Sequential Resource Allocation Schemes in Wireless Mesh Networks

Jae-Ryong Cha

School of Electrical and Computer Engineering

Ajou University

February, 2013

Abstract

Wireless mesh networks (WMNs) are emerging communication networks consisting of nodes that automatically establish an ad-hoc network and maintain mesh connectivity. With the popularity of WMNs, supporting quality of service (QoS) over multihop radio links is becoming an important issue because end-to-end (ETE) delay increases quickly with the increase in the number of hops. Various QoS-aware scheduling schemes based on time division multiple access (TDMA) have been proposed for supporting a variety of applications such as voice and video calls in multihop WMNs. Basically, they have been focusing on determining minimum length schedules. Although such schemes reduce a frame length, they may bring about queuing delay which can increase ETE delay because they share a slot for multiple flows in a link. Meanwhile, the order of timeslots scheduled in a flow also may have an effect on ETE delay in multihop WMNs. Some papers have proposed scheduling schemes considering the order of timeslots. However, they all have assumed that there is always a centralized station in a network. Recently, many

researches on network coding (NC) scheme have been introduced to increase the utilization of valuable resources in multihop WMNs. So far, almost all conventional works on NC have focused on the improvement of network throughput efficiency that is the original objective of NC. However, if an appropriate link schedule for NC is not considered, ETE delay may be increased even though NC gain can be obtained.

Therefore, this dissertation first proposes a fully-distributed resource allocation scheme called sequential link schedule (SLS) that not only eliminates queueing delay but also considers the order of timeslots scheduled on a path. In the proposed SLS scheme, channel locking algorithm called time slot acquisition (TSA) is employed for interference free slot allocation in a distributed manner. Then, the multihop slot allocation (MSA) algorithm is carried out to sequentially allocate slots on the path. According to the analysis results, in case of deterministic packet arrival, the proposed SLS scheme shows shorter ETE delay, even though it starts the packet transmission with slightly greater frame length than that in case of the minimum length schedule (MLS). For the non-deterministic packet arrival having exponential distribution, the proposed SLS scheme shows a slightly lower delay performance. However, the proposed SLS scheme is more tolerable for a high packet interarrival rate than the MLS. In the next proposal, two bandwidth allocation schemes jointly combined with NC are proposed to reduce ETE delay and enhance resource utilization in the network. The first proposed section-based sequential scheduling scheme, which is flow-based one, employs a new concept, 'section', so that the slots scheduled on a path are sequentially arranged within a frame even when NC operation is performed. The second proposed scheme is a 'duplicated allocation followed by resource release' (DARR) based sequential scheduling scheme. The basic idea of the proposed DARR-based scheme is that, when the MSA algorithm has been initiated from the non-reference NC flow, an NC coordinator not only transfers an slot allocation (SA) packet to the next node of the non-reference NC flow but also again transfers another SA packet to the next node of reference NC flow before releasing the initially-allocated slots. By the simulation results, it is known that the proposed schemes show better delay performance than the conventional SLS-NC. Therefore, by applying the conventional XOR-based NC scheme to the link scheduling, the proposed schemes give more delay-efficient slot assignments that result in better channel utilization while at the same time using less network resources and energy. In conclusion, the proposed sequential scheduling schemes can give the sequentiality with NC gain guaranteed, thereby resulting in decreasing ETE delay and enhancing the resource utilization in multihop WMNs.

Contents

List of Figures

List of Tables

Abbreviation

ACK acknowledgement

AODV adhoc on-demand distance vector

AP access point

BFS bottleneck first scheduling

BS base station

CAC call admission control

CBR constant bit rate

CCH common channel

CSLS conventional sequential link scheduling

CSMA carrier sensing multiple access

DARR duplicate allocation followed by resource release

DCH data channel

DPA deterministic packet arrival

EDF earlier deadline first

ETE end-to-end

FCFS first come first serve

GF(2) galois field of two elements

GFLS global frame length synchronization

ID identification

IEEE institute of electrical and electronics engineers

IFLS initial frame length synchronization

ILP integer linear programming

IP internet protocol

LP linear programming

MAC medium access control

MBS mesh base station

MLS minimum length schedule

MSA multihop slot allocation

NC network coding

NDPA non-deterministic packet arrival

OFDM orthogonal frequency division multiplexing

OFDMA orthogonal frequency division multiple access

PHY physical

PMP point to multi-point

QoS quality of service

QP queuing point

RAV Reception AVailable

RLS random link scheduling

SA slot allocation

SLS sequential link scheduling

SS subscriber stations

TAV Transmission AVailable

TDMA time division multiple access

TRAV Transmission/Receiption AVailable

TSA time-slot acquisition

TX transmission

UAV UnAVailable

UWB ultra wide band

WBN wireless backbone network

WiFi wireless fidelity

WiMAX worldwide interoperability for microwave access

WLAN wireless local area network

WMN wireless mesh network

1

Introduction

1.1 Background and Motivation

Recent years have witnessed the emergence of a variety of wireless services such as video conferencing, IP TV, music downloading, and online gaming. Motivated by the concept of ubiquitous computing, these wireless services are designed to be available for people anytime and anywhere. WMNs have been considered as a promising technology which can support these kinds of services because of the future needs for seamless and cheap connectivity. The core idea of WMNs is that multiple nodes collaborate to form a wireless backbone which can then be used to route packets from source nodes to destination nodes possibly via multiple hops. It also enables users to connect to a node on the backbone of the WMN, and then access the resources presented by the WMN backbone to communicate with other nodes on the WMN. In addition, if any node in the WMN backbone happens to have access to the Internet via wired

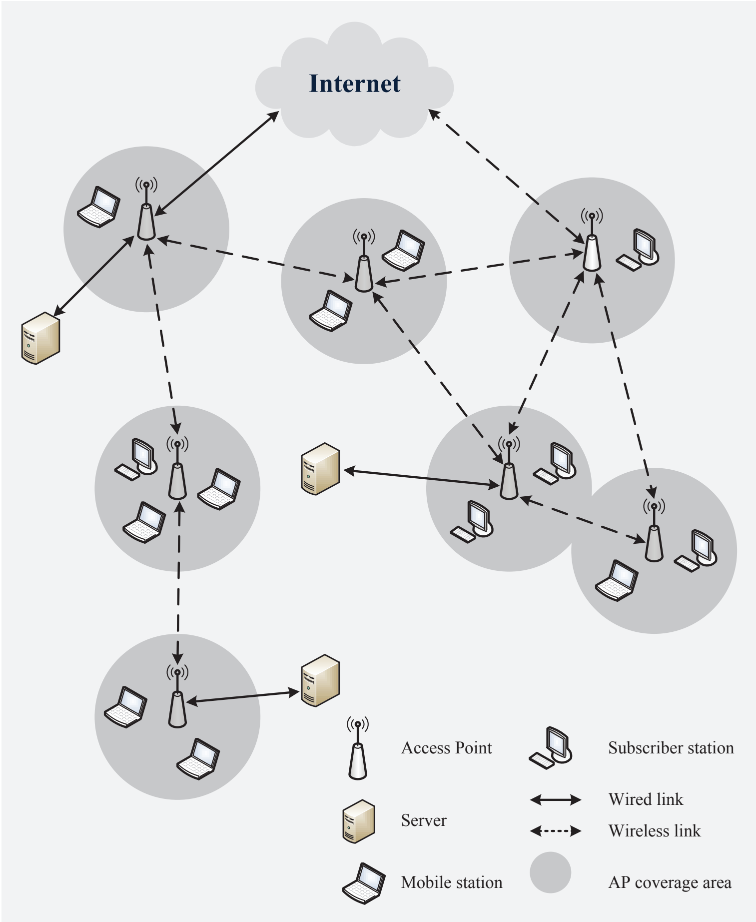

Fig. 1.1. Example of a WMN

or wireless links, all the nodes connected to the WMN and on the WMN backbone can communicate with systems on the Internet[1]. Fig. 1.1 shows an example of a WMN. What makes WMNs especially interesting is that these are self-organizing and can be set up much cheaper than networks with a wired backbone. If additional coverage is needed, it is easy to deploy additional nodes in the necessary areas which join the rest of the WMN backbone, making extension of the wireless backbone very flexible. Given these benefits, the IEEE 802.16 standard[2] introduces an additional and optional MeSH mode of operation in addition to the PMP mode of operation. In this mode, nodes in the network can communicate with each other and the base station via routing packets over multiple hops. In contrast to the MeSH mode of operation currently being standardized by the IEEE 802.16 working group, the MeSH mode supports topologies which need not have to be a strictly tree topology rooted at the BS. WMNs are also being followed by interest within the IEEE 802.11 working group which has led to the working group 802.11s. IEEE 802.11s is concerned with extensions to the IEEE 802.11 standard to enable efficient setup of WMNs using the 802.11 standard. The goal here is to be able to connect nearby mobile devices (e.g., laptops) to form a local mesh network which may or may not provide access to the Internet. WMNs are also seen as a promising approach to setup flexible industrial sensor networks for factory/process automation. The Wireless HART standard[3] supports the setup of wireless mesh topologies for the application scenarios of these networks. Many universities (Roofnet[4], QuRiNet[5], Fractel[6], Lo3[7]), as well as industrial labs (VillageNet[8]) have on-going research projects on various aspects of mesh networking and several technology leaders (Firetide[9]) and startups are building mesh networking platforms and deploying services for communication and data transfer[10].

However, although WMNs can support various wireless services with seamless and cheap connectivity, the bandwidth in such networks still remains a scarce resource. Recently, network coding has been investigated as a novel mechanism to permit the saving of valuable bandwidth in such WMNs for individual transmissions, thereby increasing the traffic-carrying capacity of WMNs. Up-to-date, the practical investigations for the deployment of network coding have been limited to WMNs based on the IEEE 802.11 standard. There have been no significant investigations on the deployment of network coding, and its benefits in TDMA-based multihop WMNs. Given the fact that the next generation of WMNs would be using bandwidth reservation schemes to support realtime applications such as advanced multimedia services and video conferencing, it is vital that network coding be investigated in the light of such WMNs to meet QoS requirements. Specifically, we formulate a general framework, which is applicable to any transmission schemes with or without NC, to increase the resource utilization and decrease ETE delay in TDMA-based multihop WMNs. Our framework features to support stringent QoS requirements (e.g., delay bound) with NC gain guaranteed. Under this developed framework, we propose joint link scheduling and NC schemes. We also perform extensive simulations to validate and evaluate the performance of our proposed schemes.

1.2 Contributions

With the popularity of WMNs, supporting QoS over multihop radio links is a critical issue because ETE delay is quickly increased with the increase in the number of hops. Meanwhile, although WMNs can support various wireless services with seamless and cheap connectivity, the bandwidth in such networks still remains a scarce resource. Recently, many researches have been performed on NC to increase the utilization of valuable resources in WMNs. However, if an appropriate link scheduling for NC is not performed, ETE delay may be increased although NC gain can be obtained. Therefore, when designing a scheduling scheme in WMNs, considering these two factors (i.e., ETE delay and scarce resources) is very important in order to support QoS and increase resource utilization. Under this necessity, there are several contributions in this dissertation as follows:

- General framework for fully-distributed sequential schedule was presented. This makes it possible to sequentially allocate slots on the path in a flow without collision, resulting in reducing ETE delay in multihop WMNs;

- Two sequential scheduling schemes jointly combined with NC were presented. The proposed schemes can not only get the same NC gain as the conventional scheme but also guarantee the sequentiality with small overhead, thereby resulting in decreasing ETE delay in multihop WMNs;

- Simple scheme to cope with asymmetric flow conditions was presented. This prevents one flow related to NC from waiting for another flow, ultimately resulting in no additional delay caused by NC operation.

2

Related Work

The goal of this section is to introduce in brief the readers of this dissertation to the work in the literature which is closely related to the work in this dissertation as well as associated concepts. The scheduling and its related conventional works in WMNs are first introduced and the basic concept of NC and the requirements for NC to be used in TDMA are described.

2.1 Scheduling in WMNs

Recently, wireless mesh networking has emerged as an interesting and challenging area of research. It is attracting significant interest to support ubiquitous communication and broadband access using low-cost networking platforms. Essentially, nodes in a wireless network have the mesh capability, wherein the nodes not only transmit local data but also support flows of other mesh nodes through them, thus forming a multihop

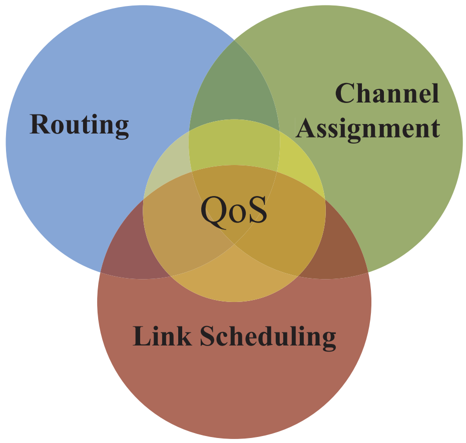

Fig. 2.1. Scheduling in terms of an integrated problem.

network. The mesh capability increases coverage area and scalability, eases out deployment and maintenance activities, adds self-healing ability (in case of node failure) and results in much cheaper network with the use of commodity hardware and software. Owing to these features, mesh networking is being used for realizing several applications in the context of enterprize networking, community or metro-scale networking and public emergency-control systems.

In such multihop WMNs, among the challenging issues, the scheduling of transmissions for efficient channel access at the MAC layer is an important issue. This scheduling of transmissions at the MAC layer decides how efficiently the channel is going to be utilized. In a typical scheduling scheme, the scheduling of transmissions is considered to achieve a goal, e.g., maximizing the network throughput for a given problem setting. However, as shown in Fig. 2.1, the scheduling for multihop wireless networks is a highly integrated problem with numerous sub-problems such

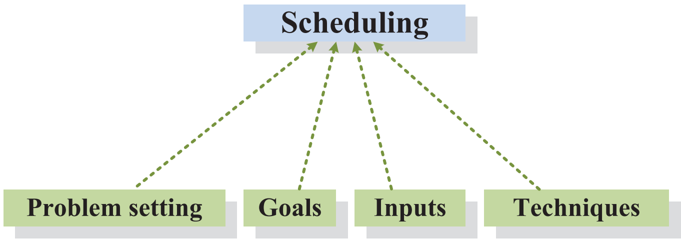

Fig. 2.2. Classification framework for scheduling schemes.

as how to find optimal routing path, how to assign optimal channel to the network, and how to perform interference-free link activation for the optimal link scheduling[10]. Several of these sub-problems, e.g. optimal channel assignment, are proven NP-hard problems[11] and thus the overall problem of scheduling is necessarily complex. In addition, application constraints like providing quality of service is also one of the important aspects that scheduling has to take into account. Given a problem setting and a set of inputs, scheduling transmissions in multihop WMNs is about employing a technique to allocate time and channel (frequency) resources to mesh nodes/links to achieve a set of goals.

Fig. 2.2 shows classification framework for scheduling in multihop mesh networks based on problem settings, goals, inputs, and techniques. The first dimension of the classification framework, 'Problem setting', classifies a scheduling mechanism based on types of scheduling controls, types of channel access protocol, antenna type and types of network topologies considered. The type of scheduling control can be centralized, where a central node takes the scheduling decisions, or distributed where the set of network nodes mutually converge on a schedule. The type of channel access protocol can be either CSMA or TDMA. Particularly, WiMAX mesh standard employs a TDMA based multihop mesh protocol. Next, antenna type can be either omni-directional, directional or sector antenna. Network topology can be further classified into tree or graph. Tree topology is prominently considered in several WiMAX mesh scheduling mechanisms. However, in general, scheduling mechanisms for multihop wireless mesh consider a generic graph as the underlying network topology. The second dimension, 'Goals', classifies a scheduling mechanism based on the goals of the problem. One of goals in a scheduling mechanism is to schedule the resources to maximize the throughput of the network. Other goals include scheduling to maximize number of flows admitted, scheduling to satisfy minimum bandwidth requirement of each flow and scheduling to satisfy strict constraints like delay and jitter for real-time applications. The third dimension, 'Inputs', classifies a scheduling mechanism based on the types of inputs considered for the problem. A scheduling mechanism considers a subset of inputs from: (1) number of channels available for scheduling, (2) number of radios present at the mesh nodes, (3) ETE flow requirements of the flows (e.g., data rate), (4) routing paths provided for the flows, (5) interference map specifying conflicts in link scheduling, (6) channel-state information, and (7) quality of service parameters (e.g., minimum and maximum capacities on data rates). The fourth important dimension, 'Techniques' decides the effectiveness of scheduling mechanisms. The types of techniques are mostly driven by the problem setting and goal of scheduling mechanism. The stricter the goal gets, the harder the scheduling technique becomes.

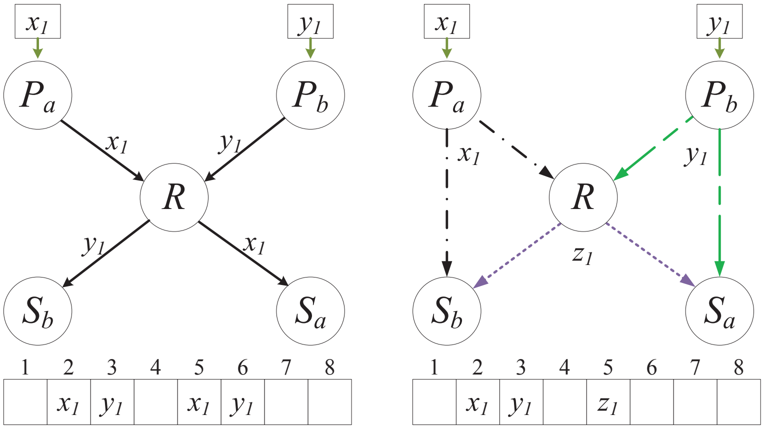

Fig. 2.3. Example of X constellation with opportunistic listening.

As mentioned earlier, the NP-hard sub-problems make the scheduling problem even more "complex". Typically, the scheduling problem is formulated as an ILP and the relaxed LP is solved to approximate the solution. Other techniques include max-flow based algorithms, heuristics (greedy algorithms), and algorithms using graph properties. Table 2.1 and 2.2 summarize the comparison of conventional works according to a subset along both scheduling algorithms and classification dimensions based on the classification framework explained[10].

2.2 Network Coding

NC is becoming an emerging communication paradigm that can provide the performance improvement in throughput and energy efficiency. NC was originally proposed for wired networks, and the throughput gain was illustrated by the well-known example of "butterfly" network[24].

