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Vikas Bollapragada Subrahmanya
Clemson University, bsvkas@gmail.com

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A CHANNEL-ACCESS FRAMEWORK FOR SCHEDULING TRANSMISSION ASSIGNMENTS IN AD HOC NETWORKS WITH RATE ADAPTIVE RADIOS

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Electrical Engineering

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by
Vikas Bollapragada Subrahmanya
August 2020

Accepted by:
Dr. Harlan B. Russell, Committee Chair
Dr. Daniel L. Noneaker
Dr. Kuang-Ching Wang
Dr. James Martin

Abstract

In mobile ad hoc networks transmission-scheduling channel-access protocols are of interest because they can ensure collision free transmissions and provide fair access to the channel. The time taken to gain access to the channel is deterministic and hence these types of protocols can also guarantee a certain quality of service. However, these protocols suffer from two major drawbacks. The first issue is poor utilization of the channel due to fixed slot assignments. Once the slot assignments are decided they are held constant for a period of time. As a result the node to which a slot is assigned may not always have a packet to transmit in its assigned slot. This results in wasted slots and leads to poor utilization of the channel. The second issue is that there is no support for networks with rate adaptive radios. In this work a combined solution to both of these shortcomings is presented.

In order to make transmission-scheduling channel-access protocols support networks with rate adaptive radios, a process called slot-packing is developed. The design of slot-packing ensures that it works with any transmission-scheduling channel-access protocol. Using slot-packing, we design and investigate a new protocol called adaptive recovering mini-slot transmission scheduling (RMTS-a) that tackles both the shortcomings and improves the performance of the network significantly. A key feature of our RMTS-a protocol is that if a radio assigned to a transmission opportunity is unable to utilize all of the time slot, other radios in the local neighborhood are given

the opportunity to transmit in the remaining time. Additionally, because multiple radios within communication range of a transmitter are likely to be able to decode the payload, packets to multiple neighbors can be packed within a single transmission.

Dedication

To my parents, Dr. Ramana and Dr. Sreenivas, for being great role models.

To my brother, Dr. Varun, for mentoring and inspiring me.

Acknowledgments

Over the last 8 years, I have received the support of many people. Dr. Harlan Russell has been a great advisor. His constant encouragement and feedback have made this process rewarding and enjoyable. I would like to thank the faculty at the Clemson wireless group for providing me with the necessary background to conduct this research. I would also like to thank Dr. Noneaker, Dr. Wang, and Dr. Martin for serving on my dissertation committee. Finally, I would like to express my deepest gratitude to the Clemson community who have been very welcoming.

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Chapter 1

Introduction

An ad hoc network is a special type of network in which there is no centralized support. Ad hoc networks are a key enabling feature that support new networking paradigms such as vehicular networks and internet of things. These networks operate without reliance on a carefully planned infrastructure of access points. The nodes in the network have to depend on each other to transfer the data from one point to the other. Traditionally, ad hoc networks have been used by the military and by first responders to setup a temporary network when either there is no existing infrastructure or when the existing infrastructure has failed. With the advent of smart devices almost every electronic device is equipped with a radio. Ad hoc networks provide a quick and cost effective method to setup a temporary network or extend an existing network. See [1] for a discussion on the background, challenges posed, and applications of ad hoc networks.

In the absence of centralized support in ad hoc networks it is imperative that all the nodes in the network must be able to self-organize and self-configure. This requires the link- and network-layer protocols to be distributed and robust. In order to limit the overhead in the network it is important that the decisions made by these protocols are as localized as possible. Furthermore, the design of channel-access protocols must ensure fairness.

Many applications of ad hoc networks require the data to be relayed through multiple hops. Because the radios have limited communication range, they must have the ability to discover their neighbors and build the forwarding tables to route packets to their destinations or gateways. Investigations in [2, 3, 4, 5] have shown the importance of cross-layer design to achieve good network performance. Accordingly, it is not enough for the networking protocols to just categorize the links as good and bad. They need to consider the quality and capacity of the links as well. Similarly, the channel-access protocols can benefit from the information at the networking layer regarding the demands on particular links while establishing the channel-access opportunities.

In wireless networks the channel conditions vary due to fading, shadowing, and multiple-access interference. Rate adaptation is a link level feature that allows a node to adapt its transmission rate depending on the channel conditions. The node can transmit at a faster rate if the channel conditions are good to achieve a higher throughput. If the channel conditions are poor, the transmitter can reduce the transmission rate to ensure reliable delivery. Hence, rate adaptation plays a critical role in achieving a good performance in wireless networks and the protocols designed for ad hoc networks must also be able to support rate adaptation.

1.1 Medium Access Control (MAC)

The MAC protocol controls how nodes share access to the channel by coordinating transmissions to achieve both a high probability of packet reception and efficient use of the channel. The efficiency of shared channel access is the crux of this dissertation and is a critical factor in achieving good network performance. When nodes transmit simultaneously they cause interference at the receiving nodes. This results in the received signal at a specific receiver to be a mixture of the signal from intended transmitter and the signal from other transmitters. The presence of signals at a receiver other than from the intended transmitter is called as multiple-access interference. A receiver can tolerate some level of multiple-access interference depending up on the quality of the signal from intended transmitter at the receiving node, the modulation and coding characteristics, and the properties of the underlying channel.

A collision occurs if a receiver is not able to decode a transmission intended for it due to the presence of multiple-access interference from other transmitters. Collisions result in poor performance as the packets are either discarded or need to be re-transmitted. A MAC protocol must utilize the physical layer characteristics, channel conditions, and information from the network layer to maximize the concurrent transmissions while minimizing packet loss due to collisions. The MAC protocol for a wireless network must account for the properties of the channel, including signal fading, shadowing, the hidden terminal problem, the exposed terminal problem, and interference from devices not participating in MAC protocol. Channel-access protocols can be classified into two types: contention-based and contention free.

1.1.1 Contention-Based MAC Protocols

In contention-based MAC protocols, as the names suggests, the nodes contend with each other for access to the channel. Aloha [6] is the first MAC protocol designed for a wireless packet data network. It is a contention based protocol in which the nodes transmit whenever they have data. Whenever a collision is detected nodes defer their transmissions and transmit later. This approach is very simple and works well when the traffic is very low. However, the performance drops off rapidly as the traffic increases. In slotted-aloha [7] the time is divided in to slots. Nodes that have data will now have to wait for the beginning of a slot to transmit. This reduces the chances of collisions and hence it performs better than aloha.

Later carrier sensing multiple access (CSMA) based protocols were introduced in which the nodes sense the channel and only transmit if no other transmission is detected. This approach suffers from hidden terminal and exposed terminal problems. To rectify these problems carrier-sense multiple-access with collision avoidance (CSMA/CA) was introduced. Two new control messages are utilized: request-to-send

(RTS) and clear-to-send (CTS). Two of the earliest protocols to utilize these control messages are described in [8, 9]. If the transmitter does not detect a busy channel it sends a RTS message. The receiving node then replies with a CTS message. Upon receiving the CTS message the transmitter will transmit the data. According to [9], all the other nodes which receive the RTS and CTS are blocked from transmitting until the data packet and a subsequent acknowledgment are transmitted. This was later incorporated into the IEEE 802.11 standard for WiFi networks [10]. While CSMA/CA approaches address the stability concerns of basic CSMA, they still under perform when traffic loads in the network are high [11]. One other major disadvantage of contention-based protocols is that they can be unfair to the nodes which have less traffic than the nodes with more traffic. See [12] for a survey on contention based protocols for ad hoc networks.

1.1.2 Contention Free MAC protocols

Contention free MAC protocols are also called transmission scheduling protocols. In this class of protocols the nodes reserve the channel instead of contending for it. The channel reservation is based on time in TDMA, frequency in FDMA, and code in CDMA. In this work we focus on TDMA based MAC protocols for ad hoc networks. In TDMA based MAC protocols the time is divided into slots. Nodes are then assigned to transmit in particular slots. These slot assignments are then repeated periodically. The repeating slot assignments constitute a frame. In traditional TDMA approaches the frame size is equal to the number of nodes in the network and each node gets a single slot in the frame. Spatial-TDMA is an improvement over TDMA in which multiple nodes can transmit in the same slot provided these nodes do not create excessive multiple-access interference. We refer to spatial-TDMA protocols as schedule-based MAC protocols throughout this document.

The central idea behind scheduling-based MAC protocols is to select as many nodes as possible that do not interfere with each other to transmit in a slot whilst ensuring that every node is assigned at least one opportunity per frame. Hence, these protocols are fair and collision free. Also, the time taken to gain access to channel is deterministic and hence these protocols can guarantee certain level of quality of service (QOS). For this reason schedule-based MAC protocols have been of interest in ad hoc networks.

In one of the earliest works [13], the authors show that assigning collision free broadcast schedules in multi-hop wireless network is NP hard. Both centralized and distributed algorithms are developed that run in polynomial time and provide approximate solution to the problem. However, this approach does not adapt well to changes in connectivity as all the nodes in the network need to agree up on a frame size and the schedules need to be re-build every time there is a change in the network.

An approach that is very popular in transmission scheduling is to assign color numbers to the nodes and then use them to build the transmission schedules. In [14] the author surveys the underlying methodology of such protocols and proposes a centralized scheduling algorithm called RAND. The DRAND protocol [15] is a distributed extension to RAND. In DRAND there is a contention phase followed by a reservation phase. In the contention phase the slot schedules are decided and slot synchronization is not required. The performance of DRAND is analyzed and then shown to be similar to that of RAND. A similar color based scheme is used in Lyui's protocol [16] but the algorithm that uses color numbers to assign the transmission slots is different. The novelty on this approach is that every node in the network requires only the color numbers of the nodes in it's 2-neighborhood to calculate it's slot assignments. In [17] the performance of Lyui's protocol is evaluated and is shown to be similar to that of DRAND. Some additional advantages of Lyui's algorithm include supporting mobility and maximizing the slot schedules.

In the prior approaches discussed above, the slot assignments are fixed. Every node is guaranteed at least a single slot in a frame irrespective of the traffic levels. In another class of protocols the nodes reserve multiple slots in a frame depending on the projected traffic levels. The USAP protocol [18] is an example of such method where the nodes in the network can request for multiple slots to be allocated to them from a pool of un-assigned slots depending up on the traffic demand. The nodes have the capability to resolve any conflicts with their 2-neighbors that arise from these slots assignments. In [19] a new delay efficient protocol is presented where the slots are assigned to a traffic flow instead of individual nodes. A traffic flow consists of multiple nodes that form a path between two nodes. The central idea behind this protocol is to assign consecutive slots to the nodes that constitute a traffic flow. As a result, once the packet leaves the first node it does not incur any further queuing delay. This protocol works better than color based schemes for deterministic packet arrivals. However, for non-deterministic packet arrivals, the delay is higher than for color based schemes.

Another approach is to use psuedo-random number generators (PRNG) to decide the state of a node. Nodes exchange the seeds of their PRNG with their neighbors and can deterministically predict the states they are in. SEEDEX [20] is an example of such protocol where the nodes publish their schedules by exchanging the seeds of their PRNG with their 2-neighborhoods.

A key feature of this dissertation is that in every slot instead of having a single (primary) transmitter there are multiple (auxiliary) transmitters that are eligible to transmit in that slot in the event the primary transmitter does not transmit. These auxiliary transmitters cause a similar multiple-access environment to the one created by a primary transmission. The investigations that come closest to this work in that respect are presented in [21, 22].

In [21] a mini-slotted approach is presented. In a network with N nodes every slot is extended by $N\text{-}1$ mini-slots. In each slot the nodes are assigned different priorities by some rule. The node with the highest priority gets the first opportunity to transmit followed by the node with next highest priority and so on. In this manner the slot is unused only when every node in the network does not have a packet to transmit. While this approach works well for small networks it does not scale well for large networks as the overhead required for the mini-slots increases with the size of the network. Additionally, the algorithms to assign priority does not extend to multi-hop networks.

In [22] a protocol called CAMA, which is an extension of USAP [18] is presented. In this method the network is divided in to multiple cliques. The slots are assigned to a clique instead of individual nodes. At the beginning of a slot nodes in the clique to which it is assigned compete with each other for the slot via mini-slots using a non-persistent CSMA algorithm [23]. However, the authors of [22] point out that the implementation is quite complex, requires careful tuning based on connectivity details, and has higher overhead than required by USAP.

1.2 Issues with Scheduling Protocols

There are two major drawbacks of scheduling algorithms. The first issue is poor utilization of the channel due to fixed slot assignments. In scheduling protocols once the slot assignments are decided they are held constant for a period of time. As a result the node to which a slot is assigned may not always have a packet to transmit in its assigned slot. This results in wasted slots and leads to poor utilization of the channel. The second issue is that there is no support for networks with rate adaptive radios. In scheduling protocols the time is divided in to slots. The slot duration must be constant throughout for the nodes in the network to remain synchronized. The networks in which the radios can adapt their transmission rates the packet transmission times are not constant. The irregular transmission times pose an issue in a system with fixed slot lengths. After an extensive literature review, we have not found a transmission scheduling protocol designed for an ad hoc network that provides guaranteed reservations but also addresses rate adaptation and slot utilization.

1.3 Dissertation Statement

This dissertation focuses on large ad hoc networks with topologies that often require multiple relays for the packets to be delivered to their destinations. It is expected that the networks can support periods of high traffic and the network resources are efficiently utilized to guarantee a certain level of QOS. During the periods when the network is heavily utilized, the nodes in the network are assumed to be either static or to have limited mobility. A typical application for these networks is to provide backbone connectivity to various wireless applications. In this setup, scheduling-based channel access is preferred in order to be able to support periods of high traffic efficiently.

As discussed previously scheduling protocols have two major drawbacks. In order to rectify the first shortcoming of poor utilization of transmission assignments we develop and investigate a protocol that takes advantage of unused slot assignments and improves the efficiency of the channel usage. In our prior investigations, we designed and studied a protocol called recovering mini-slot transmission scheduling (RMTS, [24, 25]). It was shown to address the problem of poor utilization in scheduling protocols effectively using auxiliary transmissions.

The central contribution of this dissertation is to develop a new transmission scheduling MAC protocol that addresses both shortcomings of traditional scheduling protocols for ad hoc networks. We define a process called slot packing that enables existing scheduling protocols to effectively exploit rate adaptive radios to achieve better efficiency for fixed transmission slots. The technique utilizes a frame aggregation method designed for the specific details of our MAC protocol. A key feature of slot packing is that it easily integrates into a wide variety of existing scheduling protocols. Our new MAC protocol integrates slot packing and adaptive transmission with RMTS, and it is called RMTS-a. Preliminary investigations of the RMTS-a protocol are reported in [26].

A key component of our new RMTS-a protocol is cross-layer integration with the network layer. We show that design of a routing metric, called inverse bit-rate, is essential to achieve good network performance. This metric accounts for how a radio has access to the channel with the RMTS-a protocol. Performance of RMTS-a combined with the new routing metric for multi-hop networks is examined with a custom simulation. The integration of slot packing, RMTS, and the inverse bit-rate routing metric are shown to combine well to achieve substantial improvements in network performance. A major reason for the gains is due to higher utilization of the scheduled transmission opportunities.

Another key feature of the protocol is the ability to support nodes with varying traffic loads through auxiliary assignments. This allows RMTS-a to maintain a high level of network performance in scenarios for which the performance of traditional scheduling algorithms drops off drastically. We demonstrate this by investigating scenarios in which the offered traffic rate from each node is not equal. Instead a different generation rate is specified for each node, using a gamma distribution, to create significantly different offered loads in the network. In another scenario, the destination for all packets is specified for a common sink node, creating an environment in which demands for channel access are much heavier nearer the sink.

The rest of the document is organized as follows. The system design is described in Chapter 2. The RMTS protocol is presented in Chapter 3 and our new protocol is developed in Chapter 4. The network layer models are described in Chapter 5 and the simulation design is described in Chapter 6. The results are presented in Chapter 7 and conclusions are presented in Chapter 8.

Chapter 2

System Design

In this chapter the design details and modeling assumptions of the system are described. We begin by describing the characteristics of the radios. Then the model for multiple-access interference is described. This is followed by a description of the time-slotted system, and we end this chapter with a description of the path-loss model.

2.1 Channel Model

All the nodes in the network have similar attributes. The communication between the nodes is half-duplex, that is, a node can either transmit or receive at a given time but not both. The nodes are equipped with omni-directional antennae and radiate power equally in all directions. The nodes use direct-sequence spread-spectrum (DSSS) signaling to communicate with each other with BPSK as the underlying modulation technique. The chip rate for DSSS modulation is fixed, however, nodes can adapt their data rates depending on the quality of the links. A signal-to-noise-plus-interference ratio (SINR) threshold, β_n, is the minimum SINR required for communication to be possible when transmitting using a specific spreading factor. A transmission is considered to be successful only if the SINR at the receiving node is greater than a threshold β_n, which depends on the spreading factor selected for the transmission. For a transmission from node x to node y to be successful, the SINR of the link denoted by $\xi_{x,y}$ must satisfy the following condition.

$$\xi_{x,y} = \frac{P_r(x,y)N_s(n)T_c}{N_o + \sum\limits_{\forall z \neq x} P_r(z,y)T_c} \geq \beta_n \tag{2.1}$$

where $P_r(x,y)$ is the received power of the signal at node y from a transmission from x, $N_s(n)$ is the spreading factor used for this transmission, T_c is the chip duration, N_o is the measure of the white noise. The multiple-access interference at the receiving node y is the interference from nodes other than x that transmit in the same slot, and is denoted by $\sum\limits_{\forall z \neq x} P_r(z,y)T_c$.

A transmitter can adapt its data rate depending on the channel conditions by varying its spreading factor. Five different spreading rates are permitted: N_s, $N_s/2$, $N_s/4$, $N_s/8$, and $N_s/16$. Table 2.1 shows the SINR ranges for each spreading factor and their corresponding SINR threshold (β_n).

The time is divided in to equal slots. The nodes are assumed to be synchronized to the slot boundaries. See [27, 28] for examples of approaches to achieve slot synchronization. The slot duration is set equal to the time taken to transmit a packet

Table 2.1: The values of $N_s(n)$ and β_n

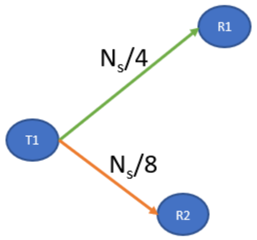
n	$N_s(n)$	SINR Range	β_n	Fraction
1	N_s	$\beta \leq SINR < 2\beta$	β	1
2	$N_s/2$	$2\beta \leq SINR < 4\beta$	2β	1/2
3	$N_s/4$	$4\beta \leq SINR < 8\beta$	4β	1/4
4	$N_s/8$	$8\beta \leq SINR < 16\beta$	8β	1/8
5	$N_s/16$	$16\beta \leq SINR$	16β	1/16

using the slowest data transmission rate (or using the largest spreading factor). The fraction of the slot required to transmit a packet using different transmission rates is provided in Table 2.1. Accordingly, for $n = 5$ a node can transmit 16 packets in a slot.

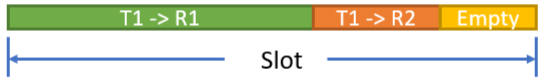
In this work a node is allowed to transmit packets to different receivers in the same slot. In this event the node orders the packets in decreasing order of the spreading factors required to transmit them. If the packets intended for a receiver that utilize a smaller spreading factor are transmitted first then a receiver that requires a larger spreading factor might not be able to acquire the transmission. By beginning a transmission with the packet (or packets) intended for the receiver with the largest spreading factor, all of the other receivers can also acquire this transmission. Furthermore, the SINR at each receiving node must satisfy Equation 2.1 from the start of the reception through the portion of the transmission that contains packets intended for it. All the packets intended for a receiver are dropped if the SINR does not satisfy equation 2.1 at any time during the reception.

Additionally, in this work different nodes are allowed to transmit in the same slot. This happens when a node is unable to use the slot assigned to it completely. In this event a node close to it will try and utilize the rest of the slot. The channel conditions are assumed to be same for the duration of a slot. However, the multiple-access interference environment might still vary depending on two factors. First, a node might not utilize all of the slot assigned to it. Second, different transmitters can transmit during different portions of the slot. While the channel conditions like fading are assumed to be constant during the duration of the slot the multiple-access interference can vary. These two features are explained in detail in Chapter 4.

To illustrate these points consider a simple networking scenario shown in Figure 2.1. A transmitter *T1* is assigned to transmit in some slot and it transmits packets to two receivers, *R1* and *R2*. Node *T1* transmits two packets intended for *R1* first as they are required to be transmitted at a larger spreading factor. The remainder of $T1's$ transmission consists of two packets for $R2$. Also, the SINR at *R1* satisfies Equation 2.1 for the duration of the slot that *T1* transmits to *R1*, and the SINR at *R2* satisfies Equation 2.1 for the complete duration of the transmission. In this case *T1* does not use the slot completely. A node close to $T1$ can use the rest of the slot to transmit as illustrated in Figure 2.2. In this example, *T2* uses the rest of the slot to transmit two packets to *R2*. In this manner we have two different transmitters utilizing the same slot. Note that the multiple-access environment changes during the slot as the transmitters change.

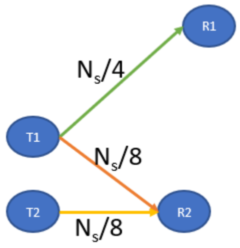


(a) Simple Network Scenario 1

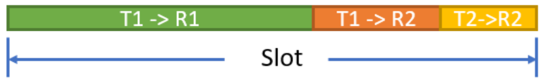


(b) Slot 1

Figure 2.1: A Simple Network Scenario With a Single Transmitter and Multiple Receivers



(a) Simple Network Scenario 2



(b) Slot 2

Figure 2.2: An Example With Two Transmitters That Share One Time Slot

2.2 Path Loss Model

An urban area cellular path loss model described in [29] is used throughout this work. Accordingly, the power received at node y from a transmission from node

x denoted by, $P_r(x, y)$, is given by the following equation.

$$P_r(x, y) = P_t \times \left(\frac{c}{4 \times \pi \times \nu \times d_{x,y}} \right)^{\alpha} \tag{2.2}$$

where P_t is the transmit power, c is speed of the light, ν is the frequency of the signal, $d_{x,y}$ is the Euclidean distance between the nodes x and y, and α is the path loss exponent.

All the nodes are assumed to be transmitting at the same power. The transmit power (P_t) is set in such a way that the SINR with no multiple-access interference is equal to β_1 at a distance of R from the transmitter using the largest spreading factor (i.e., $n = 1$). The distance R is called the range of a node. The value of P_t is given by the following equation.

$$P_t = \frac{N_0 \beta}{N_s T_c} (\frac{4\pi R \nu}{c})^{\alpha} \tag{2.3}$$

All of the system parameters are listed in Table 2.2.

Table 2.2: System Parameters

Parameter	Symbol	Value
Chip Duration	T_c	$2.9 * 10^{-7}$
Frequency	ν	2.4 GHz
Path Loss Exponent	α	3.5
SINR Threshold	β	6.8
One-sided spectral density	N_o	$4 * 10^{-21}$
Spreading Factor	N_s	128

Chapter 3

Recovering Mini-slot Transmission Scheduling (RMTS)

The approach to designing transmission scheduling protocols is to make slot assignments with a goal to maximize the channel re-use while minimizing the multiple-access interference and ensuring fairness. Because these protocols are contention free they tend to work very well at high traffic levels. However, at low traffic levels they suffer from poor utilization of the channel. Once the slot assignments are made they are fixed irrespective of the traffic at the nodes. While this is a desirable feature as it ensures fairness in channel assignments, it leads to wasted slot assignments as some of the nodes may not have packets to transmit in their assigned slots.

The objective of RMTS is to recover these wasted slot assignments and try to re-use them to improve the utilization of the channel. Recovering slots using RMTS is designed to be compatible with traditional scheduling algorithms. In RMTS every slot consists of two types of transmitters: primary and auxiliary. The primary transmitters are assigned by some distributed scheduling algorithm. Additionally, each node in the network is required to choose some of its close 1-neighbors as auxiliary transmitters (each node can choose up to N_a number of nodes as auxiliary transmitters). In each slot the primary transmitter assigned by the base scheduling algorithm has the first opportunity to transmit. In the event that the primary transmitter does not have a packet to transmit in its assigned slot, its auxiliary nodes have the opportunity to claim the slot. That slot is not wasted if one of the auxiliary nodes is able to transmit a packet. In order to facilitate the auxiliary transmissions every slot is extended by N_a number of mini-slots as shown in the Figure 3.1. The number of mini-slots is equal to the maximum number of auxiliary nodes a primary node can select. The duration of the mini-slot is very small compared to the original slot and hence the resulting overhead is limited when the number of mini-slots is small.

Mini-Slot #1	**Mini-Slot #2**	**…**	**Mini-Slot #N_a**	**Original Slot in a Scheduling Algorithm**

Figure 3.1: Structure of the New Slot in RMTS

At the beginning of the slot the primary node in that slot attempts to transmit a packet. By the end of the first mini-slot if the first auxiliary node does not detect a transmission then it has the opportunity to transmit. Similarly, by the end of second mini-slot if the second auxiliary node still does not detect a transmission then it has the opportunity to transmit and so on. A slot will not be utilized only if the primary node and all the auxiliary nodes associated with it do not have a packet to transmit. Our investigations show that this protocol results in a higher probability that a slot will be utilized.

In traditional scheduling algorithms the slot assignments are chosen such the multiple-access interference from concurrent transmissions in a given slot is minimal. Hence, care has to be taken when choosing auxiliary nodes. An auxiliary node creates a different multiple-access interference environment and could potentially disrupt other transmissions scheduled in that slot. Auxiliary nodes are chosen such that the multiple-access environment created is similar to that which would have resulted from a primary transmission. The eligibility of a 1-neighbor of a node to be picked as an auxiliary node depends on the SINR of the link between the two nodes. Whenever a node receives a transmission it stores the value of SINR of the link in its neighbor table. These SINR values are used to select the auxiliary nodes. For a node x to be eligible to be selected as an auxiliary node of node y the SINR of link between them, $\xi_{x,y}$, must satisfy the following condition.

$$\xi_{x,y} \geq P \times \beta \tag{3.1}$$

where P is a multiplication factor that decides how large the SINR of the link has to be. If the value of P is large then the multiple-access environment created by the auxiliary transmission will be close to that of a primary transmission. However, there might not be many eligible nodes to chose from. If the value of P is small then there will be a large pool of eligible nodes but the multiple-access environment created by these nodes will be different from that of a primary transmission. Selecting a moderate value of P typically creates a sufficiently large set of eligible nodes and ensures that the multiple-access interference environment is similar to that created by the primary transmission. A node x traverses its neighbor list to check for the nodes that satisfy Equation 3.1 and forms a list of eligible nodes $\mathbb{S}_x$. Node x then creates a sub-graph, $\mathbb{G}_x$, using the nodes from $\mathbb{S}_x$ as the vertices. An edge exists between two nodes in $\mathbb{G}_x$ only if these nodes list each other as 1-neighbors in their respective neighbor tables.

