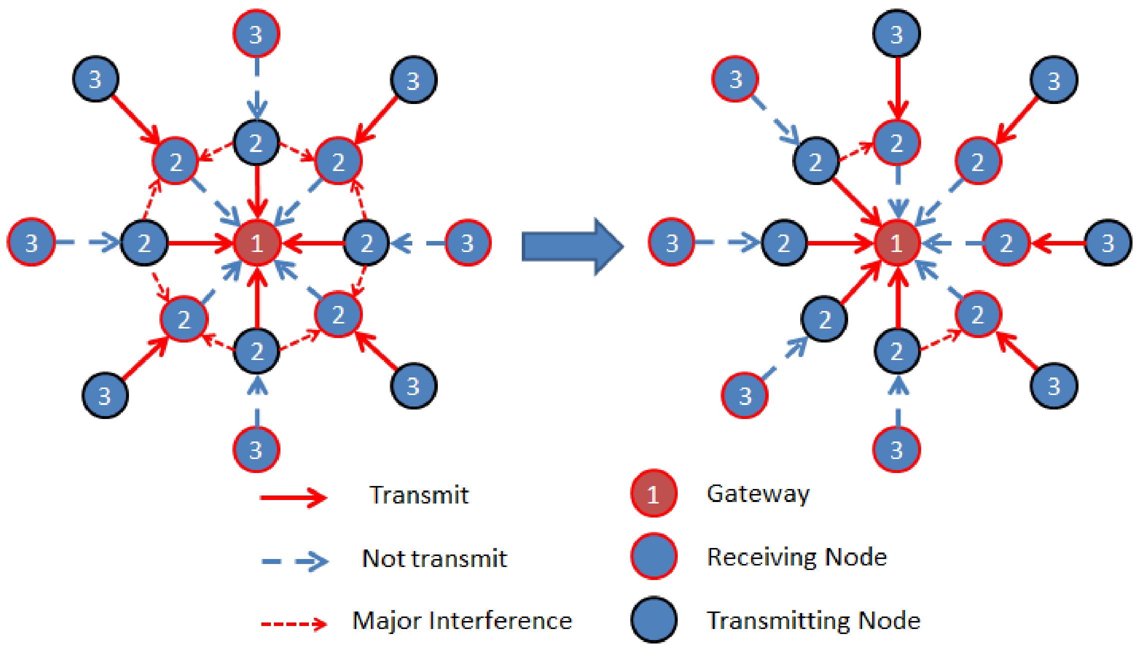

Figure 3-7 The schedule of a CDMA network with the multi-chain topology

3.4. PN Code Sequence Correlation

In this subsection, we will analyze the effects of the PN code. Since each user gets the wanted data by a correlation receiver, the following operation can be performed:

$$Z_i = \int_0^T r(t) a_i(t) \cos(\omega_c t) dt, \tag{3.5}$$

As shown in [5], and it can be reduced to

$$Z_i = \sqrt{\frac{P_i}{2}} b_{i,0} T + \int_0^T n(t) a_i(t) \cos(\omega_c t) dt$$

$$+ \sum_{\substack{k=1 \\ k \neq i}}^{K} \sqrt{\frac{P_k}{2}} \left(b_{k,-1} \cdot R_{k,i}(\tau_k) + b_{k,0} \cdot \hat{R}_{k,i}(\tau_k) \right) \cdot \cos(\emptyset_k), \tag{3.6}$$

where

$$R_{k,i}(\tau) = \int_0^{\tau} a_k(t-\tau)\, a_i(t) dt$$

$$= C_{k,i}(l-N)\big((l+1)T_c - \tau\big) + C_{k,i}(l+1-N)(\tau - lT_c), \tag{3.7}$$

and

$$\hat{R}_{k,i}(\tau) = \int_{\tau}^{T} a_k(t-\tau)\, a_i(t) dt$$

$$= C_{k,i}(l)\big((l+1)T_c - \tau\big) + C_{k,i}(l+1)(\tau - lT_c), \tag{3.8}$$

and $lT_c \le \tau \le (l+1)T_c$. $C_{k,i}$ is a discrete aperiodic cross correlation function and is given by

$$C_{k,i}(l) = \begin{cases} \sum_{j=0}^{N-1-l} a_j^{(k)} \cdot a_{j+l}^{(i)} & ,0 \le l \le N-1 \\ \sum_{j=0}^{N-1+l} a_{j-l}^{(k)} \cdot a_j^{(i)} & ,1-N \le l < 0 \\ 0 & ,|l| > N \end{cases} \tag{3.9}$$

The calculation of two partial cross correlation functions, $R_{k,i}(\tau)$ and $\hat{R}_{k,i}(\tau)$, are shown in Figure 3-8. The delay τ affects the error rate. In the CDMA network we consider, all nodes are asynchronous; therefore, the delay can be seen as uniformly distributed in $[0, T]$. This is good for the performance since the correlation of the different signals would be low. However, the TDMA network needs to synchronize the nodes periodically in order to perform precise scheduling. As a result, the delay of the signal of each node would be small. In addition, all nodes use the same PN code sequence in the TDMA network. This leads to a very high cross-correlation, which may result in vary high interference and low error performance. To simplify the problem, we suppose that the difference in delays of one node to all other nodes is uniformly distributed in $[-BT_c, BT_c]$. Through adjusting B, we would know how sensitive the performance of the TDMA network is to the delay difference.

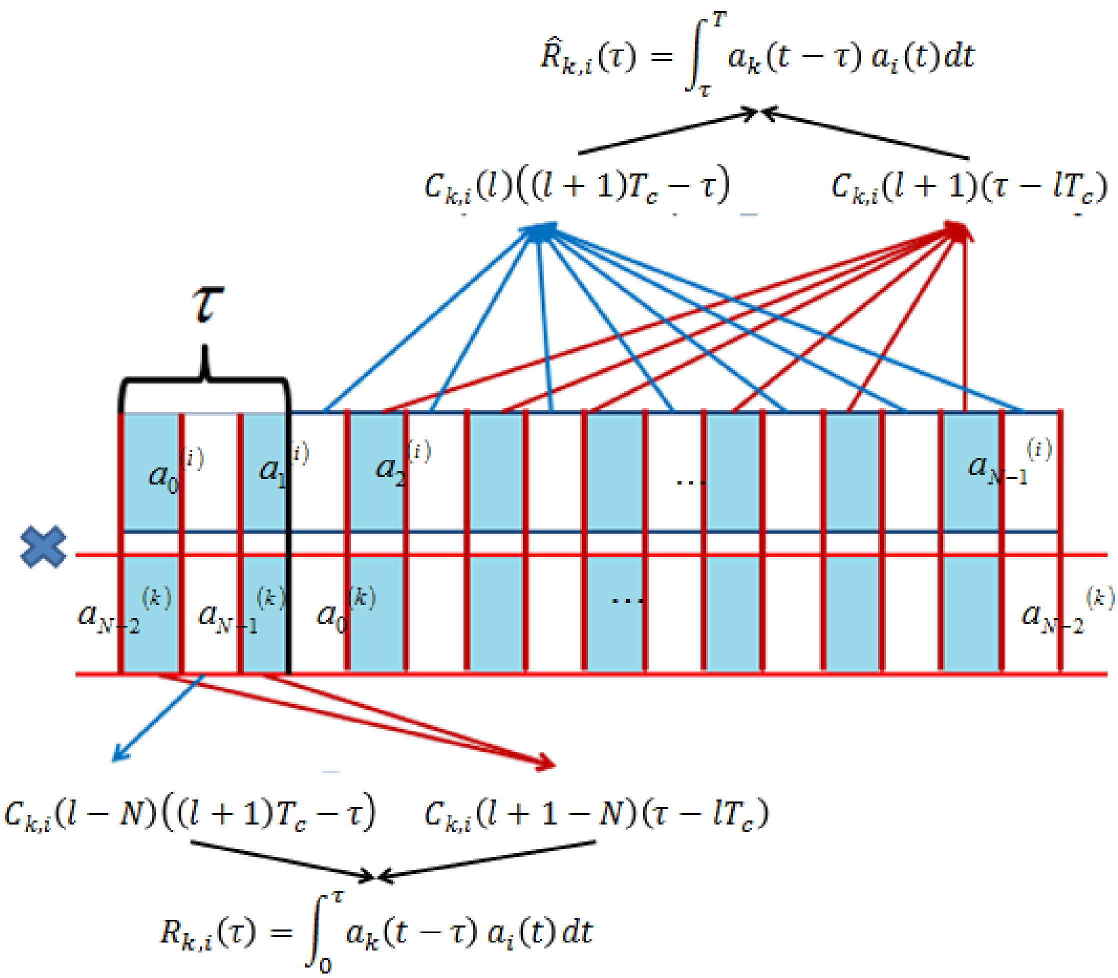

Figure 3-8 PN code cross correlation

3.5. Performance Metrics

With the result presented in Subsection 3.4 and in [5], we know that the SINR can be expressed as the square of the expected value of Z_i divided by the variance of Z_i. After the calculation, the SINR of the received packet transmitted via the link of the i-th node in a CDMA network can be expressed as

$$\mathrm{SINR}_i = \frac{1}{\frac{1}{3N}\sum_{\substack{k=1 \\ k\neq i}}^{K}\frac{P_k}{P_i}+\mathrm{SNR}^{-1}}, \tag{3.10}$$

where N is the number of chips in a PN code, P_k is the received power of the transmitted signal of the k-th node measured by the corresponding receiving node of the signal of the i-th node and SNR is the received SNR value of the packet transmitted via the link of the i-th node.

