國立交通大學

資訊科學與工程研究所

碩士論文

多重射頻多跳躍無線網狀網路下之空間再利用方法

Spatial Reuse in Multi-Radio, Multi-Hop Wireless Mesh Networks

研究生：郭達人

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摘要

近來無線網狀網路已躍升為下一代無線網路的一項關鍵技術。無線網狀網路的空間再利用方法可允許多個傳輸通訊同時進行，因此可以大幅地增進整個網路的產量。然而無線網狀網路中的干擾問題是影響空間再利用的一個關鍵因素。在本篇論文中，我們提出了一個不需更改現有 IEEE 802.11 MAC 的程序機制 - RMP。RMP 將無線網狀網路中的干擾問題列入考慮，並且利用事先指定好的傳輸方式來提高空間再利用。和現有的隨機存取方法不同的是，RMP 使用了一個分散控制的存取方式來防止節點受到不必要的封包碰撞。RMP 採用了可雙向傳輸的鏈狀拓撲，在此鏈狀拓撲中所有節

點以等距離部署，使得各節點只能影響其前後兩個節點。模擬結果顯示就網路產量而言,RMP 比 Ripple [14] 高約 30%,而比現有的 IEEE 802.11 DCF 高約 200%。RMP 不僅可達到比 Ripple 更高的產量，還可維持和 Ripple 一樣的傳輸延遲及傳輸品質。RMP 對於 CBR 及 FTP 的流量皆可達到穩定的產量及較低的傳輸延遲時間。另外，RMP 的設計簡單、部署容易，並且同時解決了在 IEEE 802.11 無線網路環境中無效率的 backoff 及碰撞問題。

關鍵詞：鏈狀拓撲、干擾問題、多跳躍、多重射頻、空間再利用、無線網狀網路

Spatial Reuse in Multi-Radio, Multi-Hop Wireless Mesh Networks

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Abstract

Recently, wireless mesh networks (WMNs) have emerged as a key technology for next-generation wireless networking. Spatial reuse in a WMN can allow multiple communications to proceed simultaneously; thereby observably improve the overall network throughput. However, interferences between mesh nodes are a critical factor for maximizing the spatial reuse. In the thesis, we propose a novel scheduling mechanism without modifying the existing IEEE 802.11 MAC, called wireless *Radio-Matching Protocol* (RMP). It takes account of interferences in wireless environments to achieve maximum spatial reuse by using pre-specified radio transmissions. In contrast to existing random access approaches, RMP uses a decentralized controlled access approach to protect nodes from unintentional packet collisions. RMP adopts a chain topology of bidirectional transmissions, where nodes are equally spaced so that radios of non-neighboring nodes do not interference with each other. Simulation results indicate that the throughput of RMP is about 30% better than that of Ripple [14] and almost 200% better than that of the IEEE 802.11 DCF. Although RMP achieves higher throughput than Ripple, it still maintains the same delay time and transmission quality, as verified by our simulation results. RMP achieved a stable throughput and a low end-to-end transmission delay in both CBR and FTP traffic compared to the IEEE 802.11 DCF. In additions, RMP is simple, easy to implement, and it eliminates the back-off inefficiencies and the collision problem in IEEE 802.11 wireless environments.

Index Terms—chain topology, interference, multi-hop, multi-radio, spatial reuse, wireless mesh network

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Chapter 1

Introduction

Wireless mesh networks (WMNs) have emerged as a key technology and started an upsurge in the wireless research over the past few years [1]. Increasingly, WMNs are widely to provide connectivity to devices in the environments where wired network infrastructures do not exist or are expensive to deploy. Unlike mobile ad hoc networks (MANETs), communications generally occur between any pair of nodes through mobile relaying nodes, WMNs provide a *wireless backbone* formed by non-mobile relaying nodes for nomadic users to access the wired Internet. Instead of being another type of MANETs, WMNs diversify the capabilities of MANETs. This feature brings many advantages to WMNs, such as good reliability, high coverage, low upfront cost, and easy network maintenance.

WMNs are characterized by *multi-hop* radio broadcast environments, and *spatial reuse* can be used to increase the capacity of the networks. The medium sharing and the weakness of Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) make the IEEE 802.11 Medium Access Control (MAC) not fit the requirements of backhaul networking in WMNs [2]. The CSMA/CA mechanism for distributed access to the shared channel is extremely restrictive and prohibits any concurrent transmission or reception activities in the vicinity of either an active sender or receiver [13]. Therefore, in multi-hop environments, the interference problem causes long transmission delay and low throughput. Spatial reuse in a wireless network allows multiple communications to proceed simultaneously; hence observably improves the overall network throughput. The idea of spatial reuse is that several nodes, which are far enough in space, can make transmissions simultaneously in the same channel without a collision [8]. However, achieving maximum spatial reuse would require an ideal MAC protocol that schedules communication to maintain the optimal transmitter separation distance while minimizing interference. The performance of spatial reuse depends on various characteristics of the network, including the type of radio, network topology, channel quality requirements and signal propagation environment, etc. To increase the network performance, each backhaul router also needs to have its own scheduling module for sharing the transmission resources efficiently [2].

In this thesis, we present a novel scheduling mechanism without modifying the existing 802.11 MAC, termed as wireless *Radio-Matching Protocol* (RMP), to maximize the spatial reuse in WMNs and thus achieve better overall network throughput and higher spectral efficiency. The RMP uses pre-planning multi-radio mesh routers to form a chain and each radio is assigned a specific channel for transmitting or receiving only. With this deployment, the RMP has high spatial reuse by properly scheduling multiple transmissions in parallel to compose an efficient wireless backbone in WMNs.

The remainder of this thesis is organized as follows. Chapter 2 introduces the mesh architecture. Chapter 3 discusses the related spatial reuse researches in WMNs. Chapter 4 presents the background of interference problems and the operations of RMP. The simulation results are shown in Chapter 5. Finally, Chapter 6 concludes the thesis with concluding remarks and future work.

Chapter 2

Wireless Mesh Network Architecture

A wireless mesh network comprises of two types of nodes: *mesh routers* and *mesh clients*. Mesh routers contain additional routing functions, such as self-organization and self-configuration, to support mesh networking through multi-hop communications, and data traffic can be forwarded further without wired supports. Mesh routers have limited mobility and form a mesh backbone for mesh clients. Mesh clients can also work as routers for mesh networking, and the hardware and software for them can be much simpler than those for mesh routers.

The architecture of WMNs can be classified into three types [1]. Mesh routers form an infrastructure for clients in *infrastructure/backbone WMNs***,** as shown in Fig. 1, where dashed and solid lines indicate wireless and wired links, respectively. This architecture, also termed as *infrastructure meshing*, provides a backbone for conventional clients and enables integration of WMNs with existing wireless networks through gateway/bridge functionalities in mesh routers. Nomadic users access this wireless backbone through a base station (BS) or access point (AP). *Client WMNs*, also termed as *client meshing*, are actually the same as conventional ad hoc networks, as shown in Fig. 2. Thus, a mesh router is not required in Client WMNs. *Hybrid WMNs* are the combinations of infrastructure WMNs and client WMNs, as shown in Fig. 3. Mesh clients can access the network through mesh routers as well as directly communicate with other mesh clients. While the infrastructure WMNs provide connectivity to other networks such as the Internet, Wi-Fi, WiMAX, cellular, and sensor networks, the routing capability of clients WMNs provides improved connectivity and coverage inside hybrid WMNs.