Table 2.1. Comparison of conventional works: Scheduling

Works	Schedule control	Topologies	Multi-channel/radio	Scheduling goal
JR-MCMR[12]	Centralized	Graph	Yes/Yes	Fair allocation of wireless resources
C-WiMAX[13]	Centralized	Tree	No/Yes	Interference-free route computation
A-WiMAX[14]	Centralized	Tree	Yes/No	To satisfy minimum bandwidth and maximum allowed delay requirements of the flows
DelayAware[15]	Centralized	graph	No/No	To find minimum length schedule to minimize ETE scheduling delay
DelayBackhaul[16]	Centralized	Tree	Yes/No	Link activation schedule to bound ETE delay
CACQoS[17]	Centralized	Graph	No/No	Interference-free route computation

Table 2.2. Comparison of conventional works: Scheduling (con't)

Works	Schedule control	Topologies	Multi-channel/radio	Scheduling goal
RoutingRural[18]	Centralized	Graph	No/No	Interference-free route computation
ChannelRural[19]	Centralized	Graph	Yes/Yes	Interference-free route computation
LongTDMA[20]	Centralized	Tree	yes/No	Interference-free and delay-aware route computation
DelayCheck[21]	Centralized	Graph	yes/Yes	Maximize the number of voice calls scheduled
DRAND[22]	Distributed	Graph	No/No	Interference-free route computation
CodePlay[23]	Distributed	Graph	No/No	Schedule realtime flows in dynamic mesh topology

Recently, there is a growing interest to apply NC onto wireless networks since the broadcast nature of wireless channel makes NC particularly advantageous in terms of bandwidth efficiency and enables opportunistic encoding and decoding[25]. NC makes it possible for an intermediate node to combine packets it has received or generated itself such that one or more outgoing packets can be forwarded to the other nodes. Fig. 2.3 shows the well-known 'X constellation' for NC, which is composed of two predecessor nodes P_a and P_b, an NC coordinator R, and two successor nodes S_a and S_b. In Fig. 2.3, the solid line means unicasting transmission and other lines mean broadcasting transmission. As shown in Fig. 2.3, P_a has a packet x_1 for S_a, and P_b has a packet y_1 for S_b. The two packets from both flows have to be relayed via R. In conventional slot scheduling, four transmissions (four slots) are necessary to accomplish the delivery of two packets (x_1 and y_1) as shown in Fig. 2.3(left). However, if using NC, three transmission (three slots) are necessary to deliver the two packets as shown in Fig. 1(right): i.e.,

- P_a broadcasts packet x_1 to R and S_b in the 2^{nd} slot;
- P_b broadcasts packet y_1 to R and S_a in the 3^{rd} slot;
- R broadcasts z_1 ($x_1 \oplus y_1$) to S_b and S_a in the 5^{th} slot.

From the above example, by using this baseline NC scheme, the number of transmissions (slots) can be reduced; as a result, the network throughput efficiency can be increased. NC also can be used in case of no opportunistic listening[25], and one of these scenarios is presented in

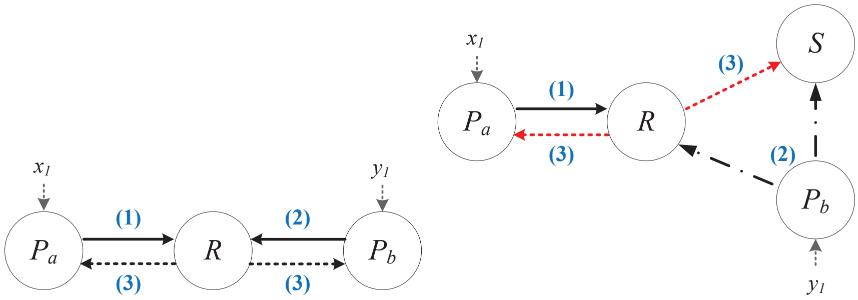

Fig. 2.4. Example of other NC constellations.

Fig. 2.4(left). In Fig. 2.4, the solid line means unicasting transmission and other lines mean broadcasting transmission. In this case, the source node P_a needs to send a packet x_1 to node P_b (1) and another source node P_b needs to send a packet y_1 to node P_a (2). Since each source is also a destination node, it has the necessary packets for decoding upon receiving the encoded packet $x_1 \oplus y_1$ from the NC coordinator R (3). Fig. 2.4(right) shows a hybrid scenario where node P_a needs no opportunistic listening and the successor node S needs the opportunistic listening from node P_b. In this case, the source node P_a needs to send a packet x_1 to node S (1). And, another source node P_b needs to send a packet y_1 to node P_a (2). At this time, node P_b broadcasts the packet y_1 for the overhearing of node S (2). After the broadcasting of the encoded packet ($x_1 \oplus y_1$) by the NC coordinator R, P_a decodes the packet y_1 ($x_1 \oplus (x_1 \oplus y_1)$) using its packet x_1. On the other hand, S decodes the packet x_1 ($y_1 \oplus (x_1 \oplus y_1)$) using the packet y_1 overheard from P_b. In both cases, instead of four packet transmissions when NC is not used, only three transmissions are necessary, thereby reducing the bandwidth utilization. As seen from the example, we can see that NC is able to increase the effective information transfer rate beyond the physical capacity (data transfer rate) which is provided by the network. We define an NC set as five nodes constructing an X constellation in Fig. 2.3, three nodes constructing a string constellation in Fig. 2.4(left), or four nodes constructing a hybrid constellation in Fig. 2.4(right). For example, at the X constellation as shown in Fig. 2.3, the criteria for the NC set are as follows:

- P_a is beyond the communication range of P_b;
- S_a is beyond the communication range of S_b;
- S_b must overhear the packets from P_a;
- S_a must overhear the packets from P_b.

However, most of the conventional works have been only theoretical in nature and restricted to the case of application of NC to multicast traffics. There has also been some work looking into the case of application of NC to unicast transmissions in networks[26],[27]. In case of a single unicast or broadcast session, the authors in [28] showed that there are no improvements over routing obtainable as far as throughput is concerned when NC is used. In case of multiple unicast transmissions, the authors in [27] showed that NC can be beneficial compared to routing. However, the benefit is strongly dependent on the network topology and the authors [27] conjecture that, for undirected networks with fractional routing, the potential for NC to increase bandwidth efficiency does not exist. For the multiple unicast transmissions case, the authors in [29] showed that NC does not provide any order difference improvement over the bound provided by the work[30] which does not consider NC. Similar results are presented by [31] for the case of multicast traffic. However, in [32] and [33], the authors showed that NC does bring a constant factor gain over routing for the multiple unicast as well as multicast traffic cases in wireless networks. This gain is very valuable in practice as it means a direct increase in the traffic which can be supported by the network[34]. Table 2.3 through 2.6 list the conventional works on NC in terms of opportunistic routing, security, retransmission strategy, and relay communication.

Table 2.3. Comparison of conventional works: NC

Works	Main characteristics	NC goals
CORE[35]	Opportunistic routing	Opportunistic listening and opportunistic listening, and specific implementation of wireless network protocol with NC.
MORE[36]	Opportunistic routing	Mix packets randomly before forwarding them to make sure that the nodes heard the same transmission do not forward the same packet.
MIXIT[37]	Opportunistic routing	Symbol-level NC with opportunistic routing is used to both ship data to sink nodes in sensor networks and multicast data in a mesh network.
BFLY[38]	Opportunistic routing	Fully make use of the information on the local topology and source routing information in the packet header.
CAOR [39],[40]	Opportunistic routing	Make forward decision of each packet based on potential coding opportunity, aimed to get higher coding gain when existed more than one concurrent unicast stream.

Table 2.4. Comparison of conventional works: NC (con't)

Works	Main characteristics	NC goal
OCR[41]	Opportunistic routing	Mainly studied how to improve the data transmission performance in WMNs by combination of opportunistic routing and NC.
ONCC[42]	Opportunistic routing	Opportunistic network coded cooperation scheme for multiple unicast transmission pairs in a single cell wireless networks.
Pollution[43]	Security research	NC method which can detect the existence of pollution attack.
SecureNC[44]	Security research	Adaptive secure NC for the difference in ability of the attacker.
Wiretab[45]	Security research	Design a secure NC model named wiretap network ,which can incorporate information security with NC.
Capacity[46]	Security research	Give the limitation of multicast capacity with the security.

Table 2.5. Comparison of conventional works: NC (con't)

Works	Main characteristics	NC goal
Privacy[47]	Security research	Propose a novel privacy-preserving scheme against traffic analysis attacks in NC.
Signature[48]	Security research	Propose a signature-based scheme against pollution attacks for securing linear NC.
NullKey[49]	Security research	Security scheme for NC that does not require large computations, nor add any redundancy to the original blocks.
Security[50]	Security research	Analyze how to improve security with NC in WMNs.
Combined[51]	Retransmission based	Propose two strategies combined of NC and retransmission
GF[52]	Retransmission based	In the field GF (2), find the problem of wireless packet retransmission packet retransmission strategy for at least a NPC problem

Table 2.6. Comparison of conventional works: NC (con't)

Works	Main characteristics	NC goal
NCWBR[53]	Retransmission based	In wireless broadcasting, combine the different lost packets with NC for retransmission.
combination[54],[55]	Relay communication	Give the combination design scheme with channel coding and NC
Security[56]	Relay communication	Propose an NC framework for wireless relay networks which took the fading and error prone nature of the wireless networks into consideration.
Joint[57]	Relay communication	Propose a joint NC and superposition coding scheme for information exchange between more than two users in a wireless relaying network to exchange information between more than two source nodes in fewer time slots.
GF[58]	Relay communication	Propose a Analog Network Coding method which can carry multiple messages in signal in physical layer.

3

System Model

In this dissertation, we model WMNs with a topology graph connecting the nodes that are present in each other's wireless range. The network can be represented with a directed connectivity graph $G(B, E)$, where $B = \{b_1, ..., b_m\}$ is a set of nodes and $E = \{e_1, ..., e_g\}$ is a set of directed links, and two nodes (u and v) are neighbors if $(u, v) \in E$. In the network, F is a set of flows, and a flow $f(\in F)$ is specified by a node set $R(f) = \{p_1, ..., p_q\}$, where p_k is the k^{th} node in a flow ($2 \leq q$; $k = 1$: the source node, $1 < k < q$: the intermediate node(s), and $k = q$: the destination node). We consider free space path loss and slow fading channel. The channels used in the network is classified into two. One is

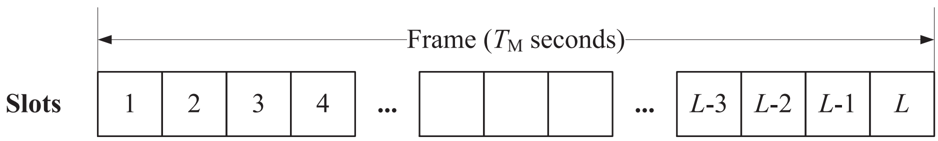

Fig. 3.1. Frame structure in DCH

a CCH that employs the channel access method based on CSMA. The CCH is used for transmitting routing messages, SA messages, or other control messages. The other is a DCH in which the nodes in the network transmit and receive data in the slots allocated as either a TN or an RN. Fig. 3.1 illustrates the frame structure in DCH. The DCH consists of the fixed frame size, L slots. In the network, all the nodes manage a frame map that represents the bitwise expression of the slot allocation status in a node. The length of the frame map is equal to the frame length L. Each slot in the frame map has the four statuses as follows:

- Transmission/Receiption AVailable (TRAV): slot can be used for both transmission and reception of data;
- Transmission AVailable (TAV): slot can be used only for transmission of data;
- Reception AVailable (RAV): slot can be used only for reception of data;
- UnAVailable (UAV): slot can not be used for transmission or reception of data.

The state called TRAV is the default state of a slot in the WMNs. It basically means that the slot can be used for the nodes to schedule not only data transmission but also data reception. Note that the multihop nature of WMNs allows spatial reuse of the TDMA slots. Different nodes can use the same time slot if they do not interfere with each other. Thus, the slot state is always associated to a particular node and reflects that node's view of the transmissions scheduled in the WMN by itself and in its neighborhood. Slots with state TAV can be used only for data transmission by the nodes. Slots with state RAV can be used by the nodes only for data reception. Slots with state UAV can not be used by nodes in the WMN for scheduling any additional data transmissions or receptions. During performing the MSA algorithm, A node's frame map is locally updated each time nodes receive an SA packet they have overheard from neighboring nodes, or on those which they have themselves transmitted.

4

Sequential Scheduling in TDMA-based WMNs

4.1 Motivation

In previous studies[59–68], TDMA scheduling is generally employed to determine MLS. However, the MLS may cause additional queuing delay, which may have a negative influence on delay-sensitive services. The QoS of realtime applications in multihop wireless networks may not be guaranteed if additional queuing delays occur. Fig. 4.1 shows a simple multihop wireless network where queuing delay occurs. In single-hop wireless networks, queuing delay occurs when the packet arrival rate in a source node is higher than the packet transmission (service) rate. In this dissertation, such a queuing delay is referred to as the primary queuing delay and primary QPs in Fig. 4.1 represent an example of such a case.

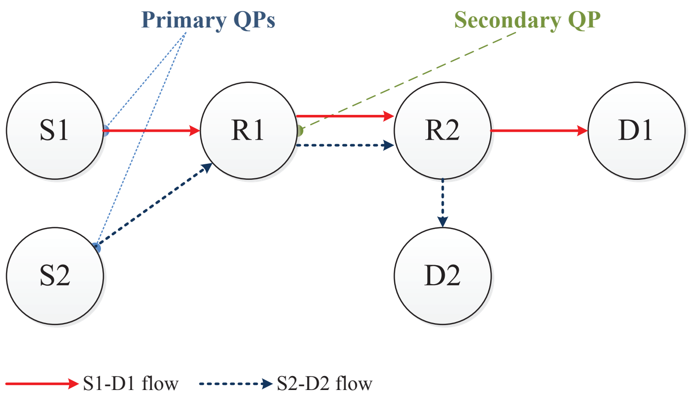

Fig. 4.1. QPs in multihop wireless networks.

On the other hand, in multihop wireless networks, additional queuing delay may occur, which is referred to as the secondary queuing delay. The secondary queuing delay occurs when multiple flows pass through an outbound link of a relay node. The secondary QP shown in Fig. 4.1 represents the point where the secondary queuing delay occurs. For example, it is assumed that, in Fig. 4.1, multiple flows pass through the R1-to-R2 link. Assume that the network employs the MLS where flows share a slot for transferring packets. Then, R1 allocates only one slot for transfering packets to R2. It is also assumed that S1 and S2 are supposed to send a packet to R1 in the 1^{st} slot and the 2^{nd} slot, respectively. Meanwhile, R1 is scheduled to transfer a packet to R2 in the 3^{rd} slot. It is also assumed that, in each node, the arrival of a packet from application layer is concurrent with the start of a frame. In the 3^{rd} slot in the frame, R1 has two packets to transfer: one from S1 and the other from S2. However, R1 can transfer the packet received from S1 in the current frame and can transfer the packet received from S2 in the next frame because it can transfer only one packet per link in a frame as prescribed by the MLS. In conclusion, the MLS may work well in single-hop wireless networks with high throughput and short delay. However, in multihop wireless networks, it causes secondary queuing delay because only one common slot is allocated for multiple flows in a node.

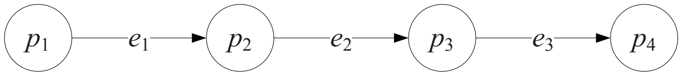

Fig. 4.2. Topology of a four-node network.

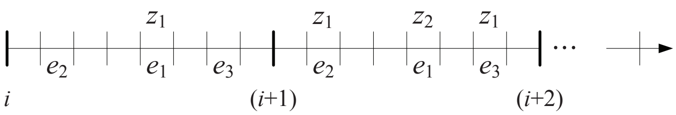

Fig. 4.3. Example of an RLS.

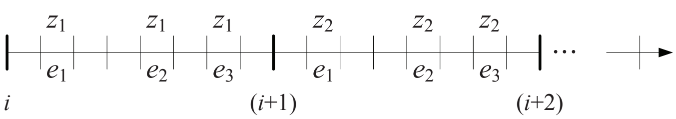

Fig. 4.4. Example of an SLS.

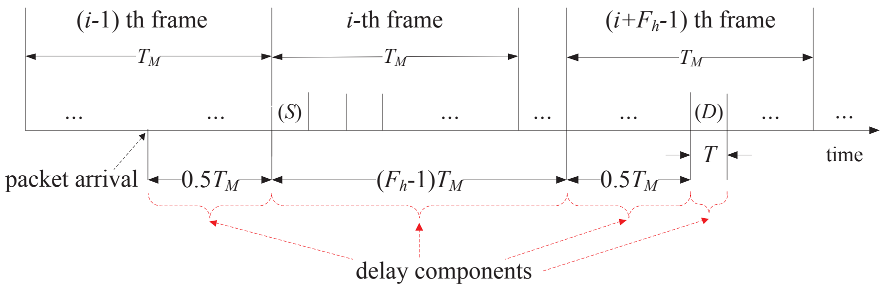

Fig. 4.5. Delay components of an RLS.

Another delay factor that occurs in multihop wireless notworks is the delay caused by the order of TDMA slots allocated on a path. Fig. 4.2 through 4.4 show examples of the delay effect caused by the allocation order of TDMA slots. In Fig. 4.2, the number of nodes, q, is 4 and the number of hops, h, is 3. h represents the distance between a source node and a destination node. It is assumed that the source node p_1 is supposed to transfer a packet z_1 from the i^{th} frame. If the slot allocation is carried out randomly ($e_2e_1e_3$), the destination, p_4, will receive z_1 in the $(i+1)^{th}$ frame (Fig. 4.3). In this dissertation, such a link schedule is referred to as an RLS and the delay caused by the RLS is referred to as random scheduling delay. However, as shown in Fig. 4.4, z_1 will be transferred to p_4 in the i^{th} frame because the slots on the path are sequentially allocated ($e_1e_2e_3$). Such a link schedule is referred to as an SLS in this dissertation. Therefore, if the SLS is not considered, the ETE delay may be quite large as the number of hops is increased.