For the TDMA network, we can derive the closed form expression of SINR_i, using the simplified equation of Z_i. Here, we consider the case of $b_{i,0} = 1$. We assume that $b_{k,-1}$ and $b_{k,0}$ are independent of $b_{i,0}$, and the probability of being 1 is the same as the probability of being 0. We also assume that τ_k and $\emptyset_k$ are independent of $b_{k,-1}$ and $b_{k,0}$. Besides, all nodes in the TDMA network use the same PN code sequence $a(t)$ to transmit data. Thus, we will use $R(\tau)$, $\hat{R}(\tau)$, and $C(\tau)$ to replace $R_{k,i}(\tau)$, $\hat{R}_{k,i}(\tau)$, and $C_{k,i}(\tau)$ presented earlier in the following equations. Then, we have

$$\mathrm{E}[Z_i] = \sqrt{\frac{P_i}{2}}T + \mathrm{E}\left[\int_0^T n(t)a(t)\cos(\omega_c t)dt\right]. \tag{3.11}$$

We assume that the noise $n(t)$ is normally distributed with mean $E[n(t)] = 0$ and variance $E[n^2(t)] = \frac{N_0}{2}$, independent of $a(t)\cos(\omega_c t)$. Thus, we have

$$\mathrm{E}\left[\int_0^T n(t)a(t)\cos(\omega_c t)dt\right] = \int_0^T E[n(t)]E[a(t)\cos(\omega_c t)]dt = 0, \tag{3.12}$$

and

$$\mathrm{E}[Z_i] = \sqrt{\frac{P_i}{2}}T. \tag{3.13}$$

Next, we will derive the closed form expression of the variance of $[Z_i]$. According to the definition of variance, we have

$$\mathrm{Var}[Z_i] = E[{Z_i}^2] - E[Z_i]^2,\ \mathrm{E}[Z_i]^2 = \frac{P_i}{2}T^2, \tag{3.14}$$

and

$$\begin{aligned} E[{Z_i}^2] &= E\left[\left(\sqrt{\frac{P_i}{2}}b_{i,0}T\right)^2\right] + \mathrm{E}\left[\left(\int_0^T n(t)a(t)\cos(\omega_c t)dt\right)^2\right] \\ &+ \mathrm{E}\left[\left(\sum_{\substack{k=1\\ k\neq i}}^K \sqrt{\frac{P_k}{P_i}}\left(b_{k,-1}\cdot R(\tau_k) + b_{k,0}\cdot \hat{R}(\tau_k)\right)\cos(\emptyset_k)\right)^2\right] \\ &+ E\left[2\cdot\sqrt{\frac{P_i}{2}}b_{i,0}T\cdot\left(\sum_{\substack{k=1\\ k\neq i}}^K \sqrt{\frac{P_k}{P_i}}\left(b_{k,-1}\cdot R(\tau_k) + b_{k,0}\cdot \hat{R}(\tau_k)\right)\cos(\emptyset_k)\right)\right] \\ &+ E\left[2\cdot\left(\sum_{\substack{k=1\\ k\neq i}}^K \sqrt{\frac{P_k}{P_i}}\left(b_{k,-1}\cdot R(\tau_k) + b_{k,0}\cdot \hat{R}(\tau_k)\right)\cos(\emptyset_k)\right)\cdot\left(\int_0^T n(t)a(t)\cos(\omega_c t)dt\right)\right] \\ &+ E\left[2\cdot\sqrt{\frac{P_i}{2}}b_{i,0}T\cdot\left(\int_0^T n(t)a(t)\cos(\omega_c t)dt\right)\right]. \end{aligned} \tag{3.15}$$

Since the probability of being 1 is equal to the probability of being 0 for $b_{k,-1}$ and $b_{k,0}$ and $E[n(t)] = 0$, we can deduce that

$$\begin{aligned} E[{Z_i}^2] &= \frac{P_i T^2}{2} + E\left[\sum_{\substack{k=1\\ k\neq i}}^K \frac{P_k}{2}\left(R(\tau_k)^2 + \hat{R}(\tau_k)^2\right)\cos^2(\emptyset_k)\right] \\ &+ E\left[\int_0^T\int_0^T n(t)n(t')a(t)a(t')\cos(\omega_c t)\cos(\omega_c t')dt\,dt'\right]. \end{aligned} \tag{3.16}$$

Since $n(t)$ is white, we have

$$E[n(t)n(t')] = \begin{cases} \frac{N_0}{2} | & t = t' \\ 0 & |otherwise \end{cases}. \quad (3.17)$$

Thus, we can rewrite the third term on the right side of (3.16) into

$$E\left[\int_0^T n(t)^2 a(t)^2 \cos^2(\omega_c t)dt\right] = \int_0^T E[n(t)^2] \cdot E[\cos^2(\omega_c t)]dt$$

$$= \frac{N_0}{2} \cdot \int_0^T E\left[\frac{1+\cos(2\omega_c t)}{2}\right] \mathrm{dt} = \frac{N_0 T}{4}, \quad (3.18)$$

and the second term on the right side of (3.16) into

$$E\left[\sum_{\substack{k=1 \\ \mathrm{k}\neq\mathrm{i}}}^{K} \frac{P_k}{2}\left(R(\tau_k)^2 + \hat{R}(\tau_k)^2\right)\cos^2(\emptyset_k)\right]$$

$$= \sum_{\substack{k=1 \\ \mathrm{k}\neq\mathrm{i}}}^{K} \frac{P_k}{2} E\left[R(\tau_k)^2 + \hat{R}(\tau_k)^2\right] E[\cos^2(\emptyset_k)]$$

$$= \sum_{\substack{k=1 \\ \mathrm{k}\neq\mathrm{i}}}^{K} \frac{P_k}{2} E\left[R(\tau_k)^2 + \hat{R}(\tau_k)^2\right] E\left[\frac{1+\cos(2\emptyset_k)}{2}\right]$$

$$= \sum_{\substack{k=1 \\ \mathrm{k}\neq\mathrm{i}}}^{K} \frac{P_k}{4} E\left[R(\tau_k)^2 + \hat{R}(\tau_k)^2\right]. \quad (3.19)$$

Combining the result of (3.14), (3.16), (3.18), and (3.19), we can obtain

$$\mathrm{Var}[Z_i] = E\left[{Z_i}^2\right] - E[Z_i]^2 = \sum_{\substack{k=1 \\ \mathrm{k}\neq\mathrm{i}}}^{K} \frac{P_k}{4} E\left[R(\tau_k)^2 + \hat{R}(\tau_k)^2\right] + \frac{N_0 T}{4}. \quad (3.20)$$

Now we need to find the closed form expression of $E\left[R(\tau_k)^2 + \hat{R}(\tau_k)^2\right]$. Since all nodes transmitting in the same time slot are synchronized in the TDMA network, the difference in delays between any two data signals from different nodes is small since the speed of electromagnetic wave is very fast, and the difference in the transmitter-receiver distances in very small. To simplify the problem, we suppose that τ_k is uniformly distributed in $[-BT_c, BT_c]\left(0 < B \leq \frac{N}{2}\right)$, where B is a parameter representing the upper bound of the delay difference in chip duration, and T_c is the duration of one chip. Then we can obtain the following expression:

$$E\left[R(\tau_k)^2+\hat{R}(\tau_k)^2\right]$$

$$=\frac{1}{2BT_c}\left(\int_0^{BT_c} R(\tau_k)^2+\hat{R}(\tau_k)^2 d\tau+\int_{(N-B)T_c}^{T} R(\tau_k)^2+\hat{R}(\tau_k)^2 d\tau\right)$$

$$=\frac{1}{2BT_c}\left(\sum_{l=0}^{B-1}\int_{lT_c}^{(l+1)T_c} R(\tau_k)^2+\hat{R}(\tau_k)^2\, d\tau+\sum_{l=N-B}^{N-1}\int_{lT_c}^{(l+1)T_c} R(\tau_k)^2+\hat{R}(\tau_k)^2\, d\tau\right)$$

$$=\frac{T^2}{6BN^2}\left(\sum_{l=0}^{B-1}\begin{array}{c}C(l-N)^2+C(l-N)C(l+1-N)+C(l+1-N)^2\\+C(l)^2+C(l)C(l+1)+C(l+1)^2\end{array}\right)$$

$$+\frac{T^2}{6BN^2}\left(\sum_{l=N-B}^{N-1}\begin{array}{c}C(l-N)^2+C(l-N)C(l+1-N)+C(l+1-N)^2\\+C(l)^2+C(l)C(l+1)+C(l+1)^2\end{array}\right). \qquad (3.21)$$

Here we assume that the probability of being 1 is equal to the probability of being 0 for all bits of a PN code and all bits of a PN code are independent of each other. With this assumption, the expected value of the expression is

$$E\left[R(\tau_k)^2+\hat{R}(\tau_k)^2\right]=\frac{T^2}{6BN^2}(2N^2+(4B-2)N). \qquad (3.22)$$

Thus

$$\mathrm{Var}[Z_i]=\frac{T^2}{12BN^2}(N^2+(2B-1)N)\sum_{\substack{k=1\\ k\neq i}}^{K} P_k+\frac{N_0T}{4}. \qquad (3.23)$$

The SINR of the received packet transmitted via the link of the i-th node in a TDMA network can then be given by:

$$\mathrm{SINR}_i=\frac{E[Z_i]^2}{Var[Z_i]}=\frac{\frac{P_iT^2}{2}}{\frac{T^2}{12BN^2}(N^2+(2B-1)N)\sum_{\substack{k=1\\ k\neq i}}^{K} P_k+\frac{N_0T}{4}}$$

$$=\frac{1}{\frac{(N^2+(2B-1)N)}{6BN^2}\sum_{\substack{k=1\\ k\neq i}}^{K}\frac{P_k}{P_i}+\mathrm{SNR}^{-1}}. \qquad (3.24)$$

If B is zero, all signals has zero delay to each other. We have:

$$b_{k,-1}\cdot R(\tau_k)+b_{k,0}\cdot \hat{R}(\tau_k)=b_{k,-1}\cdot 0+b_{k,0}\cdot NT_c=b_{k,0}NT_c, \qquad (3.25)$$

and

$$E\left[R(\tau_k)^2 + \hat{R}(\tau_k)^2\right] = E\left[{b_{k,0}}^2 N^2 {T_c}^2\right] = N^2 {T_c}^2. \quad (3.26)$$

Utilizing (3.26) and (3.20),

$$\mathrm{SINR}_i = \frac{\frac{P_i T^2}{2}}{\frac{N^2 {T_c}^2}{4} \sum_{\substack{k=1 \\ k \neq i}}^{K} P_k + \frac{N_0 T}{4}} = \frac{1}{\frac{1}{2} \sum_{\substack{k=1 \\ k \neq i}}^{K} \frac{P_k}{P_i} + \mathrm{SNR}^{-1}}. \quad (3.27)$$

Since we now know the closed form expression of the SINR in the CDMA and the TDMA networks, we can define some performance metrics to compare the performance of these two types of networks. Assuming that Binary Phase Shift Keying (BPSK) is used as the modulation format, the bit error rate (BER) of the received packets is given by

$$\mathrm{BER} = 1 - Q\left(\sqrt{\mathrm{SINR}}\right), \quad (3.28)$$

where Q-function is the tail probability of the standard normal distribution and $SINR$ is the SINR of the received packet. Assuming that all packets have D bits in length and all bit errors in a packet are independent events, the packet error rate (PER) of the received packets is given by

$$\mathrm{PER} = 1 - (1 - \mathrm{BER})^D, \quad (3.29)$$

as a packet is correct when all bits in this packet are successfully received. If we consider the case that a packet can be corrected as the number of error bits is not larger than Y, then the PER of one link now can be represented, according to binomial theorem, as

$$\mathrm{PER}_{ECC,Y} = 1 - \sum_{m=0}^{Y} C_m^D (1 - \mathrm{BER})^{D-m} \mathrm{BER}^m. \tag{3.30}$$

Since the sensor data of a node is relayed to the gateway via all of its downlink nodes, we also need to consider the route BER and route PER, i.e., BER and PER observed by the source node and the gateway in an end-to-end sense. The route PER and BER are given by

$$\mathrm{BER}_{route}=1 - \prod_{i=2}^{K} 1 - \mathrm{BER}_i \tag{3.31}$$

and

$$\mathrm{PER}_{route}=1 - \prod_{i=2}^{K} 1 - \mathrm{PER}_i, \tag{3.32}$$

respectively, where K is the number of nodes in the chain and BER_i is the bit error rate of the link of the i-th node, and PER_i is the packet error rate of the link of the i-th node. The first node is the gateway by default, and the last node is the end node of the chain. Last, we must compare the overall network throughputs of CDMA and TDMA networks. To this end, we define the effective throughput (ET) as the number of average successfully received packets at the gateway per unit time. It is influenced by both route PER and the duty cycle of a link, and is given by

$$\mathrm{ET}=(1 - \mathrm{PER}_{route}) \cdot Duty\_Cycle. \tag{3.33}$$

Intuitively, the duty cycles of the TDMA and CDMA networks with the single-chain topology are $1/3$ and $1/2$, respectively, since each link is activated every three time slots in the TDMA network and every two time slots in the CDMA network. In the

TDMA networks with the multi-chain topologies, the duty cycle depends on the number of chains in the network. Relatively, the duty cycle depends on the number of links transmitting to the gateway in the same time slot in the CDMA network with the multi-chain topologies.