Another requirement of auxiliary nodes belonging to a particular node is that they must be able to detect each other's transmissions. To ensure the auxiliary nodes are fully-connected, node x selects a maximum clique, $\mathbb{A}_x$, from the subgraph $\mathbb{G}_x$. For the RMTS protocol a simple approach is employed to limit the size of the auxiliary set to N_a nodes. Because a subset of a clique is also a clique, node x randomly selects N_a nodes from $\mathbb{A}_x$. The position of a node in this list denotes its auxiliary number. Forming a maximum clique is NP hard but there are algorithms to find maximum cliques with acceptable run times for large number of nodes ([30, 31]).

In this work the base scheduling algorithm used is called Lyui's algorithm, which was first described in [16]. Lyui's algorithm is a distributed scheduling algorithm that uses color numbers to form schedules. Each node negotiates with other nodes in its 2-neighborhood to select a unique color number and exchanges this information with other nodes in its 2-neighborhood. A node need only collect the color numbers of its 2-neighbors to be able to form its transmission schedule. For detailed explanation and performance analysis of Lyui's algorithm see [17]. See [36] for details about how Lyui's algorithm is initialized and how the initial schedules can be established in a distributed manner.

To illustrate how RMTS works consider a simple example network as shown in the Figure 3.2. In some slot nodes 1 and 6 (shown in green) are the primary nodes. Nodes 2 and 7 (shown in yellow) are their respective first auxiliary nodes. Nodes 3 and 8 (shown in blue) are their respective second auxiliary nodes. At the beginning of the slot nodes 1 and 6 have the first opportunity to transmit. By the end of the first mini-slot if either 2 or 7 (or both) do not detect a transmission then they have the opportunity to transmit. Similarly, by the end of the second mini-slot if either 3 or 8 (or both) do not detect a transmission then they get the opportunity to transmit. Notice that the order that nodes are arranged in the auxiliary set effects the probability that a node has the opportunity to access the channel. For a detailed explanation and performance analysis of RMTS see [25].

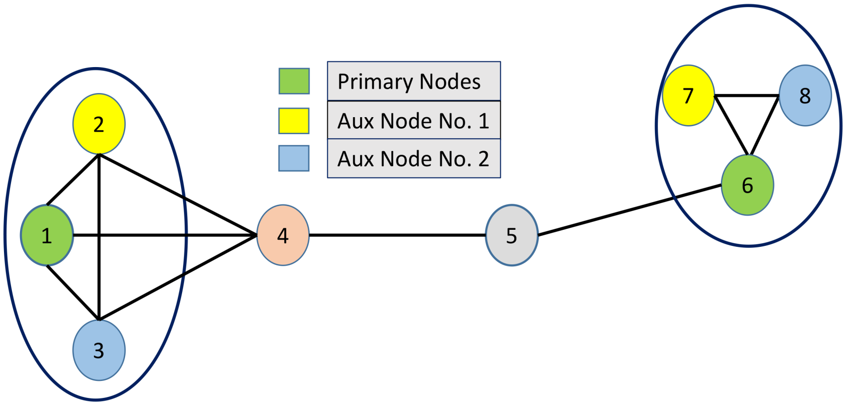


Figure 3.2: A simple Network

Chapter 4

Adaptive RMTS (RMTS-a)

Adaptive RMTS (RMTS-a) is a scheduling-based MAC protocol designed for networks with rate-adaptive radios. To the best of our knowledge this is the first scheduling-based MAC protocol that is designed for ad hoc networks with rate-adaptive radios. It is a combination of RMTS and slot-packing. In this chapter we first motivate the need for slot-packing and then describe the distributed protocol that allows multiple transmitters and multiple receivers to share an under utilized slot. Three variations for slot-packing are developed and investigated. RMTS is then integrated with slot packing for the RMTS-a protocol. Finally, we study the effect of carefully selecting the auxiliary nodes as opposed to choosing them randomly from the list of eligible nodes.

4.1 Slot-Packing

Time is divided into slots, and the duration of the slots must be equal so that the nodes can remain synchronized to the slot boundaries. The slot duration is usually set equal to time taken to transmit one packet (all packets are assumed to be of the same size). To apply scheduling to a system that employs adaptive transmission, the slot duration must be at least as long as time taken to transmit a packet using slowest possible data rate. In this environment there is not much to be gained by having the nodes transmit at higher rates. To illustrate this point consider the example network shown in the Figure 4.1. For simplicity assume that node A generates packets for node D. Nodes B and C act as the relays. Nodes are scheduled to transmit one after the other starting from A and ending with C. The spreading factors selected for the links between the nodes are as shown in the Figure 4.1.

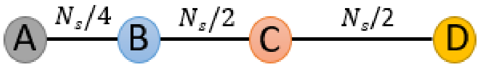


Figure 4.1: Simple Network

At the beginning of the first slot A transmits a packet to B and uses a quarter of the slot. The channel is idle for the rest of the slot as B can only start transmitting at the beginning of the second slot. B relays this packet to C in the second slot and uses half of the slot. Similarly, C relays this packet to D in the third slot and uses half of the slot. The end-to-end delay (time required for the packet to reach its destination) for this packet is 2.5 slots. Note that the delay incurred from traveling from node A to node C is 2 slots even if the nodes A and B transmitted at the lowest possible rate. In this scenario the benefit of transmitting at a faster data rate can be observed in the last hop only where the packet is delivered to node D in half a slot from node C. This is illustrated in Figure 4.2.

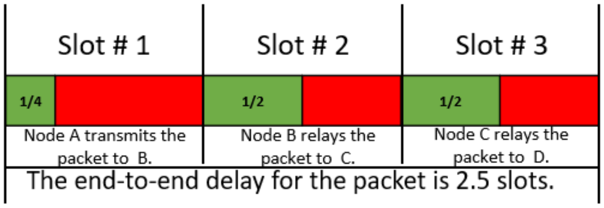


Figure 4.2: Simple Frame

In order to fix this shortcoming a process called slot-packing is introduced where a node transmitting at a faster data rate is allowed to transmit multiple packets in a slot. In the previous example A can transmit four packets in the first slot. B can then relay two of these packets to C in the second slot and C can then relay these two packets to D in the third slot. In this manner two packets are delivered in three slots instead of just one packet, reducing the average end-to-end delay and increasing the throughput.

By employing slot-packing the benefits of adaptive transmission in a scheduling environment can be exploited. We note that this approach can be used with any scheduling protocol. The idea is to have a base scheduling protocol that decides which node has the opportunity to transmit and this selected node will use slot-packing to pack the slot. In this work three variations of slot-packing are considered: sTx-sRx, sTx-mRx, and mTx-mRx. The idea is inspired from frame aggregation introduced in [32], where a node is allowed to aggregate multiple frames together and transmit them at once after it gains access to the channel. This helps to amortize the heavy overhead resulting from the 802.11 MAC protocol over multiple frames.

4.1.1 Single Transmitter-Single Receiver (sTx-sRx) Slot-packing

In this method a node can pack the slot with packets intended for a particular receiver only. In this aspect it is similar to frame aggregation in IEEE 802.11n and later standards. The node packing the slot initializes a variable *slot-percentage* to zero and sets *rx-node* to be the node to which the first packet in its queue will be relayed. The node then traverses the queue from front to back and does the following for every packet.

```
if $slot\text{-}percentage + frac \leq 1$ then
    if $next\text{-}node == rx\text{-}node$ then
        slot-percentage = slot-percentage + frac;
        Mark the packet for Transmission;
    end
end
```

where *next-node* is the node to which that packet will be relayed to next and *frac* is the fraction of the slot required to transmit that packet. Note that packets with different final destinations can still have the same next node. Once the node finishes traversing the queue it will then transmit the marked packets.

To illustrate how this method works consider a simple example where node A is given the opportunity to pack a slot using sTx-sRx packing. Table 4.1 represents the queue at node *A* before and after the slot. Each row in the table represents a packet. The first column indicates the node to which that packet will be relayed. The second column indicates the fraction of the slot required to transmit that packet. The third column indicates the current value of the variable slot-percentage as the protocol iterates through the queue. The last column can take values *1* or *0*, with *1* indicating that the packet is marked for transmission. The first packet in the queue will be relayed to the node *1* and it is fixed as the rx-node. There are three packets in the queue which will be relayed to node *1* and these are marked for transmission. Note that only $\frac{3}{8}^{th}$ of the slot will be utilized to transmit these packets.

Table 4.1: Example of sTx-sRx packing

Queue at A

Pkt #	Next	Frac	s.p	s.p + Frac	M
1	1	1/8	0	1/8	1
2	1	1/8	1/8	1/4	1
3	2	1/2	1/4	3/4	0
4	3	1/4	1/4	1/2	0
5	1	1/8	1/4	3/8	1

After the slot ⟹

Queue at A

Next	Frac
2	1/2
3	1/4

4.1.2 Single Transmitter-Multiple Receiver (sTx-mRx) Slot-packing

One advantage of scheduling based MAC protocols is that any 1-neighbor of the transmitting node can receive a packet. So while packing a slot, a node does not need to be limited to choosing the packets intended for a single receiver. In this method a node can pack the slot with packets for any of its 1-neighbors and can end up transmitting to multiple nodes in a single slot. The node packing the slot will initiate the variable *slot-percentage* to zero. The node then traverses the queue from front to back doing the following for each packet.

```
if $slot\_percentage + frac \leq 1$ then
    slot_percentage = slot_percentage + frac;
    Mark the packet for Transmission;
end
```

When transmitting to multiple receivers a node might have to transmit at multiple rates. At the beginning of the slot a node transmits the acquisition signal at slowest possible rate. If the node transmits the packets that can be transmitted a faster data rate first, then the receivers of the packets that are transmitted at a slower rate are unlikely to be able to maintain synchronization with the transmitter. The packets transmitted at a rate slower than the initial packet are unlikely to be received. However, if the packets that need to be transmitted at a slower rate are transmitted first the other receivers will still be synchronized to the transmitter. Hence, after traversing the queue the node transmits the marked packets in increasing order of the data rate required to transmit them. The header at the start of transmission is transmitted at the slowest possible rate so that it is separately decodable at each of the intended receivers and inform them when to change their spreading factors.

Consider the same example in which node A is given the opportunity to pack a slot using sTx-mRx packing. Table 4.2 represents the queue before and after the slot. Since we do not fix the receiver in this case the first four packets in the queue will

Table 4.2: Example of sTx-mRx packing

Queue at A							Queue at A	
Pkt #	Next	Frac	s.p	s.p + Frac	M		Next	Frac
1	1	1/8	0	1/8	1	After	1	1/8
2	1	1/8	1/8	1/4	1	the		
3	2	1/2	1/4	3/4	1	slot		
4	3	1/4	3/4	1	1	$\Longrightarrow$		
5	1	1/8	1	1	0			

be marked for transmission. Note that packets will be transmitted in the order #3, #4, #1, and #2 and the whole slot is utilized to transmit these packets as opposed to only $\frac{3}{8}^{th}$ of the slot if sTx-sRx packing is used.

4.1.3 Multiple Transmitter-Multiple Receiver (mTx-mRx) Slot-packing

Both of the previous methods discussed can be applied to any scheduling based MAC protocol. The mTx-mRx method, however, works for RMTS only. It utilizes the property of RMTS that in every slot there are auxiliary nodes and any one node in this set can transmit in that slot without significantly changing the multiple-access interference environment. We exploit this feature to allow more than one node the opportunity to transmit in the slot.

The primary node has the first opportunity to pack the slot. There are two possibilities. The queue at the primary node is empty. In that case the first auxiliary node will not detect a transmission after the end of the first mini-slot and it can select packets to pack the slot. On the other hand, if the queue at the primary node is not empty then it uses sTx-mRx packing to pack the slot and includes the fraction of the slot it will be utilizing in the header of the first packet it transmits. All the auxiliary nodes decode this information and know what fraction of the slot that has been used. If the primary node is not able to pack the slot completely then the first auxiliary node can pack the remainder of the slot using sTx-mRx packing and include the percentage of the slot it will utilize in the first packet it transmits. If the slot is still not completely packed then the next auxiliary node has the opportunity to pack the slot. This process is repeated until the slot is completely packed or all of the auxiliary nodes are exhausted.

Note that when an auxiliary node is given an opportunity to pack the fraction of the slot it might not always be able to do so because of two reasons: its queue might be empty or it might not have packets that fit into the remainder of the slot. In this case the next auxiliary node will not detect a further transmission and after an mini-slot has elapsed it will begin to pack the slot.

To illustrate this method consider an example where A is the primary node in some slot. Nodes B and C are its first and second auxiliary nodes respectively. The queues at these nodes before and after the slot are shown in Table 4.3. Node A uses sTx-mRx packing to pack the slot and marks both of its packets for transmission. A includes that fraction of the slot it will be utilizing in the header of the first packet it transmits. After the A has finished its transmission B does nothing as it does not have a packet that fits into the remainder of the slot. Having not detected a new transmission after A had finished transmitting, C will now pack the slot and mark both of its packets for transmission. Note that $\frac{3}{4}^{th}$ of the slot is utilized in transmitting these packets. In this case both other methods would have managed to fill half of the slot only.

Table 4.3: An example of mTx-mRx slot packing

Queue at A

Next	Frac
1	1/4
1	1/4

Queue at B

Next	Frac
1	1

Queue at C

Next	Frac
2	1/8
3	1/8

After the slot

⇓

Queue at A

Next	Frac

Queue at B

Next	Frac
1	1

Queue at C

Next	Frac

4.2 RMTS-a

Adaptive RMTS (RMTS-a) is a scheduling-based MAC protocol designed for ad hoc networks with rate-adaptive radios. It combines both RMTS and slot-packing to address the two major drawbacks of scheduling protocols. In RMTS-a the base scheduling protocol is RMTS. The transmission schedules are assigned by RMTS and then the nodes use one of the slot-packing techniques to pack the slot.

As discussed in Section 4.1 there are three slot-packing techniques. In the first two of them there is only a single transmitter as scheduled by RMTS. Accordingly, the primary node has the first opportunity to pack the slot. If it does not have a packet then the first auxiliary node has the opportunity to pack the slot and so on. However, when using mTx-mRx slot-packing, multiple transmitters have the opportunity to transmit by packing the same slot. As before, the primary node has the first opportunity to pack the slot. If the primary node is unable to fill the slot completely, the first auxiliary node takes the opportunity to fill the remainder of the slot. If the first auxiliary node is unable to fill the remainder of the slot then the next auxiliary node has the opportunity to transmit and so on.

There are two benefits to using RMTS as the base scheduling protocol. The first benefit is that it allows auxiliary nodes to pack the slot in case the primary node does not have a packet to transmit. This improves the utilization of the channel irrespective of the slot-packing technique used. If any other transmission scheduling protocol was used then only the primary node would have the opportunity to transmit and the slot would be wasted if it does not have packets to transmit. The second benefit is that the presence of auxiliary nodes enables multiple transmitters to pack the slot as described in mTx-mRx slot-packing. There are many benefits to allowing multiple transmitters the opportunity to fill a single slot. It increases the probability that a slot is fully utilized. It helps reduce the pressure on bottleneck nodes as these nodes will potentially have multiple opportunities to transmit. In addition, average delay is reduced because a node may have the opportunity to transmit as an auxiliary node in a slot that occurs before its assigned slot. The integration of RMTS with auxiliary nodes and adaptive transmission with slot-packing results in significant improvement in performance of the network. A detailed investigation of the performance is provided in Chapter 7.

4.3 Ordering the Auxiliary Nodes

During the process to calculate transmission assignments, each node compiles a list of 1-neighbors that are eligible to be its auxiliary nodes. In the basic RMTS algorithm, a node selects N_a number of neighbors at random from this list as its auxiliary nodes. Selecting the auxiliary nodes randomly ensures that auxiliary assignments are fairly distributed among neighbors and also introduces enough randomness in the channel assignments to combat the short comings of fixed slot assignments. This makes RMTS and by extension also RMTS-a very robust and results in good performance across varying network densities and packet generation models.

While selecting the auxiliary nodes randomly results in good performance, further improvement in performance can be achieved by carefully selecting the auxiliary nodes. Especially in situations where certain nodes require more access to the channel than the other nodes. More access opportunities can be given to these nodes by preferring them while selecting the auxiliary nodes. As before each node compiles a list of 1-neighbors that are eligible to be its auxiliary nodes and $2N_a$ nodes are chosen at random from this list. These $2N_a$ nodes are then ordered based on some metric and the first N_a nodes are selected as auxiliary nodes from this ordered list. Selecting $2N_a$ nodes at random from list of eligible nodes before ordering them ensures that every node does not end up with the similar set of auxiliary nodes in scenarios in which there are more than N_a candidates to be auxiliary nodes. For example, consider a clique of $4N_a$ nodes. If each node uses the same metric to order its neighbors and then selects the first N_a nodes for its auxiliary list, the result is that all nodes end up with nearly identical auxiliary lists. This is detrimental to performance because in this example one-fourth of the nodes have nearly all of the additional transmission opportunities. (The N_a + 1 node on the list has an opportunity when one of the first N_a nodes is the primary transmitter. But the remaining $3N_a$ - 1 nodes have no additional transmission opportunities.)

Utilization is an effective metric to identify the nodes that require more access priority. Utilization is defined as the fraction of the slot assigned to a node that it utilizes. A higher value of utilization indicates that a node is experiencing more traffic and requires more access priority. In networks that are prone to bottlenecks selecting the auxiliary nodes based on utilization results in further improvement in performance as compared to the case where the auxiliary nodes are picked at random. In all the results presented in this document the auxiliary nodes are ordered based on utilization unless otherwise specified.

Chapter 5

Network Layer Models

In this chapter the routing metrics used for all performance investigations are presented. We also present other network layer models including assumptions about how the routes are calculated.

Routing Metric

A popular approach to routing is to use a shortest path algorithm. Usually a cost is assigned to each link in the network and the shortest path is computed in terms of this cost. In networks with single-rate radios, traditionally all the links were considered to be same, that is, they were all assigned equal cost. Finding the shortest path equates to finding the minimum number of hops to reach a particular node. Hence, this approach is called min-hop routing. The authors in [33] show that routes formed by min-hop routing contain a large number of un-reliable links that led to poor performance. To remedy this shortcoming link-reliability is typically included when calculating the cost of a link. In [34] one such protocol is presented and we incorporate this approach into our routing metric. Henceforth, reference to min-hop routing implies min-hop routing with a penalty for un-reliable links.

While min-hop routing works well for networks with single-rate radios it does not work well for networks with multi-rate radios. Min-hop routing does not distinguish between reliable links and assigns the same cost for both the higher rate links and lower rate links. A routing metric is presented below that considers both link reliability and the rates of links while assigning the cost to the links. In order to incorporate the link-reliability into the cost metric a shape function is introduced as shown below.

$$S_{i,j}(\xi_{i,j}, \beta_n) = \begin{cases} \infty, & \xi_{i,j} < \beta_n \\ 1 - ln(\frac{\xi_{i,j} - \beta_n}{0.5 \times \beta_n}), & \beta_n \leq \xi_{i,j} < 1.5 \times \beta_n \\ 1, & \xi_{i,j} \geq 1.5 \times \beta_n \end{cases} \tag{5.1}$$

where $\xi_{i,j}$ is the SINR of the link between nodes i and j, and β_n is the SINR threshold for the rate of the link. The shape function penalizes the links with SINR values close to their respective thresholds. Finally, the cost of the link is calculated as shown below.

$$C_{i,j} = W_n \times S_{i,j}(\varepsilon_{i,j}, \beta_n) \tag{5.2}$$

where W_n is the weight associated with the link between nodes i and j. The weight is inversely proportional to the data rate of the link. Hence, this routing metric is called the inverse-bitrate (inv-bitrate) metric. The weights associated with different data rates are listed in Table 5.1.

Table 5.1: Weights assigned to a link

n	$N_s(n)$	β_n	W_n
1	128	β	16
2	64	2β	8
3	32	4β	4
4	16	8β	2
5	8	16β	1

We investigated many variations for assigning link weights, and the method defined by Equation 5.2 performed well in a wide range of scenarios, and is utilized for all results presented in this document. A key feature of the metric is that it prioritizes links with faster data rates and thus provides more opportunities for slot-packing and auxiliary transmissions.

The cost metric shown in Equation 5.2 is used to assign cost to all the links in the network. Then Dijkstra's shortest path algorithm described in [35] is used to compute the routes for each node in the network. Distributed implementation of Dijkstra's shortest path algorithm are available in literature. However, in this work for simplicity all the routes are calculated using a centralized Dijkstra's shortest path algorithm. The routes are initialized at the beginning and are held constant for the duration of the simulation. In a practical network each node broadcasts periodic control information to its neighbors to allow the various protocols to adapt to changes in topology. This allows updates to the link metrics and routing tables based on new SINR measurements. In this work we assume the network topology is static and the link metrics are not changed even if there are small variations in the multiple-access interference environment. Hence, the link weights calculated in Equation 5.2 are made under the assumption of no multiple-access interference. The simulation results show that very few transmissions fail due to a SINR below the threshold, indicating there is little value in updating the link weights in our investigations.

Chapter 6

Simulation Design

In this chapter we begin by describing the common features of the network simulator used for all investigations reported in this work. In Section 6.2 a modified model for generating packets is presented that allows for higher variability in which nodes generate packets. An alternative approach for selecting the packet destinations is described in Section 6.3. In Section 6.4 all the miscellaneous implementation details of RMTS and RMTS-a are presented.

6.1 Features of the Network Simulator

A custom network simulator, developed in C, is used to analyze the performance of the proposed protocols. The network simulator is a time-slotted system. It models the physical, link, and network layers as described in the previous Chapters. In this work it is assumed that an initial network is already setup. Initial routing tables are formed centrally at the beginning and are held constant for the duration of the simulation.

We assume that there are 100 nodes in the network. The transmission radius of the nodes R is set equal to 200 m. These nodes are located randomly across a fixed area with a uniform distribution. The area is calculated based on the required node density of the network. In this work all the experiments are run for three different network densities. These are listed in Table 6.1 where diameter of the network is the maximum number of hops a packet has to travel to reach its destination and the average hops are the average number of relays required to deliver the packets to their destinations. The values of diameter and average number of hops depend on both the density of the network and the routing scheme. When the inv-bitrate link metric is applied both the average number of hops and the diameter of the network are significantly increased.

Table 6.1: Network Densities

Name	Density	Min-hop		Inv-bitrate	
		Avg # of Hops	Diameter	Avg # of Hops	Diameter
D-1	1 node per 25^2 sq.m	1.2	2	1.94	5
D-2	1 node per 50^2 sq.m	1.9	4	3.98	13
D-3	1 node per 75^2 sq.m	3.0	7	6.15	21

The size of the queue at each node is limited to 40 packets. Each packet has a limited lifetime. When a packet is generated a time-to-live (TTL) counter is initialized to 500 slots. This counter is decremented by one in each slot, and if the counter reaches zero before the packet reaches its destination, the packet is discarded. Every node in the network has a preset probability of generating a packet at the beginning of a slot. The destination for each packet is chosen at random from the remaining nodes in the network.

The packets are dropped when any of these following events occur: queue overflow, TTL counter expires, or SINR failure. Queue overflow occurs when a packet arrives at a node whose queue is already full, and the arriving packet is dropped. This packet could either have been generated at that node or received from a neighbor and requires a relay. A SINR failure occurs when SINR at the receiving node falls below the threshold and the receiver will not be able to decode the transmission. Link level or end-to-end acknowledgments are not implemented in this work. Hence, if a node fails to decode a packet that packet is dropped because there are no re-transmissions. Because RMTS-a schedules links with limited multiple-access interference and the routing metric penalizes links that have a SINR that is close to the decoding threshold, very few packets are dropped due to SINR failure for the investigations reported in this dissertation.

Three network statistics are reported: end-to-end completion rate, end-to-end delay and end-to-end throughput. *End-to-end completion rate* is the percentage of packets generated that are delivered to their final destinations. *End-to-end delay* is the average time between when a packet is generated and when it reaches its final destination. *End-to-end throughput* is the average number of packets delivered to their final destinations per slot. Additionally, to further examine the performance of RMTS-a the percentage of the auxiliary transmissions amongst total transmissions is also reported. All the statistics for each network are obtained over 4000 slots and averaged over 100 random networks. All of the simulation parameters are listed in Table 6.2.

Table 6.2: Simulation Parameters

Parameter	Symbol	Value
Number of Nodes	N	100
Number of Slots	Slots	4000
Numbers of Simulations	Sims	100
Time to Live	TTL	500 slots
Queue Size	Qs	40 packets
Radius	R	200 m

6.2 Packet Generation Models

In this work two different packet generation models are used: uniform packet generation model and gamma generation model.

6.2.1 Uniform Packet Generation Model

In this model all the nodes have the same probability of generating packets. At the beginning of every slot each node generates a packet with a probability of γ/N where γ is average number of packets generated per slot in the network and N is the number of nodes in the network.

6.2.2 Gamma Packet Generation Model

In this model the nodes in the network have different packet generation probabilities. The packet generation rates are drawn from a gamma distribution with mean equal to $\frac{\gamma}{N}$. The gamma distribution is utilized because for the same mean value, multiple distributions with different variances are possible. We use three different gamma packet generation models. The parameter values for each of these models are listed in Table 6.3, where a is the shape parameter and b is the scale parameter.

Table 6.3: Parameters for the gamma packet generation model

Dist Name	a	b	Mean $a \times b$	Variance $a \times b^2$
Gamma1	$\frac{\gamma}{N}$	1	$\frac{\gamma}{N}$	$\frac{\gamma}{N}$
Gamma2	$\frac{\gamma}{5N}$	5	$\frac{\gamma}{N}$	$\frac{5\gamma}{N}$
Gamma3	$\frac{\gamma}{10N}$	10	$\frac{\gamma}{N}$	$\frac{10\gamma}{N}$

At each data point the mean, the maximum, and the minimum packet generation probabilities per node for different gamma models are shown in Figures 6.1, 6.3, and 6.5. In these graphs the x-axis (data points) denotes the packet generation rate in the network per slot (γ) and the y-axis denotes the packet generation probability per node. At each data point 100 random networks are simulated. The maximum value in the graph denotes the highest packet generation probability amongst all the nodes across these 100 random networks and, similarly, the minimum denotes the lowest packet generation probability amongst them. The mean in the graph denotes the average packet generation probability amongst these nodes and is approximately equal to $\frac{\gamma}{N}$, as expected. The variance in the packet generation probabilities amongst these nodes for different gamma models are shown in Figures 6.2, 6.4, and 6.6.