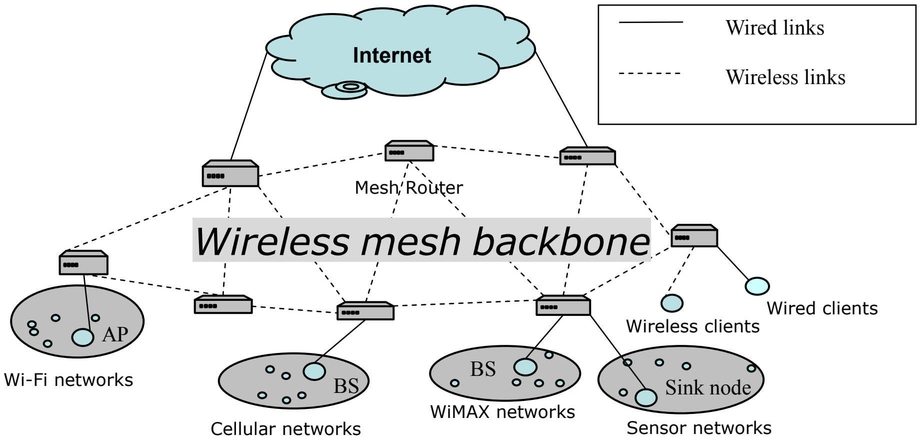


Fig. 1: Infrastructure/backbone WMNs.

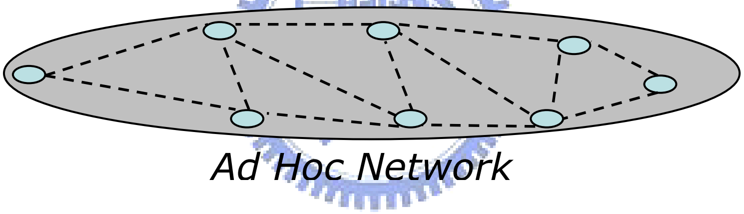


Fig. 2: Client WMNs.

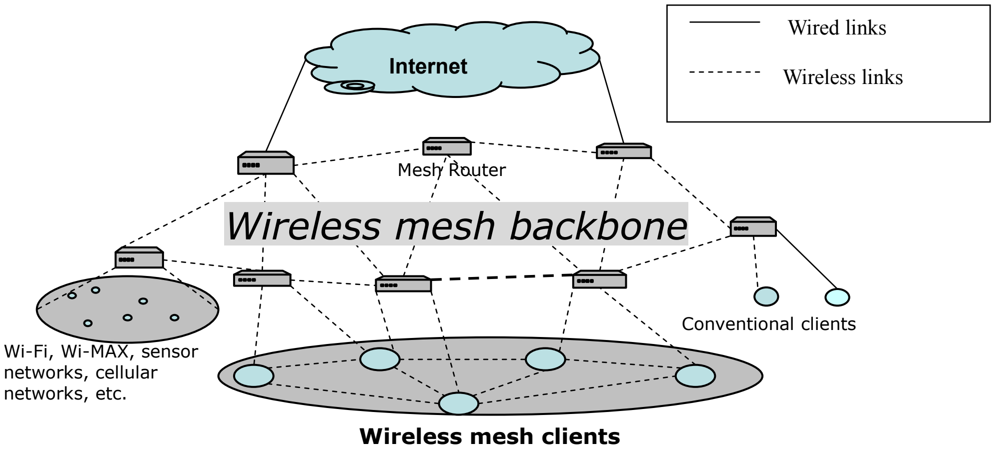


Fig. 3: Hybrid WMNs.

Chapter 3

Related Work

Existing spatial reuse schemes in WMNs can be classified into spatial reuse via the routing at the network layer and spatial reuse via collision avoidance at the MAC layer.

3.1 Spatial Reuse at the Network Layer

In multi-hop wireless networks, the performance degrades sharply due to the interference from adjacent and neighboring nodes. Several researchers have studied the problem of capacity reduction in multi-hop wireless networks from a theoretical perspective. In [3], the authors showed that the observed capacity is far below the theoretical optimum, using evidence from deployed multi-hop 802.11 wireless meshes. They observed that the throughput degrades quickly as the number of hops increases. One reason is that the 802.11 MAC is inherently unfair and it may stall the flow of packets over multiple hops. Another reason is that these networks use only a small portion of the spectrum and a single radio for transmitting and receiving packets [5]. Therefore, several spatial reuses via routing approaches at the network layer are proposed to increase aggregate throughput and alleviate the capacity reduction problem. We classify these routing protocols into three classes:

A. Multi-path routing with performance metrics – Researches in [4][5][6][7][8][9] added new performance metrics, such as collision metric, blocking metric, etc, to the design of their routing protocols for WMNs to accomplish higher throughput and lower delay. The main objectives of using multi-path routing are to perform better load balancing and to provide high fault tolerance. When a path has a broken link or low quality, an alternate path can be activated. However, by a given performance metric, the improvements depend on the availability of multiple routes between source and destination. The drawback of multi-path routing is the complexity.

B. Multi-radio routing – This class [4][5][10] includes one node with multi-channel assigned to one radio or one node with multi-radio tuned to non-interfering channels. Most of them need load-aware channel assignment algorithms to support their methods. Their main idea is to assign channels based on the expected load and the capacity of these channels so that higher traffic load can have more bandwidth. On a single node, MUP (Multi-radio Unification Protocol) [4] coordinates the operations of multiple wireless network cards tuned to non-overlapping frequency channels. The goal of MUP is to optimize local spectrum usage via intelligent channel selection in a multi-hop wireless network. The MUP working with standard-compliant IEEE 802.11 hardware does not require changes to applications or higher-level protocols, and can be deployed incrementally. A multi-radio LQSR (MR-LQSR) was proposed in [5], where a new performance metric, termed as weighted cumulative expected transmission time (WCETT), was incorporated. The WCETT takes into account both link quality and minimum hop-count metrics to achieve good tradeoff between delay and throughput.

C. Hierarchical routing – In hierarchical routing, a certain self-organization scheme, such as highest-connectivity clustering (HCC), was adopted to group network nodes into clusters. Each cluster has one or more cluster heads, and nodes in a cluster can be one or more hops away from the cluster head. Since connectivity between clusters is needed, some nodes can communicate with more than one cluster and work as gateways. In [10], a two-radio architecture for an 802.11 AP mesh was presented. One default radio is only used for control or managing traffic while the secondary radio is only used for data traffic, thereby maximizing the aggregate throughput. Distributed clustering in conjunction with a new minimum interference channel selection algorithm (MIX) is used to distribute orthogonal channels in a mesh. These approaches partition nodes into several groups and assign each interface to each group. However, the complexity of maintaining the hierarchy may compromise the performance of the routing protocol. Moreover, in WMNs, a mesh client must avoid being a cluster head because it may become a bottleneck due to its limited capability.