3.6. Path Loss Model

One of the power propagation models we use is the log-distance path loss model with log-normal shadowing. Namely, the relationship between the transmitted power and the received power can be expressed as follows:

$$PL_{dBm}(d)=P_{Tx_{dBm}}-P_{Rx_{dBm}}=PL_0+10\gamma\log_{10}\left(\frac{d}{d_0}\right)+X, \quad (3.34)$$

where $P_{Tx_{dBm}}$ is the transmitting power in dBm, $P_{Rx_{dBm}}$ is the received power in dBm, $PL_{dBm}(d)$ is the path loss at distance d in dB, PL_0 is the path loss at the reference distance d_0 in dB, γ is the path loss exponent, and X is an optional normally distributed random variable with a mean of zero to model the shadowing.

The other path loss model we use is Rician fading. In this model, each received signal is modeled as a line-of sight signal plus scattering signals. The movements of the surrounding objects and the receiver itself would cause rapid changes in the signal phase, and, in turn, rapid changes in the received signal power. To figure out if our power allocation scheme performs well in a Rician fading environment, we generate Rician signals according to [10] which modifies Clarke's model to generate Rayleigh fading variables, and add this variables to the original log-distance path loss model to represent the additional path loss caused by the small-scale fading.

3.7. Power Allocation

In this thesis, three different power allocation schemes are evaluated:

(1) *Full power allocation*: all transmitting nodes use the maximum transmission power to send packets.

(2) *ElBatt's algorithm* [4]: the algorithm can find the optimal power allocation with the objective that the total transmission power of all transmitting nodes is minimized while the SINR of any transmitting link in a particular time slot is no less than a pre-specified threshold. This kind of algorithms [4, 8, 9, 14] requires the knowledge of precise path losses between all pairs of nodes, which, in practice, need a great amount of bandwidth to obtain. Moreover, in an environment with rapid small-scale fading, it becomes impractical to track the changes of path losses between nodes, and the throughput performance also significantly degrades as the knowledge of the path losses becomes less accurate. Since the route throughput optimization is not easy to achieve, we revise ElBatt's algorithm to find the power allocation which has the maximum achievable SINR threshold under the transmission power constraint under the proposed scheduling.

(3) *Heuristic power allocation*: to address the problem of the second scheme, a

heuristic scheme which does not require the knowledge of path losses between all pairs of nodes is proposed. We find that the power allocation results obtained by ElBatt's algorithm in an environment with no fading can be closely approximated with linear functions, as shown in Figure 3-9 and Figure 3-10. The proposed heuristic scheme thus allocates the power to nodes using a linear function based on this observation. The performance of all three schemes is analyzed in Chapter 4.

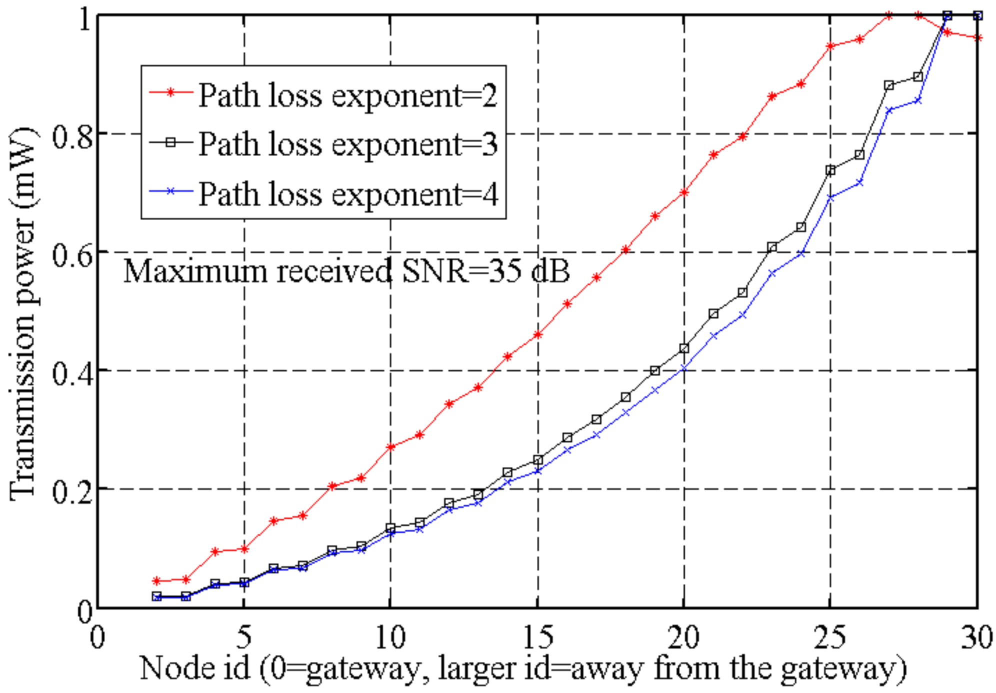

Figure 3-9 Power allocation of nodes in a 30-node chain when using ElBatt's algorithm with SNR=35 dB

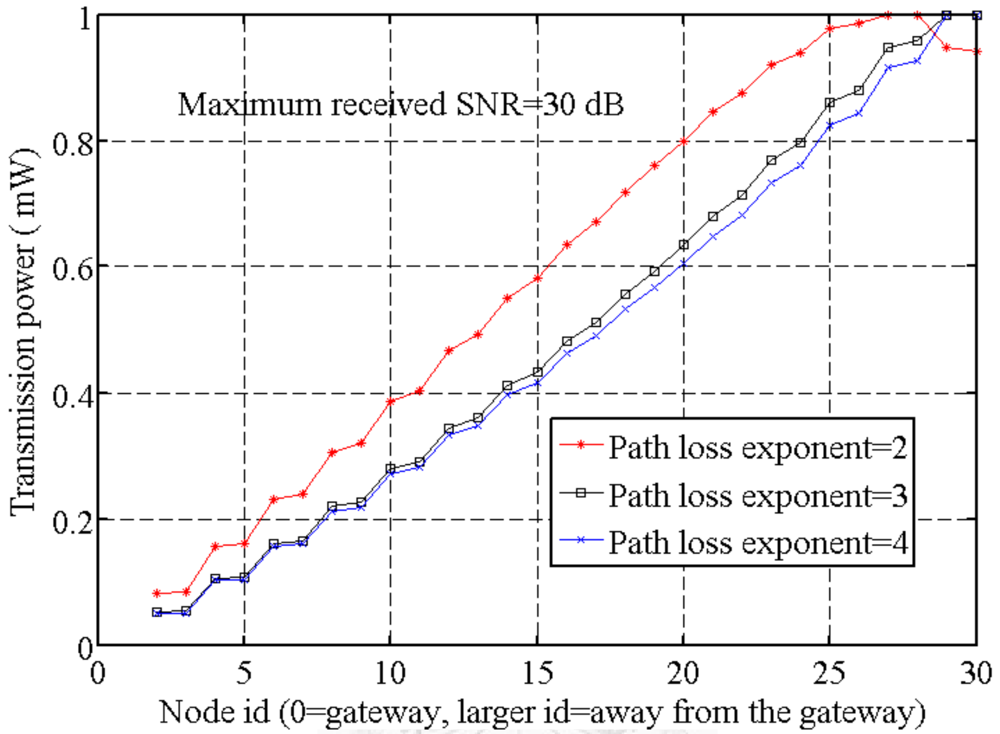

Figure 3-10 Power allocation of nodes in a 30-node chain when using ElBatt's algorithm with SNR=30 dB

Chapter 4 Results

4.1. Single-Chain Topology

First, we compare the performance of CDMA and TDMA networks in the case that they have the single-chain topology. We suppose that the distance between one node and its neighbors is set to be a constant. Thus, with the SINR expression, the path loss model, and schedules for CDMA and TDMA, we can obtain the SINR of the link of the i-th node in the network with the single-chain topology:

$$\text{CDMA:}\quad \text{SINR}_i = \begin{cases} \dfrac{1}{\frac{1}{3N}\sum_{\substack{k=2,4,\dots \\ \text{k}\neq\text{i}}}^{k\leq K} \frac{P_k}{P_i}|k-i+1|^{-\gamma}+\text{SNR}^{-1}} & , i\in\{2,4,\dots\}, i\leq K \\ \dfrac{1}{\frac{1}{3N}\sum_{\substack{k=3,5,\dots \\ \text{k}\neq\text{i}}}^{k\leq K} \frac{P_k}{P_i}|k-i+1|^{-\gamma}+\text{SNR}^{-1}} & , i\in\{3,5,\dots\}, i\leq K \end{cases}$$

$$\text{TDMA:}\quad \text{SINR}_i = \begin{cases} \dfrac{1}{\frac{(N^2+(2B-1)N)}{6BN^2}\sum_{\substack{k=2,5,8 \\ k\neq i}}^{k\leq K} \frac{P_k}{P_i}|k-i+1|^{-\gamma}+\text{SNR}^{-1}} & , i\in\{2,5,8,\dots\}, i\leq K \\ \dfrac{1}{\frac{(N^2+(2B-1)N)}{6BN^2}\sum_{\substack{k=3,6,9 \\ k\neq i}}^{k\leq K} \frac{P_k}{P_i}|k-i+1|^{-\gamma}+\text{SNR}^{-1}} & , i\in\{3,6,9,\dots\}, i\leq K \\ \dfrac{1}{\frac{(N^2+(2B-1)N)}{6BN^2}\sum_{\substack{k=4,7,10 \\ k\neq i}}^{k\leq K} \frac{P_k}{P_i}|k-i+1|^{-\gamma}+\text{SNR}^{-1}} & , i\in\{4,7,10,\dots\}, i\leq K \end{cases}$$

In the following, we consider some simulation parameter settings. We set the PN code length $N = 16$, the transmission power which can be used on a node has a continuous range from -25 dBm to 0 dBm. We first discuss the route BER performance given different SNR values and different path loss exponents for TDMA networks with different upper bound in delay difference and CDMA networks. Through adjusting the distance between adjacent nodes, we can determine the received SNR of packets via each link. Practically, it is reasonable to ensure the received SNR using the minimum transmission power is no less than 10 dB in order to overcome the fading environment. Thus, the range of the received SNR is set from 10 dB to 35 dB according to the transmission power setting.