Now, we derive the ETE delay caused by an RLS. We assume that the traffic flow between all the node pairs in the network is uniform and that the processes of new packet arrival at the different nodes are independent and identical. Therefore, we now concentrate on the characteristics of one node, and thus, it is assumed that the node transmits a packet to the first slot of each frame. If considering a typical packet generated by the node, the total ETE delay suffered by a packet, D_{RLS}, can be obtained by using the following three components (Fig. 4.5): (1) the time between its generation and the end of the current frame; (2) the average random scheduling delay, which indicates the number of frames required to transfer a packet from the source to the destination; and (3) the time between the start of the last frame and its reception at the destination. Given that all the frames are of equal length, the average time between the packet generation time and the end of the current frame is $0.5T_M$, where T_M is one-frame length in terms of time. Next, assuming that the slot scheduled for the destination is randomly distributed in a frame, we observe that the time between the start of the last frame and packet reception at the destination is $0.5T_M + T$. Finally, the average random scheduling delay $F_h (h \geq 2)$ can be calculated by

$$F_h = \left(\prod_{k=3}^{h+1} k \right) / h! = \left(\frac{h+1}{2} \right). \tag{4.1}$$

Proof. Now, we prove the above equation. It is assumed that a node is supposed to transfer z_1 from the i^{th} frame in Fig. 4.3. If slot allocation is randomly completed and $h = 3$, then cases exists as many as 3!. For each case, the random scheduling delay is T_M $(e_1e_2e_3)$, $2T_M$ $(e_1e_3e_2)$, $2T_M$ $(e_2e_1e_3)$, $2T_M$ $(e_2e_3e_1)$, $2T_M$ $(e_3e_1e_2)$, and $3T_M$ $(e_3e_2e_1)$ long. Thus,

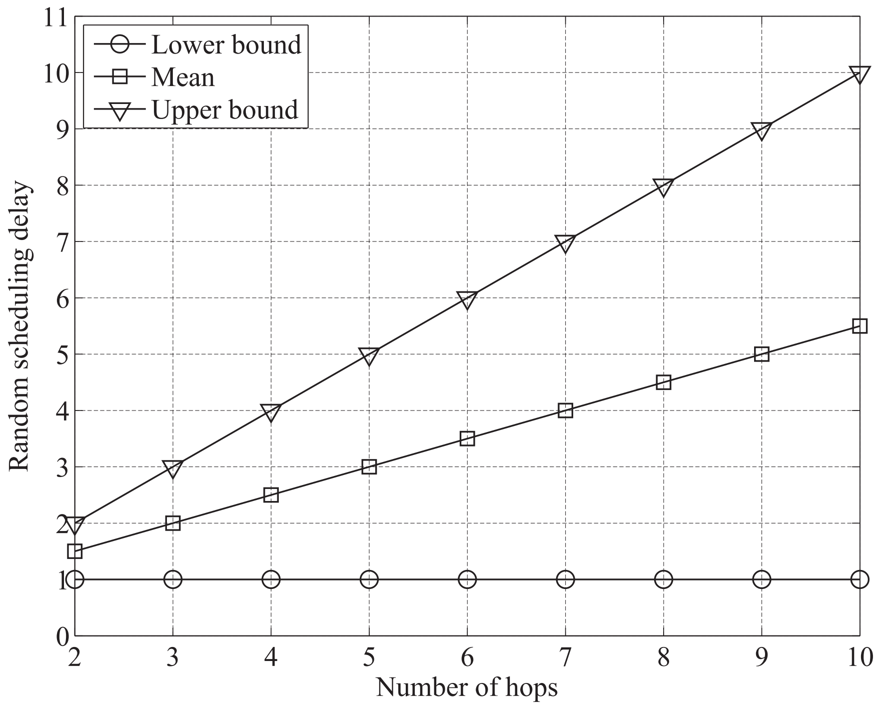

Fig. 4.6. Delay effect by an allocation order.

F_3 is $12T_M/3! = 2T_M$. If we consider each $h(\geq 2)$, we obtain

$$F_2 = 3T_M/2!,\ F_3 = 12T_M/3!, F_4 = 60T_M/4!, \cdots .$$

$\square$

Accordingly, the total ETE delay suffered by a packet, D_{RLS}, is given by

$$\begin{aligned} D_{RLS} &= 0.5T_M + (F_h - 1)\,T_M + 0.5T_M + T \\ &= F_h T_M + T. \end{aligned} \qquad (4.2)$$

Fig. 4.6 shows the random scheduling delay (number of frames) with an increase in the number of hops. In Fig. 4.6, *Lower bound* and

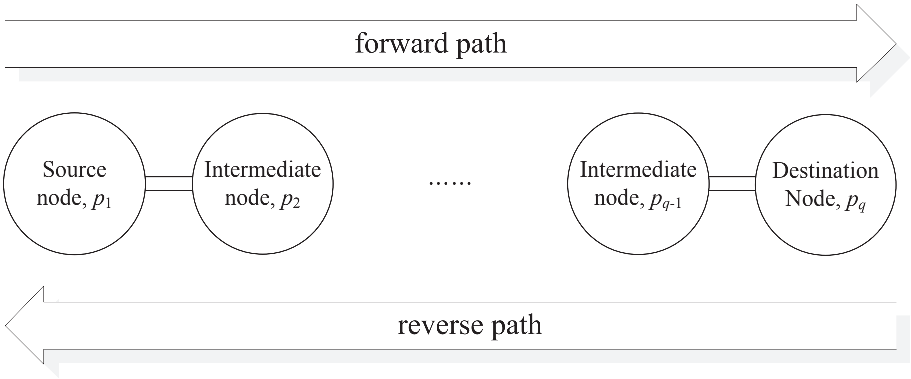

Fig. 4.7. Information on some terminologies used for the MSA algorithm.

Upper bound indicate that the links are sequentially scheduled in the order of $e_1 \to e_2 \to \cdots \to e_h$ and $e_h \to e_{h-1} \to \cdots \to e_1$, respectively. From this result, it can be found that the allocation order of TDMA slots on a path may be an important factor on performance in multihop wireless networks if the delay bound needs to be considered. Therefore, the main objective of this dissertation is to guarantee the 'sequentiality' which means that the allocated link order becomes $e_1 \to e_2 \to \cdots \to e_h$ on a path within one frame, resulting in reducing ETE delay.

4.2 Proposed SLS Scheme

In this section, the operational procedures for the proposed SLS scheme are described in detail. First of all, we make the following assumptions about the network:

- Nodes keep perfect timing. Thus, global time is available to every node;

Table 4.1. Field size of packets used for the proposed MSA algorithm

Fields	Size (bits)
Request message	8
Grant message	8
Release message	8
SA packet	8
MAC_{NEXT}	48
s_{index}	16

- Every node is able to operate the TSA algorithm;
- The network considers free space pass loss and small fading channel.

Whenever each source node generates a flow, it performs the following two steps. In the first step, the TSA algorithm is performed where each node gets a slot (or slots) for interference-free communication. The basic concept of the TSA algorithm is from [22]. The second step, where the MSA algorithm is carried out, is for allocating slots on the path in a flow based on the obtained slot. In the MSA algorithm, each node first invokes the TSA algorithm before transferring the information on the slot allocation to the next node. From the next sub-section onward, the details of each algorithm are described .

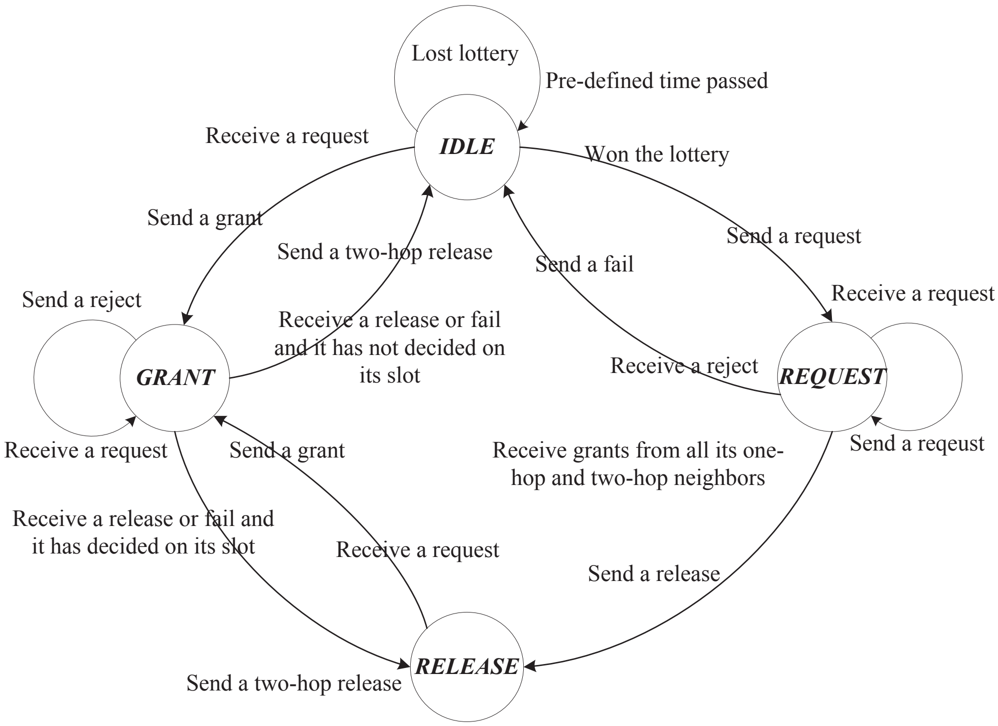

Fig. 4.8. State diagram for the TSA algorithm.

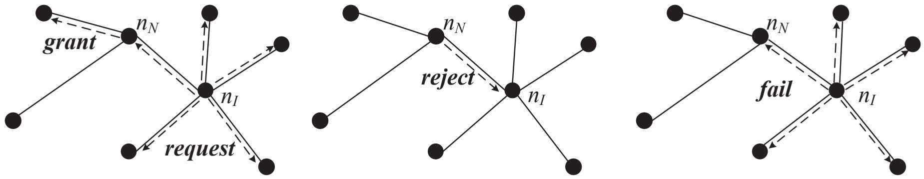

Fig. 4.9. Example of a failed round.

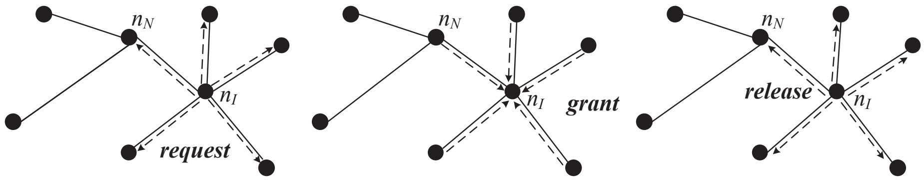

Fig. 4.10. Example of a successful round.

4.2.1 TSA algorithm

A TSA algorithm runs in rounds and the duration of each round is dynamically adjusted depending on the estimated channel access delay of the network. Fig. 4.8 shows the state diagram for the TSA algorithm. In the TSA algorithm, there are four states that a node have to maintain: IDLE, REQUEST, GRANT, and RELEASE. During the IDLE state, a initiation node, called n_I, runs a lottery that has pre-defined transmission probability. If it wins the lottery, it moves to the REQUEST state in order to broadcast a request message to its one-hop neighbors. If it loses the lottery, it remains in the IDLE state. When a one-hop neighbor node, called n_N, receives a request message, if n_N is in the IDLE or RELEASE state, it changes into the GRANT state and transfers a grant message. n_N is in these states only when (1) no neighbors of n_N have sent a request message (2) n_N has not sent any grant to any node so far; or (3) n_N has received a fail or release message after transferring a grant message. When transferring a grant message, n_N includes its frame map that represents the bitwise expression of the slot allocation status in a frame. When receiving a request message, if n_N is in the REQUEST or GRANT state, then it transfers a reject message to n_I. When receiving a reject message from any node, n_I transfers a fail message to all its one-hop neighbors and changes its state to the IDLE state. When n_N receives a fail message from n_I whose request turned n_N's current state to the GRANT state, n_N returns to the IDLE state if it has not decided on its slot already, or to the RELEASE state if it has decided on its slot.

Fig. 4.9 illustrates a failed round because n_N has sent a grant message to its another one-hop neighbor before receiving the request message from n_I. If n_I does not receive any grant or reject message from n_N within specific time, n_I retransmits a request message to those nodes that it has not received a grant message from. When a node receives a request message from another node for which it has already sent a reject message, then it retransmits the reject message to that node. As n_I receives the grant messages from its entire one-hop neighbors for the request message, it decides on its time slot out of available time slots, which has not been taken by its two-hop neighbors. After that, n_I enters the RELEASE state and broadcasts a release message containing information on its selected time slot to its one-hop neighbors. Fig. 4.10 illustrates an example of a successful round. On receiving a release message, a one-hop neighbor of n_I turns into the IDLE state if it has not decided on its slot or the RELEASE state otherwise, and re-broadcasts that the received release message to its one-hop neighbors. This second broadcasting message is called two-hop release message in this dissertation. If a neighbor node does not receive a fail or release message after transferring a grant message to n_I for some time, it retransmits the grant message. If a node receives a grant message for which it has previously sent a fail or release message, then it retransmits the fail or release message to that node. If each node experiences a successful round, each node is ready to get a slot for the interference-free communication

4.2.2 MSA algorithm

In the proposed MSA algorithm, an SA packet is employed for transferring the information on the allocated slot index to the next node and following terminologies are used.

- forward/reverse path: path to the destination/source node;
- TN/RN: a transmitting node and a corresponding receiving node in an allocated slot;
- S_{index}: the slot index allocated;
- next node: a neighbor peer node to the destination node in a forward path;
- MAC_{NEXT}: MAC address of a next node;
- MAC_{SOURCE}: MAC address of a source node;
- $MAC_{DESTINATION}$: MAC address of a destination node.

Some of the above terms are shown in Fig. 4.7.

Table 4.1 lists the size of each message field used. The field size for an ID and an address is based on the values in [69]. If a source node is ready for the slot allocation in a flow, then it unicasts the SA packet to the next node on the path after operating the TSA algorithm.

Algorithm 1 shows the MSA algorithm initiated by a source node. Further, *Algorithm* 2 shows the MSA algorithm when either an intermediate node or a destination node receives an SA packet from node

Algorithm 1 MSA in a source node

```
if k = 1 then
    p_1 first runs the TSA algorithm.
    p_1 sets s_index to the slot index of the obtained slot.
    p_1 marks the obtained slot as a TN.
    p_1 transfers the SA packet with s_index to p_2.
end if
```

Algorithm 2 MSA in an intermediate/a destination node

```
if 1 < k < q then
    Based on the received s_index, p_k allocates the slot(s) for both p_{k-1}
    and p_k as an RN.
    p_k runs the TSA algorithm.
    p_k sets s_index to the slot index of the obtained slot.
    p_k marks the obtained slot as a TN.
    p_k transfers the SA packet with s_index to p_{k+1}.
else if k = q then
    Based on the received s_index, p_q allocates the slot(s) for both p_{q-1}
    and p_q as an RN.
    p_q transfers the SA completion message to the source node p_1.
end if
```

p_k $(1 \leq k < q, q \geq 2)$ in a forward path. An intermediate node or a destination node invokes *Algorithm* 2 whenever it receives an SA packet wherein MAC_{NEXT} is equal to its MAC address. In *Algorithm* 2, when an intermediate node performs the TSA algorithm to allocate the slot as a TN, it is very important for the intermediate node to reserve the right-hand side slot for comparison with the s_{index} within the SA packet received, such that multihop links can be sequentially scheduled on a path.

4.2.3 Performance analysis

4.2.3.1 Correctness of TSA

Theorem 1. *The execution of TSA algorithm results in each node's performing conflict-free TDMA schedule.*

Proof. The validity of the slots scheduled by the TSA algorithm can be verified by the following three conditions.

- A node must receive grant messages from all the one-hop neighbors;
- Any nodes, which are two-hop away from each other, share at least one common one-hop neighbor;
- A node transfers at most one grant message per round.

□

Based on the above conditions, in the TSA algorithm, the grant messages contain the frame map that represents the information on the slots already taken by their one-hop neighbors. This property make sure that a node always selects the slot that is not taken by two-hop neighbors and any nodes within two hop neighbors can not select the same time slot.

4.2.3.2 Complexity analysis of TSA algorithm

Each node i in the network runs the TSA algorithm during up to Δ rounds. One round time is set to T_Δ seconds. Every node must try the lottery at least once and at most Δ times. In order for a node i to finish slot selection, T_Δ must be sufficiently long to (a) transfer a request message, (b) receive grant messages from all its one hop neighbors, (c) select the minimum time slot available and (d) transfer a release message.

Theorem 2. *Assuming the round time is bounded by some constants, the expected number of rounds for a node to acquire a slot is less than* $(\delta' + 1) \cdot e^{\Delta}$.

Let $p_i(k)$ be the probability that node i tries to perform the lottery in the k^{th} round. Since δ' contenders of a node i can have at most Δ lottery tries, the probability that node i acquires a slot in the t^{th} round, $p_{succ}(i, t)$, is bounded as follows:

$$
\begin{aligned}
p_{succ}(i,t) &\geq p_{succ}(i,1) && (4.3)\\
&\geq p_i(1) \prod_{j \in c(i)} \prod_{k=1}^{\Delta} (1 - p_j(k)) && (4.4)\\
&\geq \frac{1}{\delta' + 1} \prod_{j \in c(i)} (1 - p_j(k))^{\Delta}, && (4.5)
\end{aligned}
$$

where δ' denotes two-hop degree that means the maximum number of two-hop neighbors in the network.

Because $p_j(\Delta) \geq p(k)$ for $1 \leq k \leq \Delta$, equation (4.5) can be replaced by

$$\frac{1}{\delta'+1}\prod_{j\in c(i)}(1-p_j(\Delta))^{\Delta}. \tag{4.6}$$

Next, because δ' is two-hop degree, $p_j(\Delta) \leq 1/(\delta'+1)$. Therefore, equation (4.6) can be given by

$$\frac{1}{\delta'+1}\prod_{j=1}^{\delta}{}'(1-\frac{1}{\delta'+1})^{\Delta} \tag{4.7}$$

$$= \frac{1}{\delta'+1}(1-\frac{1}{\delta'+1})^{\delta'\Delta} \tag{4.8}$$

$$> \frac{1}{\delta'+1}e^{-\Delta}. \tag{4.9}$$

where $(1-1/(\delta'+1))^{\delta'} > e^{-1}$.

Since the above result is independent of i and k, it gives the lower bound on the probability that a node acquires a slot in any round. Let M be the random number representing the number of rounds before a node acquires a slot with the lower bound probability. M definitely has a geometric distribution[22].

$$\Pr(M=k) = p_{low}(1-p_{low})^{k-1}, \tag{4.10}$$

where $p_{low} = 1/\left[(\delta'+1)\cdot e^{\Delta}\right]$.

From the above result, we can obtain the upper bound on the expected number of rounds that a node takes to acquire a slot as follows:

$$E\left[M\right] = \frac{1}{p_{low}} = (\delta'+1)\cdot e^{\Delta}. \tag{4.11}$$

Theorem 3. *Assuming that the message delay is bounded by a constant, the expected message complexity of the TSA algorithm is* $\mathrm{O}(\delta')$.

Proof. In each round, a contender can try the lottery for Δ times. In each try, it can be a winner and gets rejected, thus transferring O(1) messages. Therefore, in one round, it can transfer O(Δ) messages. Since there are O(δ') rounds on average, each process can transfer O($\Delta \times \delta'$) messages on average. □

4.2.3.3 Overhead analysis

In this section, we evaluate the overhead of the proposed MSA algorithm in terms of the power consumed for the scheduling by all the nodes in the network. The proposed scheme gets the map information on its one-hop neighbors in each hop on the path before transferring the SA packet to the next node. Considering all the possible combinations, we find that the total power consumed for performing TSA and MSA algorithms, P_{total}, consists of the following four components.

- P_{REQ}: power consumed by request messages by all the nodes;
- P_{GRN}: power consumed by grant messages by all the nodes;
- P_{REL}: power consumed by release messages by all the nodes;
- P_{SA} : power consumed by SA packets by all the nodes.