3.2 Spatial Reuse at the MAC Layer

Besides the above routing protocols aimed at maximal spatial reuse for WMNs, in this section, we review existing MAC protocols that also aimed to maximize spatial reuse in WMNs. The performance of IEEE 802.11 MAC protocol is not satisfactory in wireless multi-hop environments [2]. We surveyed and compared several papers [11][12][13][14], which focused on this problem and did some modifications to 802.11 MAC. Without pre-planning, nodes in a wireless ad-hoc network rely on detect-and-transmit schemes to discover (re)usable channels [21]. A representative method is the CSMA/CA algorithm that forms the basis of the Distributed Coordination Function (DCF) multiple access protocol in 802.11 [20]. A node attempting channel access defers for a random period (backoff time) when it detects either a busy channel or a potential collision from one of its transmissions. Some nodes can suffer from severe throughput degradation in access to the shared channel when load of the channel is high, which also results in unbounded medium access delay and unfair resource distribution for the nodes. There is a considerable interest in determining how the performance of such MAC algorithms scales spatial reuse in a multi-hop network.

A Wireless Token Ring Protocol (WTRP) [11][12] was proposed to eliminate the backoff inefficiencies and the collision problems in a ring topology. The WTRP is a distributed MAC protocol and partial connections are enough for full connectivity. The stations *holding tokens* take turns to transmit and are forced to suspend the transmission after having the medium for a specified amount of time. The WTRP supports guaranteed QoS in terms of bounded latency and reserved bandwidth which are crucial constraints of the real time applications and are inapplicable in an IEEE 802.11 network. Although the WTRP improves efficiency by reducing the number of retransmissions due to collisions; however, the network is underutilized since spatial reuse is not adopted.

MACA-P – MACA-P is an RTS/CTS based MAC protocol [13], which enables simultaneous transmissions in WMNs. The key idea of the MACA-P is to allow neighboring nodes to synchronize their reception periods so that, at explicitly defined instants, one-hop neighbors can switch their roles between transmitting and receiving in unison. The MACA-P added a set of enhancements to the 802.11 MAC and obtained higher concurrency in spatially diverse wireless networks by adding extra information, such as *control gap*, in the RTS and CTS messages. A control gap between the RTS/CTS exchange and the subsequent DATA/ACK exchange was introduced to schedule the DATA transmissions at the end of the control gap to avoid unnecessary backoff time caused by RTS/CTS. MACA-P's principal goal is the enhancement of the four-way handshake to allow parallel communication.

Ripple [14] – It proposed a wireless token-passing protocol for WMNs. Unlike random-access-based approaches, Ripple adopted a controlled-access-based approach to prevent nodes from inevitable collisions in WMNs. Ripple considers a WMN with a chain topology, where nodes are equally spaced and radios of nodes that are not neighbors do not interfere with each other [19]. A frame type named Ready-To-Receive (RTR) is added to this protocol as a token. A node is allowed to send a DATA frame only if it holds a token. With this specific token-passing scheme, the operations of transmission could be as the same as a ripple made by a pebble. The Ripple assumes both the transmission range and interference range are equal to one-hop radius. However, this assumption is not realistic and taking a higher interference range than the transmission range into consideration is necessary in the real world.

3.3 Qualitative Comparison

Since the proposed approach, wireless Radio-Matching Protocol (RMP), which will be described in Chapter 4, is also targeted at the MAC layer, in this section, we compare 802.11 MAC, WTRP, MACA-P, Ripple, and proposed RMP qualitatively. The following five metrics are considered: *network fabric*, *interference range*, *spatial reuse*, *transmission delay*, and *main difference form 802.11 MAC*, as shown in Table 1. First, the network fabric indicates which kind of topology is applicable to. In the WTRP, Ripple, and RMP, nodes form a ring or chain topology, while the others are unaware of the topology. Secondly, a realistic radio interference range is adopted by 802.11 MAC, WTRP, MACA-P, and RMP. Thirdly, we consider the adoption of spatial reuse, which is not used in the 802.11 MAC and WTRP. Fourthly, in the transmission delay, we found that the ring or chain topology can achieve lower delay. Fifthly, for each approach, the main difference from the 802.11 MAC is listed.

Approach	802.11 MAC [20]	WTRP [11][12]	MACA-P [13]	Ripple [14]	RMP (proposed)
Network fabric	Random	Ring	Random	Chain	Chain
Interference range	Based on 802.11 MAC scheme	Based on 802.11 MAC scheme	Not mentioned	Equal to transmission range	Based on 802.11 MAC scheme
Spatial reuse	No	No	Low	Medium	High
Transmission delay	High	Low	Medium	Low	Low
Main difference form 802.11 MAC	Same as 802.11 DCF	Token Holding Time (THT)	Control gap	Ready To Receive (RTR)	Same as 802.11 DCF

Table 1: Qualitative comparison of the 802.11 MAC, WTRP, MACA-P, Ripple, and the proposed RMP.

Chapter 4

Design Approach

4.1 Preliminary

A node in the chain topology may attain an optimal utilization of 1/3 by applying spatial reuse in theory [19]. If each node in the chain topology can properly schedule its frame transmission interval, a data packet could be forwarded without interfering with each other by a multi-hop transmission. The chain topology can be easily generalized to be a tree topology and both topologies are mainly used by the public WMN deployment in Taipei city [14]. With the progress of hardware supports, the multi-radio technology is used to maximize the aggregate throughput by coordinating the operation of multiple wireless network cards tuned to non-overlapping frequency channels. A network node has multiple radio interfaces and each one owns its own MAC and physical layers, so communications in these radio interfaces can be totally independent. Providing each node with multiple radio interfaces has some advantages over one single radio interface: 1) nodes can transmit and receive simultaneously; 2) nodes do not need to synchronize with other nodes for the channel; 3) nodes do not need to modify the MAC layer protocol and maintain backward compatibility; 4) IEEE 802.11 interfaces are off-the-shelf commodity and the price drops rapidly, etc. In fact, one radio interface can have multiple channels in this case; but for simplicity of design and applications, one single fixed channel is usually applied in each radio interface [1].