(a) Performance of CDMA and TDMA using the full power allocation scheme

In this subsection, we compare the route BER of TDMA and CDMA networks. As described previously, TDMA networks usually perform synchronization, and, as a result, the difference in delays between different transmissions is small. In the analysis, we configure B, the maximum delay difference, to a few values, and observe the performance difference.

From Figure 4-1 to Figure 4-4, the x-coordinate represents the length of single chain, that is, the number of nodes, including the gateway, and the y-coordinate represents the value of the route BER in log scale. In Figure 4-1, with path loss exponent $\gamma = 2$ and the received $\mathrm{SNR} = 10\mathrm{dB}$, the route BER curve of TDMA with random delay time $(B = 8)$ outperforms the curve of CDMA, but one can also see that the curve of CDMA nearly matches the curve of TDMA with $B = 3$, and all other TDMA curves with smaller B values show worse route BER performance. As previously mentioned, all signals have very short delay with each other in the TDMA network since the transmitting nodes in the same time slot are synchronized. Therefore, the most realistic curve of TDMA is the one of TDMA with a small B value, and it is obvious that CDMA outperforms TDMA in a realistic situation under our assumptions. We can also find a similar phenomenon in Figure 4-2 with path loss exponent $\gamma = 3$. At the first glance, the curve of CDMA performs not so well, compared to the curves of TDMA. One of the reasons is the larger path loss exponent. If the path loss exponent is larger, the radio attenuation is more severe. Under the same received SNR but a larger path loss exponent, the interference is less significant. Therefore, the anti-interference capability of CDMA is not fully utilized. Nevertheless, as pointed out earlier, the realistic TDMA network is more likely to be the upper curve, then CDMA is still a good choice under the circumstance that the path loss exponent is large.

In Figure 4-3 and Figure 4-4, the received SNR is set to be 15 dB. We can also observe similar phenomena to the one shown in Figure 4-1 and Figure 4-2. Even though we claim that CDMA is better than TDMA in realistic cases from the route BER performance curve, the situation when the route BER curve of realistic TDMA is the lower curve in these figures should be considered. In that case, we compare the effective throughput of CDMA and TDMA networks with random difference in the delays of different transmissions, whose performance can be considered as the upper bound for all TDMA cases. The ratio of the duty cycles of the links in TDMA to that in CDMA is 2/3, and thus the effective throughput of CDMA could outperform that of TDMA. In Figure 4-5 and Figure 4-6, one can observe that the effective throughput of CDMA outperforms that of TDMA when the received SNR of each link is more than 13 dB with no error correction code. On the other hand, it decreases so fast as the number of nodes in the chain increases or the received SNR decreases, it is exceeded by the effective throughput of TDMA in the case that the number of nodes in the chain is less than 10 and the received SNR under 10 dB. Consider the case that an error correction code which can correct one bit of error per packet is used, as shown in Figure 4-7. We can find that the curve of CDMA is greatly improved and it outperforms the curve of TDMA when the received SNR is more than 10 dB. In Figure 4-8, when the path loss exponent $\gamma = 3$, a similar phenomenon can be observed. This means that when we choose a good error correction code technique, we can have a much higher overall throughput in a CDMA network with single-chain topologies.