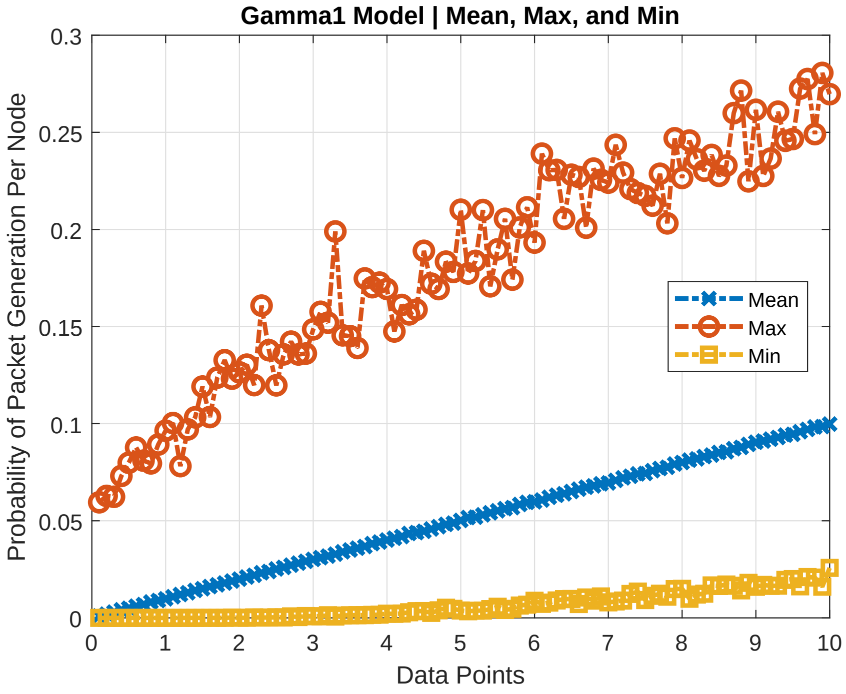


Figure 6.1: Mean, Maximum, and Minimum Packet Generation Probabilities for Gamma1 Model

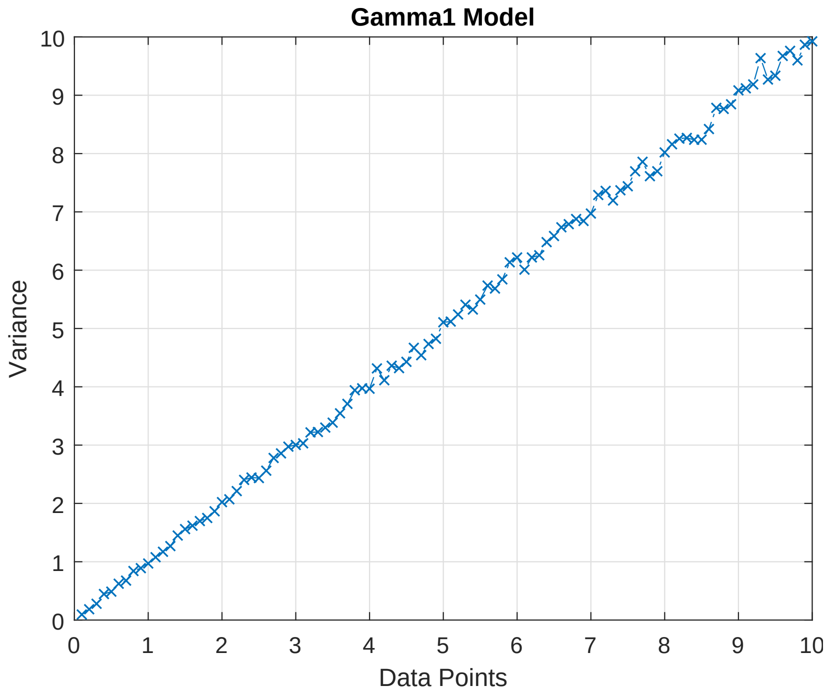


Figure 6.2: Variance in Packet Generation Probabilities for Gamma1 Model

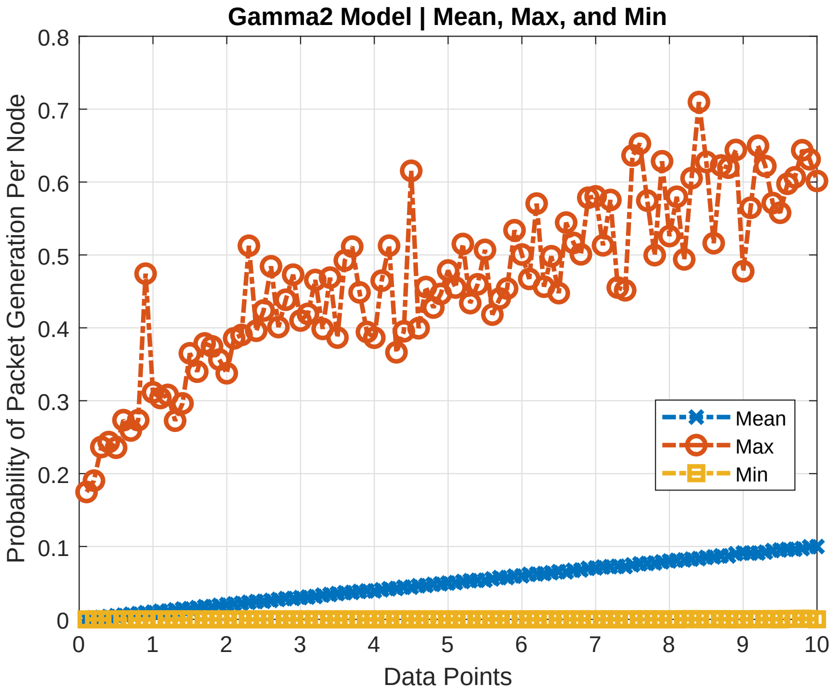


Figure 6.3: Mean, Maximum, and Minimum Packet Generation Probabilities for Gamma2 Model

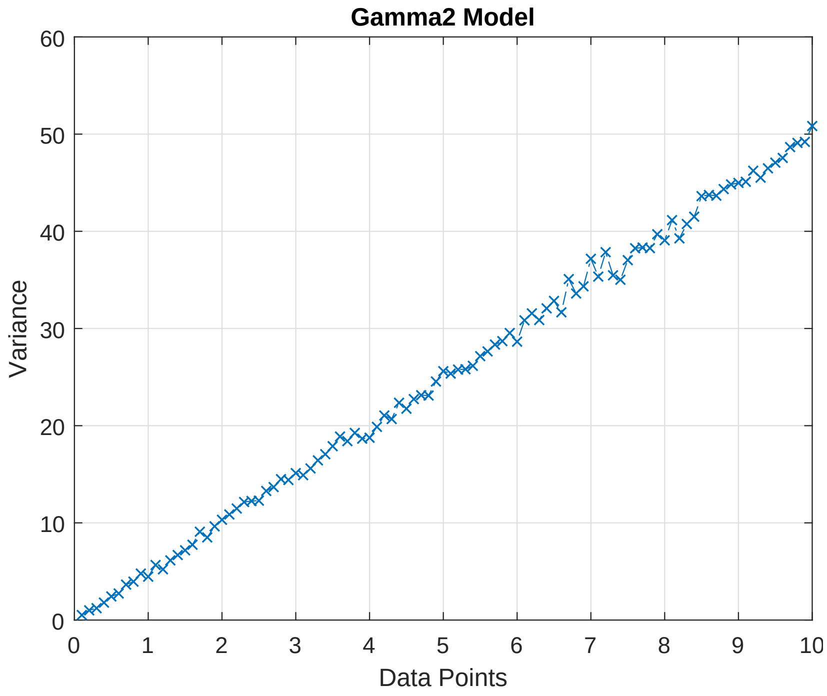


Figure 6.4: Variance in Packet Generation Probabilities for Gamma2 Model

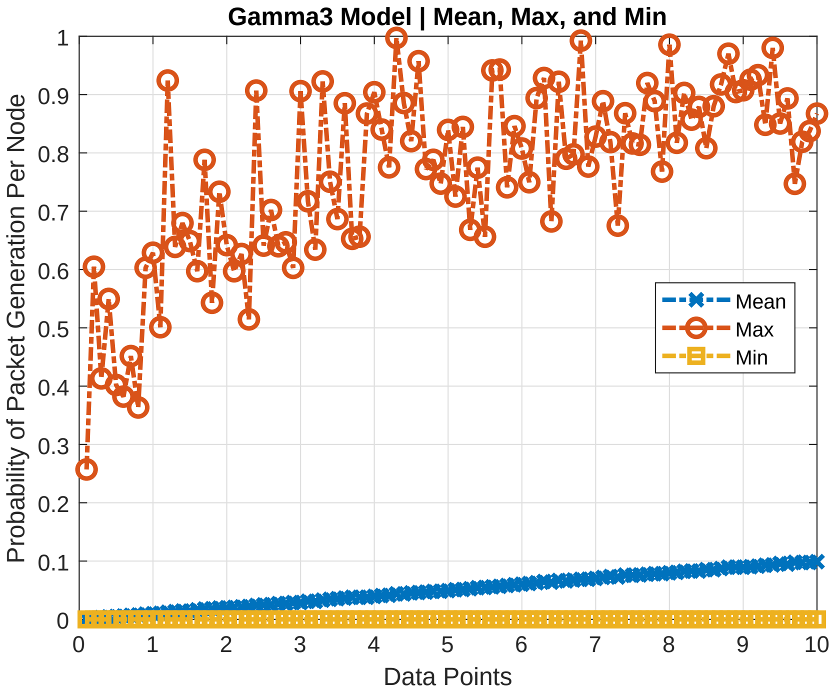


Figure 6.5: Mean, Maximum, and Minimum Packet Generation Probabilities for Gamma3 Model

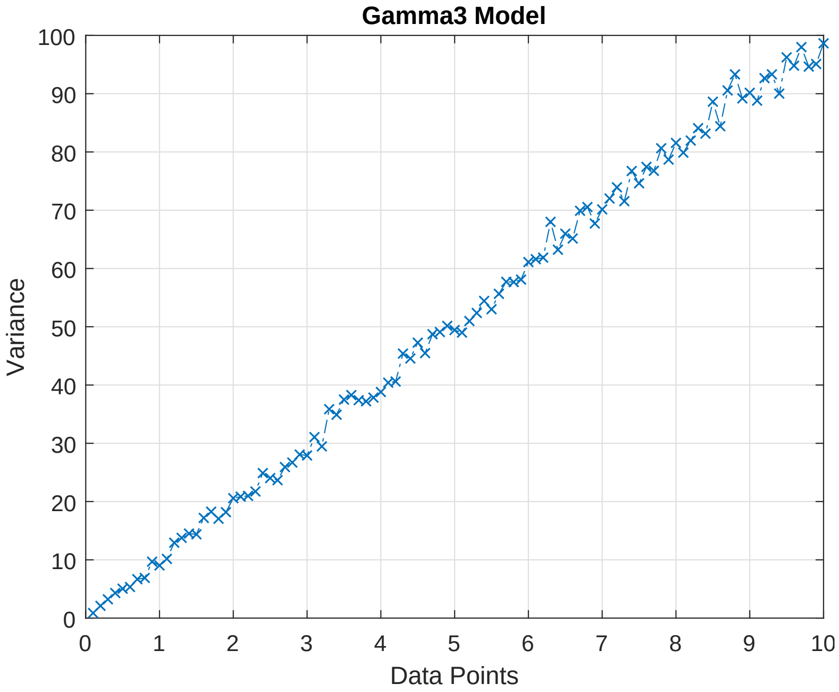


Figure 6.6: Variance in Packet Generation Probabilities for Gamma3 Model

6.3 Sink Mode Operation

In this mode the networks consist of a single sink node. All the packets generated in the network are directed to this sink node. As mentioned earlier each network spans a fixed area and the area depends on the density of the network. In this mode the sink node is fixed at the center of this area and the rest of the nodes are distributed randomly.

6.4 RMTS and RMTS-a Implementation Details

In all the investigations reported in this work the value of N_a is equal to 5 nodes and the value of the parameter P is equal to 10. These values were established in our prior investigations. See [25] for a detailed discussion on how these values are chosen.

Whenever a node needs to compute its auxiliary set it first calculates a list of eligible nodes. From this list a random subset of $2N_a$ nodes are selected. This subset is then ordered based on some metric and then the first N_a number of nodes are chosen as the auxiliary nodes. As discussed in Chapter 4 a subset of $2N_a$ nodes are selected at random to prevent neighboring nodes from having similar auxiliary sets. In networks with a low and medium node density, the average size of the list of eligible nodes is less that $2N_a$. Selecting a subset in this manner has no significance on the performance in these networks. However, in the networks with a high node density the average size of the list of eligible nodes is approximately 34 and as a result there is a significant overlap in these lists. Hence, in networks with a high node density it is critical to select a random subset of nodes from the list of eligible nodes before they are ordered to prevent a significant overlap in the auxiliary sets of nodes in the network. We evaluated the network performance for 5 different subset sizes: $2N_a$, $3N_a$, $4N_a$, $5N_a$, and $20N_a$. A subset size of $2N_a$ (i.e., 10) resulted in the best network performance and subsequently all the other simulations were run with a subset size of $2N_a$.

Two metrics are used to order the auxiliary nodes: *queue length* and *utilization*. *Queue length* is the number of packets queued up at a node. *Utilization* is defined as ratio of time a node spends transmitting to the time it is alloted to transmit. The value of utilization varies from 0 to 1, with a value closer to 1 indicating that the node is busy. Each node in the network maintains two counters: *Total alloted time* and *Total transmit time*. *Total alloted time* is incremented whenever a node is given an opportunity to transmit. It is incremented by 1 slot duration if the transmission opportunity arises due to a primary assignment. If the transmission opportunity arises due to an auxiliary assignment then the *Total alloted time* is incremented by the amount of slot left unused. *Total transmit time* is incremented whenever a node transmits with the duration of the transmission. Utilization is calculated as shown below.

$$\frac{Total\ transmit\ time}{Total\ alloted\ time} \tag{6.1}$$

Nodes recalculate their auxiliary sets after every 1024 slots. Whenever a node transmits it reports the values of utilization and queue length to all of its 1-neighbors. The latest values of the reported metric values are used during the auxiliary set updates. Simulations were run that update auxiliary sets after every 128, 256, 512, and 1024 slots. Updating the auxiliary sets after every 128 slots resulted in the best performance. However, there was not a significant difference in the performance between any of the cases so all simulation results presented in this document use an update interval of 1024 slots. Note that during every update each node selects a new random subset of $2N_a$ nodes from the list of eligible neighbors, orders the list if a metric is enabled, and then selecting the auxiliary list from the ordered subset.

Whenever a node calculates its list of eligible nodes it needs the SINR estimate of the links to all of the its 1-neighbors. At the beginning of a simulation SINR values with no multiple-access interference are used to calculate the list of eligible nodes. These SINR estimates work well as evident from a very few dropped packets as the result of SINR failure. So the same list of eligible nodes are used for the periodic update of the auxiliary sets.

Chapter 7

Results

In this chapter the simulation results are presented and analyzed. We investigate the performance of RMTS-a under a variety of network scenarios and demonstrate that the design of the protocol is robust under a wide range of variations. These variations are created by considering different networking densities, packet generation models, and packet destination distributions. In the first section, the results for simulations with the uniform packet generation model are presented where all the nodes in the network generate the same average level of traffic and the destination for a packet is selected randomly with a uniform distribution. In the second section, network performance is examined with a packet generation model based on the gamma distribution. This models scenarios in which the level of traffic generated by the nodes varies significantly. In the third section, the model for the packet destinations is changed so that all packets are routed to a single sink node. Like for the first investigations, all nodes generate traffic at the same rate.

In each of these sections the performance of RMTS-a is analyzed for three different network densities listed in Table 6.1: low, medium, and high. Simulations with the low density networks investigates network performance when packets require the largest number of relays, on average, to reach their destinations and it is possible to have more than one transmitter active at the same time. For the highest density networks we consider topologies in which it is possible to reach any destination with at most one relay and there can only be a single transmitter active at any given time. However, because the focus is on radios with adaptive transmission, link weights set with the inv-bitrate metric typically result in packets requiring more than one relay. See also Table 6.1 for the average and maximum number of relays observed. Furthermore, in each of these sections the effect of carefully selecting the auxiliary nodes is studied.

7.1 Uniform Packet Generation Model

In all the results presented and discussed in this section each node in the network has the same probability of generating a packet in a slot. To analyze the performance of RMTS-a, networks with a variety of node densities are considered. The first set of investigations focus on networks with the lowest density in which the nodes have a smaller number of neighbors. Figure 7.1 shows the end-to-end completion rate for RMTS-a with different slot-packing techniques for networks with low density. The solid lines in the figure indicate the data with the inverse bitrate (inv-bitrate) routing metric and the dash-dot lines indicate the data with the min-hop routing metric. The data for simple RMTS (that is, the radios in the network do not employ adaptive transmission; abbreviated as RMTS-s in the graph) is included to show the scope of improvement possible through RMTS-a. A significant conclusion is that the inv-bitrate routing metric substantially out performs the min-hop routing metric. Notice that if min-hop routing is employed, there is little difference in completion rate for any of the scheduling schemes. With min-hop routing, the nodes are unable to take advantage of adaptive transmission or slot-packing. This highlights the importance of choosing an appropriate routing metric that takes rate adaption in to account while assigning costs to the links in the network. We found similar trends in all the other scenarios for all the subsequent results presented in this chapter. Hence, in subsequent graphs only inv-bitrate routing is shown.

Amongst the different slot-packing techniques, the mTx-mRx slot-packing protocol has the best performance as shown in the Figure 7.1 (Recall, this protocol allows multiple transmitters to share a time slot and each transmitter can send to multiple receivers). The end-to-end completion rate threshold, denoted by Γ, is defined as the packet generation rate (γ) at which the end-to-end completion rate is 90%. Because end-to-end acknowledgments and retransmissions are not simulated in this work, Γ is used an indicator for network congestion. At packet generation rates greater than Γ, there is significant congestion and dropped packets and network performance is poor. So the performance of the different scheduling and slot packing techniques is focused on the value of Γ. Accordingly, the mTx-mRx slot-packing method has 192.8% improvement in the value of Γ over sTx-sRx and a 73.7% over sTx-mRx slot-packing methods when the inv-bitrate routing metric is employed.

A higher value of Γ indicates that the network is able to support more traffic. The ability of a slot-packing protocol to support more traffic depends on its capacity to utilize a slot as much as possible. The Γ values reflect the ability of each slot-packing protocol's capacity to utilize the slot. In the sTx-sRx slot packing protocol only a single transmitter is allowed to pack the slot with packets intended for a single receiver only. This protocol has the smallest value of Γ compared to our other approaches to slot packing. Similarly, the sTx-mRx slot-packing protocol allows only a single transmitter to pack a slot but it can pack the slot with packets intended for different receivers. As a result it is better able to utilize the slot resulting in a higher Γ value than the sTx-sRx protocol. In the case of mTx-mRx slot-packing, if a slot is only partially utilized then the auxiliary nodes can utilize the rest of the slot. So multiple nodes can pack a single slot resulting in better utilization of the channel and consequently this protocol the highest value of Γ.

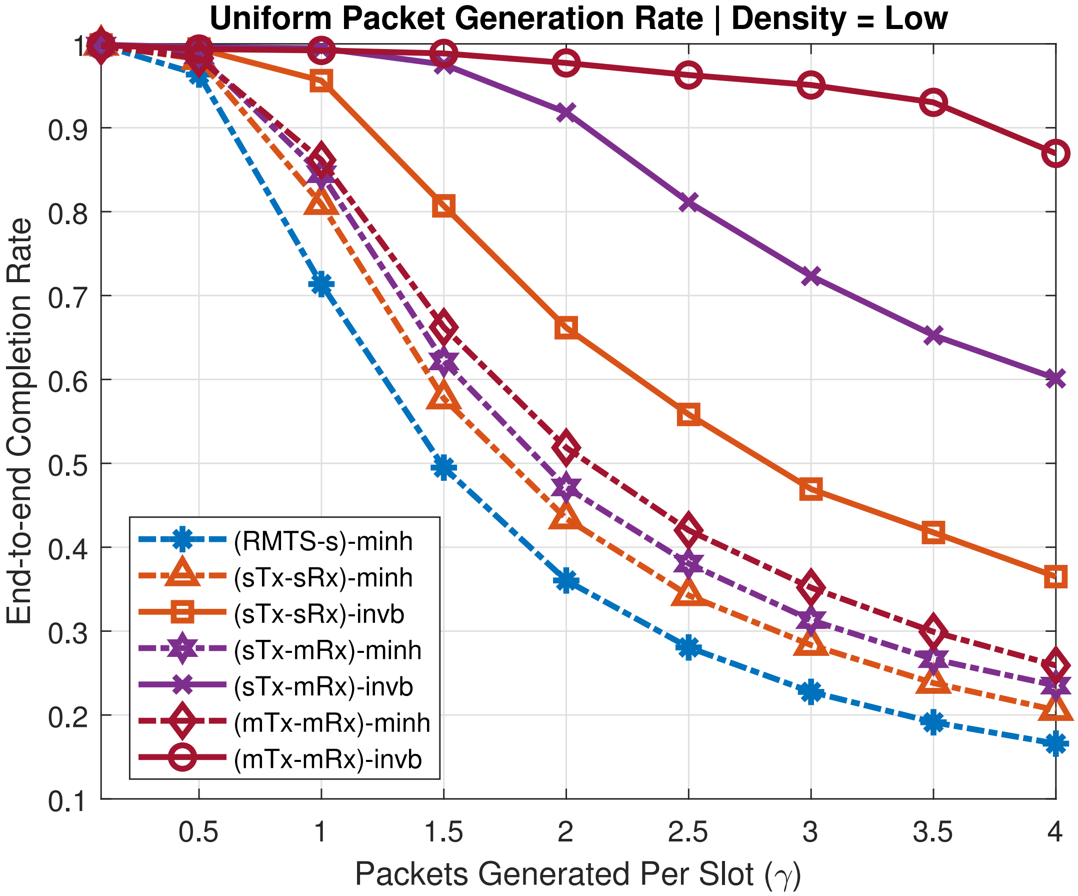


Figure 7.1: End-to-end Completion Rate for Low Density Networks

Figure 7.2 shows the end-to-end delay results for different slot-packing techniques in networks with a low node density. At low packet generation rates, min-hop routing metric results in lower delay than inv-bitrate metric because min-hop routing metric reduces the number of relays. However, this is a minor improvement that only holds at very low packet generation levels. At higher packet generation levels it is critical to use inv-bitrate routing metric to achieve lower delay. So for this routing metric, the delay performance of the scheduling and slot-packing protocols are compared.

The mTx-mRx slot-packing technique has the best performance for generation rates greater than 0.5. Since both the sTx-sRx and sTx-mRx slot-packing techniques have Γ values smaller than that of mTx-mRx, we compare the delay of sTx-sRx and sTx-mRx slot-packing with that of mTx-mRx slot-packing at their respective $\Gamma's$. In the case of sTx-sRx slot-packing the value of Γ is equal to 1.24. At this packet generation rate the sTx-sRx slot-packing has a 531% increase in delay over mTx-mRx slot-packing. In the case of sTx-mRx slot-packing the value of Γ is equal to 2.09. At this packet generation rate sTx-mRx slot-packing has a 214% increase in delay over mTx-mRx slot-packing. The improvement in the delay performance results in an improvement in the end-to-end throughput and is shown in the Figure 7.3.

The improved performance in the delay results from reduction in queuing delay. Queuing delay is defined as the time a packet waits in the queues of different nodes before it reaches its final destination. In the mTx-mRx slot-packing protocol multiple nodes can transmit in a single slot. This allows a node to potentially transmit in a slot before its scheduled primary transmission, thus reducing the queuing delay. The number of packets in the queue at a bottleneck node is often large and results in significant queuing delays. A bottleneck node will likely have multiple opportunities to transmit within a frame increasing the service rate and leading to smaller queuing delay.

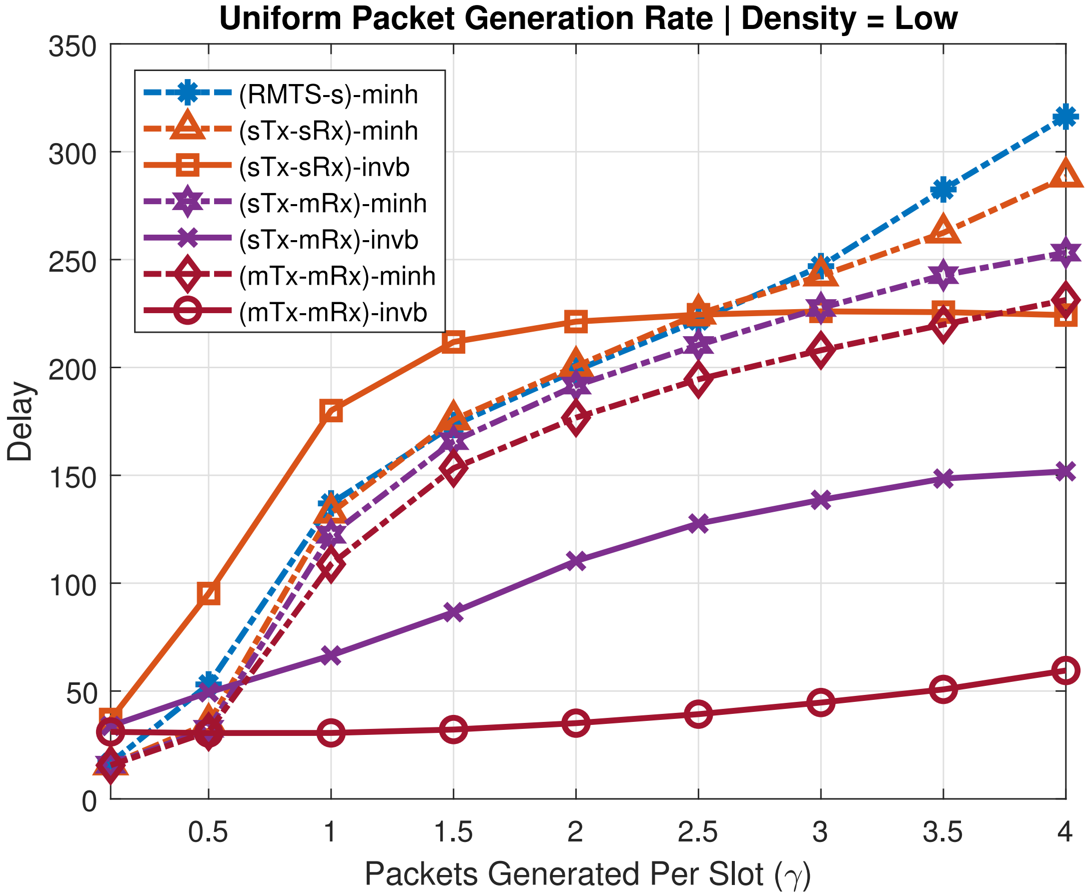


Figure 7.2: Delay for Low Density Networks

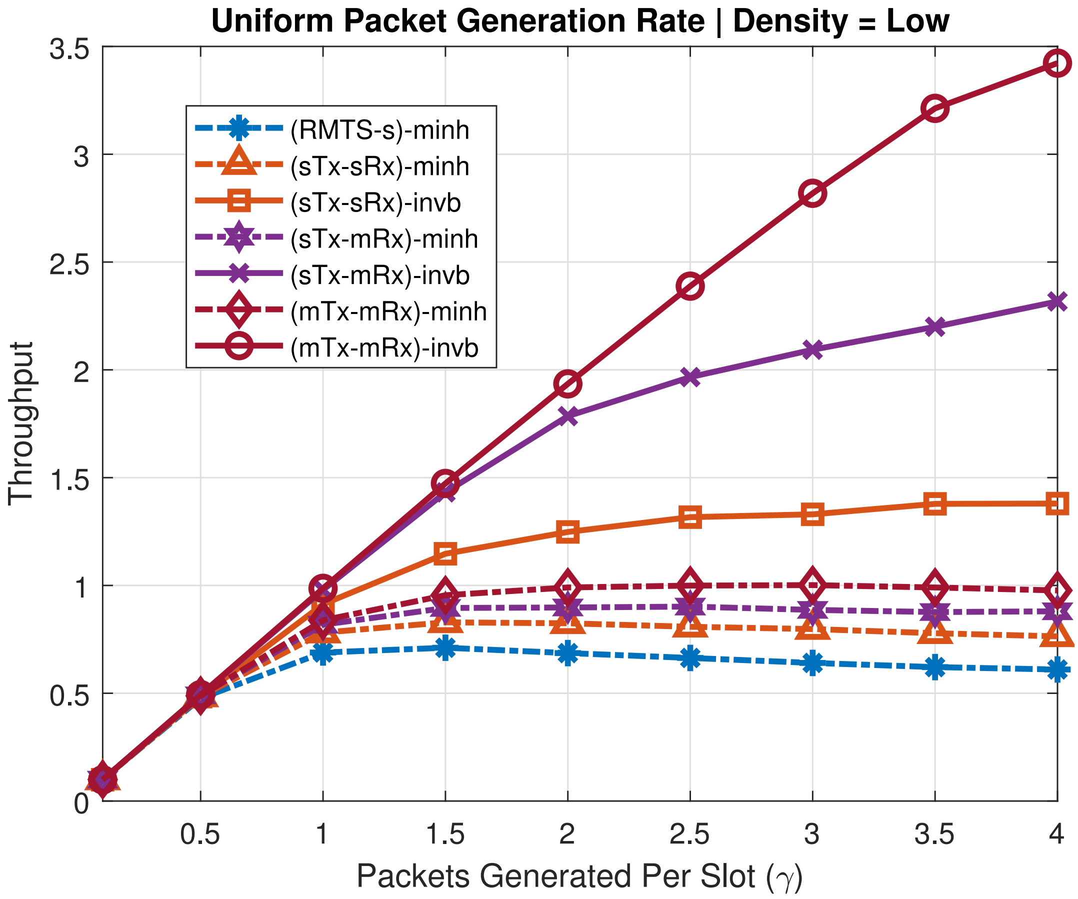


Figure 7.3: Throughput for Low Density Networks

Figure 7.4 shows the average percentage of auxiliary transmissions per node for different slot-packing techniques in networks with a low node density. This metric is calculated as shown below.

$$\frac{\sum_{i=1}^{N} \frac{Auxiliary\ Tx(i))}{Total\ Tx(i)}}{N} \tag{7.1}$$

where *Auxiliary Tx(i)* represents the number of packets that node i transmits as an auxiliary transmitter, *Total Tx(i)* represents the number of packets that node i transmits in total (that is, both as primary and auxiliary transmitter), and N is total number of nodes in the network.