There are three types of ranges related to packet transmission in the IEEE 802.11 MAC scheme [17]: 1) the transmission range (R): the range inside which nodes are able to receive or overhear the packet transmission; 2) the carrier sensing range (R_s): the range inside which nodes are able to sense the signal, even though correct packet reception may not be available; and 3) the interference range (R_i): a new transmission may interfere with the packet reception of nodes within its interference range. It is generally assumed that the transmission range is smaller than the carrier sensing range and the interference range, i.e., $R < R_s$, and $R < R_i$. In ns-2 [15], the interference range is by default set to a value of $R_i = 2.2R$. This means that if we assign the transmission range as one hop distance, a node will interfere with nodes that are two hops far away; while at long enough distance, the interferences become negligible. Consider a network using a chain topology [19], as shown in Fig. 4, where node 1 is the source and node 6 is the sink. Nodes 1 and 2 cannot transmit at the same time because node 2 can not transmit and receive at the same time. Nodes 1 and 3 can not transmit at the same time because node 2 can not hear node 1 correctly if node 3 is sending. Nodes 1 and 4 can not send data at the same time because node 2 is within the interference range of node 4. However, we should consider a real situation: the situation becomes worse if one assumes that radios will interfere with each other beyond the range where they can communicate successfully. For example, in ns-2, it assumes that 802.11 nodes can correctly receive packets from nodes at 250 meters, but can interfere with nodes 550 meters away. Hence, in Fig. 4, packet transmissions of node 4 will interfere with RTS packets sent from node 1 to node 2. This prevents node 2 from correctly receiving node 1's RTS transmission or sending the corresponding CTS. This is the main problem we intend to solve in this thesis.

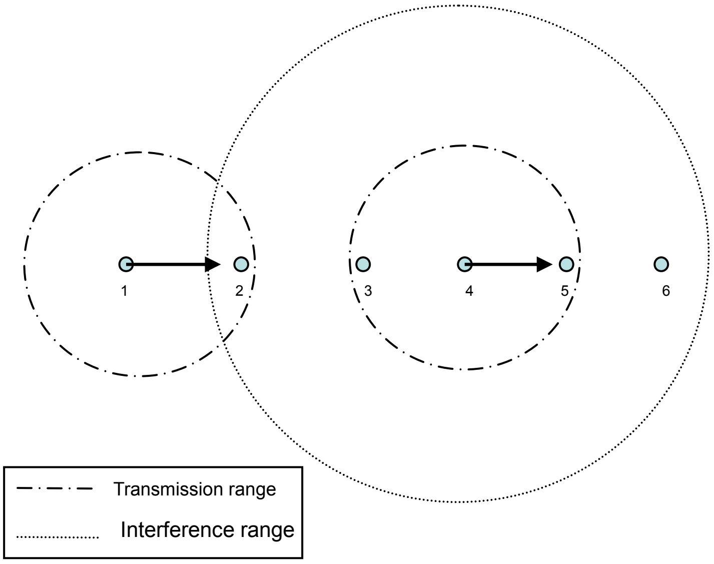
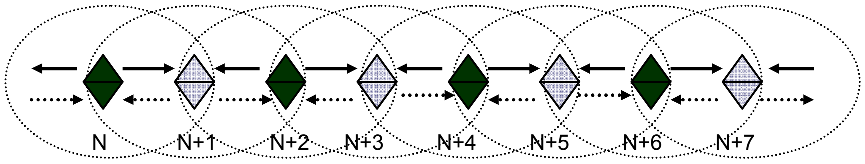


Fig. 4: MAC interference among a chain of nodes.

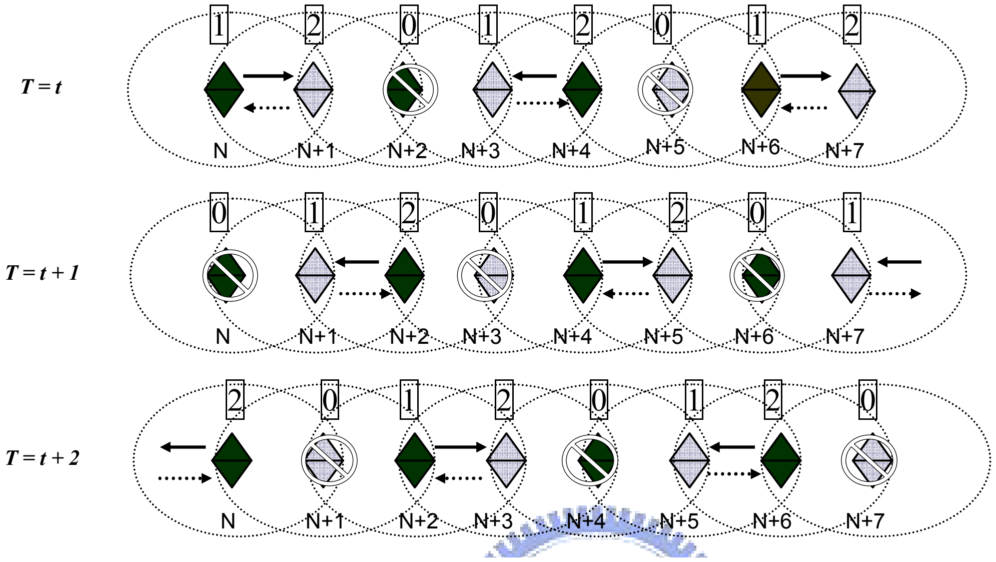
4.2 The Operation of the Proposed RMP

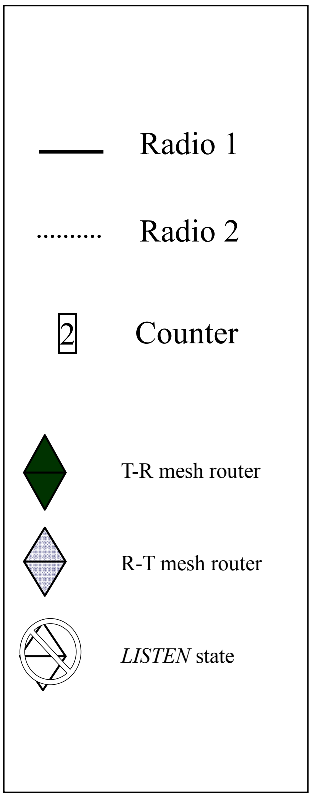
Here, we propose a novel scheduling mechanism without modifying the existing 802.11 MAC protocol. This mechanism is applied to chain-based and multi-radio WMNs. By means of matching radios between mesh routers, we name our pre-planning deployment and scheduling mechanism as a *Radio-Matching Protocol* (RMP), which can achieve the maximal spatial reuse. In the RMP, mesh routers are equally spaced to form a chain topology, where mesh routers that are not neighbors do not interfere with each other. Every mesh router is equipped with two wireless radio interfaces; one for transmitting and the other for receiving. In the RMP, there are two types of mesh routers:

- *T-R mesh router*: For T-R mesh routers, the first channel is only for transmitting packets, and the second channel is only for receiving packets.
- *R-T mesh router*: Similarly, for R-T mesh routers, the first channel is only for receiving packets, and the second channel is only for transmitting packets.



(a) The deployment of mesh routers and associated transmission directions.





(b) The communication process of RMP in different time intervals.

Fig. 5: A chain topology consists of two kinds of mesh routers that use the RMP scheduling to achieve the maximum spatial reuse.