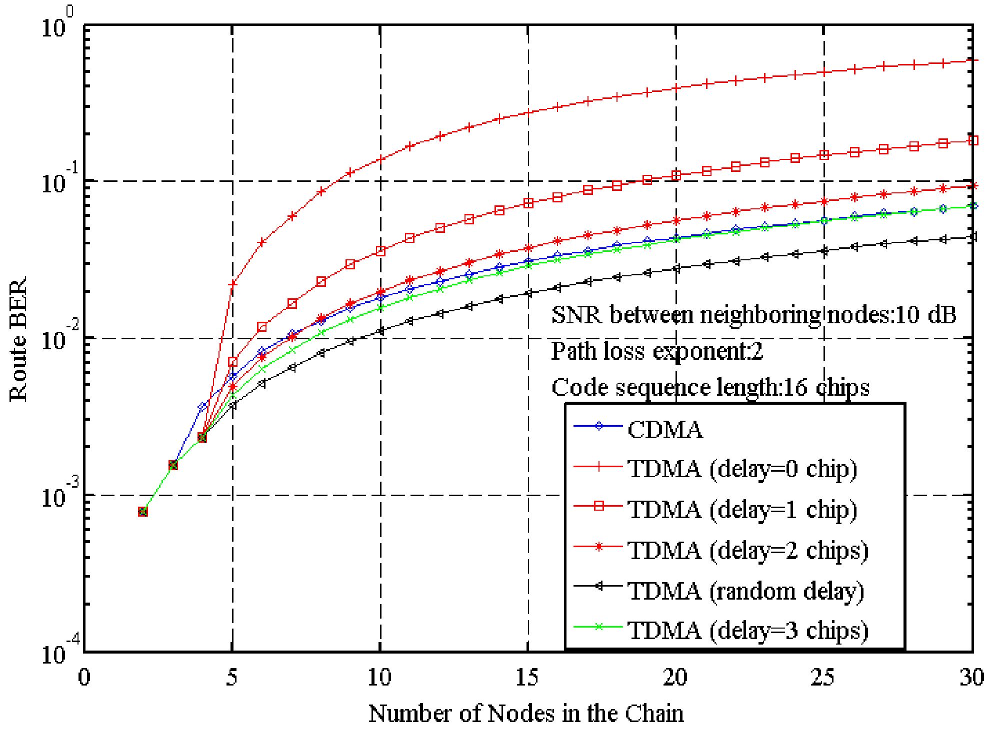

Figure 4-1 Route BER of CDMA and TDMA with SNR= 10dB and $\gamma = 2$

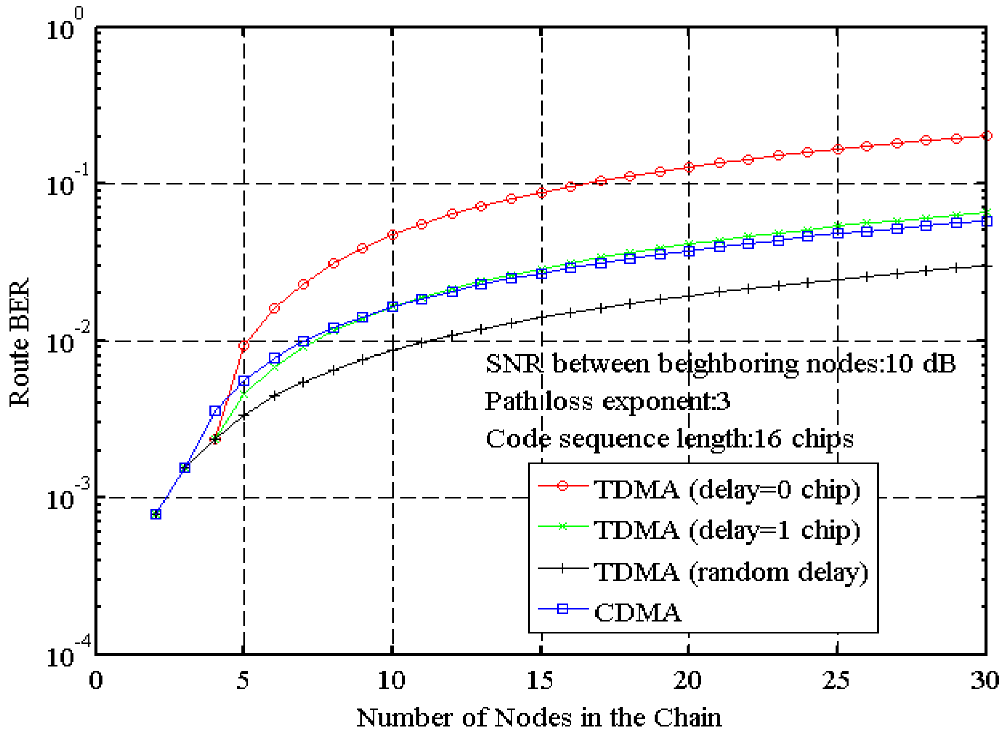

Figure 4-2 Route BER of CDMA and TDMA with SNR= 10dB and $\gamma = 3$

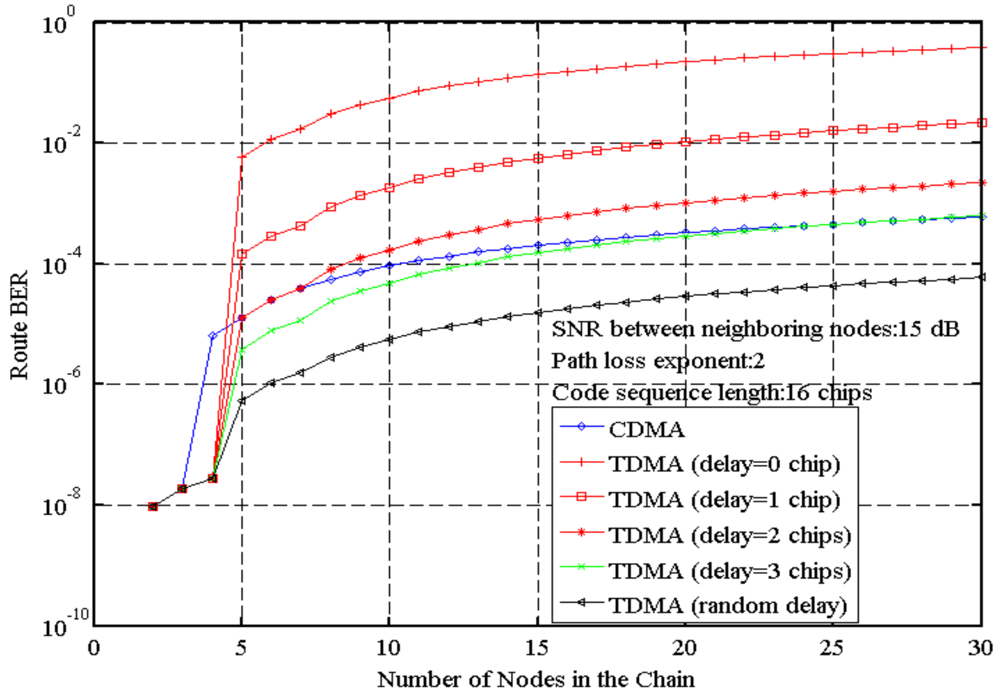

Figure 4-3 Route BER of CDMA and TDMA with SNR= 15dB and $\gamma = 2$

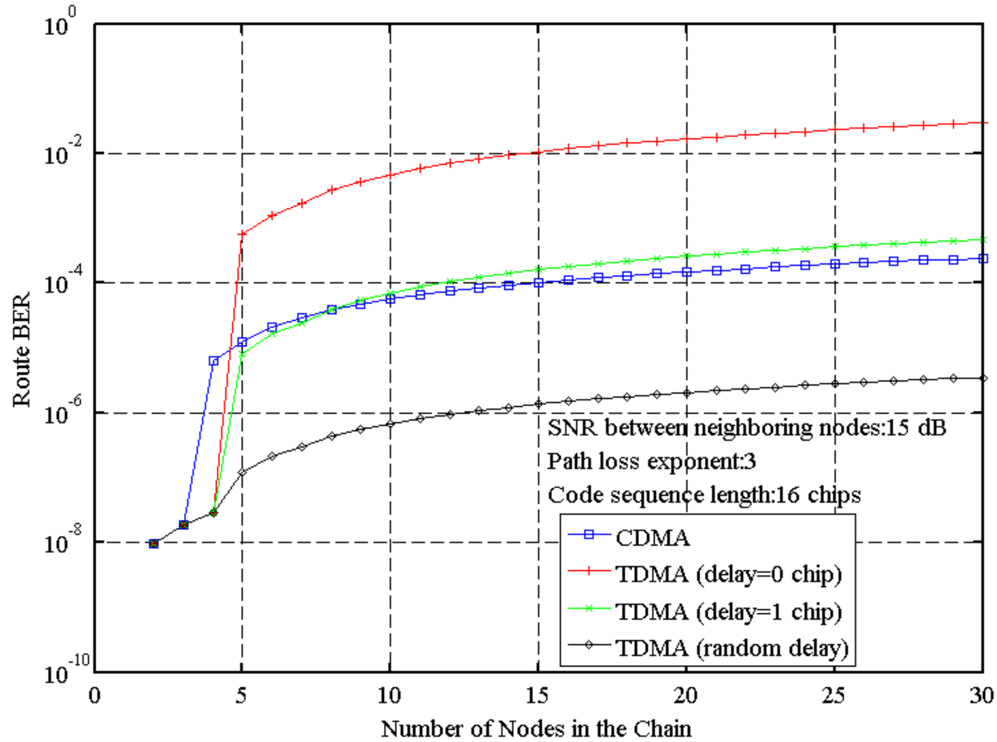

Figure 4-4 Route BER of CDMA and TDMA with SNR= 15dB and $\gamma = 3$

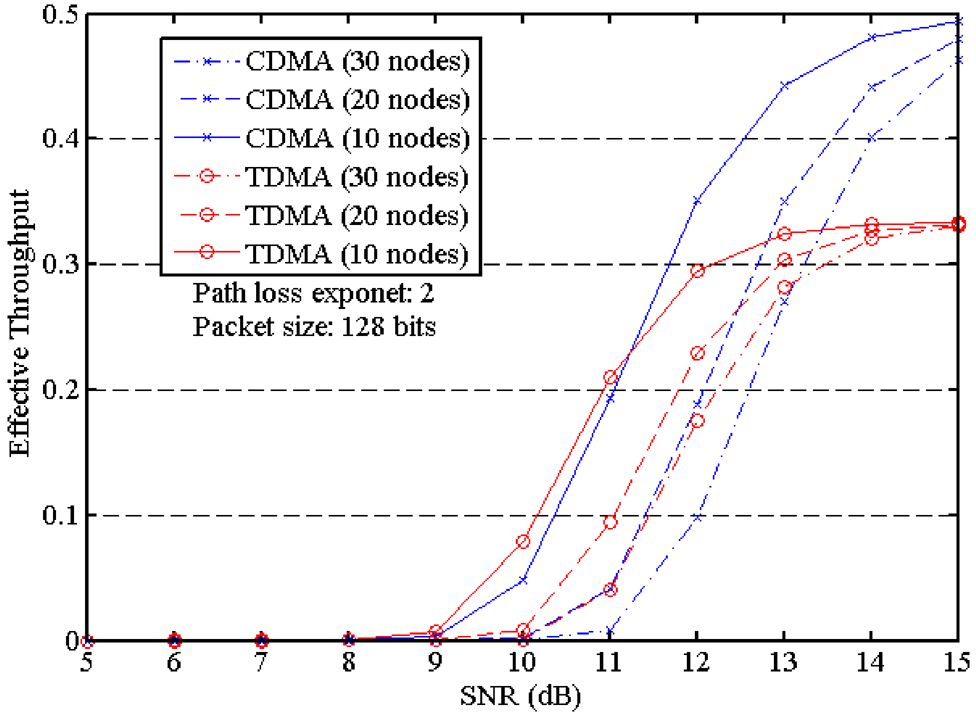

Figure 4-5 Effective throughput of CDMA and TDMA with $\gamma = 2$

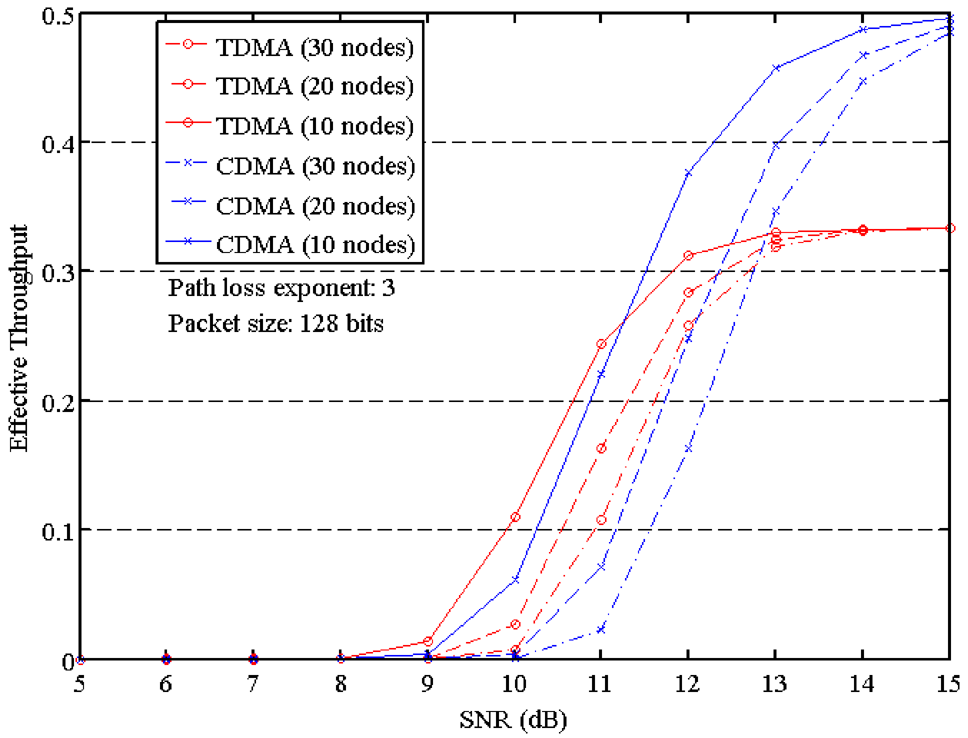

Figure 4-6 Effective throughput of CDMA and TDMA with $\gamma = 3$

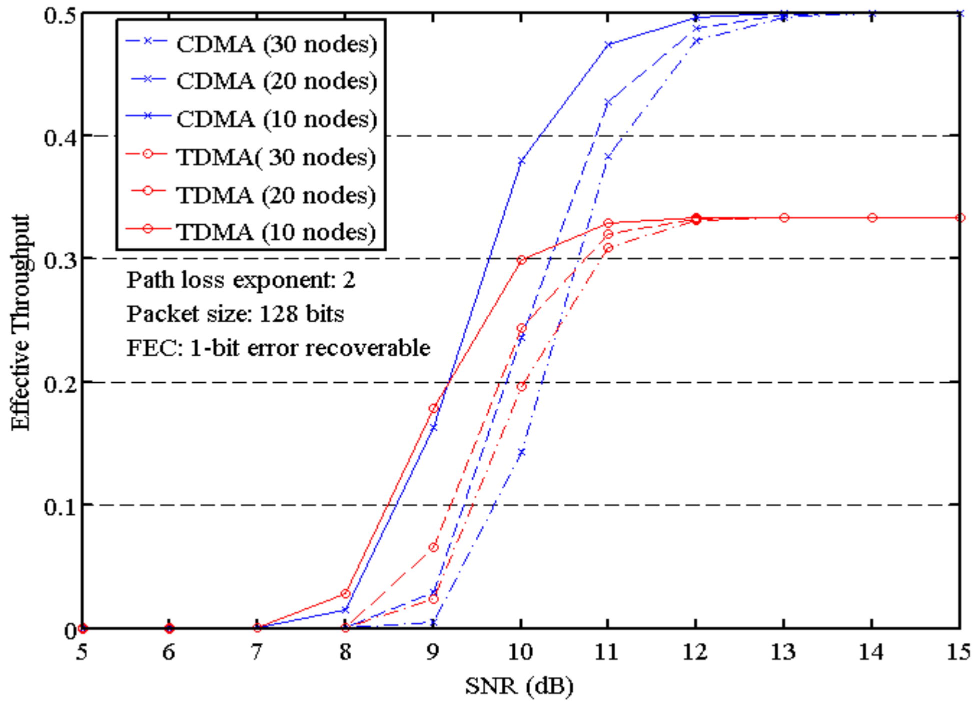

Figure 4-7 Effective throughput of CDMA and TDMA with $\gamma = 2$ (1-bit error recoverable)

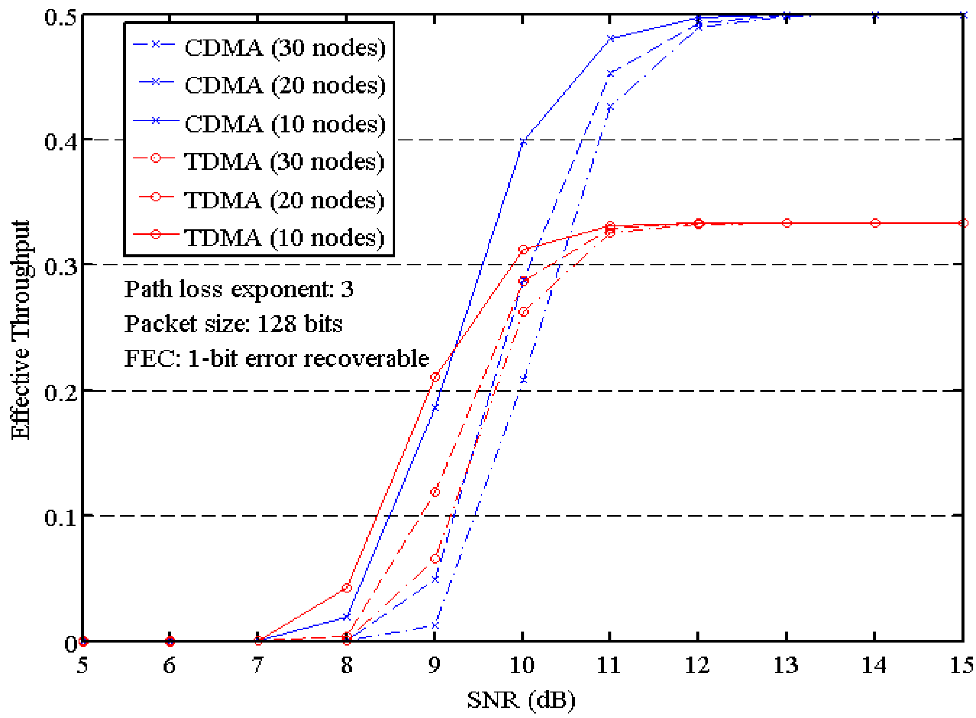

Figure 4-8 Effective throughput of CDMA and TDMA with $\gamma = 3$ (1-bit error recoverable)

(b) Performance comparison in non-fading environments

Here we compare the performance of the full power allocation scheme, our heuristic power allocation scheme, and ElBatt's algorithm in a CDMA network with single-chain topologies. In the analysis in this subsection, we assume that there is no fading in the environment. According to the range of transmission power of the sensor node in our assumption, ranging from -25 dBm to 0 dBm, the range of the received SNR is from 10 dB to 35 dB. Since the deployment of sensor networks with a specific topology is usually made by human, it is reasonable to choose the between-nodes distance and make the received SNR larger than 10dB when using the minimum transmission power.