At lower packet generation rates all three slot-packing protocols have a similar percentage of auxiliary transmissions. As expected, the percentage of auxiliary transmissions is high because the probability a node does not have a packet to transmit in its assigned slot is high. The number of primary transmissions increase as the packet generation rates increases. This trend is visible in the Figure 7.4 as the percentage of auxiliary transmissions drop with an increase in the packet generation rate for both the sTx-sRx and sTx-mRx slot-packing techniques. However, in the case of mTx-mRx slot-packing the value does not drop with increasing packet generation rates.

At higher packet generation rates there is a higher probability that a node assigned to transmit in the slot has at least one packet to transmit. Because both sTx-sRx and sTx-mRx slot-packing protocols are limited to allowing a single transmitter, this reduces the opportunity for an auxiliary node to have access to the channel even when the slot is not fully utilized. Hence, with increasing packet generation rates the percentage of auxiliary transmissions drop. In the mTx-mRx slot-packing protocol if the primary transmitter has not utilized all of the slot, the auxiliary nodes each have an opportunity to use the remaining time in the slot. Even at higher packet generation rates it is unlikely that the primary nodes are able to fully utilize the slots assigned to them leaving gaps for auxiliary transmitters to fill. Hence, the average percentage of auxiliary transmissions does not drop with increasing packet generation rates for the mTx-mRx slot-packing protocol.

Even though the sTx-sRx and sTx-mRx slot-packing protocols have similar percentages of auxiliary transmissions, sTx-mRx out performs sTx-sRx slot-packing significantly in terms of end-to-end completion rate, delay, and throughput metrics. This is because the sTx-mRx slot packing protocol allows a node to pack the slot with packets intended for multiple receivers. Recall, the sTx-sRx slot-packing protocol only allows a node to pack the slot with packets intended for a single receiver. Hence, the nodes using the sTx-mRx slot-packing protocol have a better probability of filling up a slot than the nodes using the sTx-sRx slot-packing protocol. This leads to a better network performance.

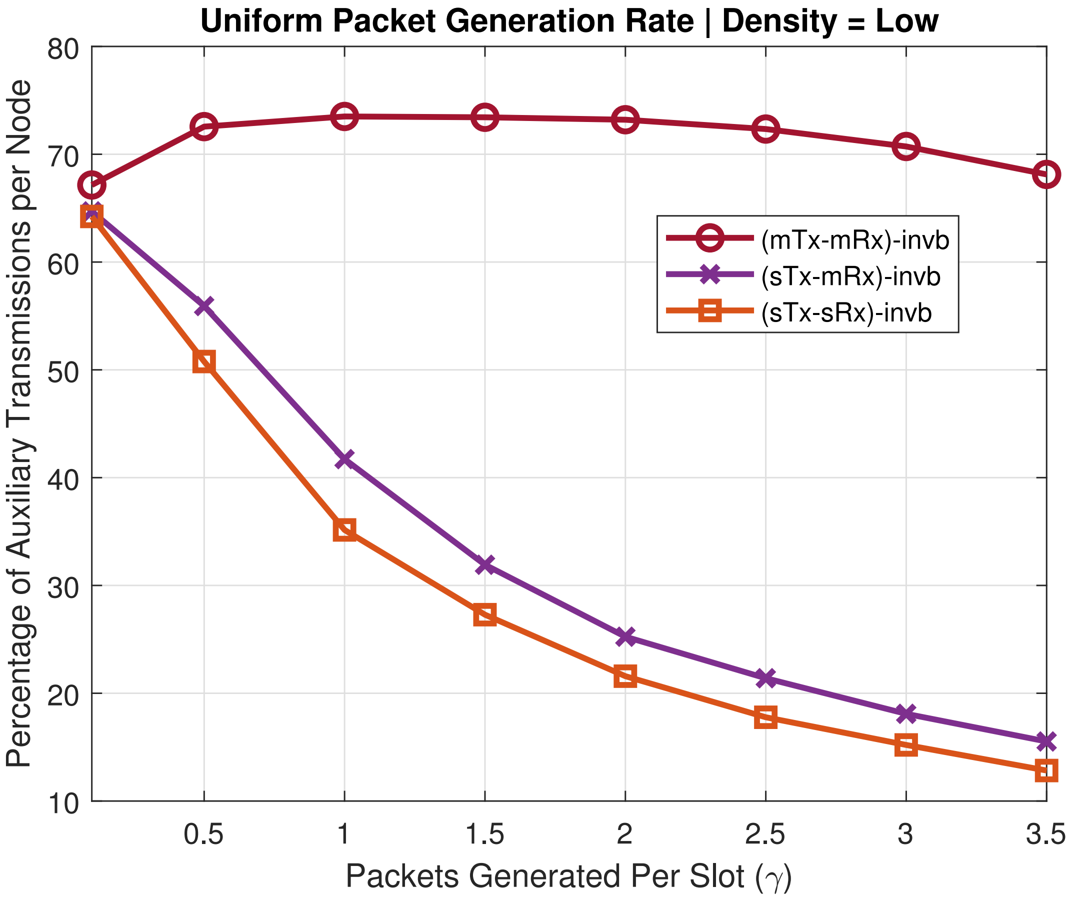


Figure 7.4: Percentage of Auxiliary Transmissions in Low Density Networks

Figure 7.5 shows the end-to-end completion rate for RMTS-a with different slot-packing techniques for networks with medium node density. Once again the mTx-mRx slot-packing protocol has the best performance. The values of Γ are compared for different slot-packing protocols. Accordingly, the mTx-mRx slot-packing protocol has a 719% improvement in the value of Γ over the sTx-sRx protocol and a 138.2% gain over the sTx-mRx protocol.

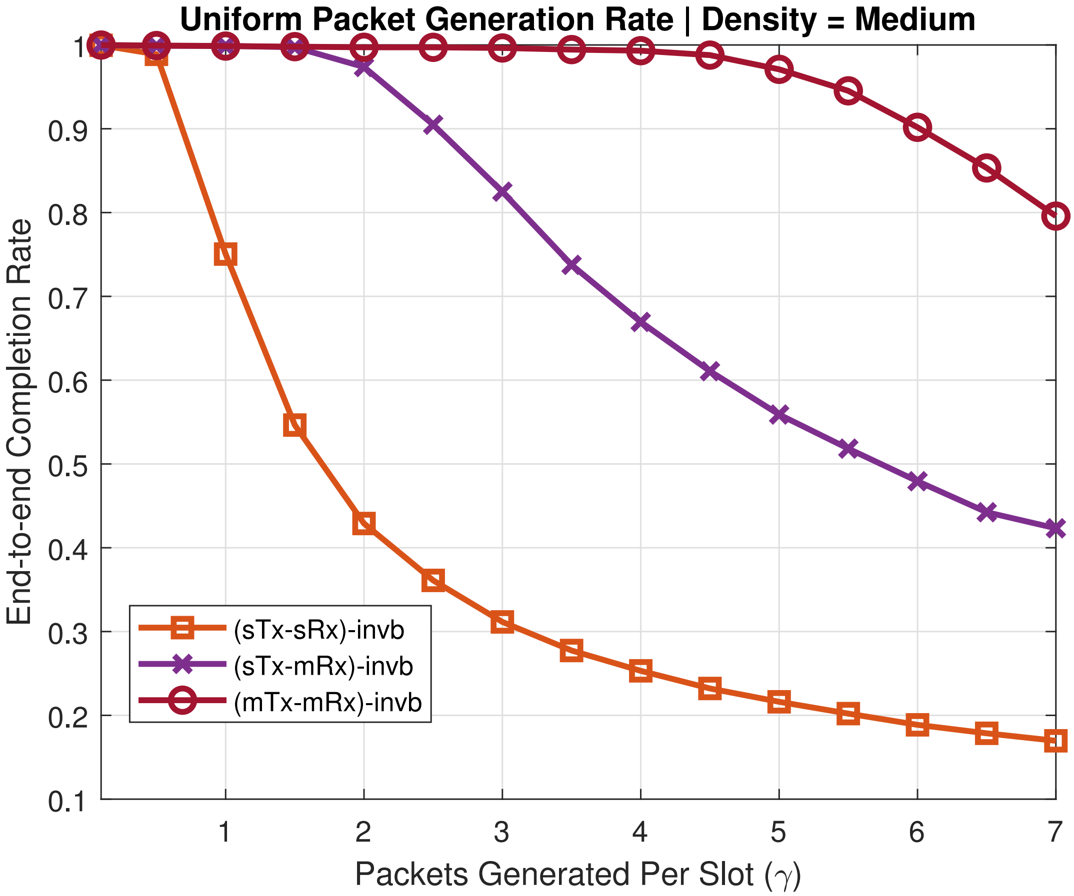


Figure 7.5: End-to-end Completion Rate for Medium Density Networks

Figure 7.6 shows the end-to-end delay results for different slot-packing protocols for networks with a medium node density. Again, the mTx-mRx slot-packing protocol has the best performance. Similar to the investigations with the low node density networks, we compare the delay values of the sTx-sRx and sTx-mRx slot-packing protocols with that of the mTx-mRx slot-packing protocol at their respective Γ values. Accordingly, the sTx-sRx slot-packing protocol has a 501.5% increase and the sTx-mRx slot-packing protocol has a 319.3% increase in delay over the mTx-mRx protocol, respectively. The improvement in the delay performance also results in an improvement in the end-to-end throughput and is shown in the Figure 7.7.

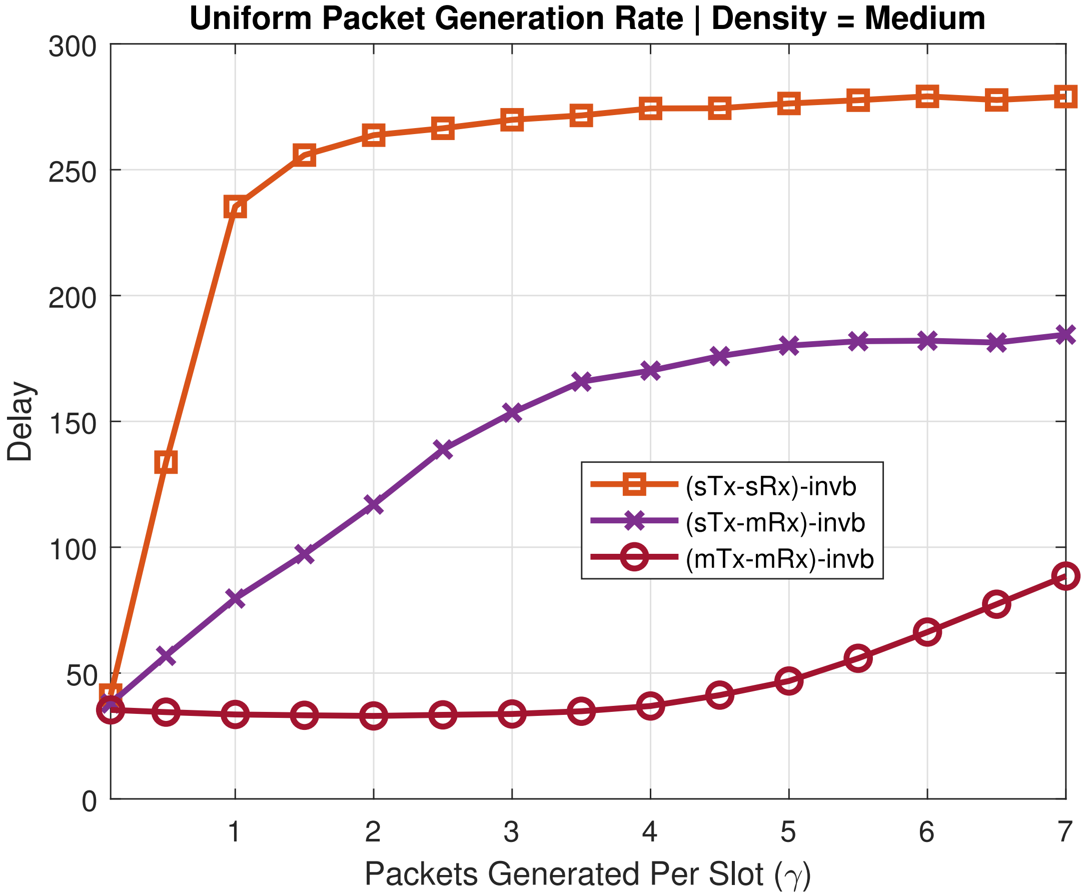


Figure 7.6: Delay for Medium Density Networks

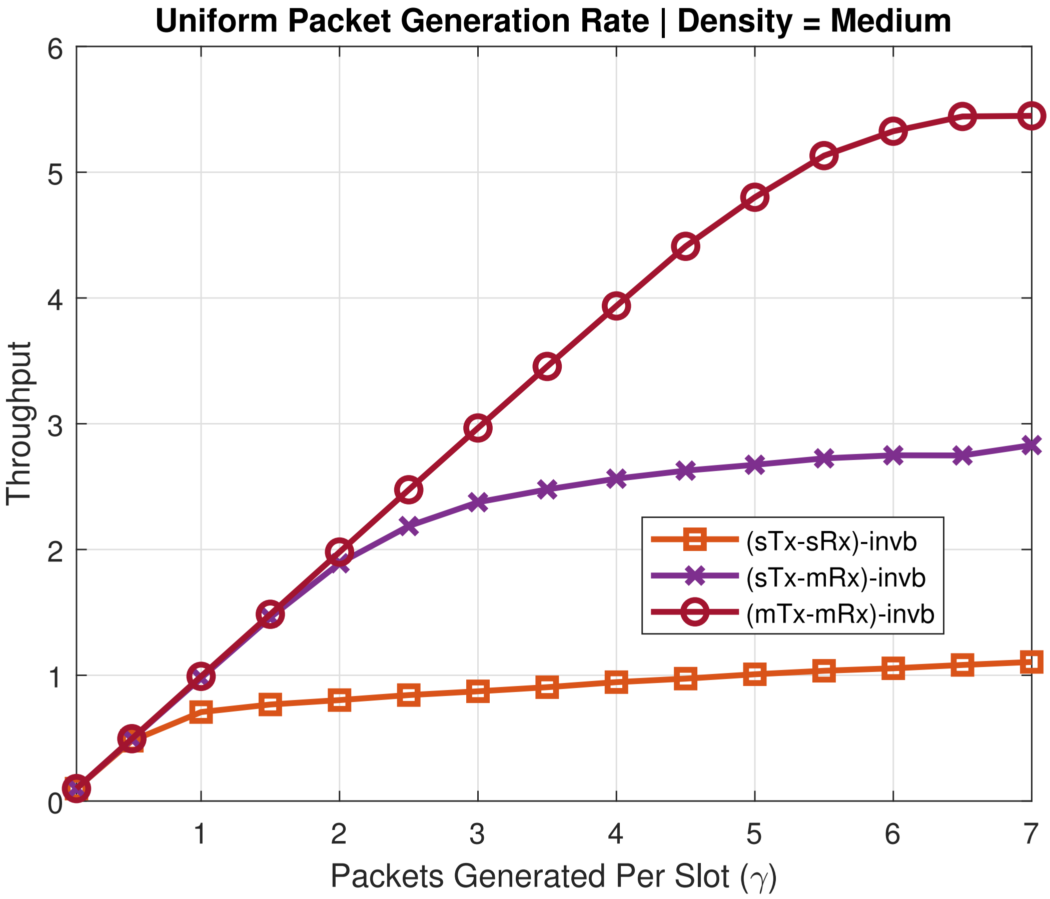


Figure 7.7: Throughput for Medium Density Networks

Figure 7.8 shows the average percentage of auxiliary transmissions per node for different slot-packing protocols in networks with a medium node density. Similar to experiments with the low node density networks, at low packet generation rates all the slot-packing protocols have a similar percentage of auxiliary transmissions. However, in the cases of the sTx-sRx and sTx-mRx slot-packing protocols the percentage of auxiliary transmissions decreases more rapidly as the packet generation rate increases. In medium density networks fewer number of nodes are scheduled to transmit in the same slot. As a result the probability that a primary node has at least one packet queued in its assigned slot is even higher than in the networks with low node density and opportunity for an auxiliary node to have access to the channel decreases more rapidly.

On the other hand the mTx-mRx slot-packing technique is able to maintain a high percentage of auxiliary transmissions despite increased number of primary transmissions. In denser networks there is an abundance of high quality links. A higher percentage of auxiliary transmissions indicates that even at higher packet generation rates the primary nodes are not able to fully utilize their assigned slots as they are likely transmitting at a faster data rate. The mTx-mRx slot-packing technique allows these gaps in the slots to be filled by auxiliary transmissions leading to a better network performance.

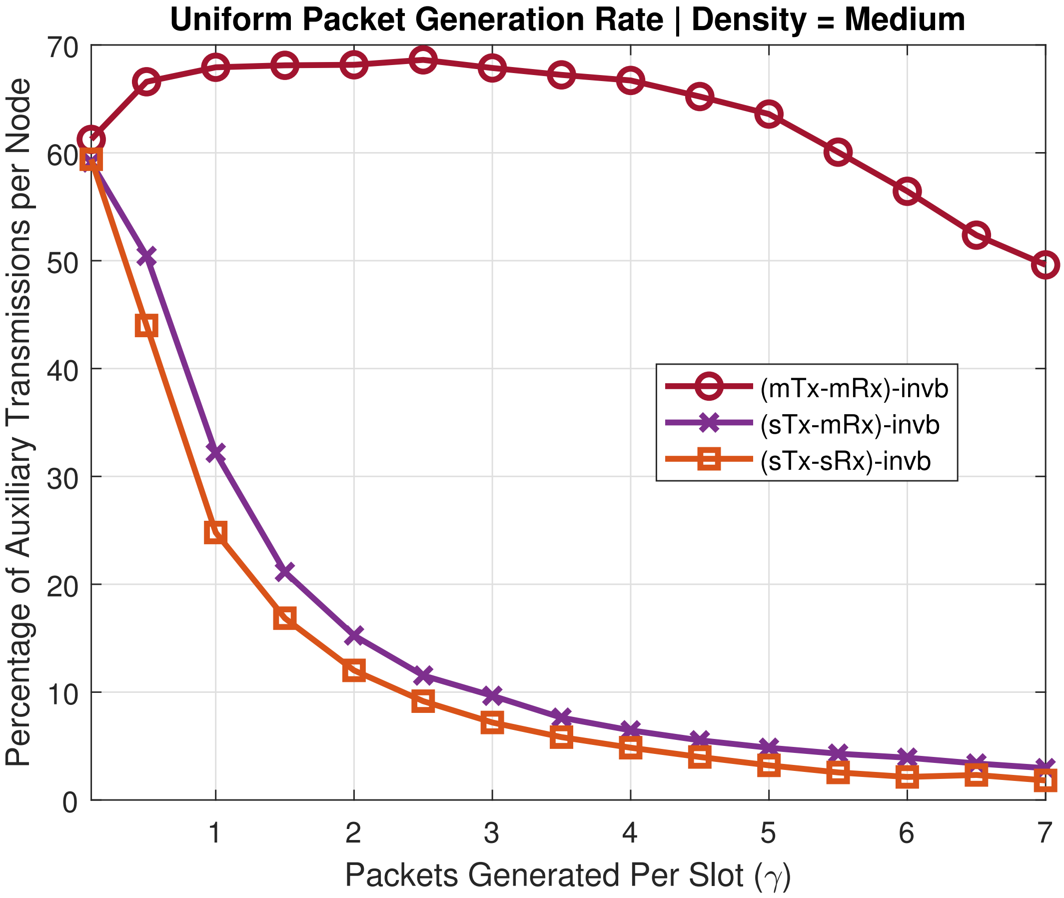


Figure 7.8: Percentage of Auxiliary Transmissions in Medium Density Networks

Figure 7.9 shows the end-to-end completion rate for RMTS-a with different slot-packing protocols for networks with high node density. Like for the investigations with the other node densities, the mTx-mRx slot-packing protocol has the best network performance. The values of Γ are compared for the different slot-packing protocols. Accordingly, the mTx-mRx slot-packing protocol has a 1244% improvement in the value of Γ over the sTx-sRx method and a 169.5% gain over the sTx-mRx method.

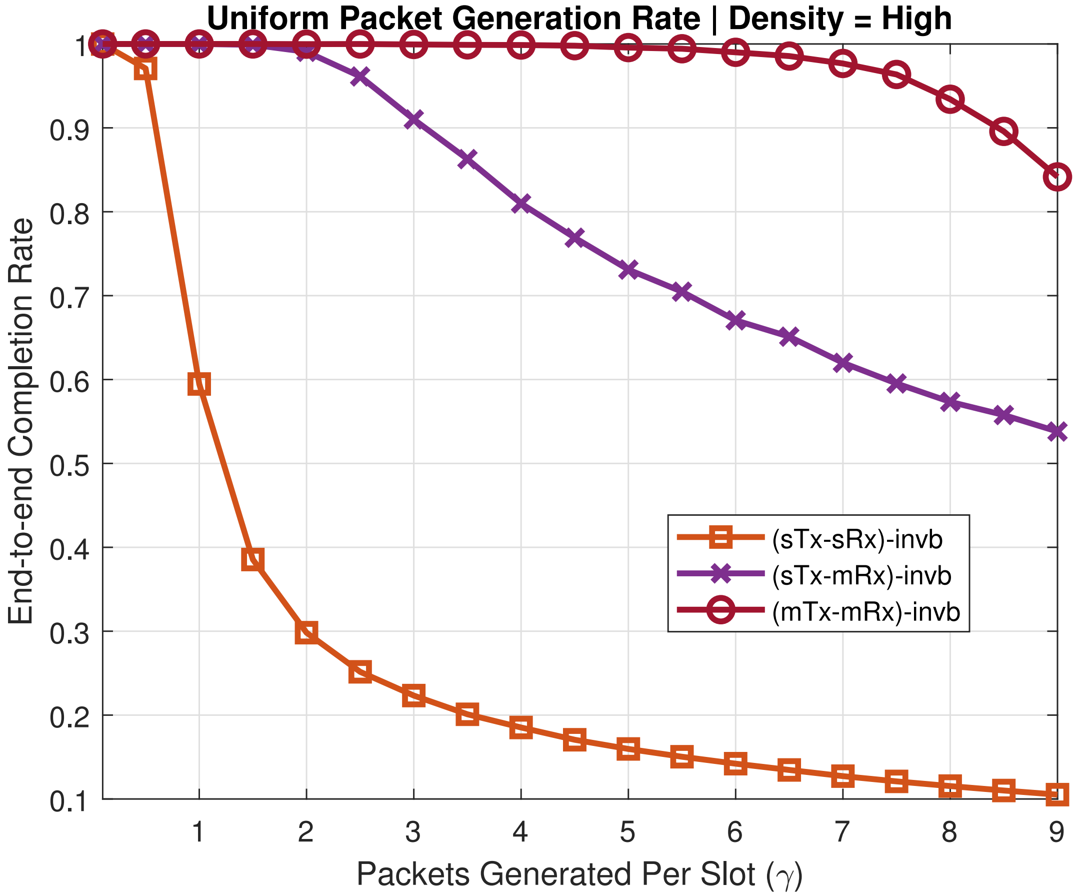


Figure 7.9: End-to-end Completion Rate for High Density Networks

Figure 7.10 shows the end-to-end delay results for the different slot-packing protocols for networks with high node density. Again, the mTx-mRx slot-packing protocol has the best delay performance. Similar to the previous cases we compare the delay of the sTx-sRx and sTx-mRx slot-packing protocols with that of the mTx-mRx slot-packing protocol at their respective Γ values. Accordingly, the sTx-sRx slot-packing technique has a 329.5% increase and the sTx-mRx slot-packing technique has a 252.1% increase in delay over the mTx-mRx method, respectively. The improvement in the delay performance results in an improvement in the end-to-end throughput and is shown in the Figure 7.11.