Assuming that all the nodes in the network are evenly distributed, one-hop degree δ of all nodes is same. Therefore, P_{REQ} can be calculated by

$$P_{REQ} = \sum_{i=1}^{N} \sum_{j=1}^{h(i)} \left(\begin{array}{l} l_{REQ} \cdot p_{tx} + \delta \cdot l_{REQ} \cdot p_{rx} \\ + l_{ACK} \cdot p_{tx} + \delta \cdot l_{ACK} \cdot p_{rx} \end{array} \right), \tag{4.12}$$

where N denotes the total number of nodes; $h(i)$, the total number of hops necessary for the i^{th} source node to transfer its packet to its destination node; δ, the one-hop degree in a node; l_{REQ}, the sum of l_{req} and l_{M+P}; l_{M+P}, the sum of the overhead in MAC and PHY layers; and l_{ACK}, the length of the ACK packet. Further, p_{tx} denotes the energy spent in transmitting a bit over a distance of 1-meter, and p_{rx} denotes the energy spent in receiving a bit. In case of P_{GRN}, all one-hop neighbor nodes, whose number is δ, respond to the request message transferred from the initiation node n_N. Therefore, P_{GRN} can be calculated by

$$P_{GRN} = \sum_{i=1}^{N} \sum_{j=1}^{h(i)} \left\{ \begin{array}{l} \delta \cdot (l_{GRN} \cdot p_{tx} + \delta \cdot l_{GRN} \cdot p_{rx}) \\ + \delta \cdot (l_{ACK} \cdot p_{tx} + \delta \cdot l_{ACK} \cdot p_{rx}) \end{array} \right\}, \tag{4.13}$$

where l_{GRN} denotes the length of the grant message whose length is same as the sum of l_{grn} and l_{M+P}.

Similar to the calculation of P_{REQ}, P_{REL} can be given by

$$P_{REL} = \sum_{i=1}^{N} \sum_{j=1}^{h(i)} \left(\begin{array}{l} l_{REL} \cdot p_{tx} + \delta \cdot l_{REL} \cdot p_{rx} \\ + l_{ACK} \cdot p_{tx} + \delta \cdot l_{ACK} \cdot p_{rx} \end{array} \right), \tag{4.14}$$

where l_{REL} denotes the length of the grant message whose length is same as the sum of l_{rel} and l_{M+P}.

Finally, during performing the MSA algorithm in the network, the SA packets are transferred as many as $\delta \times h \times N$. Therefore, similar to the calculation of P_{REQ}, P_{SA} can be calculated by

$$P_{SA} = \sum_{i=1}^{N} \sum_{j=1}^{h(i)} \left(\begin{array}{l} l_{SA} \cdot p_{tx} + l_{SA} \cdot p_{rx} \cdot \delta \\ + l_{ACK} \cdot p_{tx} + l_{ACK} \cdot p_{rx} \cdot \delta \end{array} \right). \tag{4.15}$$

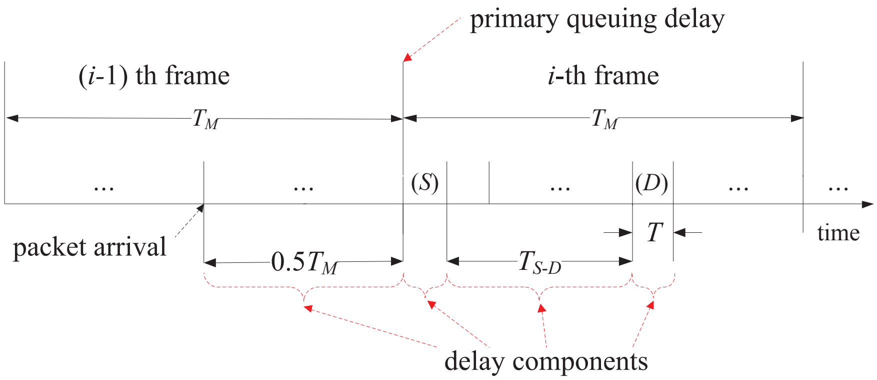

Fig. 4.11. Delay components of the proposed SLS scheme.

Accordingly, the total power consumed by scheduling is given by

$$P_{total} = P_{REQ} + P_{GRN} + P_{REL} + P_{SA}. \qquad (4.16)$$

4.2.3.4 ETE delay analysis

In this section, we derive the average ETE delay of the proposed SLS scheme. Similar to the analysis in the RLS, the delay suffered by a packet, D_{SLS}, can be obtained using the following four components (refer to Fig. 4.11): (1) the time between its generation and the end of the current frame, (2) the primary queuing delay to allow all the packets already queued to be transmitted in a source node, (3) the distance between the first slot and the slot allocated for the destination node, and (4) packet transmission time in both the source and destination nodes. The first component is identical to that in case of the RLS, whose value is $0.5T_M$, and the fourth component, which is the packet transmission time in both the source and destination nodes, is $2T$. To compute the second component, i.e., primary queuing delay, (once the end of the current frame is reached), we observe that the queue behaves exactly like the one with a deterministic service time of T_M. If we assume a Poisson arrival process of λ packets/s for a user and that the number of packets that can be stored in a queue is not bounded, then the primary queuing delay is identical to the queuing time in an M/D/1 queuing system in which the deterministic service time is T_M. Thus, the expected primary queuing time of a packet, W_q, is given by [70],[71]

$$W_q = \frac{\rho}{2(1-\rho)} \cdot T_M = \frac{\rho}{2(1-\rho)} \cdot L_{SLS} \cdot T, \tag{4.17}$$

where $\rho = \lambda \cdot T_M$. If we consider a deterministic packet arrival and a deterministic service time, then W_q is equal to zero[14]. On the other hand, the third component, which is the distance between the first slot and the slot allocated for the destination node, T_{S-D}, can be calculated by averaging all the possible combinations. Fig. 4.12 shows an example of the calculation of T_{S-D} when $h = 3$. First, if there is no vacant slot (A_0) among all the allocated slots on the path, then T_{S-D} is T and one case (${}_{3-2}C_{3-2}$) exists, where ${}_{\alpha}C_{\beta}$ denotes the combination of α things taken β at a time and T denotes unit slot size in terms of time. Second, when there is one vacant slot (A_1), T_{S-D} is $2T$ and two cases (${}_{4-2}C_{3-2}$) exist. Next, when there are two vacant slots(A_2), T_{S-D} is $3T$ and three cases (${}_{5-2}C_{3-2}$) exist. Therefore, for all N, T_{S-D} can be given by

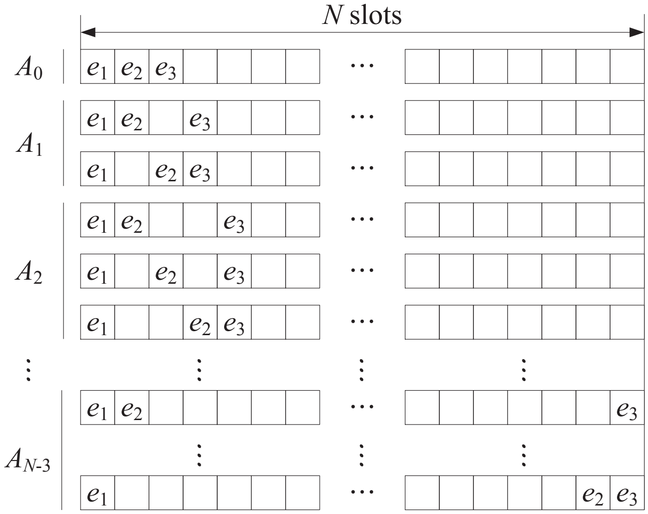

Fig. 4.12. Example of T_{S-D} calculation.

$$T_{S-D} = \frac{\sum_{j=h}^{L} \begin{pmatrix} j-2 \\ h-2 \end{pmatrix} \cdot (j-2)}{\sum_{j=h}^{L} \begin{pmatrix} j-2 \\ h-2 \end{pmatrix}} \cdot T. \tag{4.18}$$

Accordingly, the total ETE delay suffered by a packet, D_{SLS}, is given by

$$D_{SLS} = 0.5T_M + W_q + T_{S-D} + 2T. \tag{4.19}$$

4.2.4 Performance evaluation

For the performance evaluation, two scenarios are considered. In *Scenario* #1, to observe the queuing behavior of the conventional MLS scheme using distance-2 graph coloring and the proposed SLS scheme, we simulate five X by X grid networks, where X is set as 3, 4, 5, 6, and 7 when only one packet is transferred from each source node. In the simulated network, the distance between two adjacent nodes are 100 meters and the communication range of each node is 100 meters. After each node allocates slots by using distance-2 graph coloring, each source node transfers one packet in its allocated slot. If any intermediate nodes receive packets from the previous node on the path, they transmit the received packet in the allocated slot. This study considers ten different seeds for this scenario, and their simulation results are averaged. On the other hand, in *Scenario* #2, to compare the performance of the proposed SLS scheme with that of the MLS scheme using distance-2 graph coloring as carried out in [15], this study simulates two TDMA networks with different topologies. One is the X by X grid network, where X is set as 7. In the grid network, the vertical and horizontal distances between two adjacent nodes are 100 meters. The other is the network with 100 nodes randomly distributed in a square area of 200 $\times$ 200 meters. In both networks, the communication range of each node is 30 meters. In *Scenario* #2, as a consideration of primary queuing delay, we also consider both a DPA and an NDPA having exponential distribution. These two cases are considered for observing the behavior for both non-constant and constant packet interarrival characteristics. As soon as all the source nodes complete the proposed MSA algorithm successfully, they generate packets before transmitting them in the allocated slot. If intermediate nodes receive packets from the previous node on the path, they transmit the received packets in the allocated slot for each flow. For the grid network,

Table 4.2. Preliminary results

	Grid network(N=49)	Random network(N=100)
unit slot time (T)	0.001 sec.	0.001 sec.
L_{MLS}	21	88
L_{SLS}	75	200
one-hop degree	3.35	7.5
two-hop degree	5.67	11.9
h	4	4.4

this study considers five different seeds. In case of random topologies, this study considers ten different random topologies and their simulation results are averaged. Table 4.2 summarizes some preliminary results obtained from the simulation. In Table 4.2, L_{MLS} denotes the frame length of the MLS scheme using distance-2 graph coloring and L_{SLS} denotes the frame length of the proposed SLS scheme. The conventional MLS scheme shares a common slot in a link. Therefore, the frame length of the MLS scheme only depends on the two-hop degree. On the other hand, the proposed scheme allocates different slots to each link in a flow. Therefore, the frame length of the proposed SLS scheme is affected on the number of nodes in the network, the average number of hops, and the number of flows per node. The more the number of nodes, the average number of hops, and the number of flows per node become, the bigger the frame length.

Table 4.3. Parameters for overhead calculation

Parameters	Value (bits)
L	400
l_{M+P}	496
l_{ACK}	496
l_{req}	8
l_{grn}	$8 + L$
l_{rel}	8
l_{sa}	$8 + 48 + 8$
l_{REQ}	$l_{M+P} + l_{req}$
l_{GRN}	$l_{M+P} + l_{grn}$
l_{REL}	$l_{M+P} + l_{rel}$
l_{SA}	$l_{M+P} + l_{sa}$

4.2.5 Numerical and simulation results

In this section, we first discuss the results of the overhead analysis. Next, the simulation results from *Scenario* #1 are discussed. Finally, the simulation results from *Scenario* #2 and the related analysis results are discussed.

Table 4.4. MSA overhead: power consumption

	49 nodes (Joules)	100 nodes (Joules)
P_{REQ}	0.1120	1.2474
P_{GRN}	0.1567	1.7464
P_{REL}	0.1120	1.2474
P_{SA}	0.0356	0.1769
P_{total}	0.4163	4.4181

Table 4.5. MSA overhead: Routing and SA time

Operations	Average time (seconds)
Routing (simulation)	0.0109 (per node)
SA process (simulation)	16.8780
SA process (analysis, Δ=1)	2.2046
SA process (analysis, Δ=2)	5.9927
SA process (analysis, Δ=3)	16.2899
SA process (analysis, Δ=4)	44.2805

Table 4.6. Preliminary results in the MLS

# of nodes	9	16	25	36	49
L_{MLS}	6	7	18	21	22
h	1.44	2.13	2.72	3.22	4.10
random scheduling delay	2.2	3.5	5.7	7.5	9.4

4.2.5.1 Results from overhead analysis

Table 4.3 lists the parameters used for calculating the MSA overhead. As same in [66],[72],[73], p_{tx} and p_{rx} are set as 0.1 nJ/bit-m^2 and 50 nJ/bit, respectively. Table 4.4 lists the energy spent by all the nodes for the proposed MSA algorithm. Typically, a distributed network having 100 nodes needs a couple of joules of energy for scheduling[66],[72],[73]. In the proposed MSA algorithm, all nodes exchange their frame maps for each hop in a flow. Therefore, the energy consumed is slightly more than that consumed in the conventional schemes. However, it is believed that these results are within the acceptable range. Table 4.5 lists the MSA overhead in terms of routing and SA time. According to the simulation, the time taken to complete the SA process is approximately 16.8780 seconds. This value is almost same as the one of the analytical result when Δ is 3, which means that each node needs about at most three rounds to complete the SA process.

4.2.5.2 Results from Scenario #1

Table 4.6 summarizes some results from the simulation of *Scenario* #1, where each source node transfers only one packet in the first frame. In Table 4.6, L_{MLS} denotes the number of slots allocated by distance-2 graph coloring and random scheduling delay denotes the number of frames elapsed for all the destination nodes to receive one packet from each source node. In the conventional MLS schemes where one common slot is allocated to multiple flows in a link, the factors that may influence random scheduling delay are primary and secondary queuing delays. In this scenario, no primary queuing delay occurs because each node generates only one packet. Intuitively, it is said that if the number of hops from a source node to a destination is h, the ETE delay in terms of frames is h. However, as shown in Table 4.6, each network (when X is 3, 4, 5, 6, and 7) needs 2.2, 3.5, 5.7, 7.5, and 9.4 frames on an average when h is 1.44, 2.13, 2.72, 3.22, and 4.10, respectively. Thus, the increase of the random scheduling delay in *Scenario* #1 is all caused by the secondary queuing delay. Accordingly, in multihop environments, the MLS causes ETE delay to be increased because of secondary queueing delay although there is no primary queueing delay.

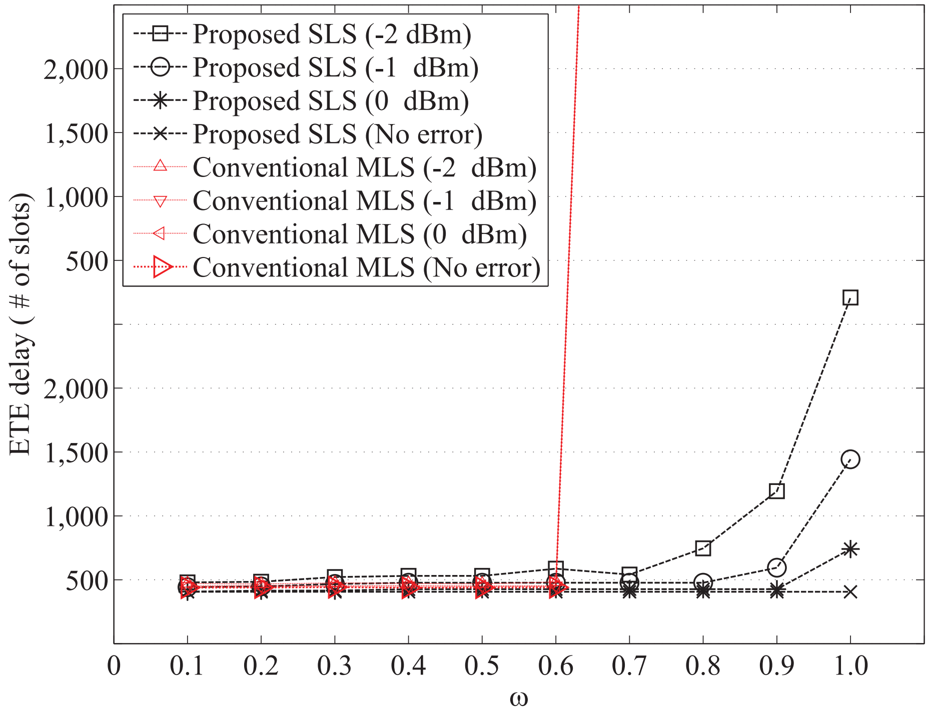

Fig. 4.13. ETE delay with different traffic load and TX power: DPA.

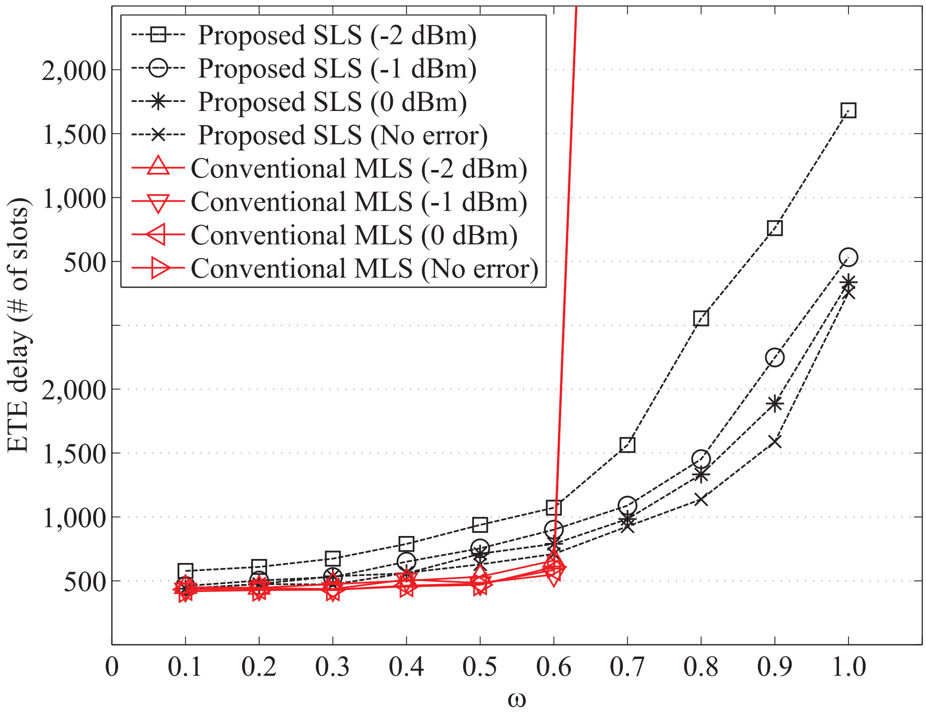

Fig. 4.14. ETE delay with different traffic load and TX power: NDPA.