In Figure 4-9, one can observe that the route BER of ElBatt's algorithm and that of the heuristic power allocation scheme outperform that route BER of the full power allocation scheme in the environment with the path loss exponent $\gamma = 2$, and one can also observe that the curve of the heuristic power allocation scheme is very close to the curve of ElBatt's algorithm. Figure 4-10 shows a similar phenomenon. Therefore, we can expect that our heuristic scheme can be well applied in CDMA networks with single-chain topologies. The original ElBatt's algorithm takes pairwise path losses between nodes into consideration, and our revised version of the ElBatt's algorithm further improves the error performance. Thus, the error performance of the ElBatt's algorithm is usually better than that of the full power allocation scheme. In our evaluation, it can improve more error performance than the full power allocation scheme with the received SNR ranging from 10 dB to 35 dB we assume, as well as our heuristic power allocation scheme which is based on ElBatt's algorithm.

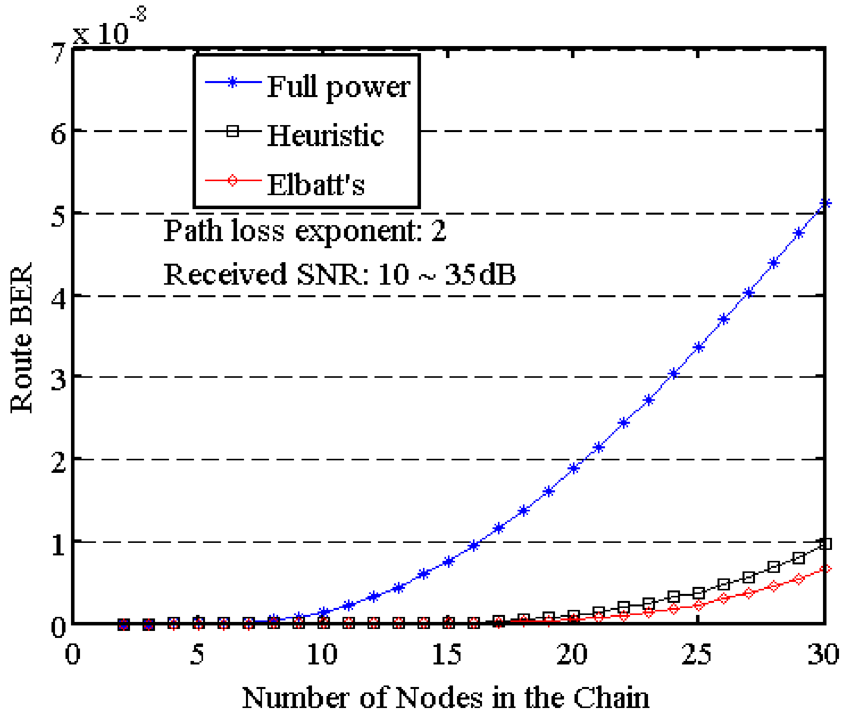

Figure 4-9 Route BER of CDMA using different power allocation schemes with $\gamma = 2$

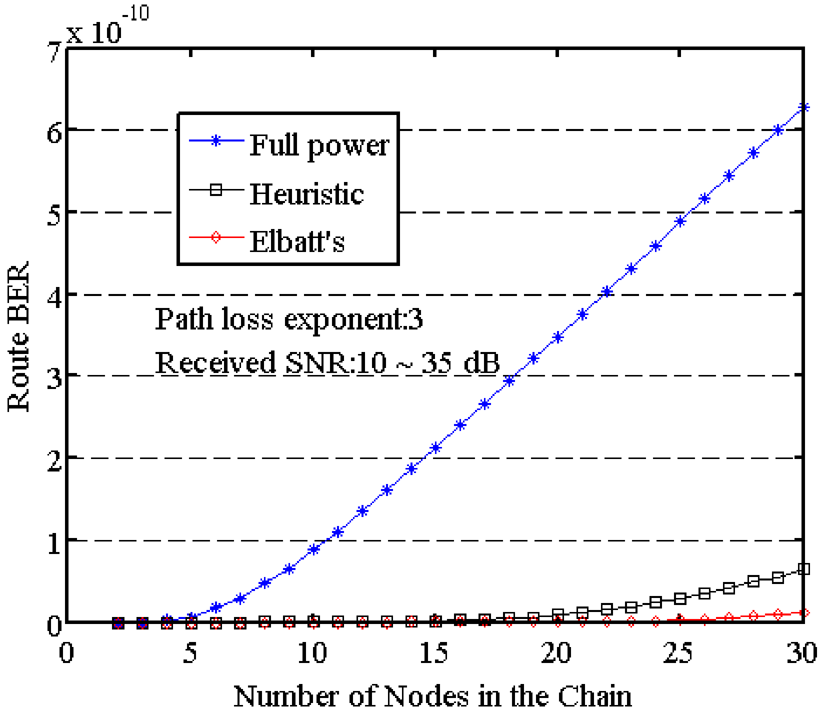

Figure 4-10 Route BER of CDMA using different power allocation schemes with $\gamma = 3$

(c) Performance comparison in fading environments

In this subsection, we compare the performance of CDMA and TDMA networks under more realistic assumptions. Instead of utilizing only the log-distance path loss model, we add both the large-scale fading (shadowing) and the Rician small-scale fading to the path loss model. Fading parameters are configured to reflect those of an indoor fading environment. First, consider a large-scale fading environment whose standard deviation is 7 dB and whose path loss exponent is 2, as shown in Figure 4-11. One can observe that CDMA with the heuristic power allocation scheme outperforms CDMA and TDMA with the full power allocation scheme, but much worse than CDMA with ElBatt's algorithm. Since we assume that the system can have the knowledge of path losses between any two nodes in the network at any given time, ElBatt's algorithm can perform much better than the heuristic power allocation scheme because the heuristic power allocation scheme does not take this knowledge into account. Then, we consider a fading environment with both shadowing and Rician fading, as shown in Figure 4-12. Since the wireless channel small-scale fading changes rapidly, the interval between measurements to obtain the path loss information should be small to accurately capture the states of the channel and use them in ElBatt's algorithm. However, the smaller this interval is, the more overhead the system has. In the analysis, we assume that the interval is one second, which already results in at least 1.5%[1] of overhead. All other parameters are presented in Figure 4-11. We find that CDMA with the heuristic power allocation scheme still performs better than CDMA and TDMA with the full power allocation scheme in the cases that the length of the chain is longer than 7 nodes, but now ElBatt's algorithm performs worse than in the large-scale fading environment, since it is exceeded by the heuristic power allocation scheme in the cases that the chain length is more than 17 nodes. ElBatt's algorithm requires precise information of the path losses between any two nodes in the network, but with small-scale fading, the channel changes rapidly. The path loss between the transmitter and the receiver at the

[1] We take CC2520 as an example. Assuming there are 30 nodes in the network, and they takes turns to send a packet with 128 bits in non-overlapped manners. The maximum data rate of CC2520 is 250 kbit/s, so the overhead of once measurement of the pairwise path losses over one second is $30 \cdot 128/(250 * 1000) \approx 0.0153$

time of transmission can be different from that at the time of the measurements of path losses (each node takes turn to transmit a dummy packet for other nodes to measure the path losses). This results in the performance degradation of ElBatt's algorithm. On the other hand, the full power allocation and the heuristic power allocation schemes do not require the knowledge of path losses, so they are not affected by the rapid changes of the channel. To sum up, it seems the heuristic power allocation scheme is realistic; that is, it does not need a surplus overhead to train the information of path losses between nodes, so the overall throughput is improved. This is good when the system changes to the high speed mode we propose in this work. In a small-scale fading environment, when the length of the chain is long, for example, when it is longer than 17 nodes, it is very suitable to use the heuristic power allocation scheme. When the chain length is short, the heuristic power allocation scheme can still be a good choice since it does not need the overhead to obtain the information of path losses between nodes.

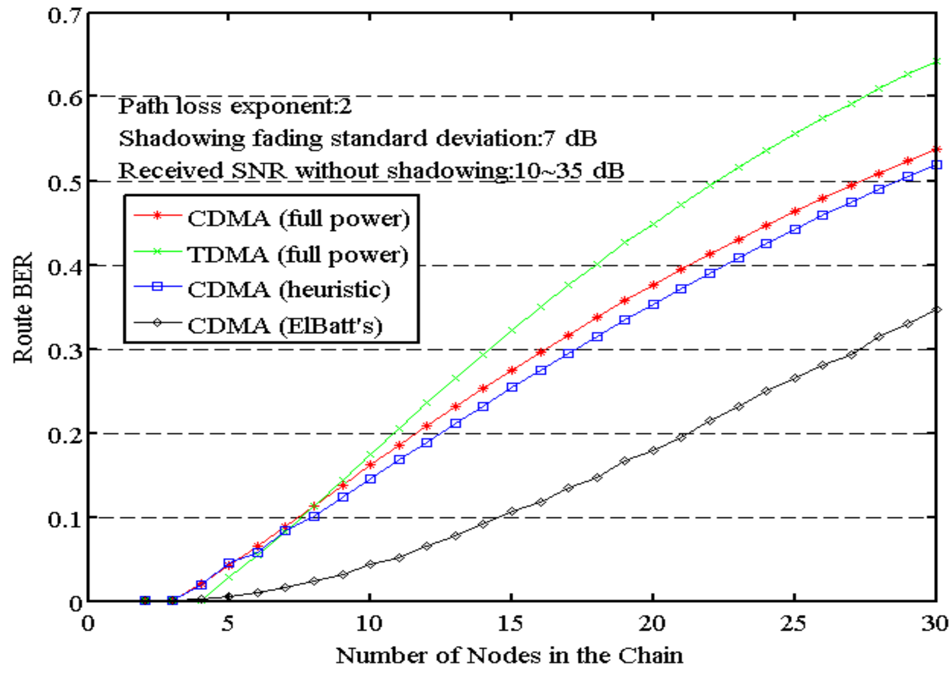

Figure 4-11 Route BER of CDMA with different power allocation schemes and TDMA in a large-scale fading environment