We form this chain by assigning these two types of mesh routers alternately. That is, the neighbors of a T-R mesh router are R-T mesh routers. Similarly, the neighbors of an R-T mesh router are T-R mesh routers, as shown in Fig. 5 (a). T-R mesh routers and R-T mesh routers are equally spaced such that the same types of mesh routers will not be neighbors. The transmission directions of each mesh router are also shown in Fig. 5. (a). The commonly used values for the transmission range and the interference range (250 m and 550 m) are adopted in both T-R and R-T mesh routers. In the following, we use mesh routers and nodes interchangeably.

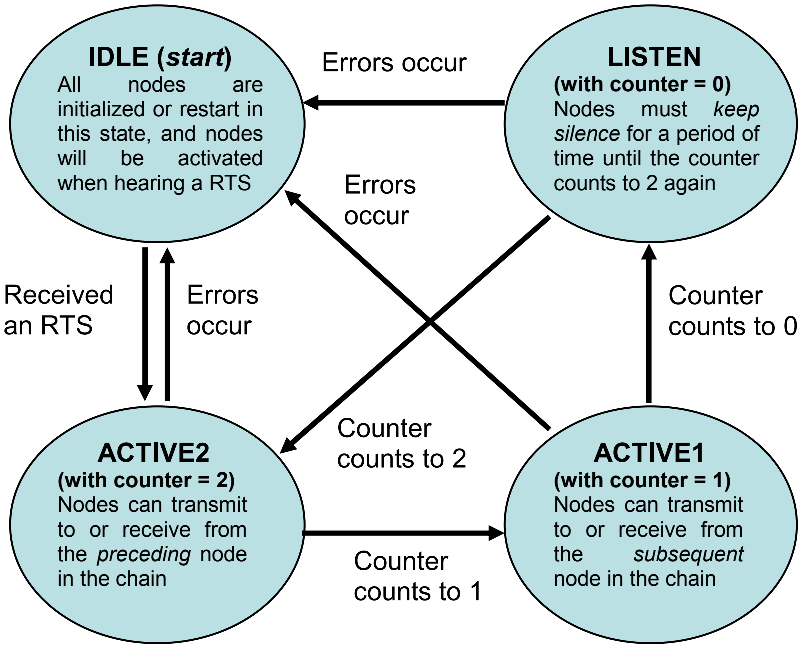


Fig. 6: Finite state machine of a mesh router using RMP

Fig. 6 shows the finite state machine of a mesh router using RMP. In the RMP, each node should be in one of the three states:

- *ACTIVE*: A node enters this state when its counter counts to 2 or 1, and it can transmit and receive packets without interferences in this state.
- *LISTEN*: A node enters this state when the counter of this node counts to 0. Nodes in this state must keep silence for a period of time.
- *IDLE*: This state is used for initialization and error handling. When an error occurs during ACTIVE or LISTEN state, the node moves to this state to restart.

Each node using RMP may transmit and receive packets for two time slots (in ACTIVE2 and ACTIVE1 states) and is then forced to suspend the transmission for one time slot (in IDLE state). Each node in this chain contains a simple counter, counting 2, 1, 0, iteratively. That is, this simple counter counts from 2 to 1, 1 to 0, and 0 to 2 again. A node is allowed to transmit or receive a packet only if its counter counts to 2 or 1. Specifically, when a counter counts to 2, the corresponding node can transmit packets to and receive packets from the preceding node in the chain. When it counts to 1, the node can transmit packets to and receive packets from the subsequent node in the chain. After having the medium for a specified amount of time, the counter counts to 0. During this period, the node does nothing but listens.

The RMP initiates with the *first* node sending an activated packet to the last node in the chain network. The function of the activated packet is to awaken every node in the chain. At the beginning of the chain operation, each node is in IDLE state. A node (except the first node) is activated by an RTS frame generated by its preceding node in order to deliver the activated packet. After that it triggers its counter starting with the value of 2. This counter counts in sequence of 2-1-0 iteratively. A node has right to transmit or receive packets when its counter is not equal to 0. If a node is in LISTEN state, it just keeps silence. With the initiation of the first node, the RMP does not need a centralized control and can achieve distributed operation and synchronization. After the awakening phase of RMP, two nodes with a spatial-reuse distance [14] of three hops can transmit simultaneously without interfering with each other. Note that 2/3 nodes in this topology will be ACTIVE at the same time to accomplish the maximum network throughput. The communication process of RMP in different time interval is shown in Fig. 5 (b).

The 802.11 DCF uses a 4-way distributed handshake mechanism to resolve contention between peers [20]. A node would transmit a CTS frame back after receiving a RTS frame; a receiver becomes a transmitter at this moment. By RMP, we ensure that nodes are two hops-away will not be interfered. In Fig. 5 (b), when $T = t$, node $N + 1$ is transmitting and receiving packets, node $N + 3$ could be ACTIVE without interference from node $N + 1$ because node $N + 1$ and node $N + 3$ are using the same type of mesh routers. The interference caused by node $N + 1$ will not be sensed by node $N + 3$ because transmission and reception of these two nodes are in two non-overlapping channels. Therefore, we use an alternative radio pattern and an efficient distributed scheduling scheme to achieve the maximum spatial reuse. Problems caused by CSMA/CA, including the hidden terminal problem, exposed terminal problem and binary exponential backoff problem, which result in severe transmission problems in wireless multi-hop networks could also be resolved by using RMP. In summary, a node using RMP can achieve the optimal utilization of 2/3 under spatial reuse by resolving the interference problem. The detail operation of the RMP is summarized in Fig. 7.