4.2.5.3 Results from Scenario #2

Fig. 4.13 and 4.14 show the ETE delay with different seed values with an increase of the value of ω. In Fig. 4.13 and 4.13, the symbols indicate the simulation results. It is assumed that the frame length 100 msec. and unit slot time is 0.5 msec. Therefore, L_{SLS} is set as 200. The packet interarrival time is set as (unit slot time $\times$ L_{SLS})/ω, where ω increases from 0.1 to 1 in steps of 0.1. ($\tau \times L_{SLS}$) means a frame length in terms of time and is the fixed value. If the value of ω is 0.5, each node generates one packet per two-frame. On the other hand, if the value of ω is 1, then each node generates one packet per one frame. Therefore, increasing the value of ω is the same as the increase of packet interarrival rate. For both DPA and NDPA cases, the conventional MLS scheme shows intolerable delay when the value of ω is equal to or greater than 0.6. This is because the network using graph coloring is overloaded in the intermediate nodes. In case of DPA, both scheduling schemes show a stable performance except in the intolerable case. However, the proposed SLS scheme shows shorter ETE delay, even though it starts the packet transmission with slightly greater frame length than that in case of the MLS. As mentioned before, the MLS shares slots (resources) for multiple flows in a link[66]. Therefore, an increase in the secondary queuing delay causes an increase in the ETE delay. For the NDPA case, the proposed scheme shows slightly longer ETE delay. The proposed SLS scheme is more efficient when there is only one packet waiting for the packet transmission at the beginning of each frame. If there are more than two packets at the beginning of each frame, then all packets but one packet to be transferred in the current frame experience a long delay because of long frame length. When considering the NDPA case in the source node, each source node has the chance to see more than two packets; i.e., the primary queuing delay may occur. Therefore, the proposed SLS scheme shows a slightly lower delay performance for the NDPA case. However, the proposed scheme is more tolerable for a high packet interarrival rate than the MLS.

4.3 Summary

In this chapter, a sequential link scheduling scheme called SLS was proposed to reduce ETE delay in multihop WMNs. The proposed scheme allocates a different slot to each flow in a link to eliminate secondary queueing delay. Additionally, all slots are allocated with the allocation order on a path considered in order to eliminate random scheduling delay, ultimately reducing ETE delay in multihop WMNs. We derived the ETE delay of the proposed scheme and validated it through a simulation. Finally, we compared the performance of the proposed scheme with that of the conventional the MLS scheme that employs distance-2 graph coloring. The important contributions of this study are as follows:

- Analysis of the delay effect caused by an allocation order of the TDMA slots was performed;

- Channel locking algorithm called TSA for interference-free communication was proposed;

- Complexity analysis of the TSA algorithm was performed;

- Fully distributed method to sequentially allocate slots on a path, called MSA, was proposed;

- Delay analysis of the proposed scheme and its simulation were performed.

According to the analysis and simulation results, for deterministic packet arrival, the proposed scheme works well irrespective of the packet interarrival rate and outperforms the conventional MLS. However, in case of non-deterministic packet arrival, the ETE delay of the proposed SLS scheme is slightly longer than that of the conventional MLS because the probability that each node has more than two packets increases at the beginning of the frame. However, the proposed SLS scheme is more tolerant for a high packet interarrival rate.

5

Sequential Scheduling jointly combined with NC in TDMA-based WMNs

In the fields of TDMA-based WMNs, several NC schemes have been proposed[34],[74]. They have focused on the improvement of network throughput efficiency that is the original objective of NC. However, although they can get NC gain, ETE delay may be varied according to the allocation order of slots in TDMA-based WMNs. Therefore, this dissertation proposes two joint scheduling and NC schemes to reduce ETE delay with NC gain guaranteed, which performs XOR-based NC operation, in distributed TDMA-based WMNs.

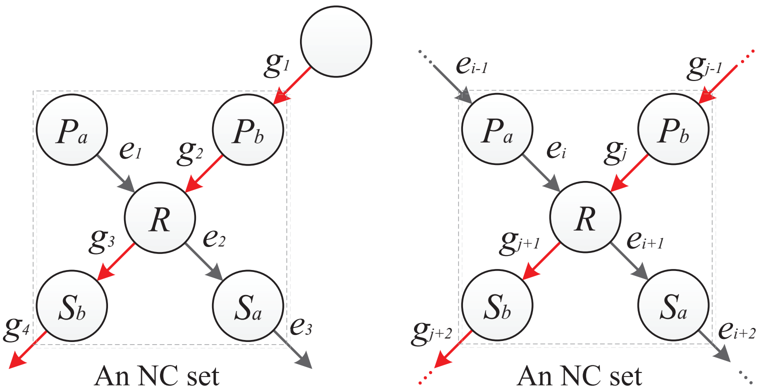

Fig. 5.1. NC constellations for scheduling

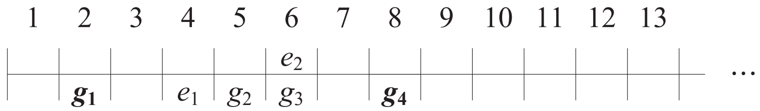

Fig. 5.2. Delay effect in an RLS with NC: case 1

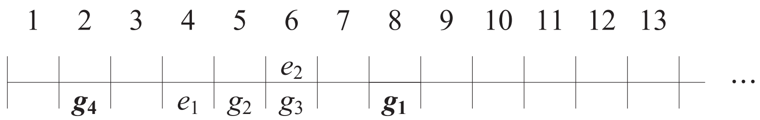

Fig. 5.3. Delay effect in an RLS with NC: case 2

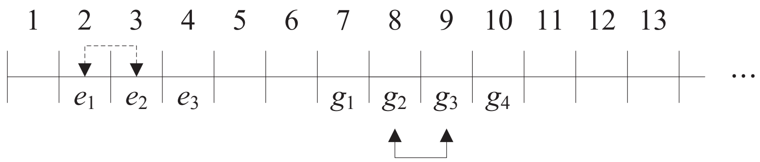

Fig. 5.4. Example of an SLS with NC

5.1 Motivation

Consider an NC set as shown in Fig. 5.1(right). An reference NC flow f_r in an NC set is referred to as the first flow that has finished a scheduling procedure and a non-reference NC flow f_n is referred to as the last flow that has finished a scheduling procedure out of two NC flows. From now onward, in each figure, we use link indexes e and g for f_r and f_n, respectively. We also define $s(e_i)$ and $s(g_j)$ as slot indexes of the links e_i and g_j, respectively, where i (≥ 1) and j (≥ 1) denote link indexes. First, we consider an RLS scheme used in an environment where there is no central node or base station in the network; i.e., in a distributed environment. Because there is no central node, link g_1 and g_4 not related to the NC operation may be allocated slots as shown in Fig. 5.2 or Fig. 5.3. It is assumed that the slots for NC flows are sequentially scheduled. In this case, the sixth slot becomes the common broadcasting slot. Let random scheduling delay be the number of frames required to transfer a packet from a source to a destination. In case of Fig. 5.2, random scheduling delay is one. However, in case of Fig. 5.3, random scheduling delay is two. Random scheduling delay varies according to both the slot allocation order within a frame and the number of hops. Therefore, this random scheduling delay must be considered to reduce ETE delay when NC is performed in distributed TDMA-based WMNs. On the other hand, consider conventional SLS schemes[15],[75] that have considered the allocation order of slots within a frame. They can guarantee the sequentiality of slots only for its own flow on a path, where, if defined in different angle, ‘sequentiality’ means the slot allocation satisfying the condition $s(e_i) < s(e_{i+1})$ for the links e_i $(1 \leq i \leq h)$ in a flow. If the slots scheduled in a flow satisfy with the sequentiality, the multihop transmission of a packet from a source node to a destination node is possible within one frame. However, if considering NC for which two flows are mixed, this sequentiality may be broken. For example, Fig. 5.4 shows an example where the sequentiality is broken in the conventional sequential link scheduling schemes. Assume that, in the NC set of Fig. 5.1(left), the links e_1 and g_2 are the ones from previous nodes and the links e_2 and g_3 are the ones to the next nodes. If we set a common broadcasting slot as $s(e_2)$, then the links of f_r are arranged in the sequence of $s(e_1)$, $s(e_2)$, and $s(e_3)$, and the links of f_n are arranged in the sequence of $s(g_3)$, $s(g_1)$, $s(g_2)$, and $s(g_4)$. Therefore, the links of f_n do not satisfy with the sequentiality. On the other hand, if we set a common broadcasting slot as $s(g_3)$, then the links of f_r are arranged in the sequence of $s(e_1)$, $s(e_3)$, and $s(e_2)$, and the links of f_n are arranged in the sequence of $s(g_1)$, $s(g_2)$, $s(g_3)$, and $s(g_4)$. In this case, the links of f_r do not satisfy with the sequentiality. Therefore, in order that NC operation is performed with the sequentiality satisfied, the slot indexes of the links e_i and g_j of two predecessor nodes must precede the slot indexes of the links e_{i+1} and g_{j+1} of two successor nodes (refer to Fig. 5.1(right)).

5.2 Proposed Section-based Scheme

The proposed section-based sequential scheduling scheme with NC, which is flow-based one, employs a new concept, 'section', so that the slots scheduled on a path are sequentially arranged within a frame even when NC is used. It is assumed that all the nodes know H that denotes the highest value of hop distance in the network. We define $h(i)$ as hop information to the destination, which a source node i obtains after the completion of routing process. Before performing the proposed section-based scheme, each source node broadcasts its own $h(i)$. When a node hears $h(i)$, if the received hop value is higher than the one it currently knows, it rebroadcasts the new value. After some predetermined dissemination time, all the nodes obtain the highest hop value H. By using this hop information, the network divides a frame to H sections. We also define $x(e_i)$ and $x(g_j)$ as the section indexes of the links e_i and g_j, respectively. We first describe the proposed section-based scheme when not using NC operation. In the proposed section-based scheme, all nodes allocate slots by using section and hop information.

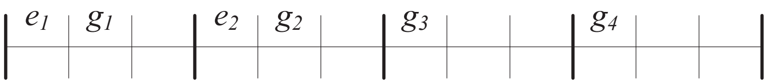

Fig. 5.5. Example of the slot allocation when h(i)= 2 and 4 for four sections

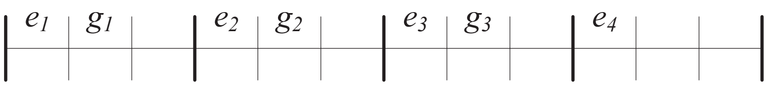

Fig. 5.6. Example of the slot allocation when h(i)= 4 and 3 for four sections

During the routing process, each node manages the routing tables (forward and reverse tables). Based on both these two tables and the criteria for NC sets explained in section 2.2, prior to performing the proposed scheme, each node finds NC sets where NC operation is possible. Although the routing table is altered because of the change of the cost metric, nodes in the network do not perform a new SA process. That is, once slots are determined by the SA process, the network exploits the slots for the lifetime of flows.

Fig. 5.5 and 5.6 show examples of the slot allocation in the proposed section-based scheme when H is 4, and $h(i)$ is either 2 and 4 or 4 and 3. Now, we describe the scheduling procedure when the proposed section-based scheme is jointly combined with NC operation. According to the result in [76], if considering energy requirements, it is reported that less than 1% of coding operations are related to the combination of more than three packets. Therefore, in this dissertation, it is assumed that an NC coordinator that performs XOR-based NC operation manages only two flows. As mentioned before, if the allocation order in each link is not considered, random scheduling delay may be increased, thereby increasing ETE delay. Therefore, when performing a slot allocation procedure, the slot indexes scheduled for the links e_i and g_j of two predecessor nodes must precede the slot indexes scheduled for the links e_{i+1} and g_{j+1} of two successor nodes (refer to Fig. 5.1(right)). If considering all possible combinations of the slot allocation in an NC set, there exist four conditions as follows:

- $x(e_i) = x(g_j)$;

- $x(e_i) = x(g_j) + 1$;
- $x(e_i) = x(g_j)$ - 1;
- $x(e_i) < x(g_j)$ - 1 or $x(e_i) > x(g_j) + 1$ where $j \neq 1$.

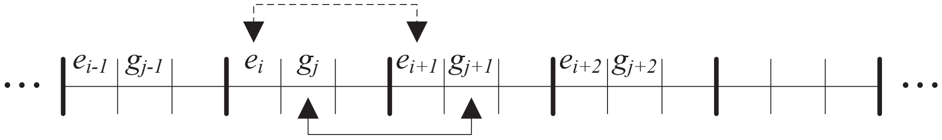

Fig. 5.7. NC condition 1: $x(e_i) = x(g_j)$

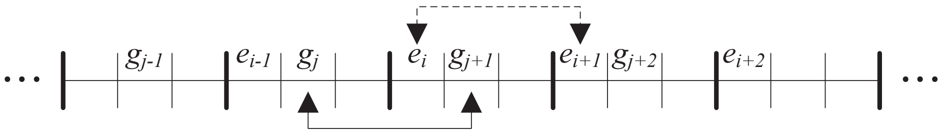

Fig. 5.8. NC condition 2: $x(e_i) = x(g_j) + 1$

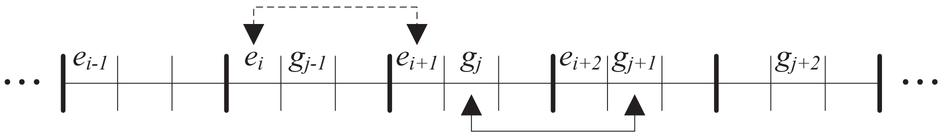

Fig. 5.9. NC condition 3: $x(e_i) = x(g_j)$ - 1

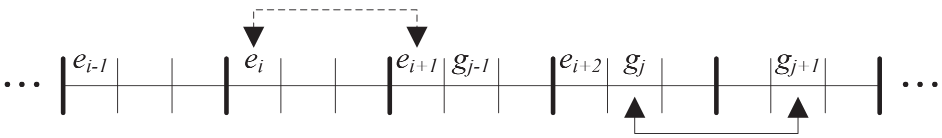

Fig. 5.10. NC condition 4: $x(e_i) < x(g_j)$ - 1 or $x(e_i) > x(g_j) + 1$

Fig. 5.7 through 5.10 illustrate four NC conditions mentioned above. The first and second conditions can guarantee the sequentiality of the slots on a path because the slot indexes of the links e_i and g_j always precede the slot indexes of the links e_{i+1} and g_{j+1}. Therefore, NC coordinator R sets either one out of the slots for the links e_{i+1} and g_{j+1} as a common broadcasting slot. In the third case, the slot index for the link e_{i+1} precedes the slot index for the link g_j. In this case, by swapping the slot indexes for e_{i+1} and g_j, we can guarantee the sequentiality. However, this case needs an overhead that the NC coordinator R exchanges another control packet with P_b. In the last case (Fig. 5.10), the slot index for the link e_{i+1} precedes the slot index for the link g_j. In this case, the NC coordinator R has two options. One is to set the slot scheduled for g_{j+1} as a common broadcasting slot, resulting in the link indexes with a sequence of e_{i-1}, e_i, e_{i+2}, and e_{i+1}. Therefore, the sequentiality is broken. The other is to select the slot scheduled for e_{i+1} as a common broadcasting slot, resulting in the link indexes with a sequence of g_{j+1}, g_{j-1}, and g_j. This case also does not satisfy with the sequentiality on a path. The NC coordinator R of the proposed section-based scheme can decide on whether or not performing an NC operation for the fourth case. The decision may be different depending on the QoS requirements of applications. *Algorithm* 3 and 4 show the SA process of the proposed section-based scheme.

Algorithm 3 Slot allocation in a source node

1: **if** $k = 1$ **then**

2: p_1 first runs the TSA algorithm.

3: p_1 sets s_{index} to the slot index of the obtained slot.

4: p_1 marks the obtained slot as a TN.

5: p_1 transfers the SA packet with s_{index} to p_2.

6: **end if**

Algorithm 4 Slot allocation in an intermediate/a destination node

if $1 < k < q$ **then**
    if (p_k = NC coordinator)&&(current flow = f_n) **then**
        if $x(e_k) = x(g_k)$ **then**
            p_k invokes Algorithm 5.
        else if $x(e_k) = x(g_k) + 1$ **then**
            p_k invokes Algorithm 6.
        else if $x(e_k) = x(g_k)$ - 1 **then**
            p_k invokes Algorithm 7.
        else
            p_k invokes Algorithm 8.
        end if
    else
        Based on received s_{index}, p_k allocates the slot for both p_{k-1} and p_k in the section $x(g_{k-1})$ as an RN.
        Then, p_k obtains the frame map of its one-hop neighbors.
        p_k allocates the commonly available slot for both p_k and p_{k+1} in the section $x(g_k)$ as a TN.
        p_k transfers an SA packet with s_{index} to p_{k+1}.
    end if
else if $k = q$ **then**
    Based on received s_{index}, p_q allocates the slot for both p_{q-1} and p_q as an RN.
    p_q transfers an SA completion message to the source node p_1.
end if

Algorithm 5 Process for 1^{st} NC condition

1: Based on received s_{index}, p_k allocates the slot for both p_{k-1} and p_k in the section $x(g_{k-1})$ as an RN.

2: p_k gets s_{index} for the link e_{k+1} and allocates the common broadcasting slot for NC as a TN.

3: p_k transfers an SA packet with that s_{index} to p_{k+1}.

Algorithm 6 Process for 2^{nd} NC condition

1: Based on received s_{index}, p_k allocates the slot for both p_{k-1} and p_k in the section $x(g_{k-1})$ as an RN.

2: p_k gets s_{index} for the link e_{k+1} and allocates the common broadcasting slot for NC as a TN.

3: p_k transfers an SA packet with that s_{index} to p_{k+1}.

Algorithm 7 Process for 3^{rd} NC condition

1: p_k swaps the slot index for the link e_{k+1} for the slot index for the link g_k.

2: p_k informs p_{k-1} of the information on the new slot index for g_k.

3: p_k sets s_{index} to the swapped new slot index for the link e_{k+1}.

4: p_k transfers an SA packet with s_{index} to p_{k+1}.

Algorithm 8 Process for 4^{th} NC condition

1: Based on received s_{index}, p_k allocates the slot for both p_{k-1} and p_k in the section $x(g_{k-1})$ as an RN.

2: Then, p_k obtains the frame map of its one-hop neighbors.

3: p_k allocates the commonly available slot for both p_k and p_{k+1} in the section $x(g_k)$ as a TN.

4: p_k transfers an SA packet with s_{index} to p_{k+1}.