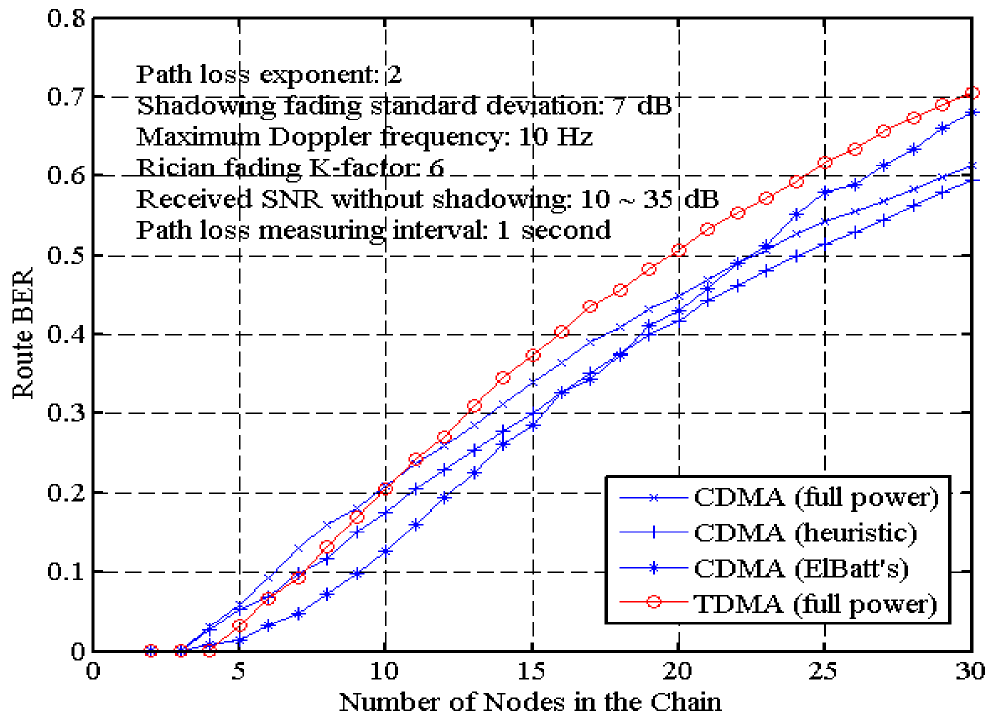

Figure 4-12 Route BER of CDMA with different power allocation schemes and TDMA in large-scale plus small-scale fading environment

4.2. Multi-Chain Topology

We have compared the performance of CDMA and TDMA networks with single-chain topologies. CDMA outperforms TDMA when the received SNR adjusted by choosing different between-node distance is configured to reasonable value and using the full power allocation scheme, and the heuristic power allocation scheme is simple and realistic to be implemented with the off-the-shelf products since it does not need to obtain the information of path losses between nodes in the network, and has good performance. Now we consider the scenario where the network has a multi-chain topology. All the parameters are the same as those for single-chain topology, as presented in Subsection 4.1, but in the multi-chain topology the gateway is connected to multiple chains of nodes. In this subsection, we will investigate if CDMA has the potential to outperform TDMA in networks with multi-chain topologies.

(a) Performance comparison between full power allocation scheme and ElBatt's algorithm

Since the heuristic power allocation scheme is an acceptable choice to achieve good performance in a CDMA network with single-chain topologies, it is of interest to know if it can also be applied to the one with multi-chain topologies to enhance the performance. First, we assume that each chain uses the same schedule where the nodes closest to the gateway in all chains transmit packets to the gateway in the same time slot.

In Figure 4-13, we can find that the performance difference of the route BER between the full power allocation scheme and ElBatt's algorithm in a network with the two-chain topology is smaller than that with the single-chain topology. Moreover, the performance of the full power allocation scheme exceeds that of ElBatt's algorithm in a network with the three-chain topology, as shown in Figure 4-14. If we use the same principle that all chains uses the same schedule, the SINRs of the packets from different transmitters drop significantly since the gateway receives the signals of more than one transmitter. The SINRs of packets sent to all other receivers could also drop when ElBatt's algorithm is applied. Another solution is using the same scheduling principle for TDMA, that is, in each time slot there is only one node transmitting packets to the gateway. However, in this case, we cannot take advantage of the flexibility provided by CDMA, i.e., multiple nodes transmitting in the same time slot within the range of a receiving node. In the next subsection, we will examine whether the scheduling principle mentioned earlier can improve the overall throughput.

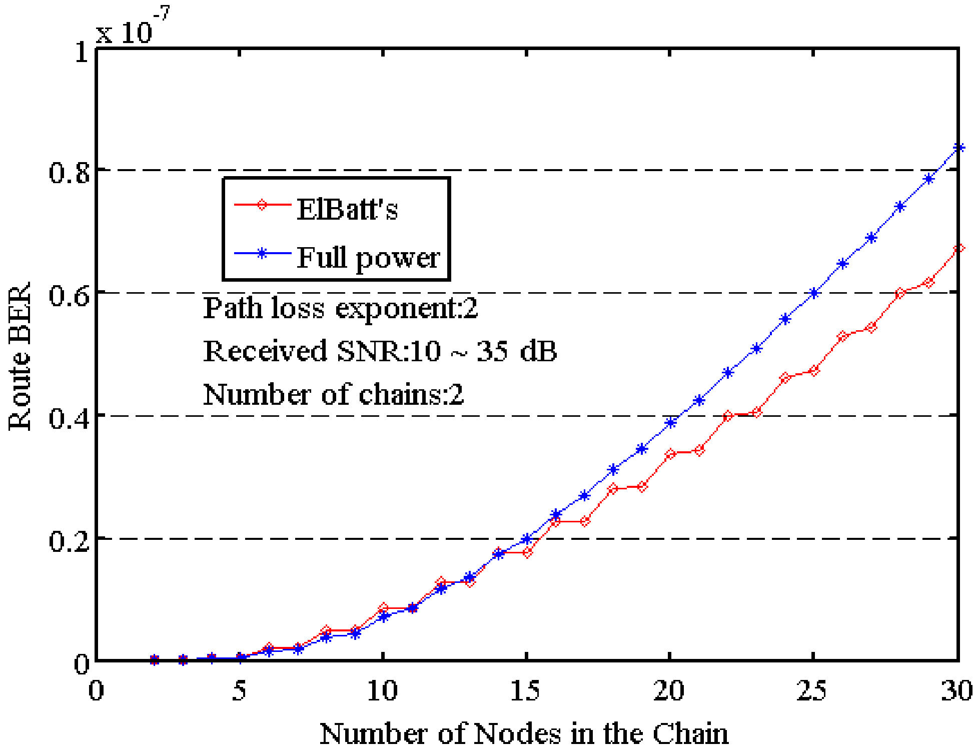

Figure 4-13 Route BER of CDMA using the full power allocation scheme and ElBatt's algorithm in a network with two chains

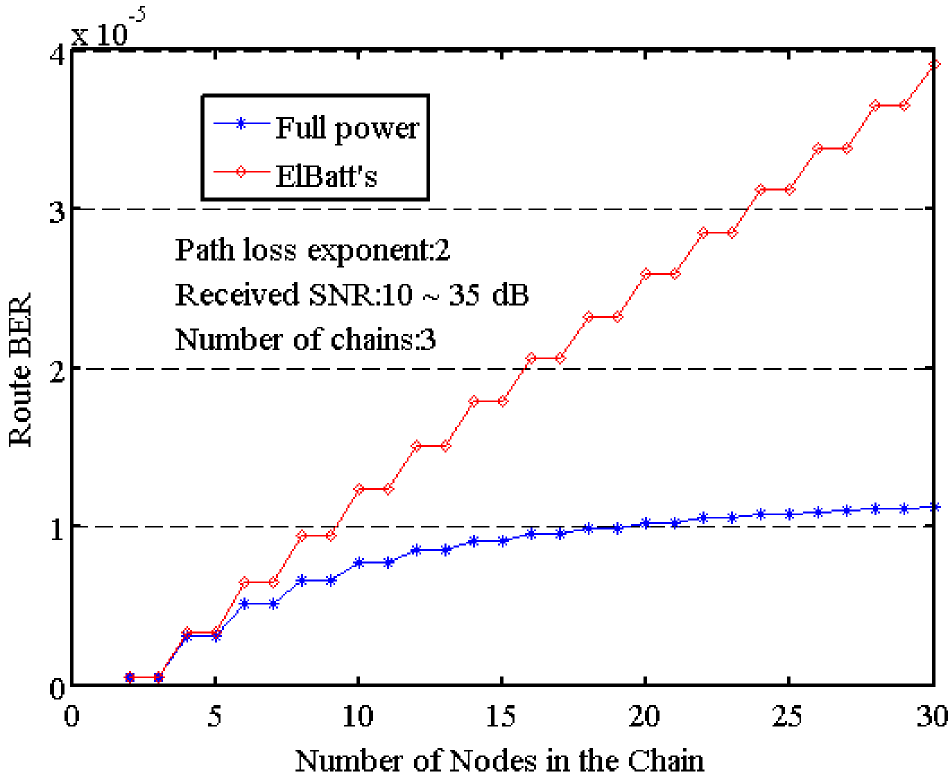

Figure 4-14 Route BER of CDMA using the full power allocation and ElBatt's algorithm in a network with three chains

(b) Performance comparison of CDMA using different schedules and TDMA

In the previous subsection, we find that ElBatt's algorithm does not perform well in a network with multi-chain topologies. We then turn to verify the performance of our proposed scheduling approach. We choose networks with four chains, six chains, eight chains, and twelve chains to be evaluated. As shown in Figure 4-15, the effective throughput of centralized and interleaving schedules is twice that of the schedule of TDMA. They seem both good to use. However, the decreasing interference effect of the centralized scheduling is not obvious in networks with a smaller number of chains. As the number of chains grows to 6, as shown in Figure 4-16, although the centralized and interleaving schedules with two nodes transmitting to the gateway in each time slot still performs almost the same, the effective throughput of the centralized scheduling with three nodes transmitting to the gateway in each time slot has large improvement and outperforms the interleaving schedule. In Figure 4-17 and Figure 4-18, we can find similar phenomena to Figure 4-16, but in Figure 4-17, as the number of nodes transmitting to the gateway in each time slot increases to four, the improvement in effective throughput of the centralized schedule decreases, so does the interleaving scheduling. Moreover, both the centralized and the interleaving schedules with six nodes transmitting to the gateway in each time slot perform much worse than aforementioned schedules we suggest, as shown in Figure 4-18. The use of the centralized scheduling with no more than three nodes transmitting to the gateway in each time slot as a good principle to improve the overall throughput of a CDMA network with multiple-chain topologies.