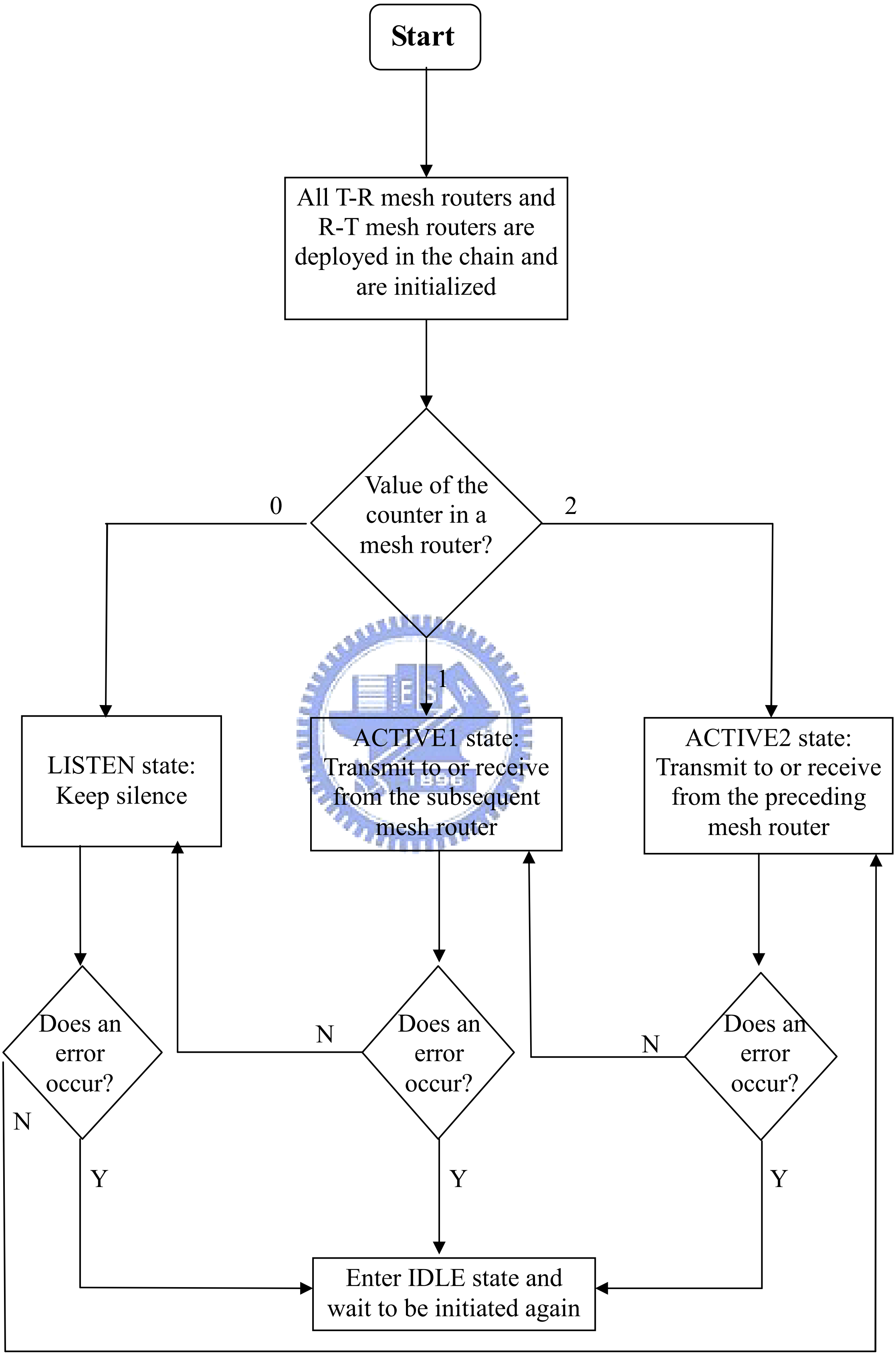


Fig. 7: The RMP algorithm.

Chapter 5

Simulation Results and Discussion

5.1 Simulation Model

The simulations of RMP were performed using ns-2 [15]. A chain of homogeneous nodes spaced by equal distance is shown in Fig. 8. Each node in the RMP had two radios, and a single fixed channel was used in each radio. Communications in these two radios are totally independent. The two radios equipped in each node have an effective transmission range of 250 *m*, and the distance between nodes is 200 *m*. Considering the fact that each node may interference with the data reception at another node, even though they are beyond the transmission range, a 550 *m* interference range was adopted in our simulation. The real time traffic and non-real time traffic, CBR and FTP, were used for performance evaluation. The link capacity is 1 Mb/s. A 1000-byte packet size and a 32-byte TCP Receiving Window were used when simulating FTP; the CBR simulation used various data rates and packet sizes [18]. Each sample was obtained by averaging 100 outcomes and each outcome was collected within 500 seconds [14]. Finally, network performance was evaluated by the *end-to-end throughput* and *end-to-end delay*.

5.2 Comparison with 802.11 DCF and Ripple [14]

We compared RMP with 802.11 DCF and Ripple. Ripple assumes both the transmission range and interference range are equal to one-hop radius. However, most of today's 802.11

MAC implementations have a static interference range, or do not allow the interference range to be independently tunable [15][16]. As a result, taking the actual interference rage of 802.11 devices with interference range into consideration is necessary and indispensable. With this concern, when a node in a chain topology with the circumstances that the interference range is almost 2.2 wider than the transmission range, it would interfere with nodes two hops away. Therefore, the spatial-reuse distance of Ripple will be four hops away to prevent from the unintended interferences. For the RMP, the spatial-reuse distance could still be three hops because of the specific deployment of mesh routers. Due to mounting two radios to each RMP mesh router, we only evaluated unidirectional throughput of RMP for fair comparison. Finally, we investigated the performance of 802.11 DCF, Ripple and RMP, and assumed that each node always had CBR or FTP traffic to transmit. We placed a gateway at each end (nodes 0 and 11 in Fig. 8) of the chain, where the gateway acts as a source as well as a sink. In our simulations, the traffic source is always backlogged (i.e., offered load = 0.4 Mb/s) and the end-to-end throughput excluding the control overhead is evaluated at the sink node [14]. The simulation parameters are shown in Table 2.

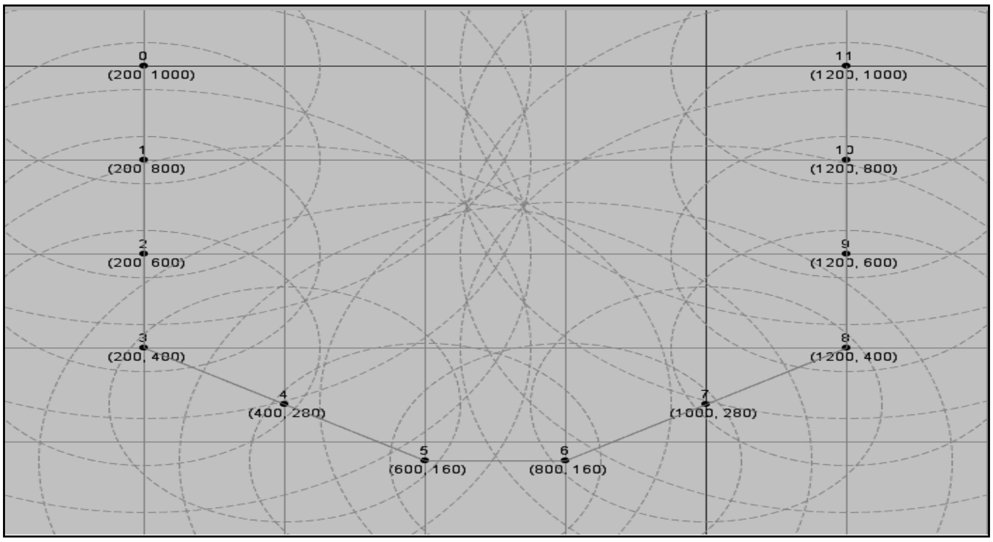


Fig. 8: A chain topology of RMP.

Parameter	Value
Channel capacity	1 Mbps
Transmission range	250 meters
Interference range	550 meters
Distance between nodes	200 meters
Number of nodes	2 nodes – 20 nodes
Simulation time	500 seconds
Offered traffic	CBR and FTP

Table 2: Simulation parameters.