5.2.1 Performance analysis

5.2.1.1 Power consumption analysis

For calculating the power consumed by the proposed section-based scheme, two additional components should be considered as compared with the proposed SLS scheme. In the 3^{th} NC condition of the proposed section-based scheme, NC coordinator R informs the node p_{k-1} of the information on the new slot index for g_k. This additional transmission to the node p_{k-1} is the first consideration. According to the simulation, the ratio of such cases to total NC points is less than approximately 10%. Therefore, this dissertation ignores this consideration because the power consumed by these transmissions is very small compared to the total power consumed. On the other hand, the proposed SLS scheme exchanges the frame map whose length is equal to the one of the frame length. However, the proposed section-based scheme exchanges the frame map whose length is $(\lceil l_{grn}/H \rceil + l_{M+P})$. Therefore, we can obtain the total power consumed by the proposed section-based scheme by replacing l_{GRN} to $(\lceil l_{grn}/H \rceil + l_{M+P})$ in equation (3.13). Then, the total power consumed by the transmission of the grant messages is calculated by

$$P_{GRN}(SEC) = \sum_{i=1}^{N} \sum_{j=1}^{h(i)} \left[\begin{array}{l} \delta \cdot \left\{ \begin{array}{l} (\lceil l_{grn}/H \rceil + l_{M+P}) \cdot p_{tx} \\ +\delta \cdot (\lceil l_{grn}/H \rceil + l_{M+P}) \cdot p_{rx} \end{array} \right\} \\ +\delta \cdot (l_{ACK} \cdot p_{tx} + \delta \cdot l_{ACK} \cdot p_{rx}) \end{array} \right], \quad (5.1)$$

where $\lceil * \rceil$denotes a smallest integer more than or equal to $*$. Accordingly, the total power consumed by the proposed section-based scheme is given by

$$P_{total}(SEC) = P_{REQ} + P_{GRN}(SEC) + P_{REL} + P_{SA}. \tag{5.2}$$

5.2.1.2 ETE delay analysis

In this section, the ETE delay analysis of the proposed section-based scheduling scheme without NC is performed. In the proposed scheme, all nodes allocate slots by using section and hop information. First of all, assume that the hop distance $h(i)$ of source node i is evenly distributed. For example, the number of source nodes having the hop distance of one, two, ..., H is all same where H denotes the maximum number of hops in the network. Thus, all N nodes in the network try to allocate slots in the section $x(1)$. In the section $x(2)$, $(N - N/H)$ nodes try to allocate slots and ,in the last section $x(H)$, N/H nodes try to allocate slots. Accordingly, given L slots, the number of slots necessary in i^{th} section, L_i, can be calculated by

$$L_i = \begin{cases} \left\lfloor \dfrac{N-(i-1)\frac{N}{H}}{\sum\limits_{j=1}^{H}\left\{N-(j-1)\frac{N}{H}\right\}} \cdot L \right\rfloor & , i \neq H \\ L - \sum\limits_{k=1}^{H-1} \left\lfloor \dfrac{N-(k-1)\frac{N}{H}}{\sum\limits_{j=1}^{H}\left\{N-(j-1)\frac{N}{H}\right\}} \cdot L \right\rfloor & , i = H \end{cases} \tag{5.3}$$

where $\lfloor * \rfloor$ means the integer less than or equal to *. Also, the ETE delay a packet experiences in the section $x(i)$ is composed of three components: (1) time between the start of the frame and the end of $(i-1)^{th}$ section, (2) time between the start of i^{th} section and the slot scheduled for the destination in i^{th} section, and (3) the transmission time at the destination. If

Algorithm 9 Slot allocation in a source node

1: **if** $k = 1$ **then**
2: p_1 first runs the TSA algorithm.
3: p_1 sets s_{index} to the slot index of the obtained slot.
4: p_1 marks the obtained slot as a TN.
5: p_1 transfers the SA packet with s_{index} to p_2.
6: **end if**

considering the above components, the ETE delay a packet experiences in the section $x(i)$ is given by

$$D_{SEC}(i) = \left(\sum_{j=1}^{i-1} L_j \right) \cdot T + \frac{L_j}{2} \cdot T + T \tag{5.4}$$

$$= \left\{ \left(\sum_{j=1}^{i-1} L_j \right) + \frac{L_j}{2} + 1 \right\} \cdot T, \tag{5.5}$$

where T denotes unit slot time.

Finally, the average ETE delay is given by

$$D_{SEC} = \frac{\sum_{k=1}^{H} D_{SEC}(k)}{H}. \tag{5.6}$$

From equation (5.6), it can be seen that the average ETE delay is the function of the frame size L. Therefore, the average ETE delay of the proposed scheme is increased as the frame size is increased.

5.3 Proposed DARR-based Scheme

Algorithm 9 and 10 show the MSA algorithm of the proposed DARR-based scheme. In *Algorithm* 9 and 10, s_{index} denotes an allocated slot

Algorithm 10 Slot allocation in an intermediate/a destination node

if $1 < k < q$ **then**

  if (p_k = NC coordinator)&&(current flow = f_n) **then**

    Based on received s_{index}, p_k allocates the slot(s) for both p_{k-1} and p_k as an RN.

    p_k runs the TSA algorithm.

    p_k sets s_{index} to the slot index of the obtained slot.

    p_k marks the obtained slot as a TN.

    p_k transfers an SA packet with s_{index} twice to two p_{k+1} nodes of f_r and f_n.

  else

    Based on received s_{index}, p_k allocates the slot(s) for both p_{k-1} and p_k as an RN.

    p_k runs the TSA algorithm.

    p_k sets s_{index} to the slot index of the obtained slot.

    p_k marks the obtained slot as a TN.

    p_k transfers an SA packet with s_{index} to p_{k+1}.

  end if

else if $k = q$ **then**

  Based on received s_{index}, p_q allocates the slot(s) for both p_{q-1} and p_q as an RN.

  p_q transfers an SA completion message to the source node p_1.

end if

index in a frame; TN and RN mean a transmitting node and a corresponding receiving node in an allocated slot, respectively; and frame map represents the bit-wise expression of slot allocation status in a frame. The basic idea of the proposed DARR-based scheme is that, when the MSA algorithm has been initiated from f_n, an NC coordinator not only transfers an SA packet to the next node of f_n but also again transfers another SA packet to the next node of f_r. Thus, from the links e_{i+1} to e_h of f_r, additional slots are allocated; i.e., existing slots that have been used and newly allocated slots for f_r. At this time, the NC coordinator releases the existing slots and, in the next frame, uses the newly allocated slots for the sequentiality. The released slots may be used for other flows. The extra transmissions for the slot release are an overhead of the proposed DARR-based scheme. However, it is shown that they are not big burden in the network. If considering the time difference between the slot allocations of f_r and f_n, there exist the following three cases.

- Case 1: before allocating the slot for link e_{i+1}, when NC coordinator R receives the SA packet that includes the SA information for g_j in the current frame;

- Case 2: after allocating the slot for e_{i+1}, when NC coordinator R receives the SA packet that includes the SA information for g_j in the current frame;

- Case 3: after the slot allocation for f_r has been already completed in a frame, when NC coordinator R receives the SA packet that includes the SA information for g_j in a different frame.

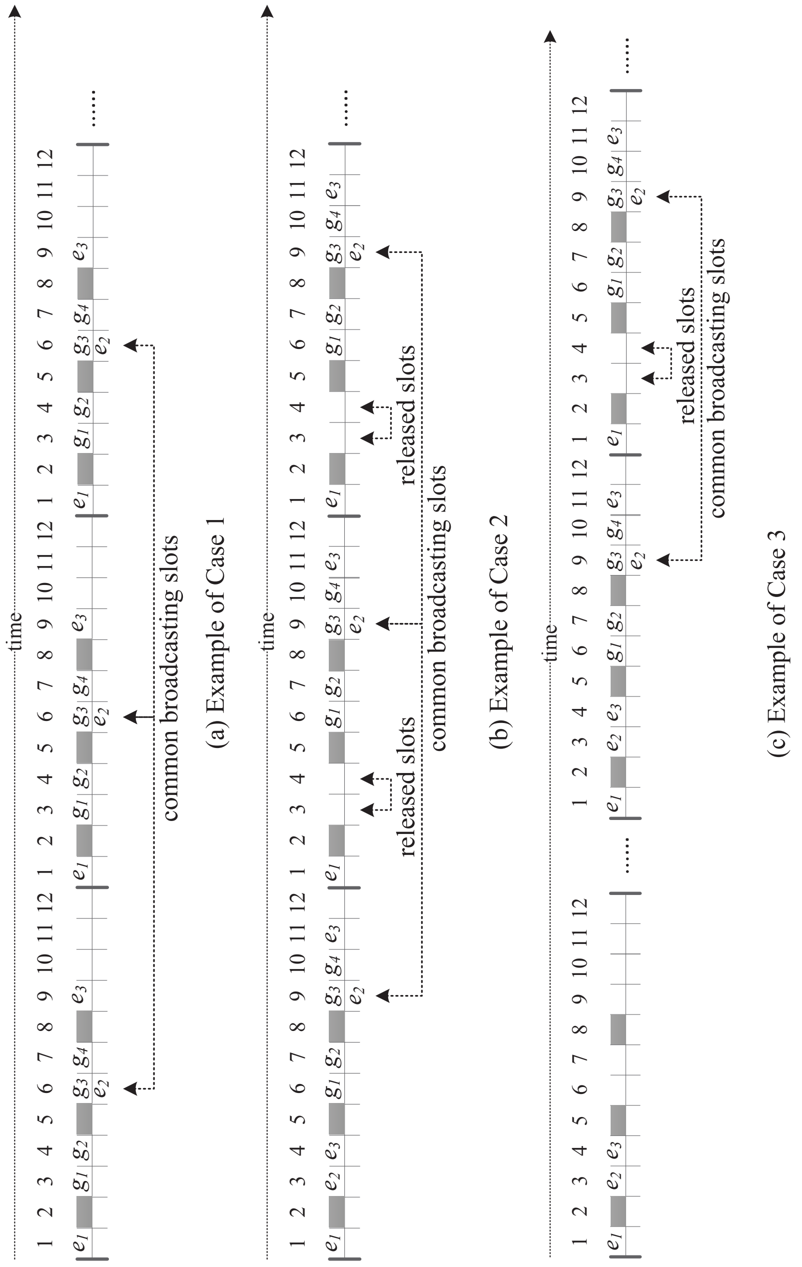

Fig. 5.11. Examples of the proposed DARR-based scheme.

Fig. 5.11 shows the examples of these three cases in the MSA algorithm. In *Algorithm* 10, when an intermediate node allocates the slot(s) as a TN, it is very important for the intermediate node to reserve the right-hand side slot for comparison with the value of s_{index} of the SA packet received, such that the sequentiality can be guaranteed on a path.

5.3.1 Performance analysis

5.3.1.1 Power consumption analysis

The proposed DARR-based scheme first performs duplicated SA process for the NC flow f_r before releasing the first allocated slots from the links e_{i+1} to e_h. If assuming that the hop distance of NC coordinator in a flow is evenly distributed, the network needs additional SA packet transmissions as much as $\lceil h/2 \rceil \cdot \psi$ where ψ denotes the number of NC points in a network. Then, the total power consumed by the exchange of the SA packets is calculated by

$$P_{SA}(DARR) = \left\{ \begin{array}{l} \sum_{i=1}^{N} \sum_{j=1}^{h(i)} \left(\begin{array}{l} l_{SA} \cdot p_{tx} + \delta \cdot l_{SA} \cdot p_{rx} \\ + l_{ACK} \cdot p_{tx} + \delta \cdot l_{ACK} \cdot p_{rx} \end{array} \right) \\ + \left\lceil \frac{h}{2} \right\rceil \cdot \psi \cdot (l_{SA} \cdot p_{tx} + \delta \cdot l_{SA} \cdot p_{rx}) \\ + \left\lceil \frac{h}{2} \right\rceil \cdot \psi \cdot l_{ACK} \cdot p_{tx} + \delta \cdot l_{ACK} \cdot p_{rx} \end{array} \right\}. \quad (5.7)$$

Accordingly, the total power consumed by the proposed DARR-based scheme is given by

$$P_{total}(DARR) = P_{REQ} + P_{GRN} + P_{REL} + P_{SA}(DARR). \quad (5.8)$$

5.4 How to Cope with Asymmetric Flow Conditions

Consider an asymmetric condition where the packet arrival rates of two flows are different as shown in Fig. 5.12. If there are two packets from f_r and f_n before the 5^{th} slot (e.g., Case 1), then R performs the baseline NC operation. However, if there is one packet from f_r because of asymmetric flow conditions (e.g., Case 2), then R has two options. First, R may wait for the packet from f_n (i.e., packet y_2 in Fig. 2) to increase the coding opportunity. Second, R may immediately transfer (i.e., unicast) that packet for delay efficiency. Intuitively thinking, the first case causes the ETE delay to increase. The fundamental purpose of this study is to reduce ETE delay regardless of whether or not NC is applied to the scheduling. Therefore, this case is not a concern of this paper. In the second case, node S_b has the packet that is overheard from P_a. However, because R has unicasted the packet x_1 to S_a, the packet queued in S_b is actually useless. In this case, S_b can not determine whether this packet should be considered (or queued) for a next NC operation because node S_b does not grasp of this situation because of unicast transmission from R to S_a.

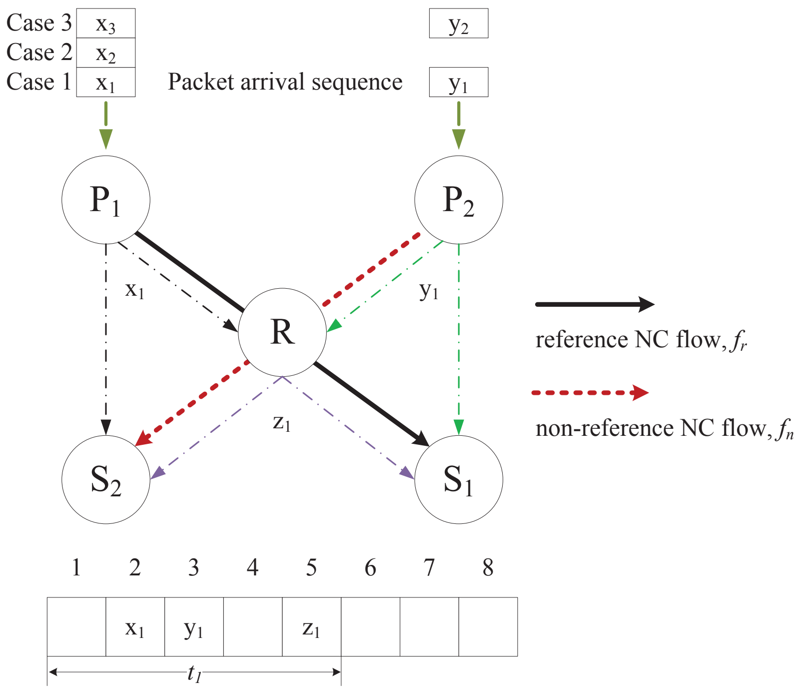

Fig. 5.12. Example network where an asymmetric flow condition occurs.

The simple solution is to transfer another control packet to S_b in order to delete that useless packet. However, in TDMA-based WMNs, additional resources (or slots) for this transferring should be a priory allocated[34], resulting in increasing the overhead per NC set per frame. On the other hand, additional information on an NC set may be included within a packet. It has been known that this overhead size is approximately 5% of a packet size[35]. These two solutions mentioned need extra slot allocation or additional control messages. Therefore, this study proposes to employ a timer called d_{timer} to eliminate the useless packet overhead at the successor node. That is, any successor node related to NC operation sets d_{timer} to 0 at the beginning of each frame. If it does not receive the encoded packet from its NC coordinator within t_1, it eliminates the overhead packet queued for NC operation. t_1 denotes time between the start of the each frame and the slot scheduled for the broadcasting slot as shown in Fig. 5.12. By making use of the timer, the network can cope with asymmetric flow condition without additional control messages or bandwidth waste.

5.5 Performance Evaluation

We have simulated a grid network with 49 nodes. The vertical and horizontal distances between two adjacent nodes are 100-meter, and the communication range of each node is set as 100-meters. During the simulation, each node creates one flow the realtime applications. As soon as all source nodes complete MSA algorithm, they generate one packet per

T_M before transmitting them in the allocated slot. Table 5.1 presents the lists and brief explanations of the scheduling schemes that have been considered for the performance comparison in this dissertation.

Table 5.1. Lists and brief explanations of scheduling schemes for the performance comparison.

SLS-NC	Conventional SLS[15] with NC, where the sequentiality was not considered when NC is applied. The other flows not related to NC can be guaranteed the sequentiality.
SECTION-T1	Proposed section-based sequential scheduling scheme with NC (Type 1).
SECTION-T2	Proposed section-based sequential scheduling scheme with NC (Type 2).
DARR	Proposed DARR-based sequential scheduling with NC.

As performance metrics, we consider average ETE delay and average coding gain. The average ETE delay means the time taken for each source node to transfer a packet to a destination. And, the coding gain is defined by

$$\text{coding gain} = \frac{h \cdot \eta_{total} \cdot N}{h \cdot \eta_{total} \cdot N - \eta_{NC}}, \tag{5.9}$$

where η_{total} denotes the total number of transferred packets per node; N denotes the total number of nodes in the network; and η_{NC} denotes the number of the transmissions reduced by NC.

Table 5.2. Parameters and preliminary results

Communication range (meters)	100
Number of nodes	100
Frame size in terms of slots	200
Frame size in terms of time	100 ms
Unit slot time	0.5 ms
h	4.1
H	13
Average one-hop degree	4
Average two-hop degree	10
Number of NC points	54
# of NC points not meeting 4-th NC condition	35

Table 5.3. Overhead comparison: power consumption (Joules)

	Conventional	Proposed SLS	Section-based	DARR-based
P_{REQ}	not applicable	1.2474	1.2474	1.2474
P_{GRN}	not applicable	1.7464	1.3608	1.7464
P_{REL}	not applicable	1.2474	1.2474	1.2474
P_{SA}	not applicable	0.1769	0.1769	0.2168
P_{total}	2	4.4181	4.0325	4.4580

Table 5.4. Average coding gain in the network

Lists	Average coding gain
Conventional SLS-NC	1.11
SECTION-T1	1.04
SECTION-T2	1.11
DARR-based	1.11

5.6 Numerical and Simulation Results

Fig. 5.13, 5.14, 5.15, and 5.16 show the ETE delay of the conventional and the proposed schemes with an increase in the value of ω, where packets arrive deterministically. The packet interarrival time is set as (unit slot time $\times$ $0.001/\omega$), where ω increases from 0.1 to 1 in steps of 0.1. If the value of ω is 0.5, each node generates one packet per two-frame. On the other hand, if the value of ω is 1, then each node generates one packet per one frame. Therefore, increasing the value of ω is the same as the increase of packet interarrival rate. When there is no error in wireless channel, all schemes show the stable performance regardless of the increase in the value of ω. This is because each node generates at most one-packet arrival per frame, resulting in no primary queuing delay in the network. However, as TX power is decreased (0 $\rightarrow$ -1 $\rightarrow$ -2 dBm), ETE delay is increased. Especially, in the high traffic load (e.g. when $\omega \geq 0.9$), the ETE delay is sharply increased. This is because the packets experience large delay owing to the packet retransmission caused by wireless channel errors, not the primary queuing delay. Meanwhile, in the conventional SLS-NC, half of NC flows experience extra delay whose value is T_M as mentioned in section 5.1. Therefore, the conventional SLS-NC scheme experiences the lowest delay performance. In Fig. 5.13, 5.14, 5.15, and 5.16, SECTION-T1 and SECTION-T2 denote the ETE delay of the proposed section-based schemes with Type 1 and Type 2, respectively. As mention in Table 5.1, 'T1' means one case where the NC coordinator performs the NC operation for the fourth NC condition and 'T2' (or Type 2) means the other case where the NC coordinator does not perform the NC operation for the fourth NC condition. In SECTION-T2, the network loses the NC gain as almost much as the number of NC points satisfying the fourth NC condition because the NC coordinator does not perform NC operation for the fourth NC condition. However, the average ETE delay is smaller than that of SECTION-T1 because the sequentiality can be guaranteed. In case of SECTION-T1, the NC coordinator does perform the NC operation for the fourth NC condition at the cost of extra delay. Therefore, it experiences higher delay than SECTION-T2. However, it can get the whole NC gain at the cost of the small increase in ETE delay. Different from the conventional SLS-NC and proposed SECTION-T1 and SECTION-T2, the proposed DARR-based scheme can guarantee the sequentiality while the network gets the whole NC gain. Therefore, the slots can be saved as much as the number of the NC points, resulting in the decrease in the ETE delay compared to SECTION-T2. On the other hand, SECTION-T2 partially gives up NC gain for the delay efficiency. Therefore, the number of NC points participated in the NC operation is decreased. As a result, DARR-based scheme shows better delay performance than SECTION-T2. Fig. 5.17, 5.18, 5.19, and 5.20 show the ETE delay of the conventional and the proposed schemes with an increase of the value of ω, where packets arrive exponentially (non-deterministically). In case of non-deterministic packet arrival, each node experiences the primary queuing delay. Each node also experiences additional delay owing to the packet retransmission caused by wireless channel errors. Therefore, even in the low traffic load, each packet goes through relatively high ETE delay compared with the deterministic packet arrival.