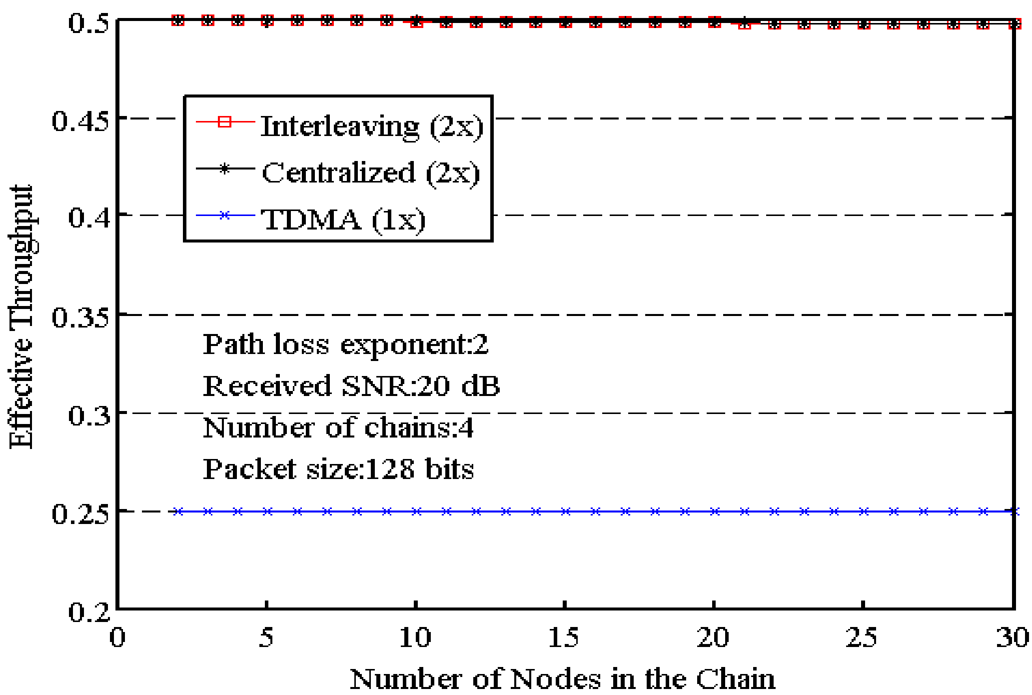

Figure 4-15 Effective throughput of CDMA with different schedules and TDMA in a network with four chains

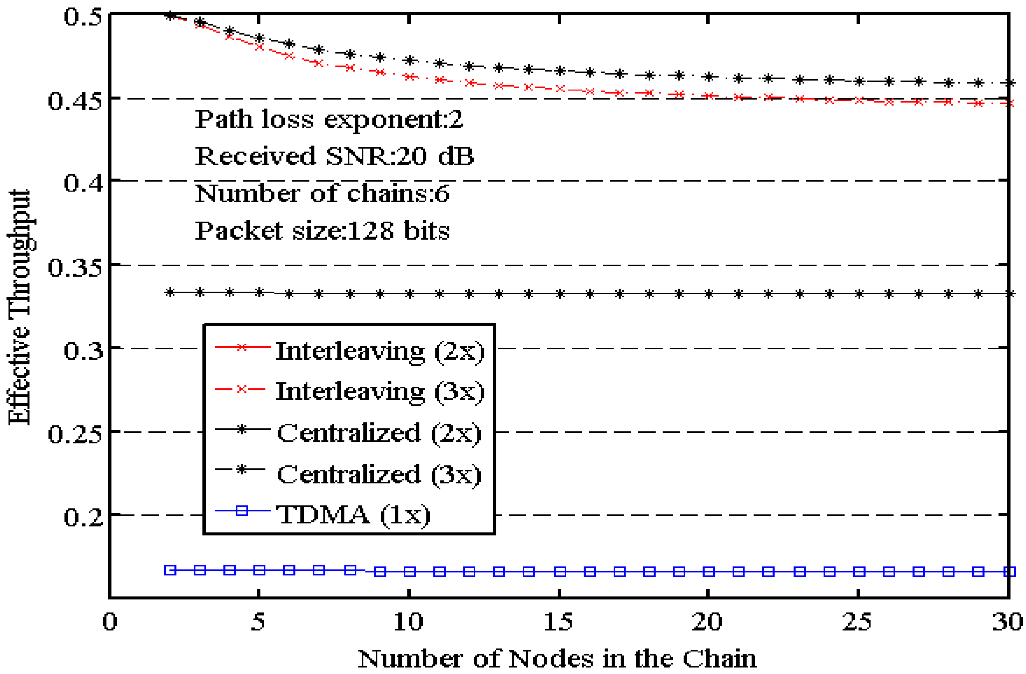

Figure 4-16 Effective throughput of CDMA with different schedules and TDMA in a network with six chains

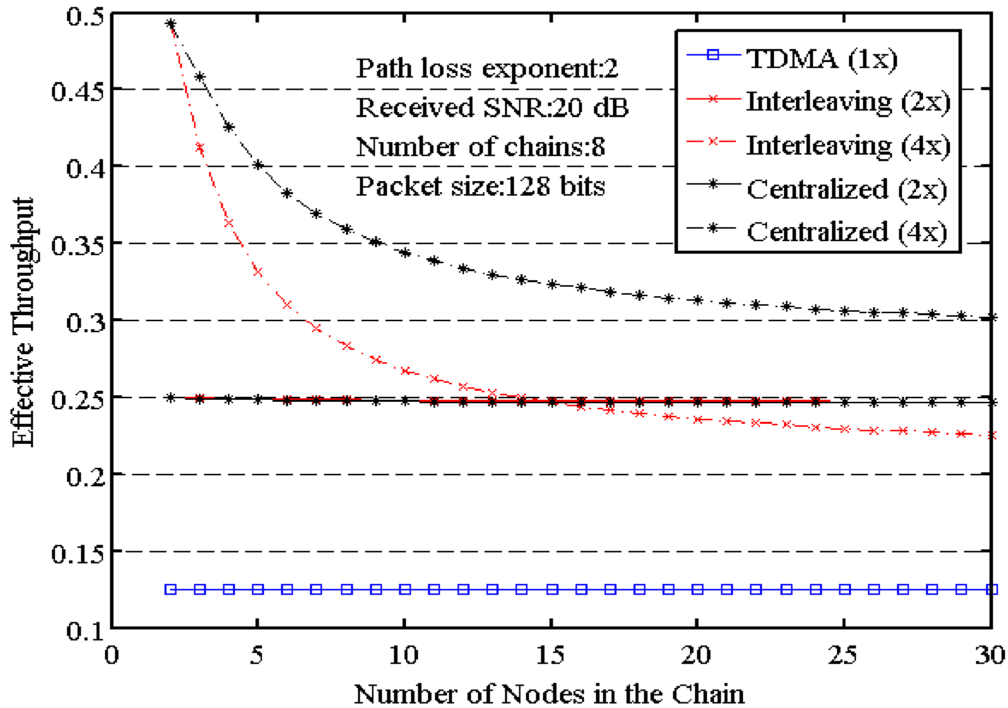

Figure 4-17 Effective throughput of CDMA with different schedules and TDMA in a network with eight chains

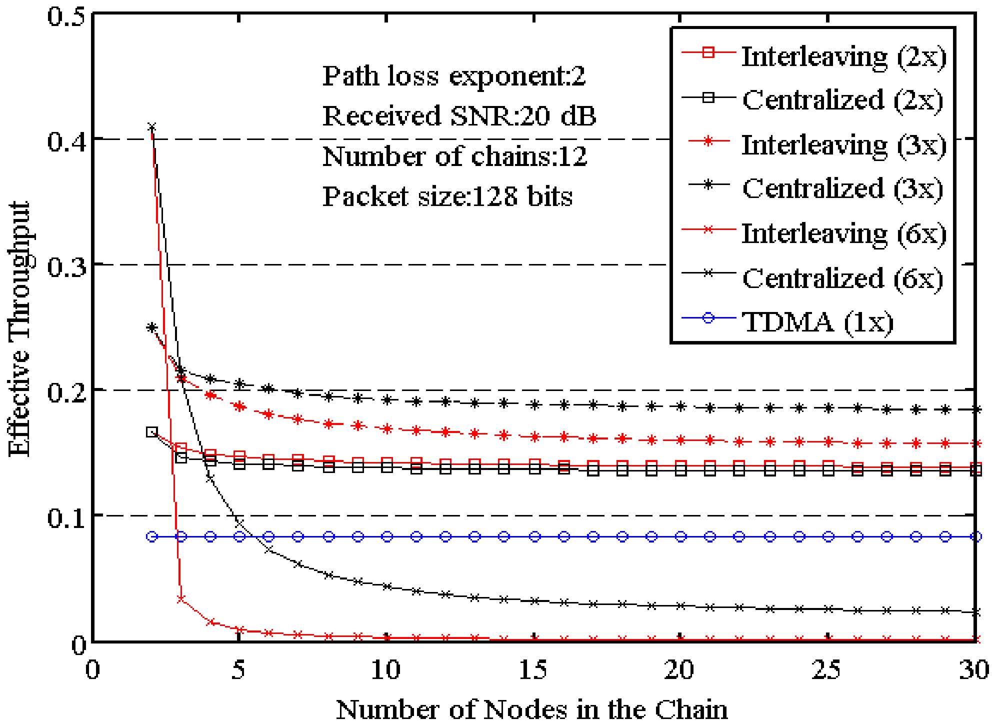

Figure 4-18 Effective throughput of CDMA with different schedules and TDMA in a network with twelve chains

Chapter 5 Conclusion and Future Work

In this thesis, we propose the use of a CDMA-based MAC protocol in dual-mode wireless sensor networks. The network would use an energy-efficient MAC protocol during its normal operation, and switch to our CDMA-based MAC protocol in emergency, due to the need of higher network throughput. It has been shown that with the full power allocation scheme, CDMA outperforms TDMA in terms of effective throughput in a non-fading environment. We also propose a heuristic power allocation scheme, which does not require the knowledge of path losses between nodes in the network, and compare its performance with the full power allocation scheme and the power allocation scheme, using ElBatt's algorithm. Results show that our proposed heuristic scheme outperforms by 14% the simple but naïve full power allocation scheme as well as the scheme using ElBatt's algorithm in the route BER performance in a 30-node single-chain network and an indoor fading environment. Moreover, the results suggest that our protocol is more scalable in terms of the number of nodes in the chain. On the other hand, we find that there is little enhancement when the power allocation scheme is applied in CDMA networks with multiple chains. Instead, we propose a multi-chain scheduling scheme for CDMA networks based on the TDMA scheduling and allow the gateway to receive data from multiple nodes in the same time slot. We find CDMA performs better than TDMA when our scheduling scheme is applied with an effective throughput almost doubled.

In summary, we believe that CDMA can greatly improve the throughput performance of networks with long-thin topologies formed by chains. Future works include the detailed design and implementation of a prototype network utilizing off-the-shelf radios with configurable spreading sequence for performance evaluation.

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