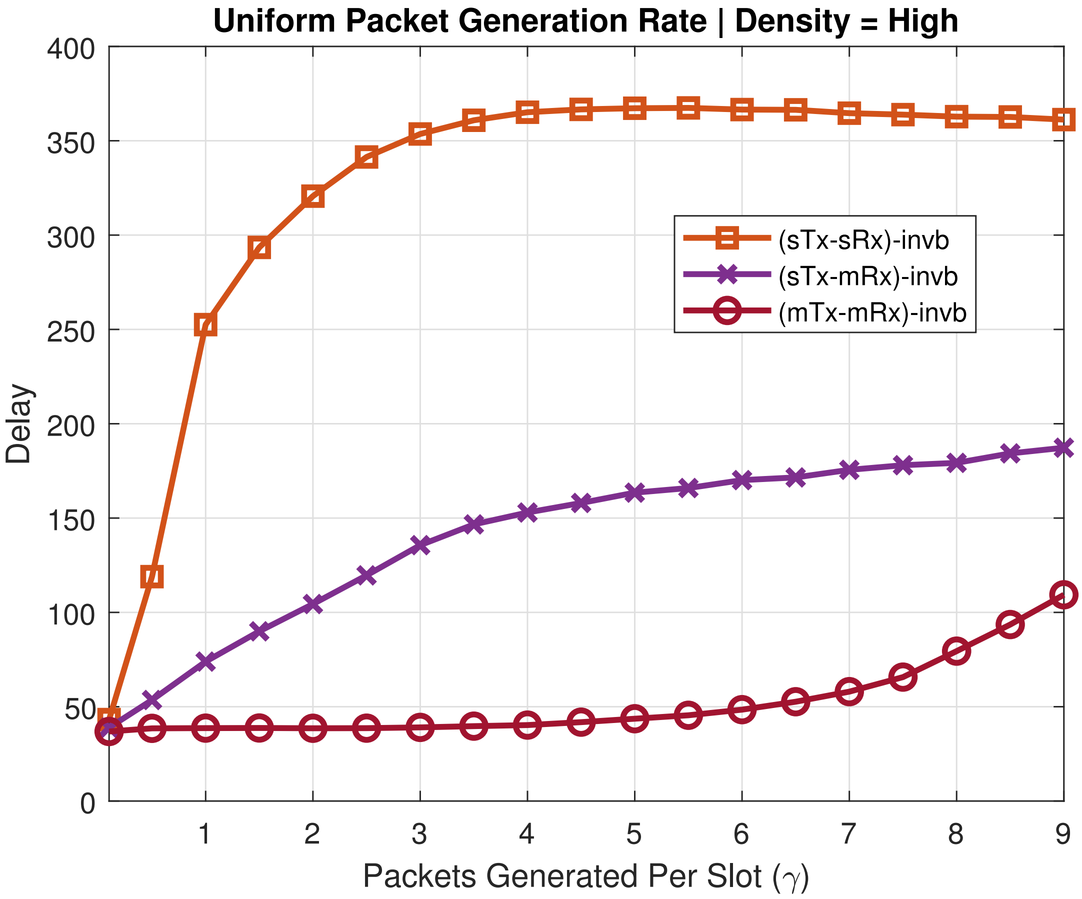


Figure 7.10: Delay for High Density Networks

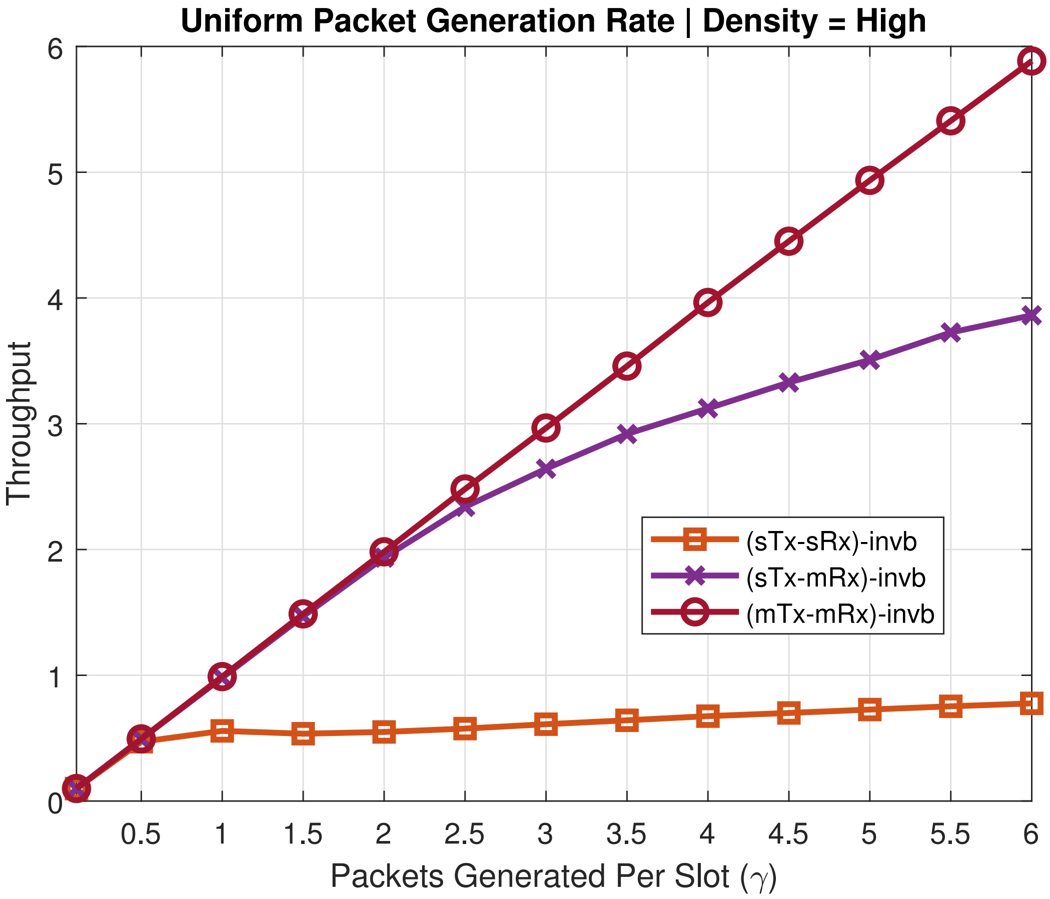


Figure 7.11: Throughput for High Density Networks

Figure 7.12 shows the average percentage of auxiliary transmissions per node for the different slot-packing protocols in networks with high node density. Because the density of the networks is highest among all the investigations the percentage of auxiliary transmissions decays even more rapidly for the sTx-sRx and sTx-mRx slot-packing protocols as the packet generation rate increases. However, the mTx-mRx slot-packing protocol maintains a consistently high level of auxiliary transmissions for the most part but it gradually starts to drop at very high packet generation rates. This indicates that even in networks with high node density where only one node is scheduled to transmit in any given slot the primary transmitters are not able completely utilize the slots assigned to them and mTx-mRx slot-packing protocol is essential to fill those gaps in these slots.

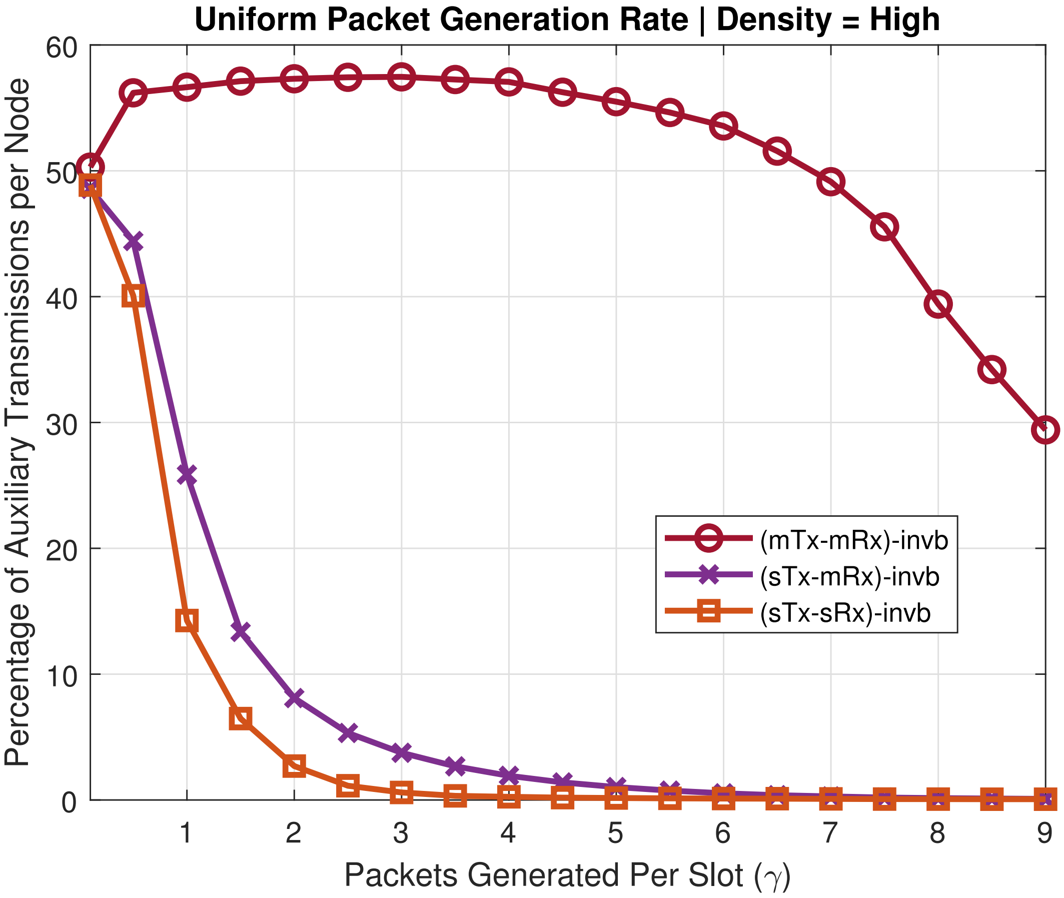


Figure 7.12: Percentage of Auxiliary Transmissions in High Density Networks

7.1.1 Summary

To summarize, the performance of RMTS-a with different slot-packing protocols and routing approaches is compared for networks with varying node densities. The RMTS-a protocol with mTx-mRx slot-packing and inv-bitrate routing metric has the best performance across all the above experiments. In order to achieve good network performance it is critical to route most of the traffic through the links that support faster data rates. While this increases the number of relays it helps utilize the slots more efficiently. Even at higher packet generation rates the nodes that are assigned to transmit in specific time slots are not able to fully utilize them. This results in gaps where the channel is idle. In the mTx-mRx slot-packing protocol there are multiple auxiliary nodes that are candidates to transmit during these idle channel gaps. This helps improve the overall utilization of the channel leading to a better network performance. In denser networks there is an abundance of links that support higher data rates. As a result, there is a higher probability that a node is not able completely utilize the slot assigned to it. Hence, the advantage of using auxiliary transmitters to fill these idle times is more significant in dense networks. The values of Γ for all of the scenarios presented in the previous section are listed in Table 7.1 and the values of percentage increase in delay over mTx-mRx packing are listed in Table 7.2.

Table 7.1: Values of Γ

Density	sTx-sRx	sTx-mRx	mTx-mRx	% imp in Γ	
				sTx-sRx	sTx-mRx
D-1 ($1/25^2$)	0.63	3.13	8.4	1244%	169.5%
D-2 ($1/50^2$)	0.74	2.53	6.04	719%	138.2%
D-3 ($1/75^2$)	1.24	2.09	3.63	192.8%	73.7%

Table 7.2: Values of Percentage Increase in Delay

Density	% inc in delay over mTx-mRx	
	sTx-sRx	sTx-mRx
D-1 ($1/25^2$)	329.5%	252.2%
D-2 ($1/50^2$)	501.5%	319.2%
D-3 ($1/75^2$)	531.7%	214.2%

For all the results that follow we only show the data for RMTS-a with mTx-mRx slot-packing method unless otherwise specified.

7.1.2 Ordering the Auxiliary Nodes

In RMTS-a each node in the network forms a list of eligible nodes that can serve as its auxiliary nodes. In this section the performance of RMTS-a with different approaches to ordering the auxiliary nodes is presented. Three different approaches to ordering the auxiliary nodes is considered: utilization, queue length, and random order.

Figure 7.13 shows the end-to-end completion results for RMTS-a using different approaches to order the auxiliary nodes for networks with low density. The improvement in performance with ordered auxiliary nodes over the case with random auxiliary nodes is not significant. In networks with a low density the average number of eligible 1-neighbors from which a node can pick its auxiliary nodes is 4.44 which is less than the maximum limit N_a (i.e., 5). Ordering them does not produce a significant improvement in performance. In all the preceding sections the delay and throughput results follow a similar trend compared to the end-to-end completion rate results. So they are not shown in this chapter but are included in the Appendix A. Figure A.1 shows the delay and throughput results for this case.

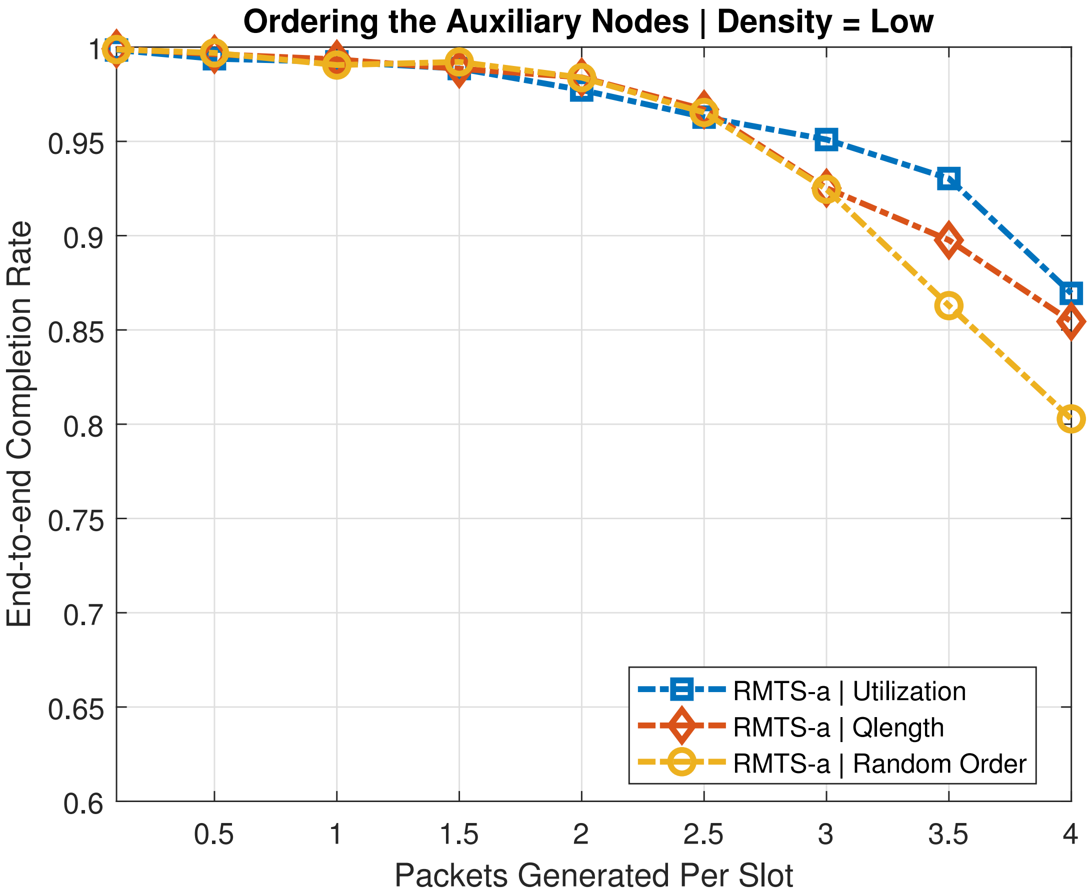


Figure 7.13: Effect of Ordering the Auxiliary Nodes for Networks With Low Density Using mTx-mRx Slot-packing

Figure 7.14 shows the end-to-end completion rate results for the three metrics for ordering of auxiliary nodes in RMTS-a for networks with medium node density. Ordering the auxiliary nodes based on utilization results in the best network performance, with an increase of 32% in the value of Γ over selecting nodes with a random order. In these networks the packets typically need to travel multiple hops to reach their destinations (in medium density networks on average a packet needs to travel four hops to reach its destination). In such multi-hop networks depending on the topology of the network certain nodes are likely to relay more packets than the others. This creates a disparity in the access priority amongst the nodes in the network. In networks with medium density the average number of eligible 1-neighbors from which a node can pick its auxiliary nodes is 9.99 which is almost double the maximum limit N_a. Thus, the algorithm for picking the auxiliary nodes from the list of eligible nodes has an impact on the network performance. A node is given more access priority by having multiple transmitters select it as their auxiliary node and this is achieved by ordering the auxiliary nodes based on utilization.

Utilization works as a better metric than queue size to identify the nodes that require more access priority. In our network simulations the majority of the packets are dropped as a result of full queues. Using the queue sizes to order the auxiliary nodes works well during the first time the auxiliary node lists are updated, and the nodes whose queues are full are given more transmission opportunities because they are selected as auxiliary transmitters more often. This results in reduced queue sizes at these nodes. The next time the auxiliary node lists are updated these nodes report a much smaller queue size and this results in reduction of transmission opportunities for these nodes because they will be selected as auxiliary transmitters by fewer nodes. This causes the queue to fill up again at these nodes and results in more dropped packets. Utilization on other hand is able to identify the nodes that are busier without having to wait for the queue sizes to grow. Additionally, we observed that the value of utilization does not vary significantly between auxiliary set updates. The delay and throughput results are shown in Appendix A (Figure A.2).

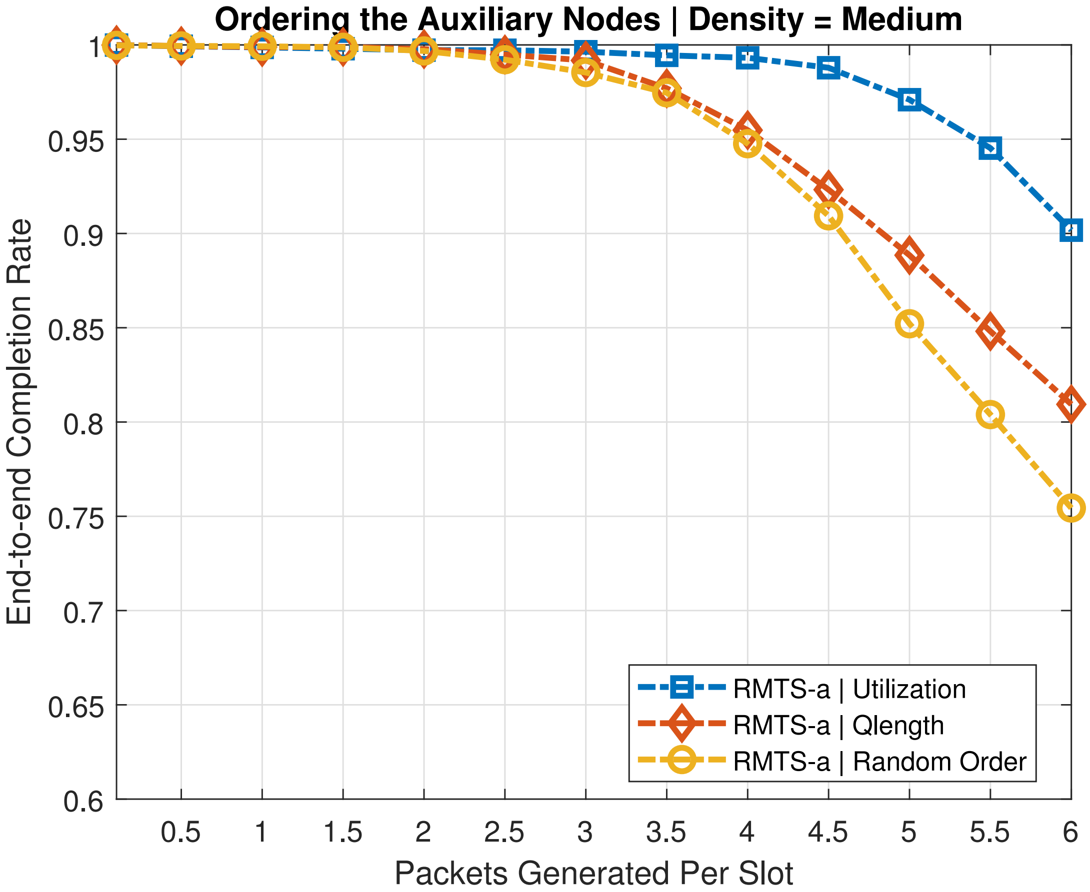


Figure 7.14: Effect of Ordering the Auxiliary Nodes for Networks With Medium Density Using mTx-mRx Slot-packing

Figure 7.15 shows the end-to-end completion data for the three variations of RMTS-a mentioned earlier for networks with high density. Once again ordering the auxiliary nodes based on utilization results in the best performance. In networks with high node density the average number of hops that a packet travels to reach its destination is approximately 2 hops. These networks are not as prone to bottlenecks as compared to networks with low and medium node density. Hence, while ordering the auxiliary nodes results in better performance the improvement is not as significant compared to the case of networks with medium node density. The delay and throughput results are shown in Appendix A (Figure A.3).

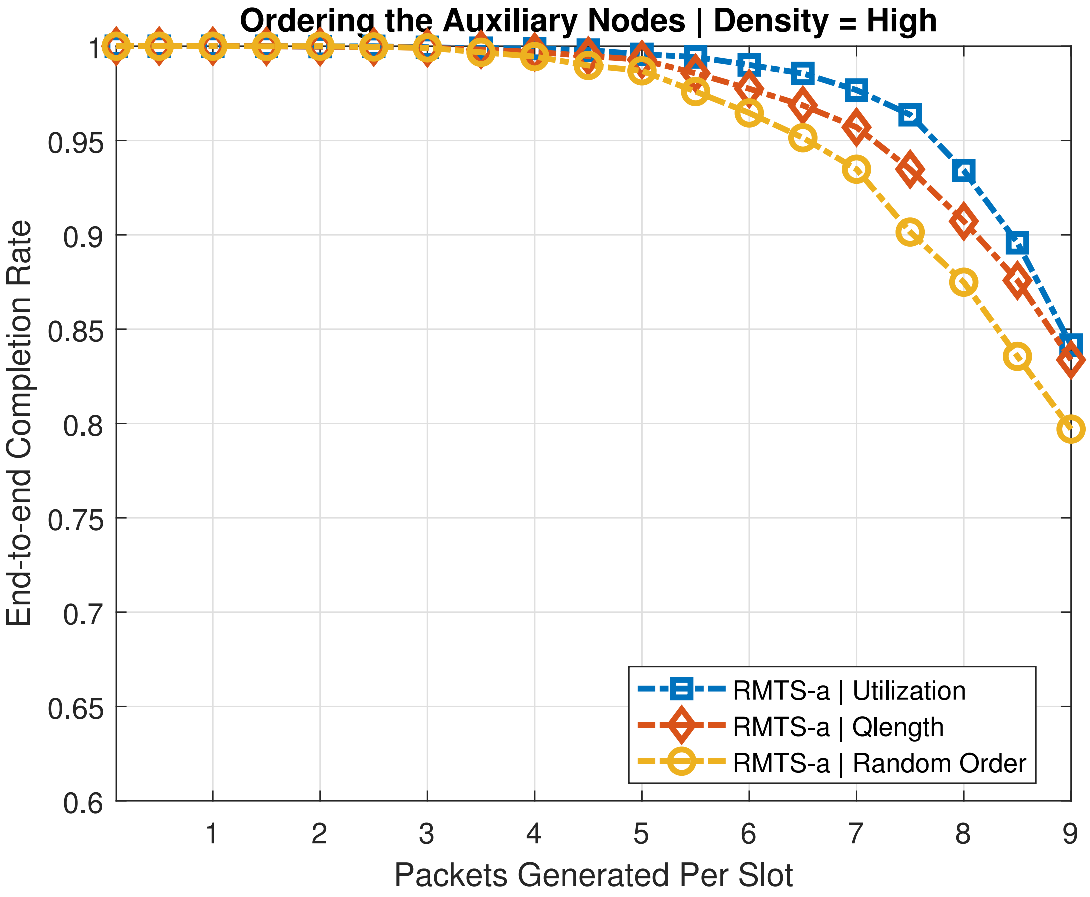


Figure 7.15: Effect of Ordering the Auxiliary Nodes for Networks With High Density Using mTx-mRx Slot-packing

7.1.3 Summary

To summarize, ordering the auxiliary nodes based on some metric ensures that the nodes that have higher value of that metric will be selected more often as auxiliary nodes. This provides more access priority to these nodes through auxiliary transmission opportunities. Nodes experiencing high level of traffic can be given more transmission opportunities by ordering the auxiliary nodes based on their utilization values as opposed to selecting them randomly. Note, however, that the improvement in network performance due to ordering the auxiliary nodes over simply choosing them randomly is significant only for the networks with a medium density of nodes. In this topology there are more than N_a candidates to be auxiliary nodes than in the networks with a low node density. Also, the need to relay packets multiple times creates more bottleneck nodes than in networks with a high node density and fewer relays. The average and maximum number of relays for each of the network densities is listed in Table 6.1.

7.2 Gamma Packet Generation Model

In all the results presented in Section 7.1 we use a uniform packet generation model in which all nodes have the same probability of generating a packet at the beginning of a slot. The motivation to test the performance of RMTS-a in networks with non-uniform packet generation model is two fold. First, while it is common to use uniform packet generation model in network simulations it does not accurately model many real network situations. Second, traditional scheduling protocols tend to perform poorly in networks with non-uniform traffic as slots are assigned almost equally to the nodes irrespective of the load at the nodes. In order to create non-uniform traffic scenarios we use a gamma packet generation model described in Chapter 6. In the gamma packet generation model each node has a different probability of generating a packet at the beginning of a slot. This results in a disparity in traffic generated at nodes resulting in different channel access requirements at different nodes.

To motivate this section, the performance of Lyui's algorithm [17] (a traditional scheduling algorithm) using sTx-mRx slot-packing is compared for four packet generation models: uniform, gamma1, gamma2, and gamma3 for networks with a high density of nodes. Here the slots are assigned by Lyui's algorithm and the candidate nodes use sTx-mRx slot-packing to pack the slot. Figure 7.16 shows the end-to-end completion rate for Lyui's algorithm with the sTx-mRx slot-packing technique for different packet generation models in networks with a high node density. The performance of Lyui's protocol drops off significantly in networks with gamma3 packet generation model as compared to the performance in networks with uniform packet generation model. This is a consequence of Lyui's algorithm assigning slots to nodes almost equally irrespective of the traffic demands. The delay and throughput graphs are included in Appendix A (A.4).