Table.5.4 shows the average coding gain of all the schemes used for the performance comparison. First of all, the conventional SLS scheme does not perform the NC operation. Therefore, there is no coding gain on it. Meanwhile, because SECTION-T1 does not perform the NC operation for the fourth NC condition, the average coding gain is lower than that of other schemes. Except for SECTION-T1, all the schemes have the same coding gain because they all performs the NC operation for all NC points.

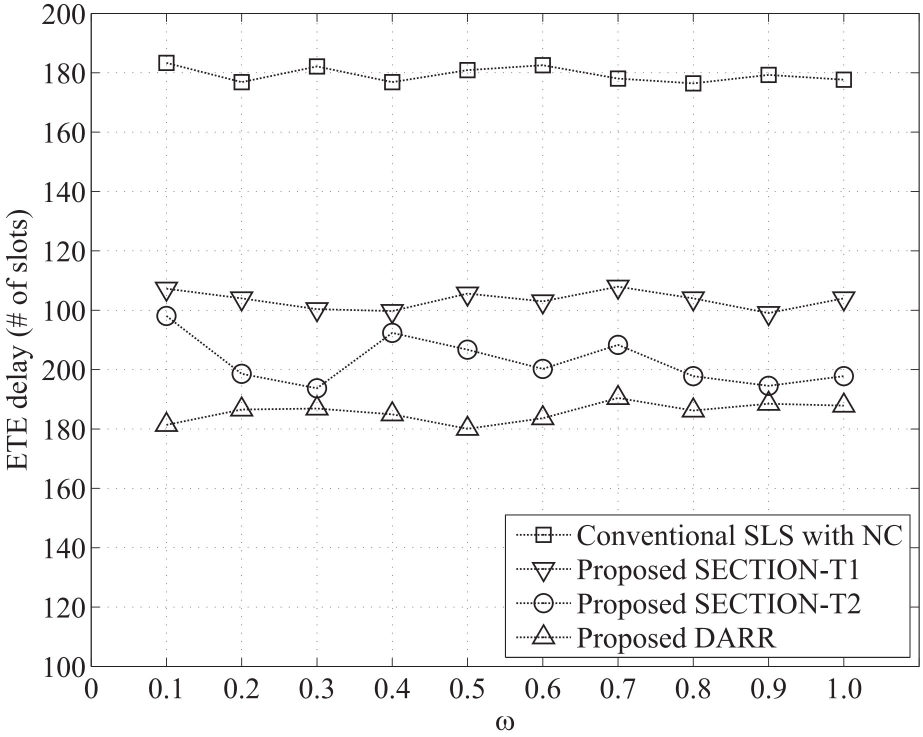

Fig. 5.13. ETE delay in DPA case: No errors.

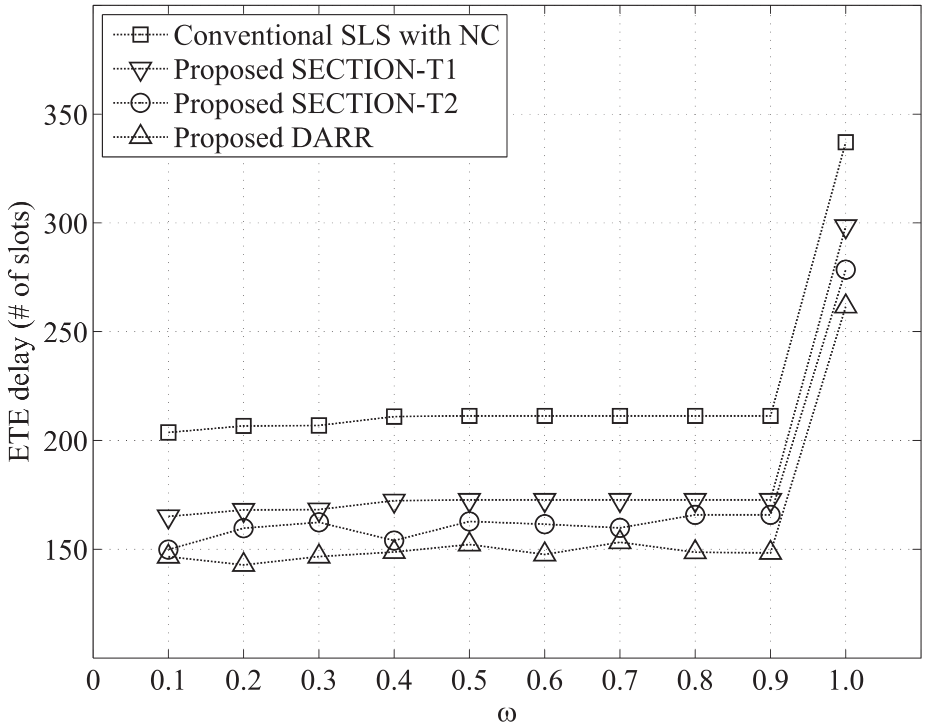

Fig. 5.14. ETE delay in DPA case: 0 dBm of TX power.

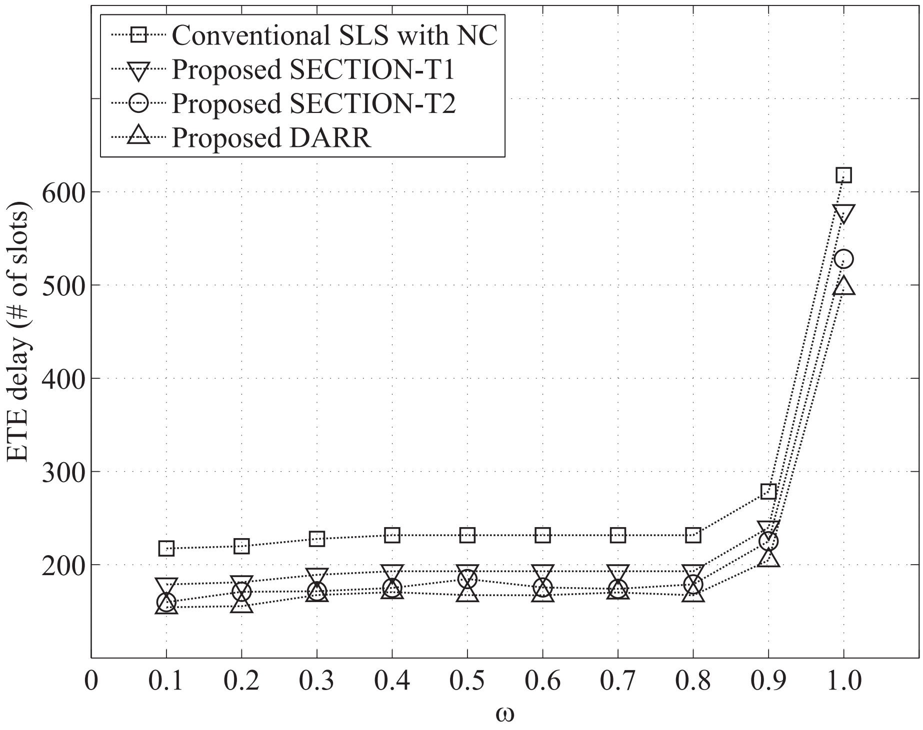

Fig. 5.15. ETE delay in DPA case: -1 dBm of TX power.

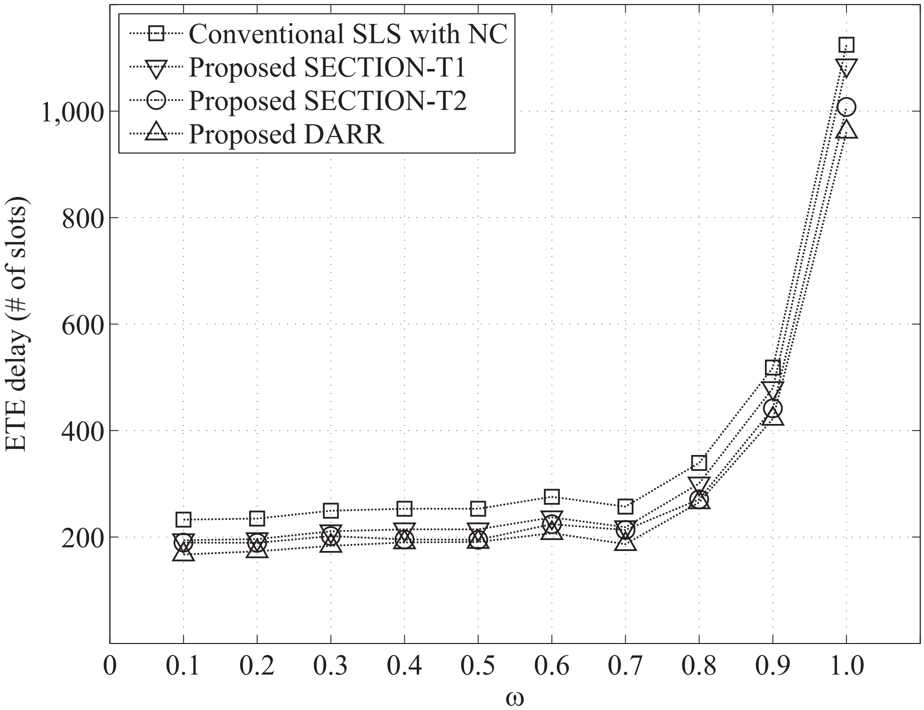

Fig. 5.16. ETE delay in DPA case: -2 dBm of TX power.

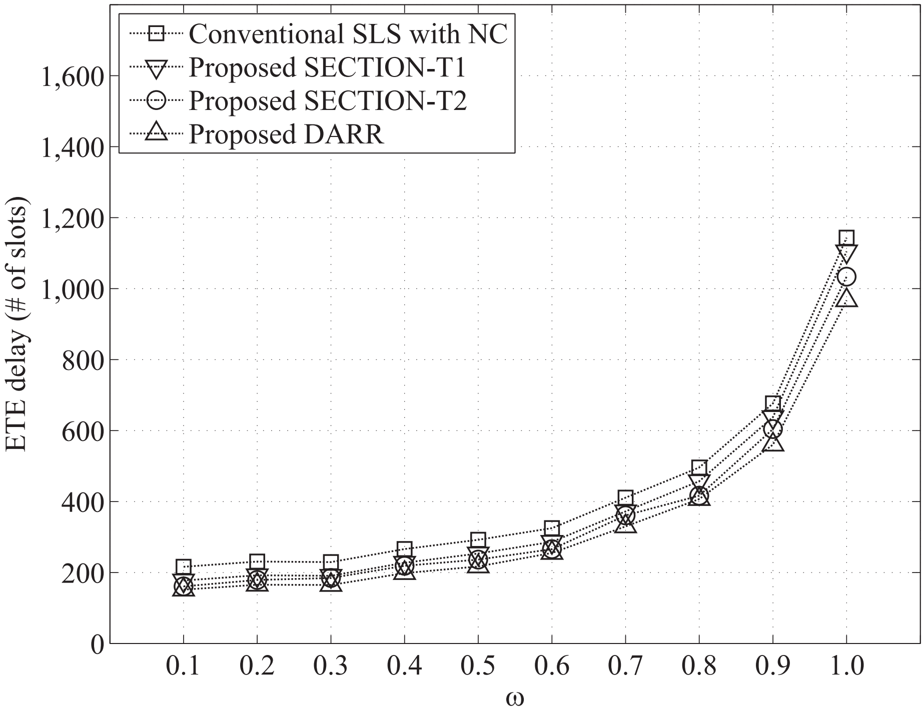

Fig. 5.17. ETE delay in NDPA case: No errors.

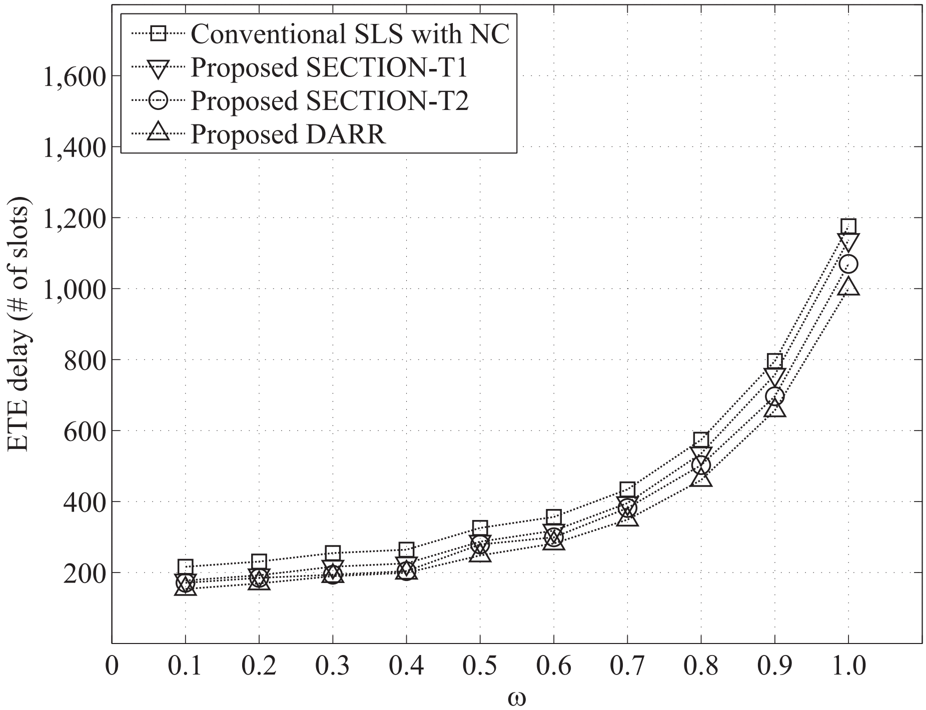

Fig. 5.18. ETE delay in NDPA case: 0 dBm of TX power.

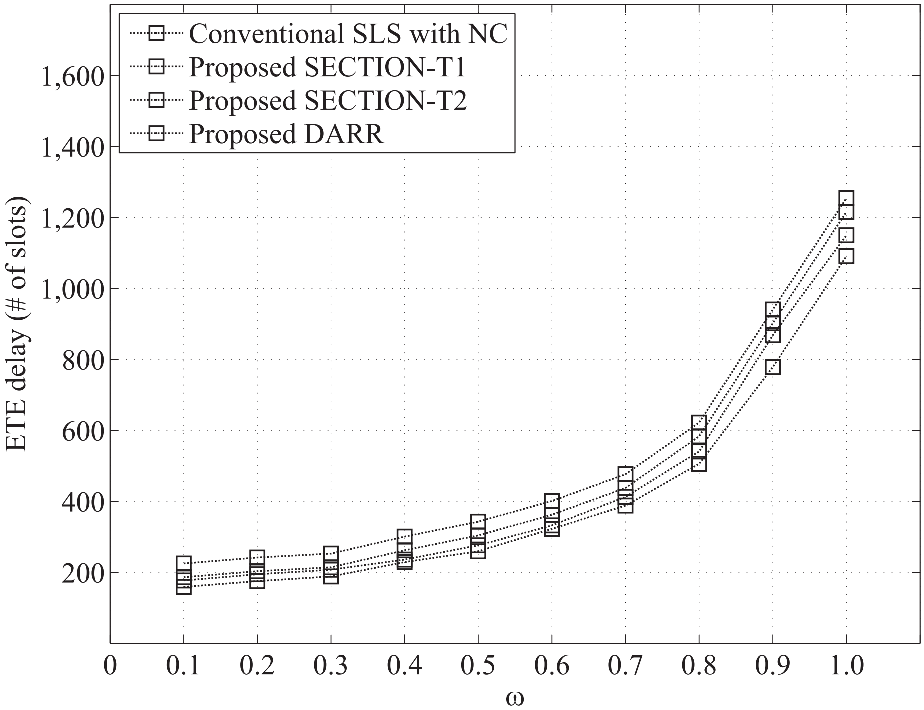

Fig. 5.19. ETE delay in NDPA case: -1 dBm of TX power.

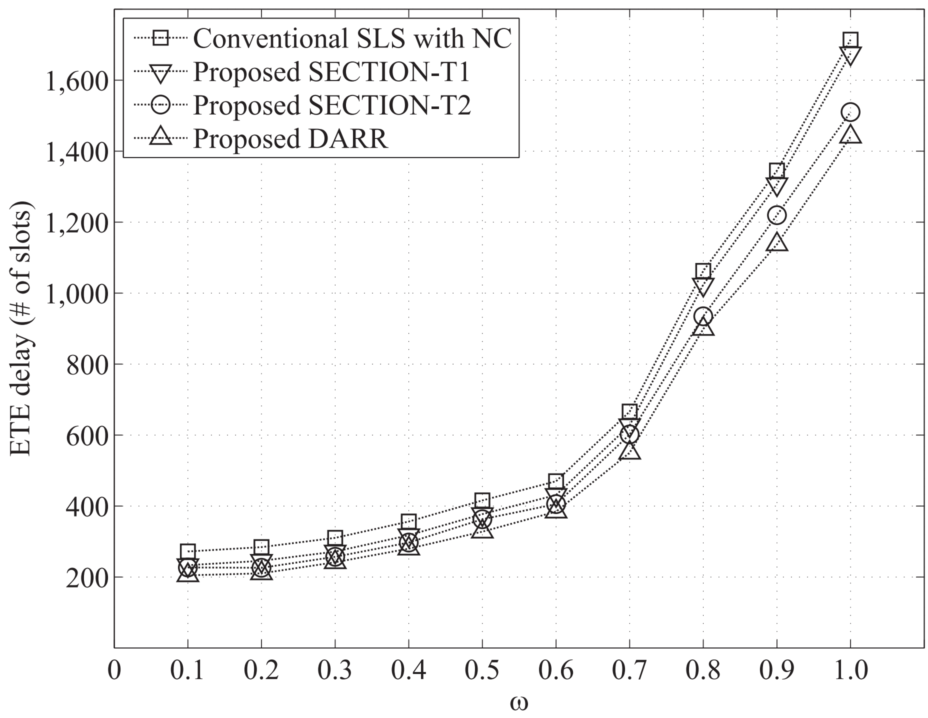

Fig. 5.20. ETE delay in NDPA case: -2 dBm of TX power.