Fig. 9 shows the end-to-end throughput of CBR traffic for various chain lengths and different DATA frame sizes, where the source and sink nodes were located at two ends of the chain. For a chain with only two nodes, 802.11 DCF attained the maximum end-to-end throughput of about 0.82 Mb/s for 1000-byte frames, because there was no packet collision. However, the end-to-end throughput of 802.11 DCF for chains with more than two nodes decreased dramatically; at last, it dropped to 0.1 Mb/s as a result of excess collision with the increasing chain length. So the end-to-end throughput of 802.11 DCF is far less than that of Ripple and RMP under spatial reuse. On the contrary, the Ripple and RMP always attained a stable throughput of 0.21Mb/s and 0.28Mb/s, respectively. Moreover, because the RMP achieves higher spatial reuse than the Ripple, the RMP has 31% higher throughput than the Ripple.

Fig. 10 shows the end-to-end throughput of FTP traffic for the three schemes under different chain lengths. The RMP and Ripple always offered more stable throughputs than 802.11 DCF, and the end-to-end throughput of RMP is 29% higher than that of Ripple.

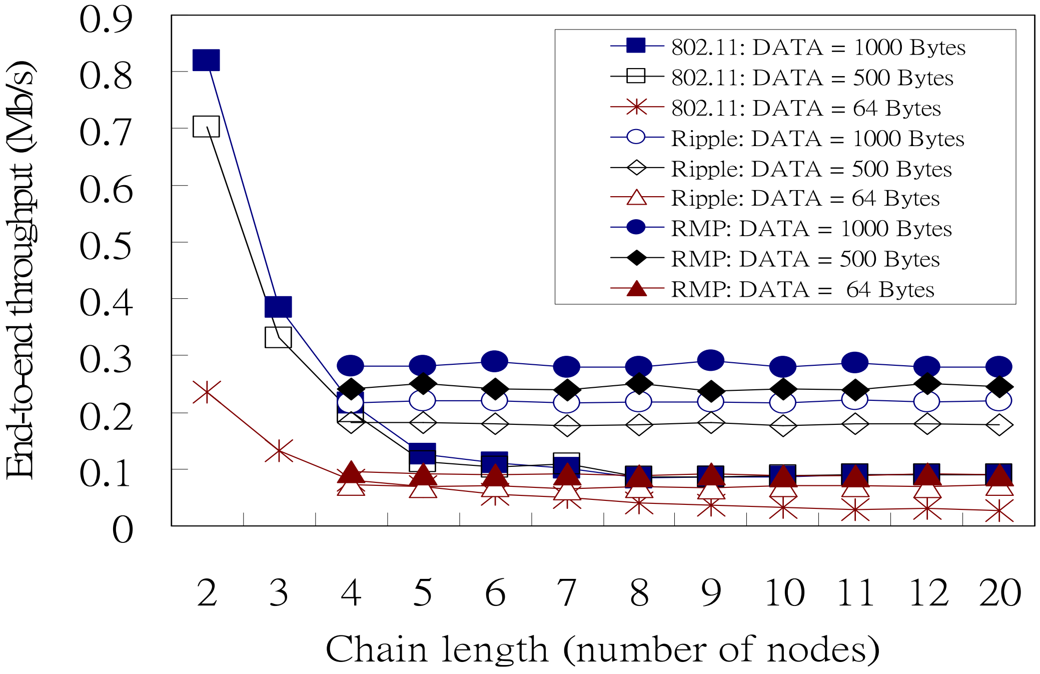


Fig. 9: End-to-end throughput of the three schemes under various chain lengths and data frame sizes for CBR traffic.

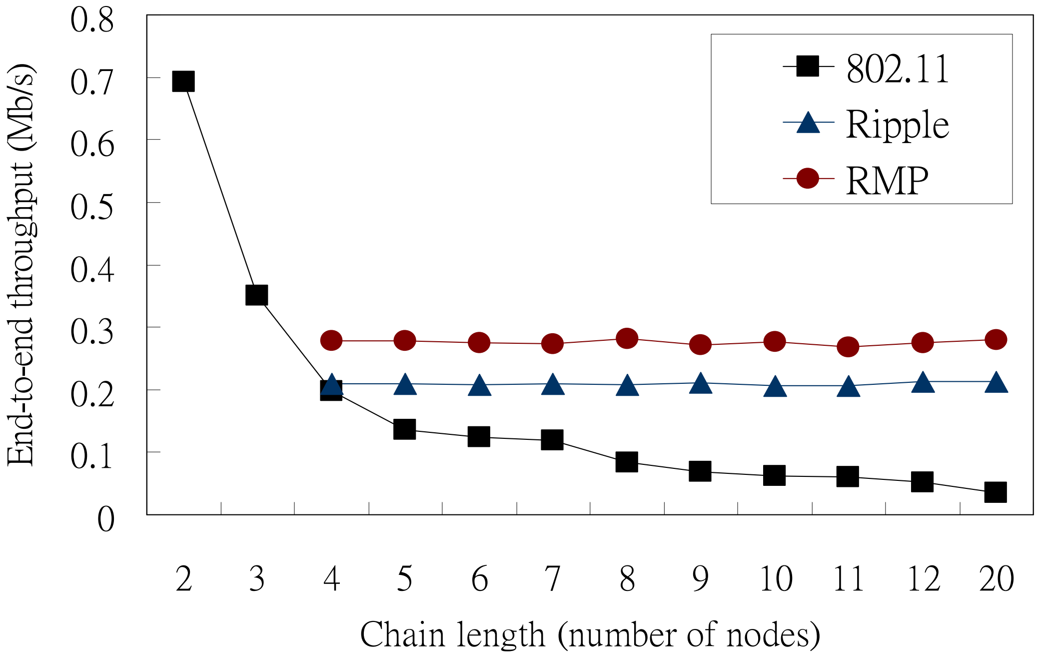


Fig. 10: End-to-end throughput of the three schemes under various chain lengths and data frame sizes for FTP traffic.

Fig. 11 illustrates the end-to-end throughput under various offered loads (CBR traffic) for a chain length of 8 nodes, and the DATA length of 1000 bytes. It is found that the end-to-end throughput of 802.11 DCF attained a maximum of about 0.2Mb/s, but dropped to 0.1Mb/s as a result of excess collision under high traffic load. The Ripple and RMP maintained a stable throughput due to no collisions.