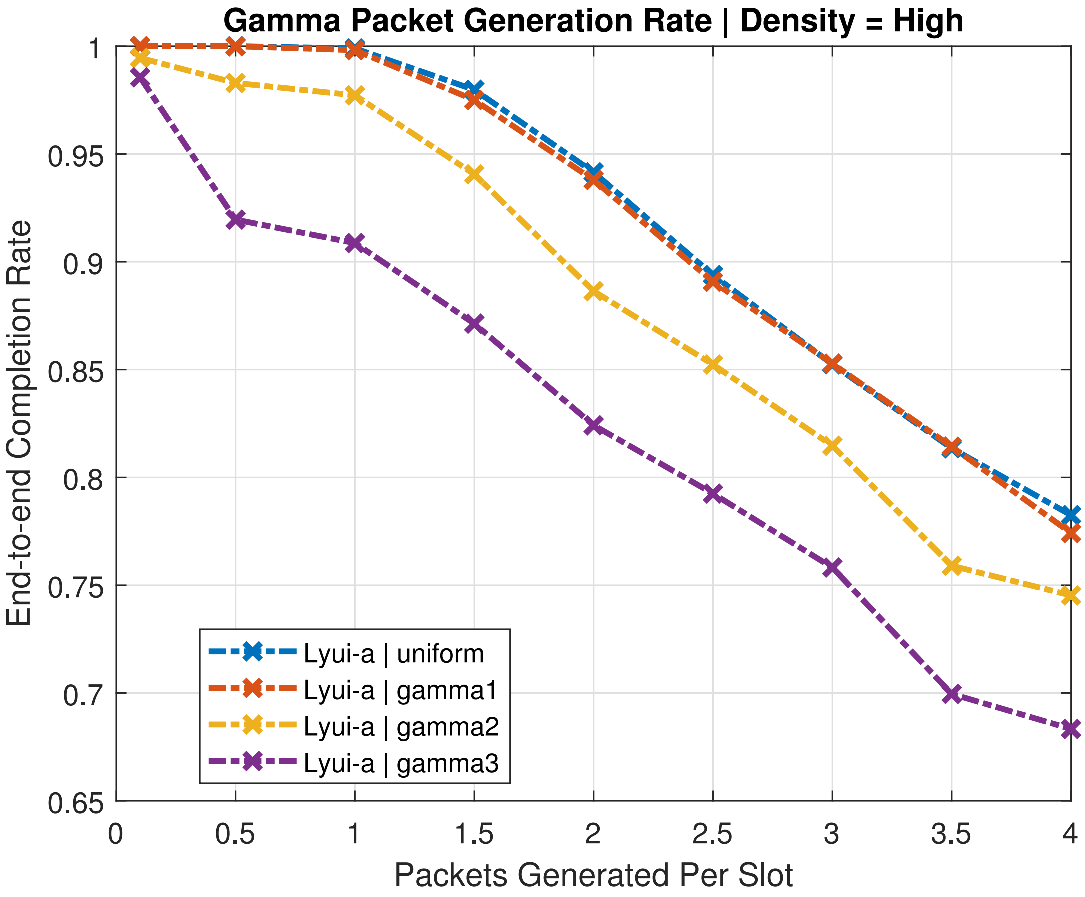


Figure 7.16: Comparison of Performance of Lyui's Algorithm Under Different Packet Generation Models for Networks With High Density Using sTx-mRx Slot-packing

The performance of RMTS-a with mTx-mRx slot-packing is compared for four packet generation models: uniform, gamma1, gamma2, and gamma3. Uniform packet generation model creates a scenario where all nodes have the same probability of generating a packet. The gamma packet generation model creates a scenario where each node has a different probability of generating a packet. Gamma1 model represents a case where the variance in the packet generation probabilities is the least and gamma3 model represents the case where the variance in highest, creating a scenario in which only a few nodes in the network generate most of the traffic. Figures 7.17, 7.18, and 7.19 show the end-to-end completion rate data for RMTS-a with the mTx-mRx slot-packing technique for different packet generation models in networks with low, medium, and high density, respectively. In all the cases RMTS-s with the mTx-mRx slot-packing technique is able to maintain the same level of performance irrespective of the packet generation model used.

Like in traditional scheduling approaches, the RMTS-a scheduling protocol assigns all the nodes in the network a similar number of primary transmissions opportunities. The nodes that generate traffic at a lower rate have many partially used or unused slots. These slots are utilized by the nodes with more traffic through auxiliary transmissions. So by design RMTS-a is able to support nodes with different traffic levels. The graphs for delay and throughput follow a similar trend and are included in Appendix A. (Figures A.5, A.6, and A.7).

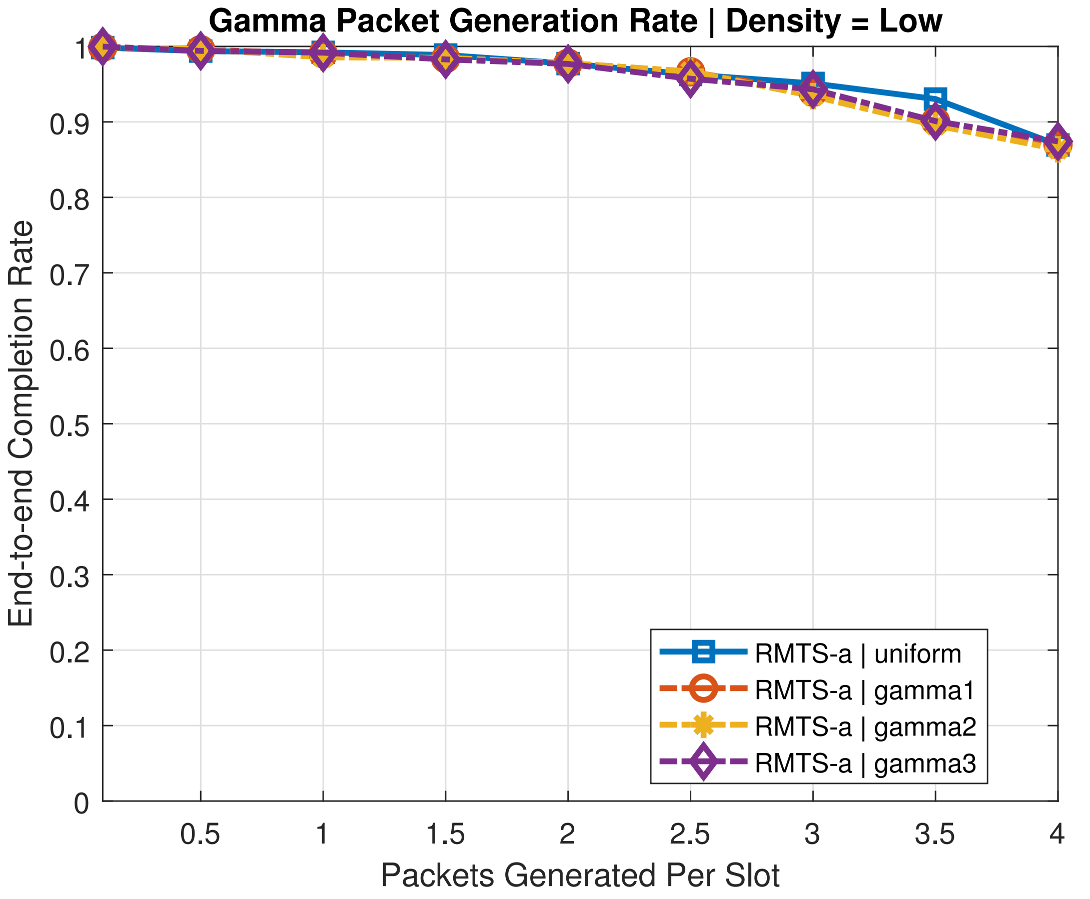


Figure 7.17: Comparison of Performance Under Different Packet Generation Models for Networks With Low Density Using mTx-mRx Slot-packing

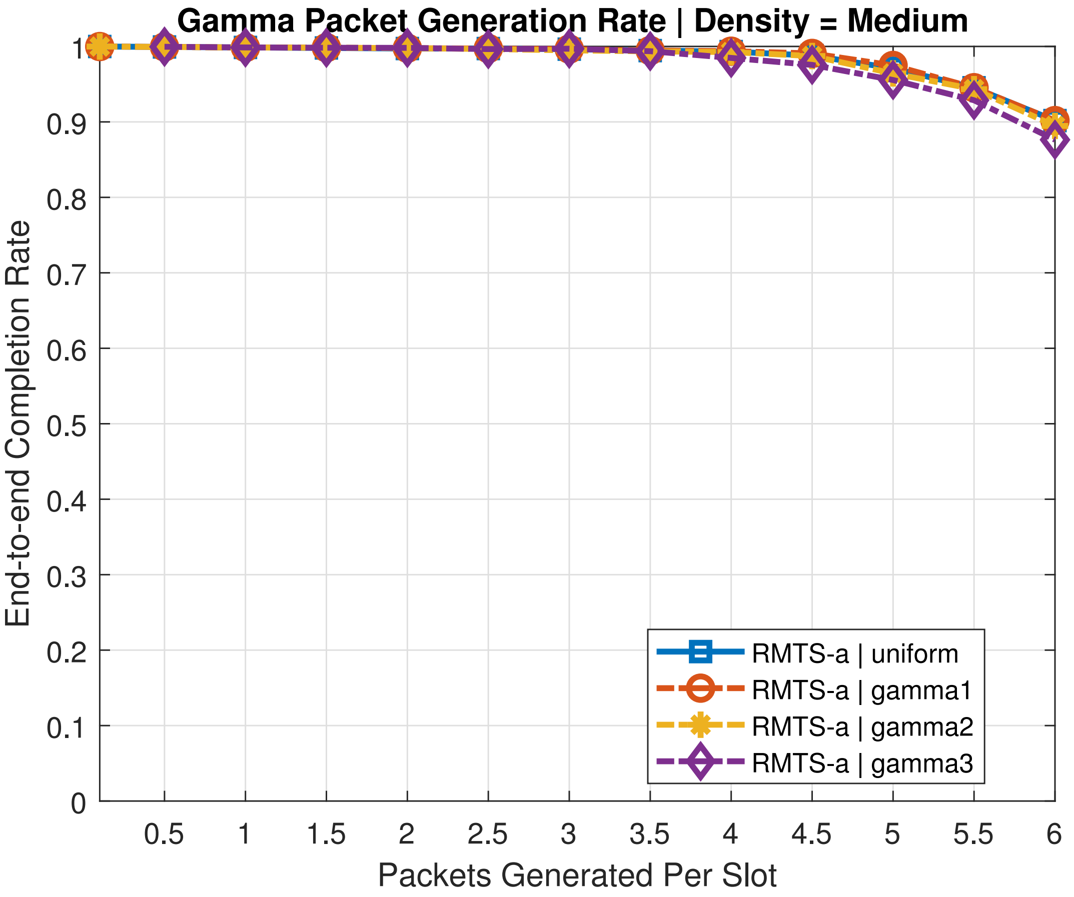


Figure 7.18: Comparison of Performance Under Different Packet Generation Models for Networks With Medium Density Using mTx-mRx Slot-packing

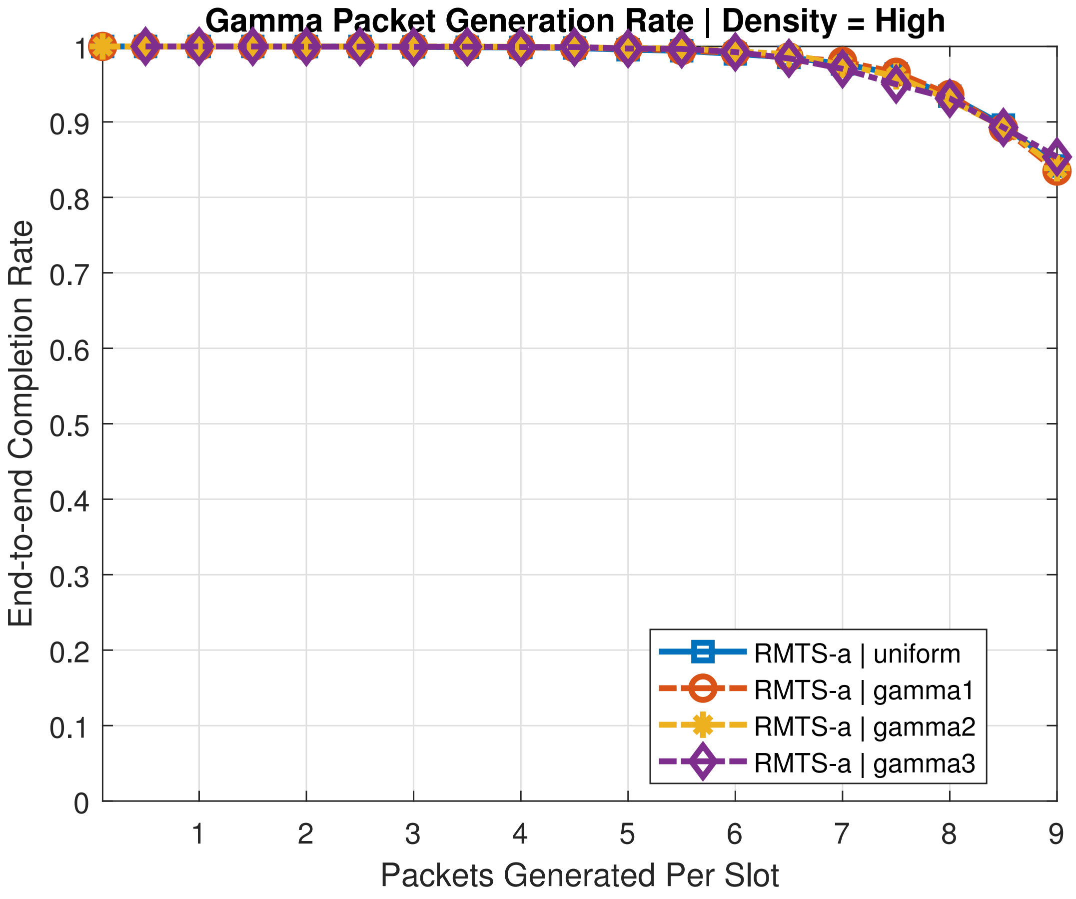


Figure 7.19: Comparison of Performance Under Different Packet Generation Models for Networks With Medium Density Using mTx-mRx Slot-packing

7.2.1 Summary

To summarize, the RMTS-a protocol is able to maintain good network performance across different networks with varying packet generation models. The nodes with higher traffic levels are provided with more transmission opportunities through the auxiliary transmissions that are available due to nodes that under utilize their assigned slots. The results included in the Appendix include a large number of additional investigations with the gamma traffic generation model. These results show a similar conclusion compared to the investigations with a uniform traffic generation model. In scenarios in which the distribution of traffic demands varies more widely and there are a large number of candidates for a role as an auxiliary node, selecting the auxiliary set to give a higher access probability to those nodes with a higher level of traffic results in significant improvement in network performance. Additional investigations not included here also show that randomizing the pool of candidate nodes for the auxiliary set before selecting those with a high utilization is important to ensure that the additional transmission opportunities in a neighborhood are not limited to a small common subset of auxiliary nodes.

7.2.2 Effect of Ordering the Auxiliary Nodes

In this section, the effect of ordering the auxiliary nodes is studied for scenarios with the gamma packet generation model. We focus on the results for networks that have a high density of nodes. In this scenario, the combination of the non-uniform model for generating traffic along with the large number of neighbors in a dense network results in network performance that is sensitive to the method for choosing auxiliary nodes. Figure 7.20 shows the end-to-end completion rate results for the three metrics for ordering of auxiliary nodes in RMTS-a for networks with a high node density using the gamma3 packet generation model. Using utilization to select the auxiliary nodes results in significant improvement in the network performance compared to selecting the auxiliary nodes randomly or based on queue size. Unlike in scenarios with the uniform packet generation model, when gamma3 packet generation model is used the networks with a high node density are prone to bottlenecks due to unequal traffic load in the network. To illustrate this a scatter plot of a high node density network operating using a gamma3 packet generation model is shown in Figure 7.21. The area of the circle in the figure denotes the normalized total transmissions for that node. Normalized total transmissions is calculated as the number of packets transmitted by a node divided by the maximum number of packets transmitted amongst all the nodes in the network. It is evident that certain nodes in the network forward more traffic. Giving these nodes more transmission opportunities by selecting them more often as auxiliary nodes results in improved network performance. The delay and throughput graphs are included in the Appendix A (A.16).

The investigations for networks with low and medium node density result in similar observations compared to the corresponding investigations with the uniform packet generation model. In these scenarios, the same conclusions as discussed in Section 7.1.2 apply. For completeness, these results are included in Appendix A (Figures A.8, A.9, A.10, A.11, A.12, A.13, A.14, A.15, and A.16).

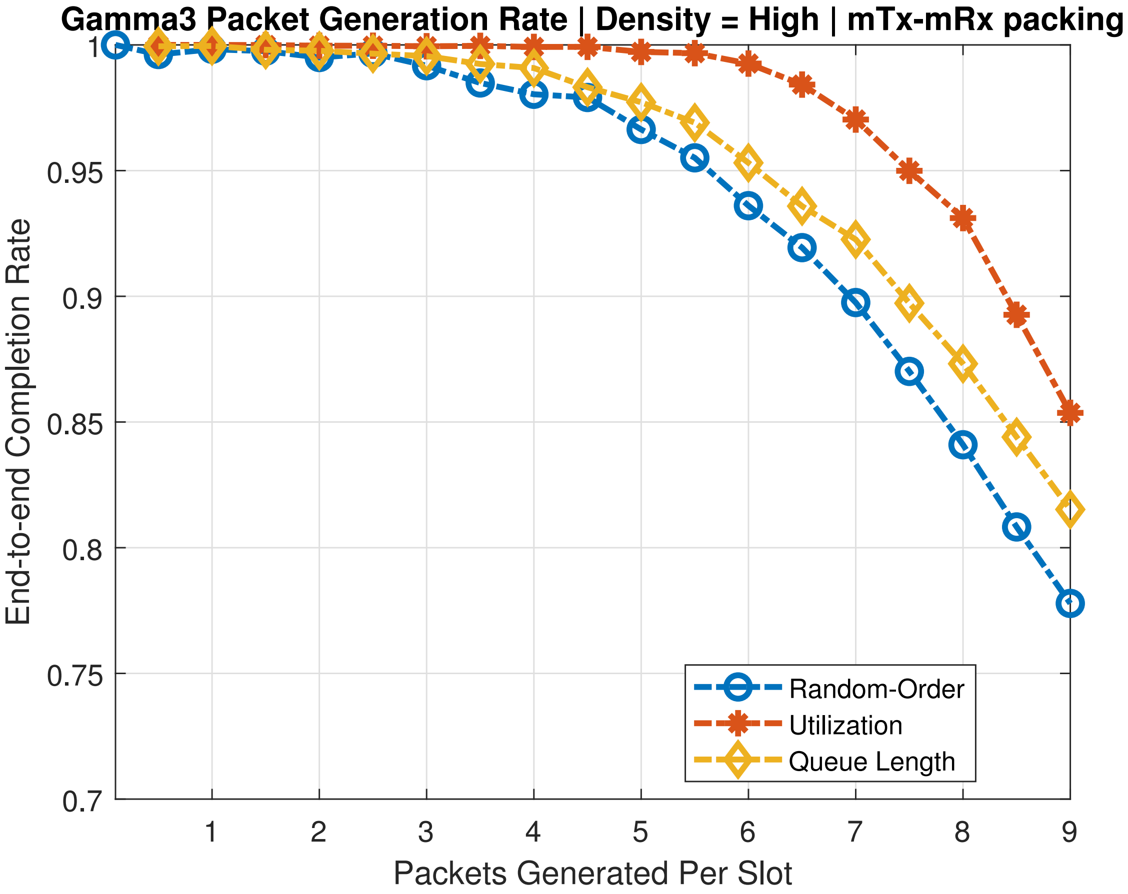


Figure 7.20: Effect of Ordering the Auxiliary Nodes for Networks With High Density Using mTx-mRx Slot-packing and Gamma3 Packet Generation Model

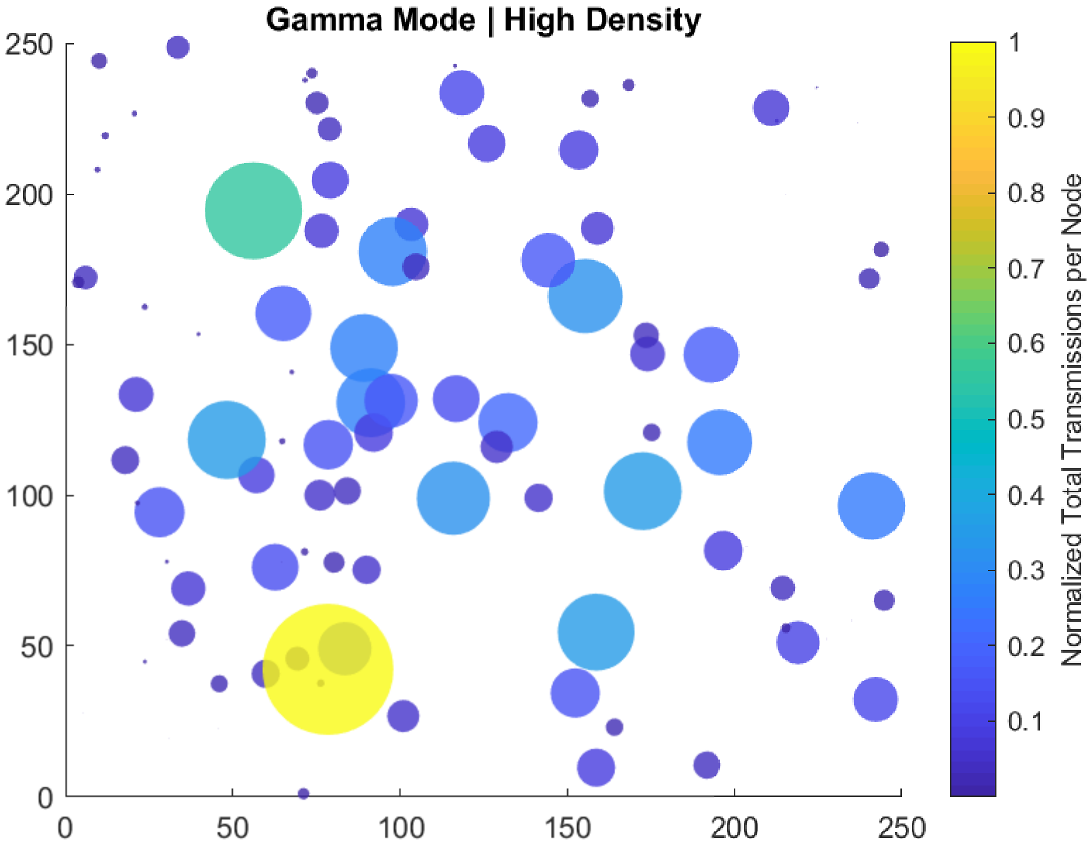


Figure 7.21: Normalized Total Transmissions in a Network With a High Density of Nodes and Gamma3 Packet Generation Model

7.3 Sink Mode Operation

In all the results presented in Sections 7.1 and 7.2 and the corresponding supplemental results in the Appendix, the destinations for the packets are distributed uniformly across all the nodes (referred to as normal mode in the results that follow). In some network applications the destinations for packets are not uniformly distributed across all nodes. For example, in some wireless sensor networks the sensors collect the data and the data is sent to a central location for further processing. To model such a scenario we consider networks in which the destination of the packets is limited to a sink node. As mentioned earlier each network spans a fixed area and the area depends on the density of the network. In this mode the sink node is fixed at the center of this area and the rest of the nodes are distributed randomly. Nodes use the uniform packet generation model.

In sink mode operation all the traffic is directed towards a central sink node. As a result the nodes in the vicinity of the sink node experience more traffic than other nodes in the network. To illustrate this a scatter plot of a low node density network operating in sink mode is shown in Figure 7.22. The nodes closer to the sink node have a higher normalized total transmissions as compared to the nodes far away from the sink. These nodes will require more transmission opportunities as a result. The goal of this section is to test the robustness of RMTS-a to automatically be able to support such networks.

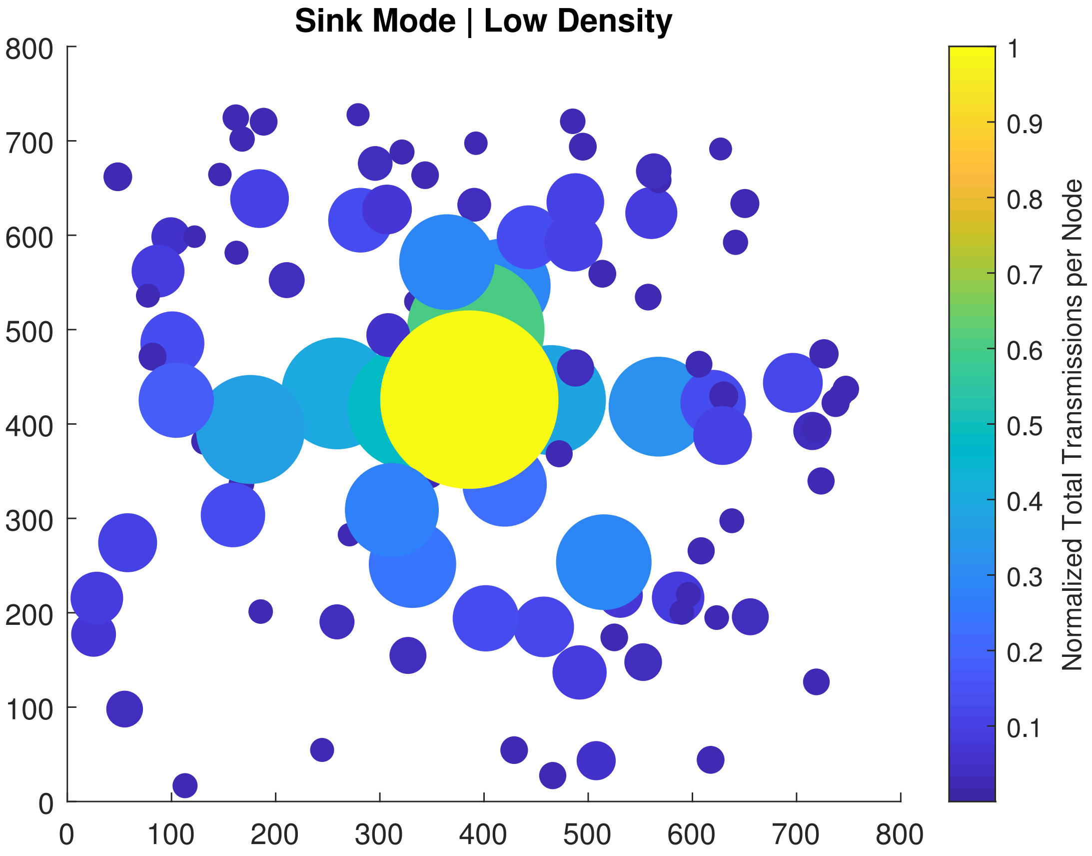


Figure 7.22: Normalized Total Transmissions in a Network With a Low Density of Nodes and a Single Destination

7.3.1 Investigations with a Uniform Traffic Model

Similar to Section 7.2 we begin by comparing the performance of Lyui's algorithm using sTx-mRx slot-packing for networks in normal mode and sink mode operation. Figure 7.23 shows end-to-end completion rate performance of Lyui's algorithm between networks in normal mode and sink mode. The performance of Lyui's algorithm is significantly poor in the sink mode as compared to the normal mode. This is the result of the inability of Lyui's algorithm to provide more transmission opportunities to the close neighbors of the sink node. The delay and throughput graphs are provided in Appendix A (A.17).