5.7 Summary

In this chapter, two sequential scheduling schemes jointly combined with NC were proposed; Section-based and DARR-based schemes. The proposed schemes can not only get the same NC gain as the conventional scheme but also guarantee the sequentiality with small overhead, thereby resulting in decreasing ETE delay in multihop WMNs. In conclusion, by applying the conventional XOR-based NC to the link scheduling, the proposed schemes give more delay-efficient slot assignments that result in better channel utilization while at the same time using less network resources and energy. The important contributions of this study are as follows:

- Two sequential scheduling schemes jointly combined with NC were proposed;
- Delay analysis of the proposed schemes and its simulation were performed;
- How to cope with asymmetric flow conditions was presented.

6

Conclusion

With the popularity of WMNs, supporting QoS over multihop radio links is a critical issue because ETE delay is rapidly increased with the increase in the number of hops. The conventional MLS scheme using distance-2 graph coloring may experience the well-known queuing delay in multihop WMNs. In case of the conventional RLS scheme where each node allocates a different slot to each flow in a link, it may experience random scheduling delay. These kinds of delay may cause ETE delay to be increased in multihop WMNs. In this dissertation, a sequential link scheduling scheme was proposed to reduce ETE delay in multihop WMNs. First, each node allocates a different slot to each flow in a link to eliminate secondary queueing delay. Second, to eliminate random scheduling delay, all slots are allocated with the allocation order considered, ultimately resulting in reducing ETE delay in multihop WMNs. To accomplish these two objectives, this dissertation proposed TSA and MSA algorithms that make it possible for each node to perform interference-free communication. Meanwhile, although WMNs can support various wireless services with seamless and cheap connectivity, the bandwidth in such networks still remains a scarce resource. Recently, many researches have been conducted on NC to increase the utilization of valuable resources in WMNs. However, if an appropriate link scheduling for NC is not performed, ETE delay may be increased although NC gain can be obtained. Therefore, when designing a scheduling scheme jointly with NC in WMNs, considering the sequentiality is very important in order to support QoS with NC gain guaranteed. To realize this objective, this dissertation proposed two scheduling schemes jointly combined with NC. By applying the conventional XOR-based NC to the link scheduling, the proposed schemes give more delay-efficient slot assignments that result in better channel utilization while at the same time using less network resources and energy. In conclusion, the proposed sequential scheduling schemes both with and without NC can guarantee the sequentiality with small overhead, thereby resulting in decreasing ETE delay in multihop WMNs. The main contributions of this study are as follows:

- Channel locking algorithm called TSA for interference-free communication was proposed;
- Complexity analysis of the TSA algorithm was conducted;
- Fully distributed method to sequentially allocate slots on a path was proposed;
- Two sequential scheduling schemes jointly combined with NC were proposed;

- How to cope with asymmetric flow conditions was presented;
- Delay analysis of the proposed schemes and its simulation were performed.

References

[1] X. Zhang and H. Su, "Network-coding-based scheduling and routing schemes for service-oriented wireless mesh networks," *IEEE Wireless Communications*, vol. 16, no. 4, pp. 40–46, Aug. 2009. 2

[2] IEEE, "802.16 standard for local and metropolitan area networks, part 16: Air interface for fixed broadband wireless access systems," *IEEE Std. 802.16-2004*, Oct. 2009. 3

[3] HART, "Hart 7 specification," *Standard*, Sep. 2007. 3

[4] Roofnet, "An experimental 802.11b/g mesh network," *http://pdos.csail.mit.edu/roofnet*, Jul. 2007. 3

[5] Qurinet, "An experimental wireless mesh and environmental sensor network," *http://spirit.cs.ucdavis.edu/quailridge*, 2007. 3

[6] B. Raman and K. Chebrolu, "Fractel: A fresh perspective on (rural) mesh network," *NSDR*, 2007. 3

[7] ——, "Lo3: A low cost, low power, local voice network for developing regions," *NSDR*, 2009. 3

[8] P. Dutta, S. Jaiswal, and R. Rastogi, "Villagenet: A low-cost, ieee 802.11-based mesh network for connecting rural areas," *Bell Lab. Technical Journal*, no. 12, pp. 119–131, 2007. 3

[9] Firetide, "reliable connectivity anywhere," *http://www.firetide.com/caseStudies.aspx*. 3

[10] V. Gabale, B. Raman, P. Dutta, and S. Kalyanraman, "A classification framework for scheduling algorithms in wireless mesh networks," *IEEE Communications Surveys Tutorials*, vol. PP, no. 99, pp. 1–24, 2012. 3, 9, 11

[11] C. S. In, R. Jain, and A. K. Tamimi, "Scheduling in ieee 802.16e mobile wimax networks: key issues and a survey," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 2, pp. 156–171, Feb. 2009. 9

[12] M. Alicherry, R. Bhatia, and L. E. Li, "Joint channel assignment and routing for throughput optimization in multiradio wireless mesh networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 11, pp. 1960–1971, Nov. 2006. 12

[13] P. Du, W. Jia, L. Huang, and W. Lu, "Centralized scheduling and channel assignment in multi-channel single-transceiver wimax mesh network," in *IEEE WCNC 2007*, Mar. 2007, pp. 1734–1739. 12

[14] D. Ghosh, A. Gupta, and P. Mohapatra, "Admission control and interference-aware scheduling in multi-hop wimax networks," in *IEEE Internatonal Conference on Mobile Adhoc and Sensor Systems*, Oct. 2007, pp. 1–9. 12, 48

[15] P. Djukic and S. Valaee, "Delay aware link scheduling for multi-hop tdma wireless networks," *IEEE/ACM Transactions on Networking*, vol. 17, no. 3, pp. 870–883, Jun. 2009. 12, 50, 64, 87

[16] G. Narlikar, G. Wilfong, and L. Zhang, "Designing multihop wireless backhaul networks with delay guarantees," in *IEEE INFOCOM 2006*, Apr. 2006, pp. 1–12. 12

[17] P. Goyal and A. Sahoo, "A scheduling and call admission control algorithm for wimax mesh network with strict qos guarantee," in *COMSNETS 2010*, Jan. 2010, pp. 1–10. 12

[18] P. Dutta, S. Jaiswal, and R. Rastogi, "Routing and channel allocation in rural wireless mesh networks," in *IEEE ICC 2007*, May 2007, pp. 598–606. 13

[19] P. Dutta, S. Jaiswal, D. Panigrahi, and R. Rastogi, "A new channel assignment mechanism for rural wireless mesh networks," in *IEEE INFOCOM 2008*, Apr. 2008, pp. 2261–2269. 13

[20] D. Panigrahi and B. Raman, "Tdma scheduling in long-distance wifi networks," in *IEEE INFOCOM 2009*, Apr. 2009, pp. 2931–2935. 13

[21] V. Gabale, A. Chiplunkar, B. Raman, and P. Dutta, "Delaycheck: Scheduling voice over multi-hop multi-channel wireless mesh networks," in *COMSNETS 2011*, Jan. 2011, pp. 1–10. 13

[22] I. Rhee, A. Warrier, J. Min, and L. Xu, "Drand: Distributed randomized tdma scheduling for wireless ad hoc networks," *IEEE Transactions on Mobile Computing*, vol. 8, no. 10, pp. 1384–1396, Oct. 2009. 13, 35, 44

[23] Z. Yang, M. Li, and W. Lou, "Codeplay: Live multimedia streaming in vanets using symbol-level network coding," in *ICNP 2010*, Oct. 2010, pp. 223–232. 13

[24] R. Ahlswede, N. C., S. Li, and R. W. Yeung, "Network information flow," *IEEE Transactions on Information Theory*, vol. 46, no. 4, pp. 1204–1216, Jul. 2000. 11

[25] J. Le, J. Lui, and D. M. Chiu, "Dcar: Distributed coding-aware routing in wireless networks," *IEEE Transactions on Mobile Computing*, vol. 9, no. 4, pp. 596–608, Apr. 2010. 14

[26] T. Ho and R. Koetter, "Online incremental network coding for multiple unicasts," in *DIMACS 2005*, Jun. 2005. 16

[27] Z. Li and B. Li, "Network coding: The case of multiple unicast sessions," in *Allerton Conference on Communications*, Jun. 2004. 16

[28] ——, "Network coding in undirected networks," in *Allerton Conference on Communications*, Jun. 2004. 16

[29] J. L., D. Goeckel, and D. Towsley, "The throughput order of ad hoc networks employing network coding and broadcasting," in *IEEE MILCOM 2006*, Oct. 2006, pp. 1–7. 16

[30] P. Gupta and P. Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory*, vol. 46, no. 2, pp. 388–404, Mar. 2000. 17

[31] S. Karande, Z. W., H. R. Sadjadpour, and J. J. Garcia-Luna-Aceves,

"Network coding does not change the multicast throughput order of wireless ad hoc networks," in *IEEE ICC 2009*, Jun. 2009, pp. 1–5. 17

[32] L. Junning, D. Goeckel, and D. Towsley, "Bounds on the gain of network coding and broadcasting in wireless networks," in *IEEE INFOCOM 2007*, May 2007, pp. 724–732. 17

[33] ——, "Bounds on the throughput gain of network coding in unicast and multicast wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 5, pp. 582–592, Jun. 2009. 17

[34] P. Mogre, N. D'Heureuse, M. Hollick, and R. Steinmetz, "Core: centrally optimized routing extensions for the ieee 802.16 mesh mode," in *IEEE LCN 2008*, Oct. 2008, pp. 58–65. 17, 61, 85

[35] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, "Xors in the air: Practical wireless network coding," *IEEE/ACM Transactions on Networking*, vol. 16, no. 3, pp. 497–510, Jun. 2008. 18, 85

[36] S. Chachulski, M. Jennings, S. Katti, and D. Katabi, "Trading structure for randomness in wireless opportunistic routing," *SIGCOMM 2007*, vol. 37, no. 4, pp. 169–180, Aug. 2007. [Online]. Available: http://doi.acm.org/10.1145/1282427.1282400 18

[37] S. Katti, D. Katabi, H. Balakrishnan, and M. Medard, "Symbol-level network coding for wireless mesh networks," *SIGCOMM 2008*, vol. 38, no. 4, pp. 401–412, 2008. [Online]. Available: http://doi.acm.org/10.1145/1402946.1403004 18

[38] S. Omiwade, R. Zheng, and C. Hua, "Butteries in the mesh: Lightweight

localized wireless network coding," in *Fourth Workshop on Network Coding, Theory and Applications*, Jan. 2008, pp. 1–6. 18

[39] J. Le, J. Lui, and D. M. Chiu, "How many packets can we encode? - an analysis of practical wireless network coding," in *IEEE INFOCOM 2008*, Apr. 2008, pp. 371–375. 18

[40] Y. Yan, B. Zhang, H. T. Mouftah, and J. Ma, "Practical coding-aware mechanism for opportunistic routing in wireless mesh networks," in *IEEE ICC 2008*, May 2008, pp. 2871–2876. 18

[41] F. Kai, L. Ling-xiong, and L. Dong-yang, "Study of on-demand cope-aware routing protocol in wireless mesh networks," *Journal on Communications*, vol. 30, no. 1, pp. 128–134, Jan. 2009. 19

[42] C. Peng, Q. Zhang, M. Zhao, and Y. Yao, "Opportunistic network-coded cooperation in wireless networks," in *IEEE WCNC 2007*, Mar. 2007, pp. 3358–3363. 19

[43] T. Ho, B. Leong, R. Koetter, M. Medard, M. Effros, and D. Karger, "Byzantine modification detection in multicast networks using randomized network coding," in *IEEE ISIT 2004*, Jun. 2004, p. 144. 19

[44] S. Jaggi, M. Langberg, S. Katti, T. Ho, D. Katabi, M. Medard, and M. Effros, "Resilient network coding in the presence of byzantine adversaries," *IEEE Transactions on Information Theory*, vol. 54, no. 6, pp. 2596–2603, Jun. 2008. 19

[45] N. Cai and R. Yeung, "Secure network coding," in *IEEE International Symposium on Information Theory*, Jul. 2002, p. 323. 19

[46] T. Chan and A. Grant, "Capacity bounds for secure network coding," in *AusCTW 2008*, Feb. 2008, pp. 95–100. 19

[47] Y. Fan, Y. Jiang, H. Zhu, and X. Shen, "An efficient privacy-preserving scheme against traffic analysis attacks in network coding," in *IEEE INFOCOM 2009*, Apr. 2009, pp. 2213–2221. 20

[48] Z. Yu, Y. Wei, B. Ramkumar, and Y. Guan, "An efficient signature-based scheme for securing network coding against pollution attacks," in *INFOCOM 2008*, Apr. 2008, pp. 1409–1417. 20

[49] E. Kehdi and B. Li, "Null keys: Limiting malicious attacks via null space properties of network coding," in *IEEE INFOCOM 2009*, Apr. 2009, pp. 1224–1232. 20

[50] J. Dong, R. Curtmola, and C. Nita-Rotaru, "Secure network coding for wireless mesh networks: Threats, challenges, and directions," *Computer Communication*, vol. 32, no. 17, pp. 1790–1801, Nov. 2009. [Online]. Available: http://dx.doi.org/10.1016/j.comcom.2009.07.010 20

[51] D. Nguyen, T. Tran, T. Nguyen, and B. Bose, "Wireless broadcast using network coding," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 2, pp. 914–925, Feb. 2009. 20

[52] S. El Rouayheb, M. Chaudhry, and A. Sprintson, "On the minimum number of transmissions in single-hop wireless coding networks," in *IEEE ITW 2007*, Sep. 2007, pp. 120–125. 20

[53] X. Xiao, Y. Lu-Ming, W. Wei-Ping, and Z. Shuai, "A wireless broadcasting retransmission approach based on network coding," in *IEEE ICCSC 2008*, May 2008, pp. 782–786. 21

[54] F. Xue and S. Sandhu, "Phy-layer network coding for broadcast channel with side information," in *IEEE ITW 2007*, Sep. 2007, pp. 108–113. 21

[55] C. Hausl and P. Dupraz, "Joint network-channel coding for the multiple-access relay channel," in *SECON 2006*, vol. 3, Sep. 2006, pp. 817–822. 21

[56] W. Pu, C. Luo, S. Li, and C. W. Chen, "Continuous network coding in wireless relay networks," in *IEEE INFOCOM 2008*, Apr. 2008, pp. 1526–1534. 21

[57] C. H. Liu and A. Arapostathis, "Joint network coding and superposition coding for multi-user information exchange in wireless relaying networks," in *IEEE GLOBECOM 2008*, Dec. 2008, pp. 1–6. 21

[58] P. Popovski and H. Yomo, "Bi-directional amplification of throughput in a wireless multi-hop network," in *IEEE VTC 2006*, vol. 2, May 2006, pp. 588–593. 21

[59] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," in *Wireless Networks*, vol. 11, Aug. 2005, pp. 4471–4487. 27

[60] H. Bo, P. T. Fung, L. Lidong, and J. Weijia, "Performance evaluation of scheduling in ieee 802.16 based wireless mesh networks," in *IEEE MASS 2006*, Oct. 2006, pp. 789–794.

[61] S. Ramanathan and E. L. Lloyd, "Scheduling algorithms for multihop radio networks," *IEEE/ACM Transactions on Networking*, vol. 1, no. 2, pp. 166–177, Apr. 1993.

[62] B. Hajek and G. Sasaki, "Link scheduling in polynomial time," *IEEE Transactions on Information Theory*, vol. 34, no. 5, pp. 910–917, Sep. 1988.

[63] T. Salonidis and L. Tassiulas, "Distributed dynamic scheduling for end-to-end rate guarantees in wireless ad hoc networks," in *ACM MobiHoc 2008*, May 2008, pp. 145–156.

[64] M. Kodialam and T. Nandagopal, "Characterizing achievable rates in multi-hop wireless mesh networks with orthogonal channels," *IEEE/ACM Transactions on Networking*, vol. 13, no. 4, pp. 868–880, Aug. 2005.

[65] G. Sharma, R. Mazumdar, and N. Shroff, "On the complexity of scheduling in wireless networks," in *ACM Mobicom 2006*, Sep. 2006, pp. 227–238.

[66] S. Gandham, M. Dawande, and R. Prakash, "Link scheduling in sensor networks: distributed edge coloring revisited," in *IEEE INFOCOM 2005*, vol. 4, Mar. 2005, pp. 2492–2501. 54, 58

[67] S. Sarkar and K. Kar, "Achieving 2/3 throughput approximation with sequential maximal scheduling under primary interference contraints," in *44th Annual Allerton Conference on Communication*, Sep. 2006.

[68] W. Hung-Yu, S. Ganguly, R. Izmailov, and Z. J. Haas, "Interference-aware ieee 802.16 wimax mesh networks," in *IEEE VTC 2005-Spring*, vol. 5, Jun. 2005, pp. 3102–3106. 27

[69] IEEE, "Draft amendment: Ess mesh networking," *IEEE 802.11s*, Oct. 2006. 40

[70] R. Rom and M. Sidi, "Multiple access protocols: Performance and analysis," in *Springer Verlag*, 1990. 48

[71] S. Dastangoo, T. Macdonald, D. Reinharth, and C. Burns, "Performance analysis of distributed time division multiple access protocols in mobile ad hoc environments," in *IEEE MILCOM 2009*, Oct. 2009, pp. 1–7. 48

[72] S. Gandham, M. Dawande, and R. Prakash, "Link scheduling in sensor networks: distributed edge coloring revisited," in *IEEE INFOCOM 2005*, vol. 4, Mar. 2005, pp. 2492–2501. 54

[73] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless micro sensor networks," in *HICSS 2000*, Jan. 2000, pp. 3005–3014. 54

[74] N. Wang and N. Ansari, "Identifying the network coding opportunity," in *IEEE Sarnoff Symposium 2010*, Apr. 2010, pp. 1–5. 61

[75] J. R. Cha and J. H. Kim, "A distributed sequential link schedule combined with routing in wireless mesh networks," *ETRI Journal*, vol. 34, no. 3, pp. 462–465, Jun. 2012. 64

[76] T. Cui, L. Chen, and T. Ho, "Energy efficient opportunistic network coding for wireless networks," in *IEEE INFOCOM 2008*, Apr. 2008, pp. 361–365. 68