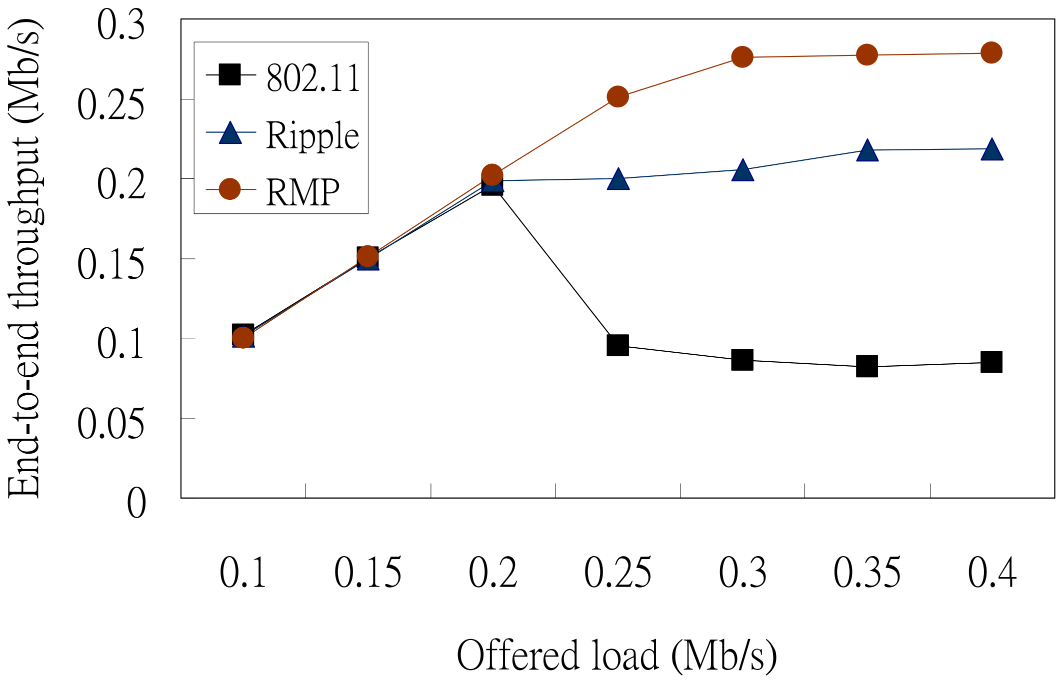


Fig. 11: End-to-end throughput of the three schemes under various offered loads.

The end-to-end transmission delay for various offered loads is presented in Fig. 12. We found that 802.11 DCF resulted in high end-to-end transmission delay with large variations. On the contrary, Ripple and RMP had low end-to-end transmission delay even under high traffic loads.

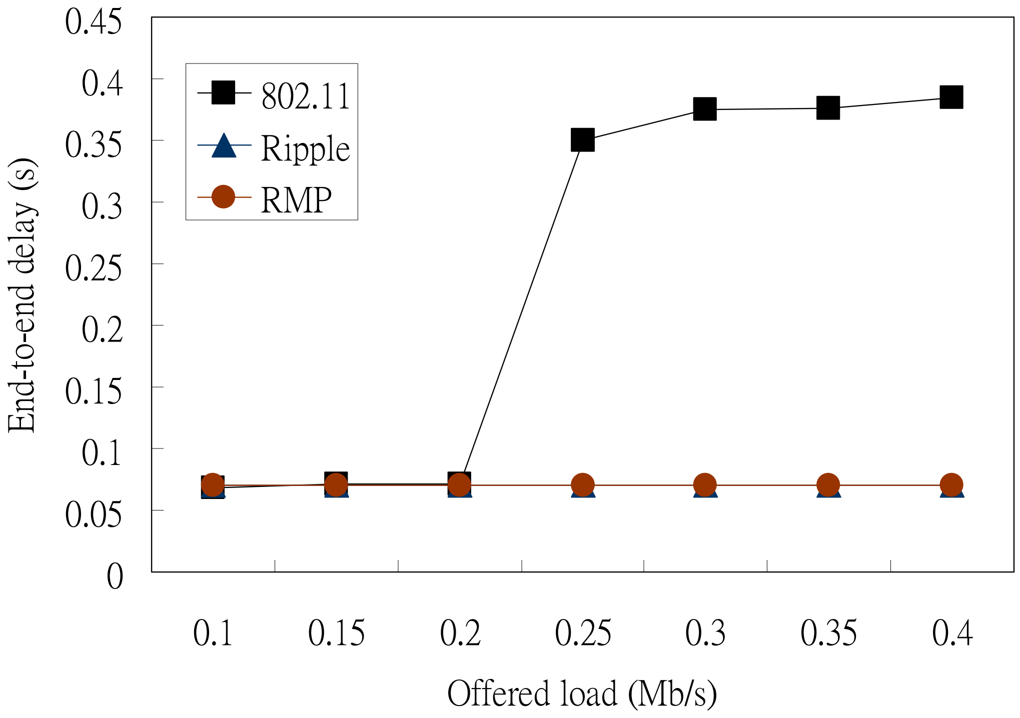


Fig. 12: End-to-end delay of the three schemes under various offered loads.

5.3 Discussion

We have compared RMP with Ripple and IEEE 802.11 DCF in terms of end-to-end throughput and end-to-end delay. In summary, the RMP achieves the highest end-to-end throughput since the collision probability is reduced by scheduling the transmissions with pre-specified transmission directions. The RMP maintains stable throughput in a fair manner among mesh routers because each node in the chain is guaranteed to transmit and receive when the counter is not counting to 0 and is then forced to give up the right to transmit or receive for a time unit. It bounds medium-access time. Simulation results show that the RMP has better end-to-end throughput than the Ripple and has comparable end-to-end delay with Ripple. This is due to that the RMP has a shorter spatial-reuse distance of 3 than Ripple, which has a spatial-reuse distance of 4. Consequently, the proposed the RMP can achieve and optimal utilization of 2/3 by using two radios.

Chapter 6

Conclusions and Future Work

6.1 Concluding Remarks

The RMP is a novel scheduling mechanism, which does not modify the existing 802.11 MAC protocol, to improve spatial reuse in WMNs by using pre-specified transmission directions. The RMP provides bidirectional transmissions with the maximum spatial reuse and fault tolerance with two radios using a chain topology. It increases the end-to-end throughput and lowers the end-to-end delay. Moreover, the RMP takes inevasible interferences into consideration. The performance of RMP with real time traffic (CBR) and non-real time traffic (FTP) has been investigated and simulation results show that the throughput of RMP is about 30% better than that of Ripple and almost 200% better than that of the IEEE 802.11 DCF. Although the RMP achieves higher throughput than Ripple, it still maintains the same end-to-end delay and transmission quality. Finally, the RMP is simple, easy to implement, and can achieve a stable end-to-end throughput and low end-to-end delay even under high traffic loads.

6.2 Future Work

Although a chain topology can enhance spatial reuse in WMNs, the fault tolerance can be further enhanced. This is because the chain topology only provides a single path in each direction. In RMP, the fault tolerance problem of the chain topology can be resolved by using two radios. However, the fault tolerance for crashed nodes still needs to be resolved. In addition, the correction of RMP relies on synchronization on counter states among mesh routers. Therefore, the above two problems: the fault tolerance for crashed nodes and synchronization of counter states in mesh routers deserve for future study. By the way, the feasibility of adding the third radio is another interesting issue for future work.

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