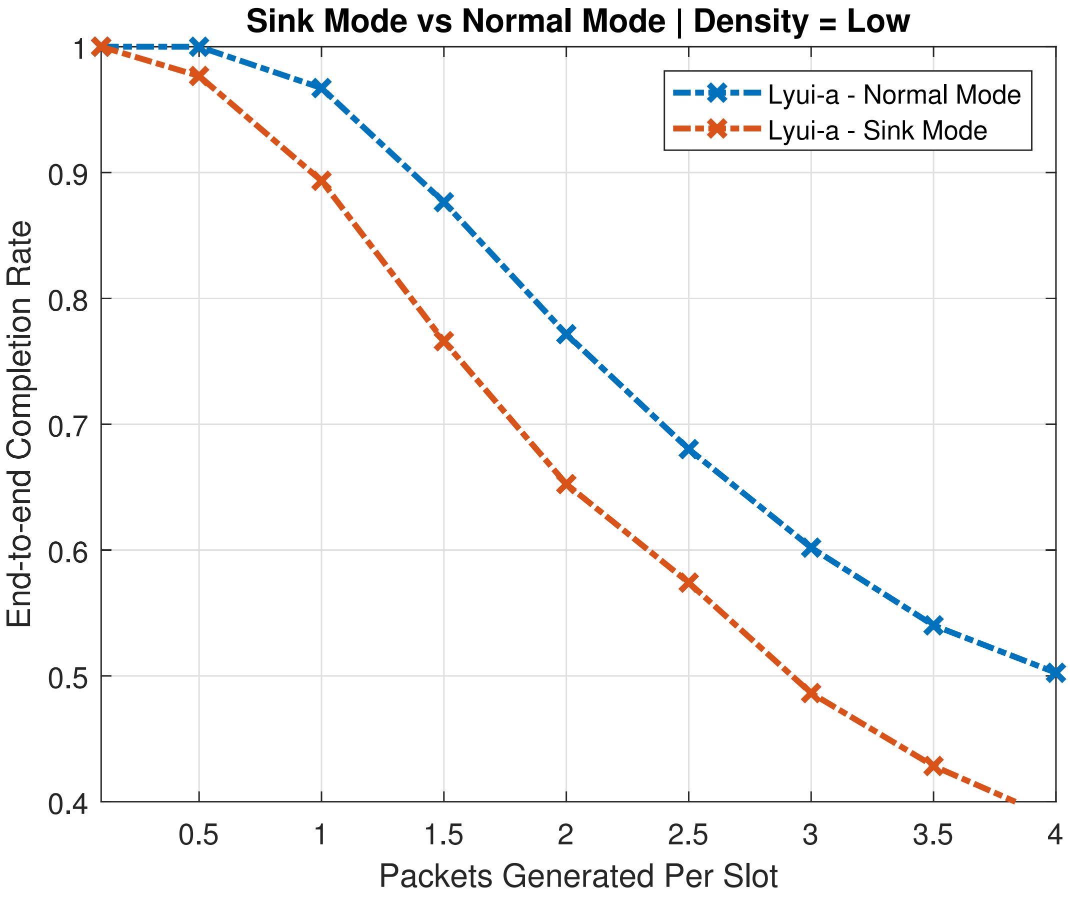


Figure 7.23: Comparison of Performance of Lyui's Algorithm Between Normal Mode and Sink Mode for Networks With Low Density

Next, the performance of RMTS-a with mTx-mRx slot-packing in normal mode is compared with performance in sink mode. In Figures 7.24, 7.25, and 7.26 the end-to-end completion rates for normal mode and sink mode are compared for networks with low, medium, and high densities, respectively. As in the previous section with unequal traffic generation rates, RMTS-a with mTx-mRx slot-packing is able to maintain a consistent level of performance in all the cases. The nodes in the vicinity of the sink-node are given more transmission opportunities through auxiliary transmissions resulting in a good performance. The delay and throughput results for these cases are included in the Appendix A (Figures A.18, A.19, and A.20).

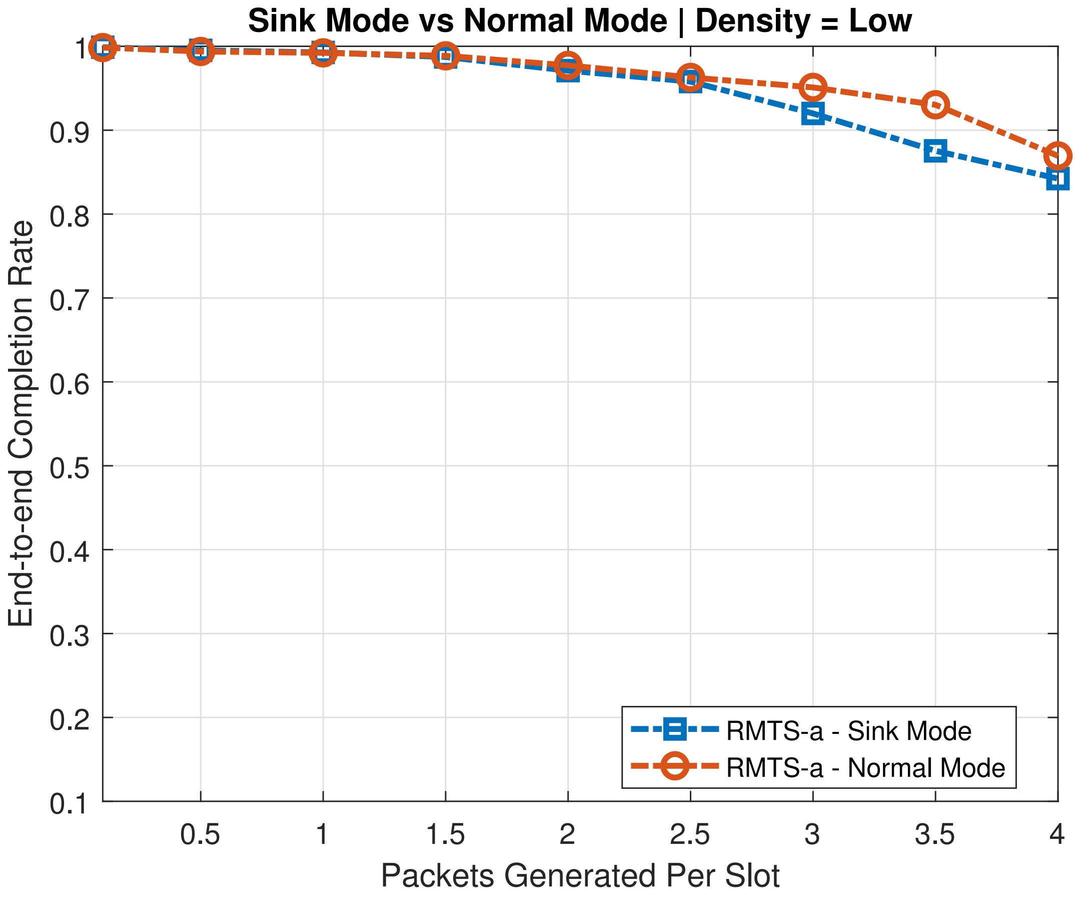


Figure 7.24: Comparison of Performance Between Normal Mode and Sink Mode for Networks With Low Density

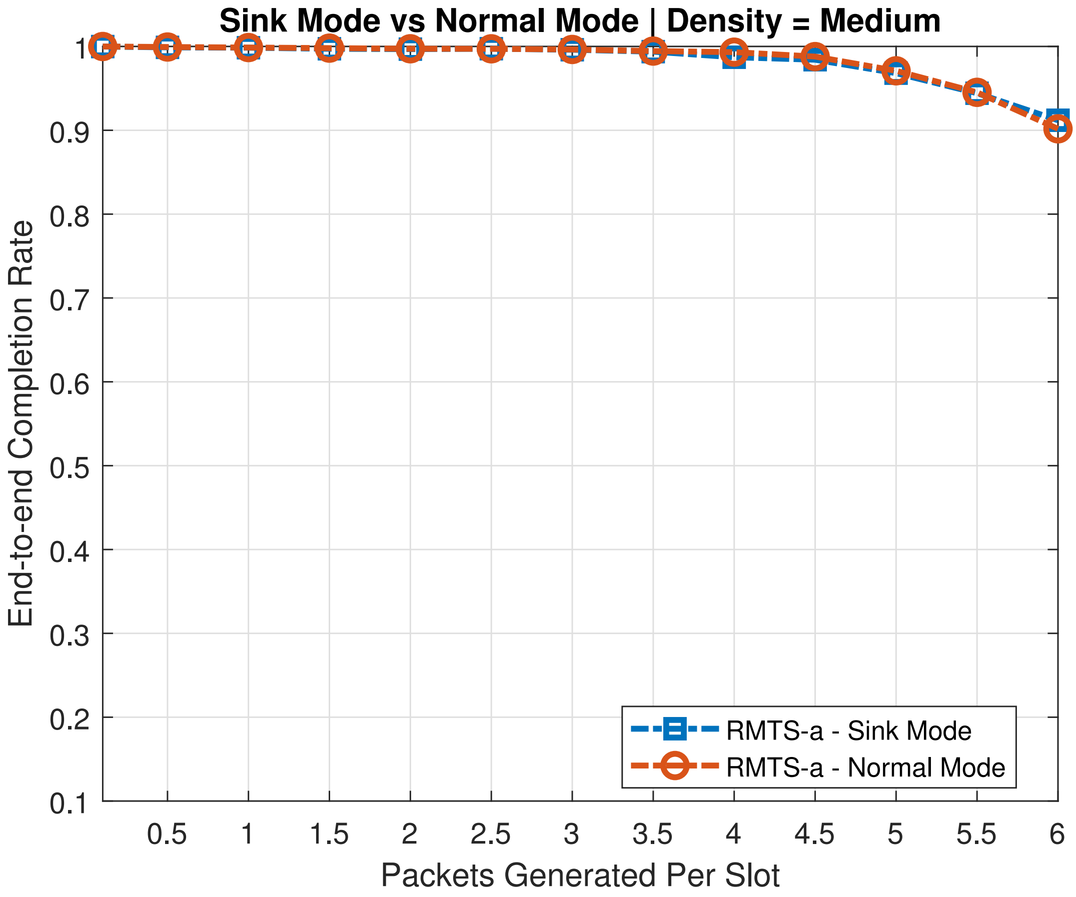


Figure 7.25: Comparison of Performance Between Normal Mode and Sink Mode for Networks With Medium Density

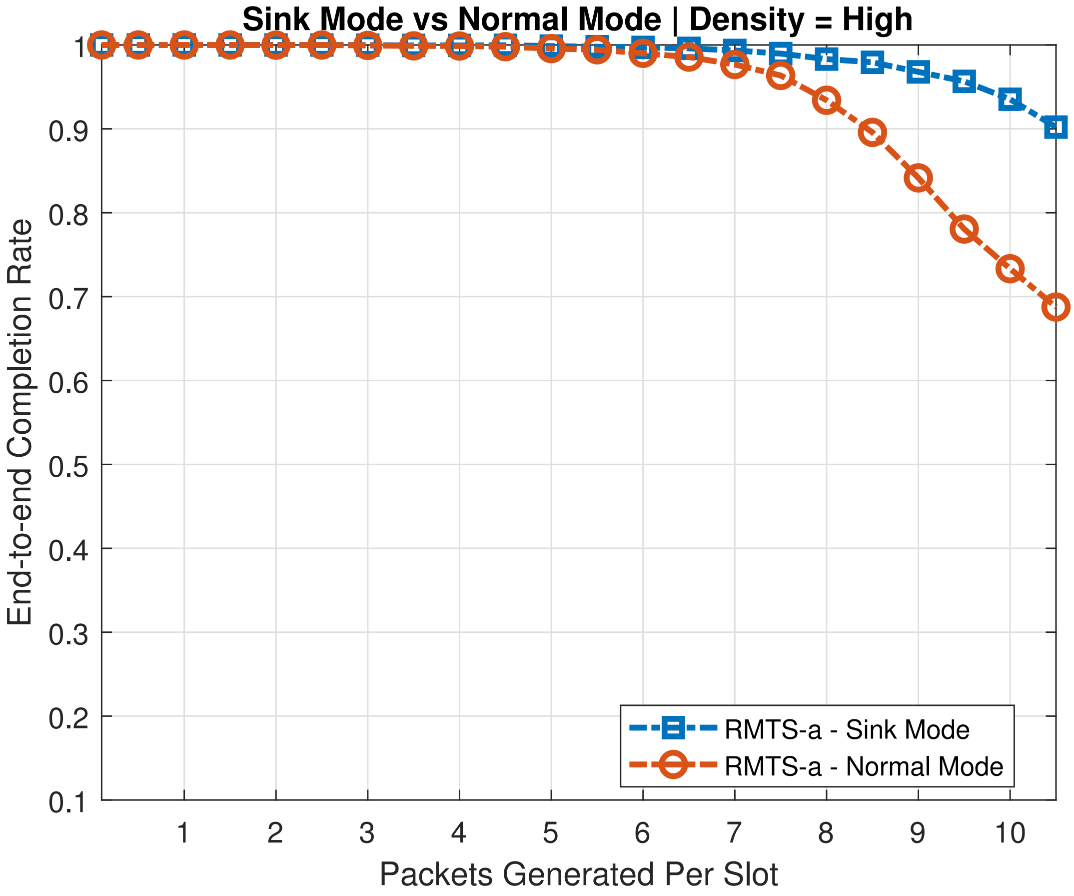


Figure 7.26: Comparison of Performance Between Normal Mode and Sink Mode for Networks With High Density

7.3.2 Effect of Ordering Auxiliary Nodes

In this section we examine the effect of ordering the auxiliary nodes in scenarios with a single sink node. As in the other scenarios in which there is a significantly unequal distribution of traffic, a critical feature of the RMTS-a protocol is the careful selection of the nodes that are provided with additional transmission opportunities. Once again the results for networks with a low and medium node density are similar to the scenario with uniform packet generation model and are shown in the Appendix

A (Figures A.21, A.22, and A.23). Figure 7.27 shows the end-to-end completion rate results for the three metrics for ordering of auxiliary nodes in RMTS-a for networks with high node density and a single destination. Using utilization to select the auxiliary nodes results in significant improvement in the network performance over the case where the auxiliary nodes are selected randomly. Like in the scenarios with gamma packet generation model, if the destination of the packet is restricted to a single sink node even networks with a high node density are prone to bottlenecks. To illustrate this a scatter plot of a high node density network operating in sink mode is shown in Figure 7.28. The nodes closer to the sink at the center are drawn with a larger area indicating that they are required to forward more traffic than the rest of the nodes in the network. Selecting these nodes more often as auxiliary nodes results in better network performance. The delay and throughput graphs are show in the Appendix A (A.23).

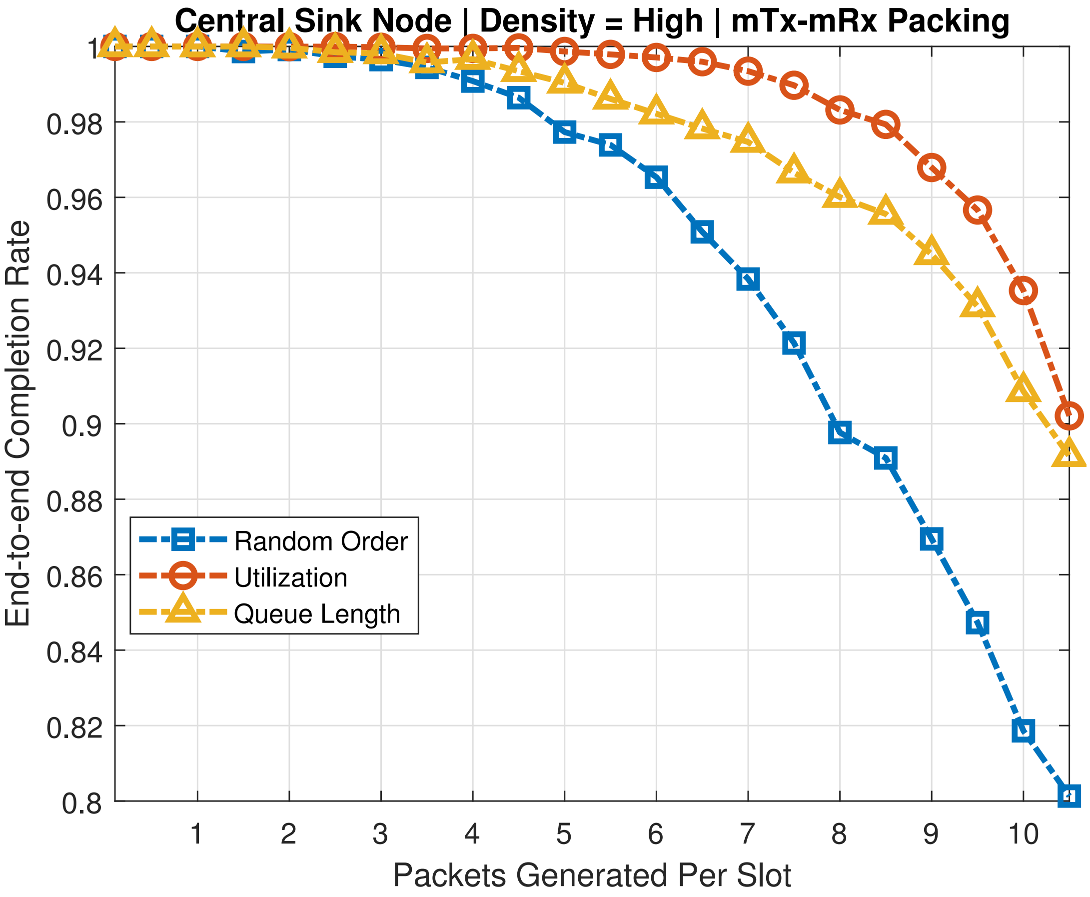


Figure 7.27: Effect of Ordering the Auxiliary Nodes for Networks With High Density Using mTx-mRx Slot-packing and a Single Destination

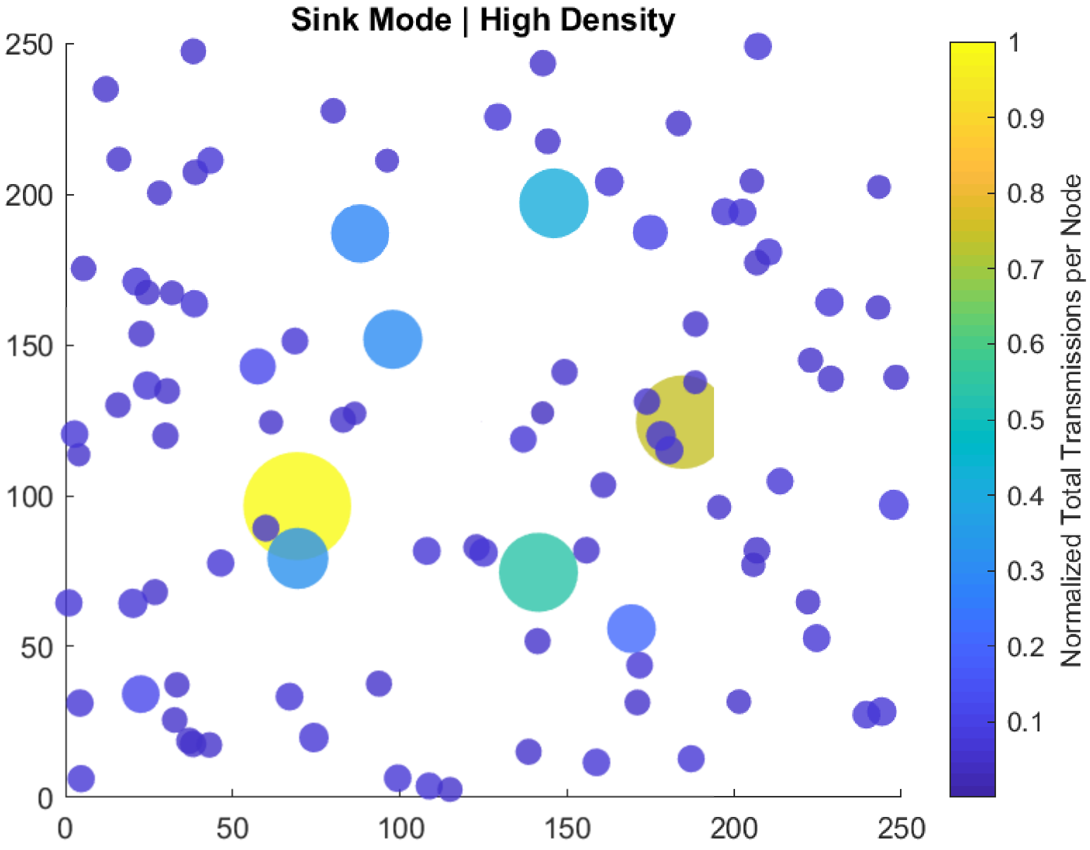


Figure 7.28: Normalized Total Transmissions in a Network With a High Density of Nodes and a Single Destination

Chapter 8

Conclusions

In this chapter, concluding remarks are presented. The investigations conducted in this dissertation can be classified into three categories. In the first set of investigations a uniform packet generation model was used. In the second set of investigations a non-uniform packet generation model was used. In the third set of investigations the destination of the packets was limited to a sink node. In all these scenarios the simulations were run for networks with low, medium, and high densities. Additionally, in each of those scenarios the effect of carefully choosing the auxiliary nodes is studied.

8.1 Conclusions

The goal of this dissertation was to design a transmission scheduling protocol for ad hoc networks that rectifies the shortcomings of traditional scheduling algorithms and is also able to support networks with in which the radios can adapt their transmission rates. Transmission scheduling protocols designed for ad hoc networks often suffer from poor utilization of time slot assignments. Furthermore, the performance of these protocols drops off tremendously in networks where there is a disparity in the traffic levels at different nodes because these protocols tend to give equal opportunities to nodes irrespective of their traffic requirements.

We show that tremendous improvement in network performance can be achieved through a combination of multiple protocols. Our previously proposed RMTS protocol allows multiple nodes within a cluster the opportunity to use a time slot if the multiple-access interference environment is not changed significantly. The presence of these auxiliary transmitters provides the ability to support nodes with varying traffic loads. Application of well-known adaptive transmission protocols permits the nodes to take advantage of high-quality channels to reduce the transmission time, while still maintaining longer links to support connectivity and control multiple-access interference. A routing metric that accounts for the adaptive transmission protocol is critical to select links that can be utilized efficiently. Finally, our new slot packing approach, mTx-mRx, permits the multiple nodes to pack the same time slot which dramatically improves the slot utilization.

In networks where the number of eligible candidates are greater than N_a and packets require multiple relays, a significant improvement in performance can be achieved in some scenarios by selecting auxiliary nodes based on their utilization value rather than selecting them randomly. Nodes that experience a high level of utilization can be assigned additional transmission opportunities by giving them preference when selecting auxiliary nodes.

Through extensive network simulations we are able to establish the robustness of the design of RMTS-a that allows it to automatically adjust to varying network conditions and be able to maintain a high level of performance. We consider two particular scenarios where the performance of traditional scheduling protocols drops off significantly: networks with gamma packet generation model and networks with a fixed sink node. In both these scenarios there is a disparity in the transmission opportunity requirements amongst the nodes is the network. Our RMTS-a protocol is able to main a good level of performance because it is able to automatically provide additional transmission opportunities to the nodes that need them.

A critical feature of this work is exploiting the characteristics of wireless channels to allow (a) multiple different candidate transmitters that can all transmit in the same slot, (b) multiple receivers that can overhear at least part of these transmissions and (c) the ability to provide more transmission opportunities to nodes through auxiliary assignments.

8.2 Limitations and Future Work

A limitation of this work is that we do not account for the mobility of the nodes. In mobile networks the topology of the network could change frequently and the effect of mobility on the auxiliary channel assignments must be carefully studied. Another limitation of this work is that we do not incorporate channel fading. Particularly, frequently changing channel conditions could have detrimental effect on the performance of auxiliary transmissions. Another limitation of this work is that overhead is not considered. Note that most of the overhead is a fixed and a small fraction of the slot. While considering the overhead could result in a slight reduction of throughput, it does not affect any conclusions of this work and hence, is not modeled in the simulations.

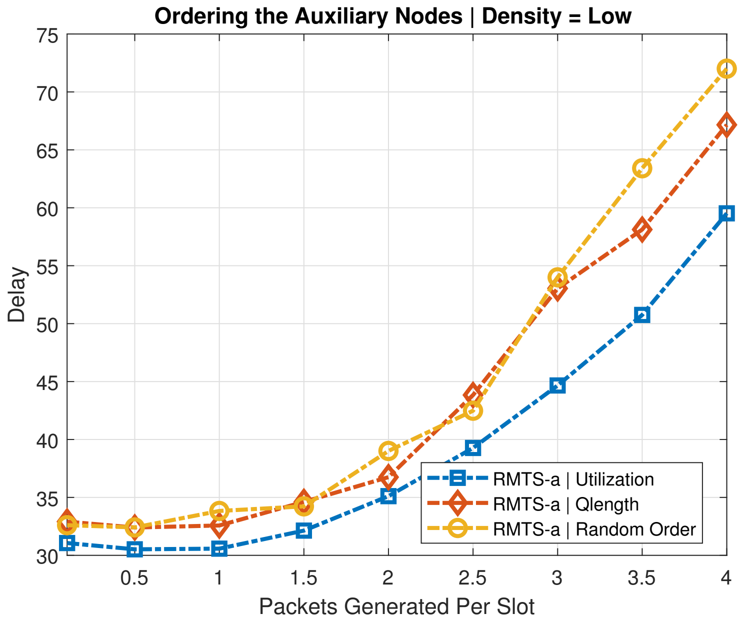
It is future work we propose to investigate the sensitivity of the performance of RMTS-a to fading. Another interesting study would be to compare the performance of RMTS-a with a contention based protocol like CSMA/CA and also investigate the scope of integrating RMTS-a into 802.11 ax systems in which scheduling will play a significant role. Finally, we propose to investigate how our RMTS-a protocol can be adapted for a hierarchical system like CBRS where there are two tiers of users: licensed and unlicensed. Licensed users can be considered as primary transmitters and the unlicensed users can be considered as auxiliary transmitters.

Appendices

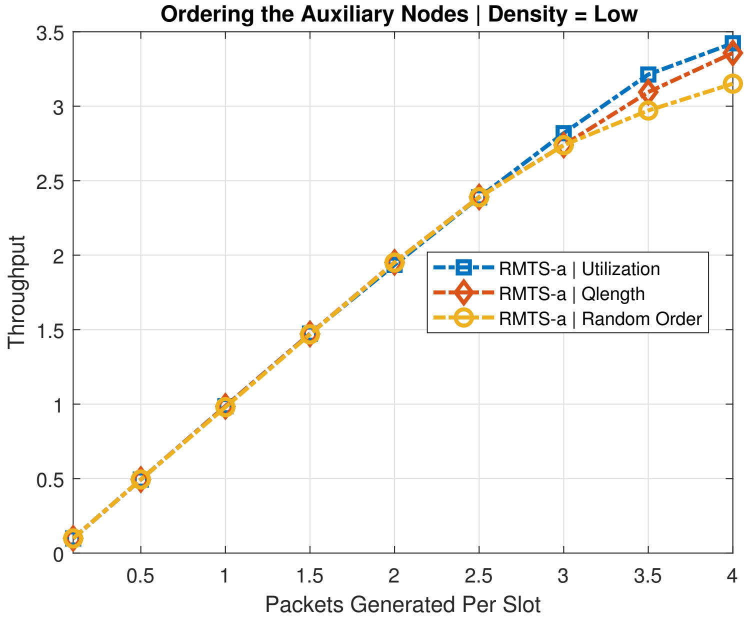
Appendix A Supplemental Results

In this chapter all the supplemental results for the material provided in Chapter 7 are presented. Each of the figures listed here are referenced appropriately in Chapter 7. In the preceding sections along with each figure the sections in Chapter 7 to which these results are supplemental are specified so that the reader can go back and forth between these chapters.

Figure A.1 shows supplemental results for Section 7.1.2. See page number 79 for the reference to Figure A.1 in Chapter 7.



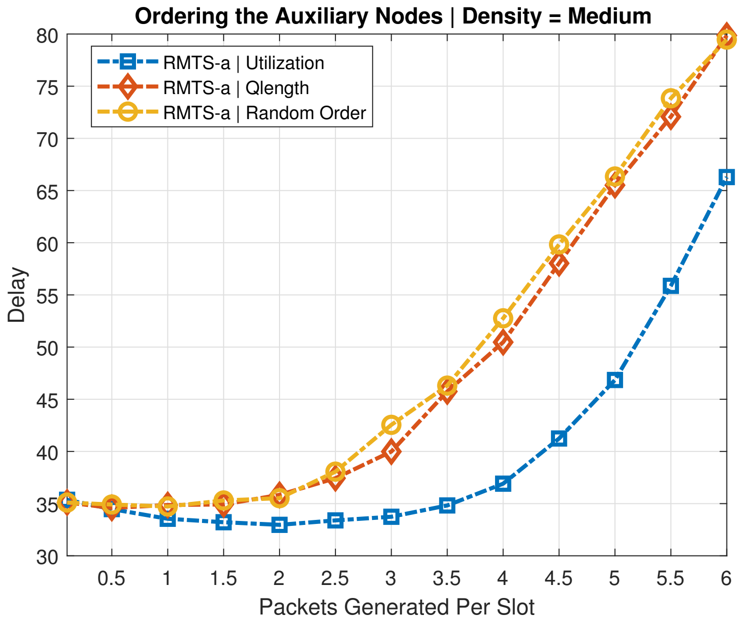
(a) Delay



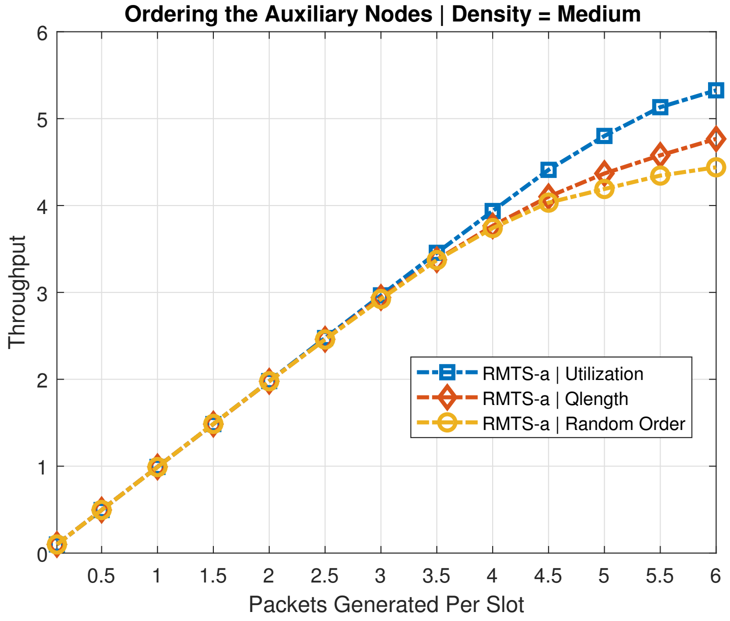
(b) Throughput

Figure A.1: Effect of Ordering the Auxiliary Nodes for Networks With Low Density

Figure A.2 shows supplemental results for Section 7.1.2. See page number 81 for the reference to Figure A.2 in Chapter 7.



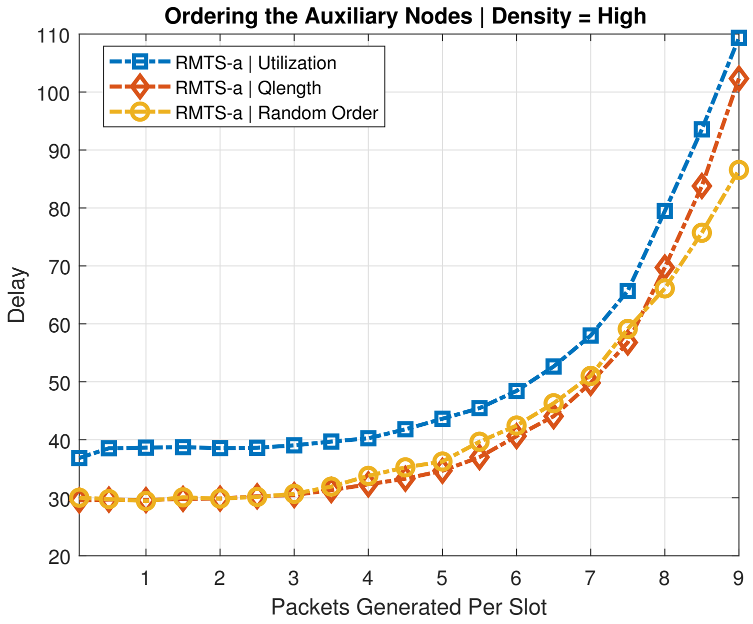
(a) Delay



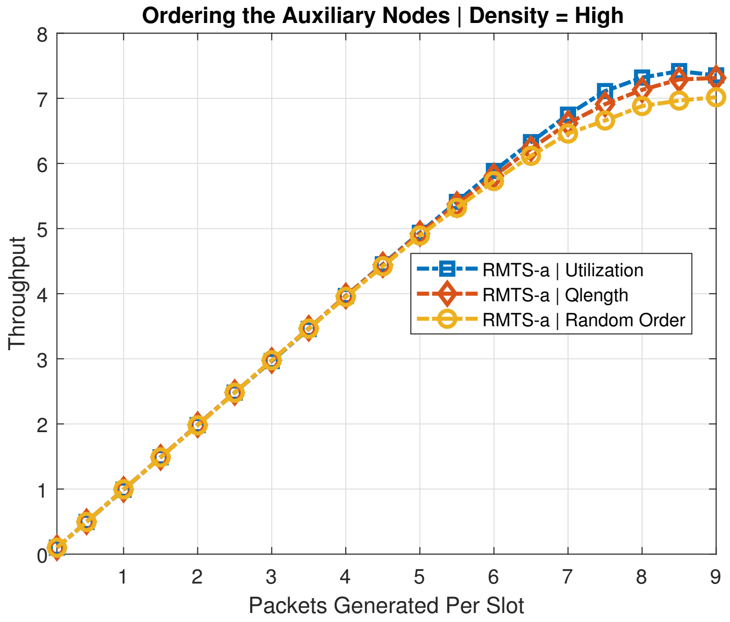
(b) Throughput

Figure A.2: Effect of Ordering the Auxiliary Nodes for Networks With Medium Density

Figure A.3 shows supplemental results for Section 7.1.2. See page number 82 for the reference to Figure A.3 in Chapter 7.



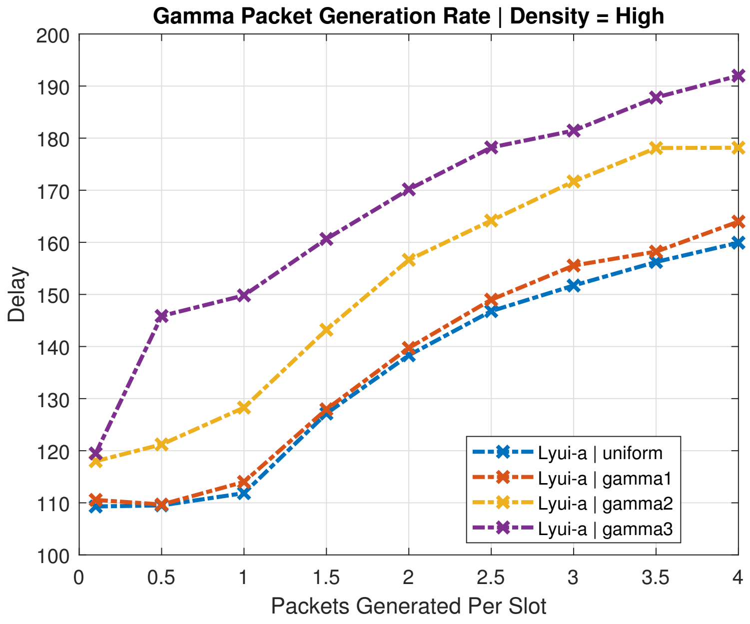
(a) Delay



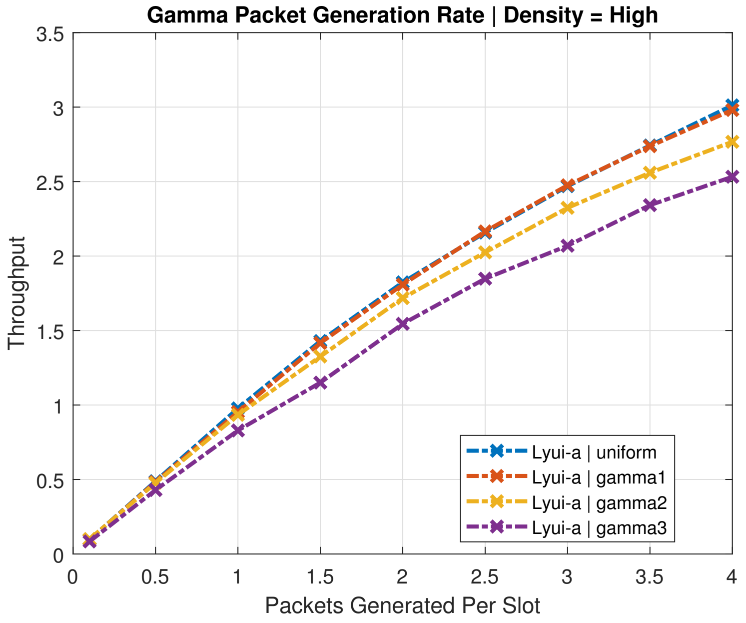
(b) Throughput

Figure A.3: Effect of Ordering the Auxiliary Nodes for Networks With High Density

Figure A.4 shows supplemental results for Section 7.2. See page number 85 for the reference to Figure A.4 in Chapter 7.



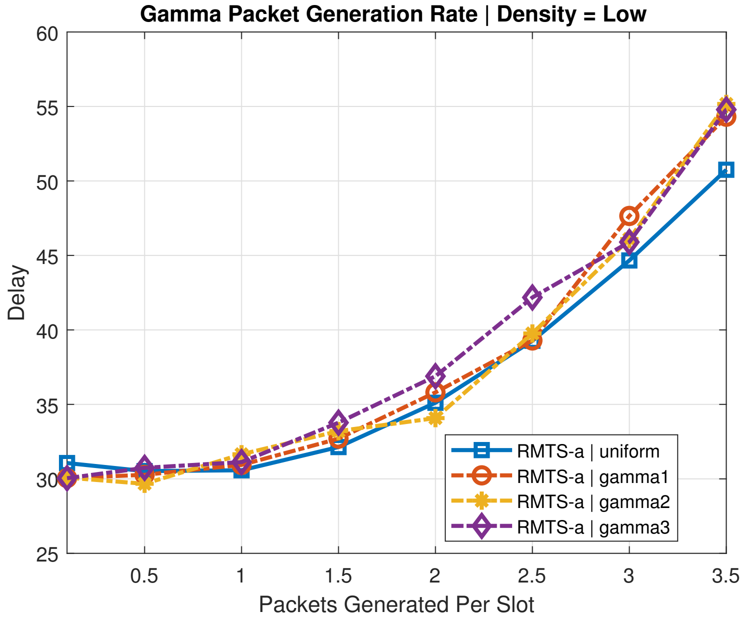
(a) Delay



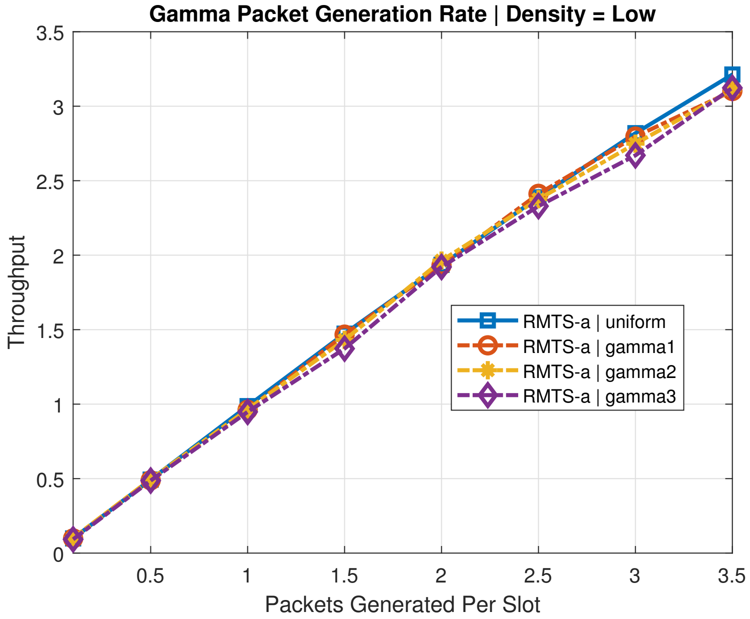
(b) Throughput

Figure A.4: Comparison of Performance of Lyui's Algorithm Under Different Packet Generation Models for Networks With High Density Using sTx-mRx Slot-packing

Figure A.5 shows supplemental results for Section 7.2. See page number 92 for the reference to Figure A.5 in Chapter 7.



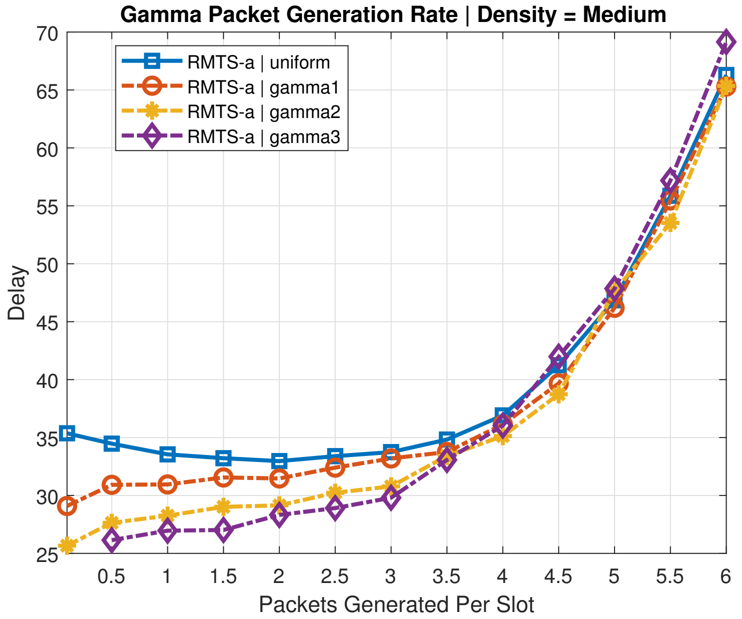
(a) Delay



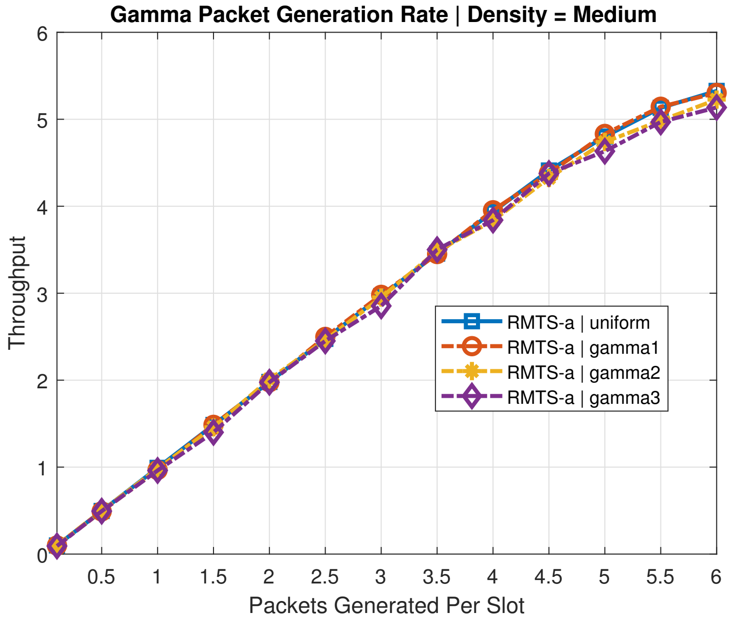
(b) Throughput

Figure A.5: Comparison of Performance Under Different Packet Generation Models for Networks With Low Density Using mTx-mRx Slot-packing

Figure A.6 shows supplemental results for Section 7.2. See page number 92 for the reference to Figure A.6 in Chapter 7.



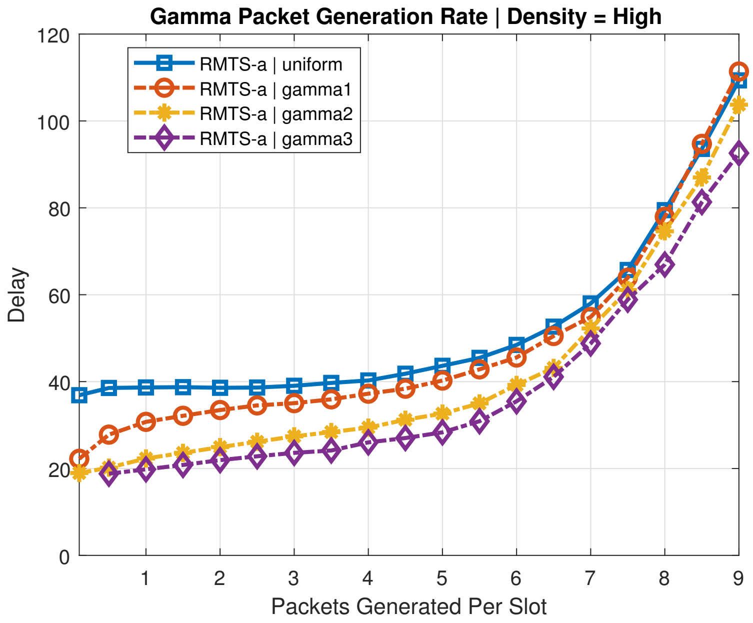
(a) Delay



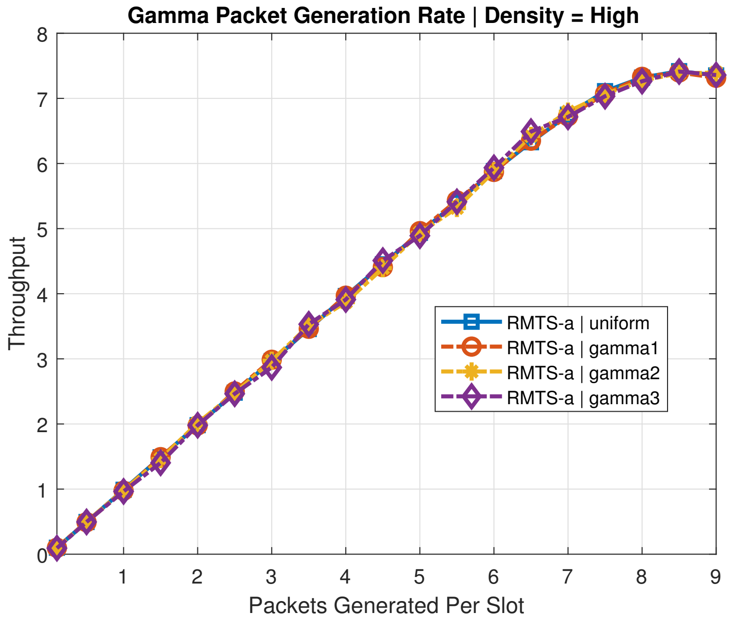
(b) Throughput

Figure A.6: Comparison of Performance Under Different Packet Generation Models for Networks With Medium Density Using mTx-mRx Slot-packing

Figure A.7 shows supplemental results for Section 7.2. See page number 92 for the reference to Figure A.7 in Chapter 7.



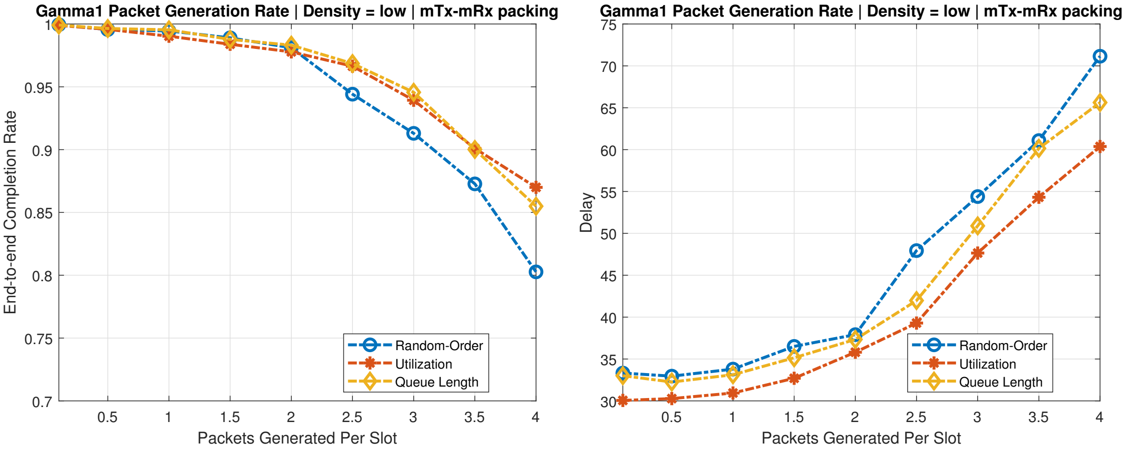
(a) Delay



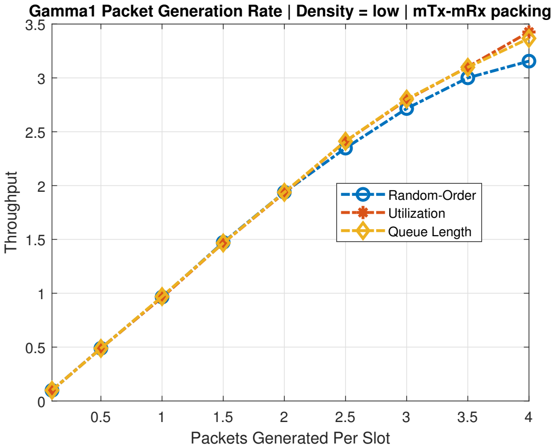
(b) Throughput

Figure A.7: Comparison of Performance Under Different Packet Generation Models for Networks With High Density Using mTx-mRx Slot-packing

Figure A.8 shows supplemental results for Section 7.2. See page number 92 for the reference to Figure A.8 in Chapter 7.



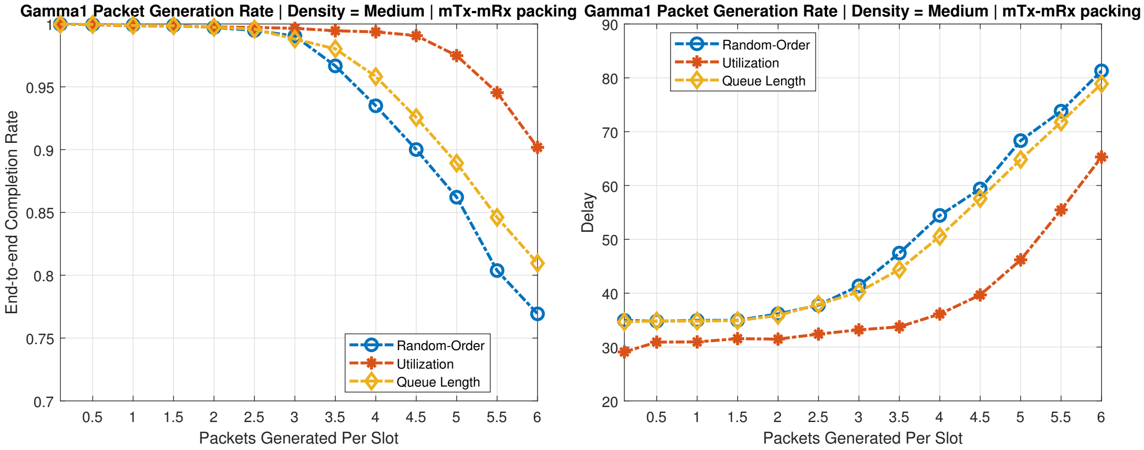
(a) End-to-end Completion Rate (b) Delay



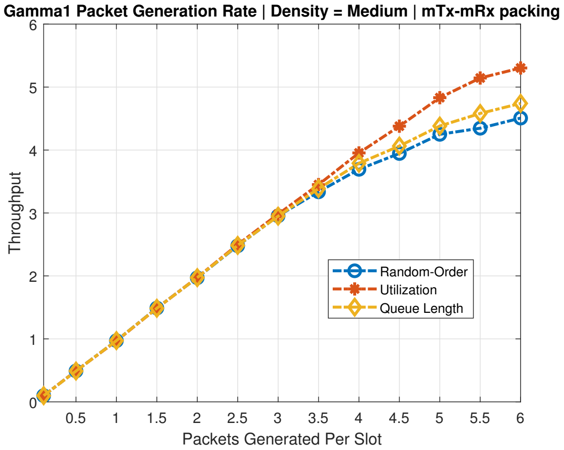
(c) Throughput

Figure A.8: Effect of Ordering the Auxiliary Nodes for Networks With Low Density and Gamma1 Packet Generation Model Using mTx-mRx Slot-packing

Figure A.9 shows supplemental results for Section 7.2. See page number 92 for the reference to Figure A.9 in Chapter 7.



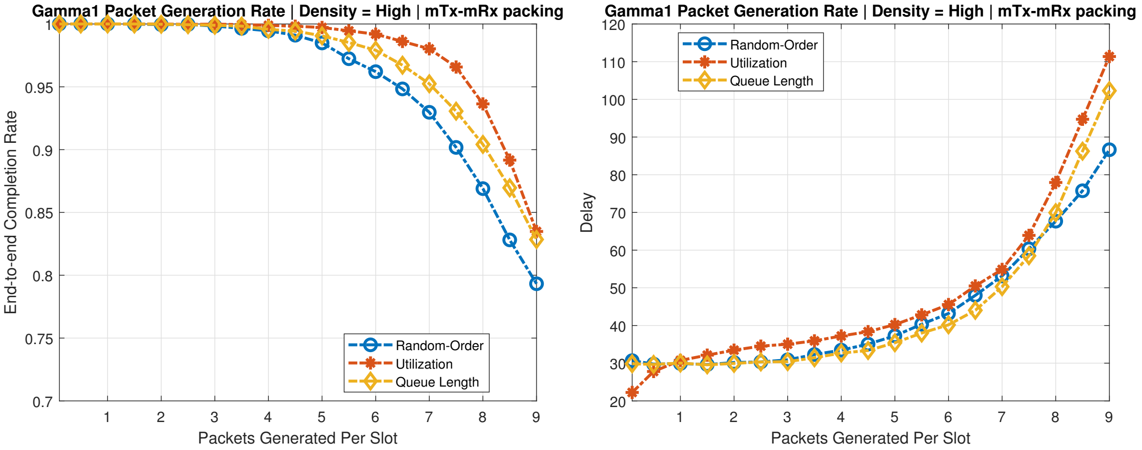
(a) End-to-end Completion Rate (b) Delay



(c) Throughput

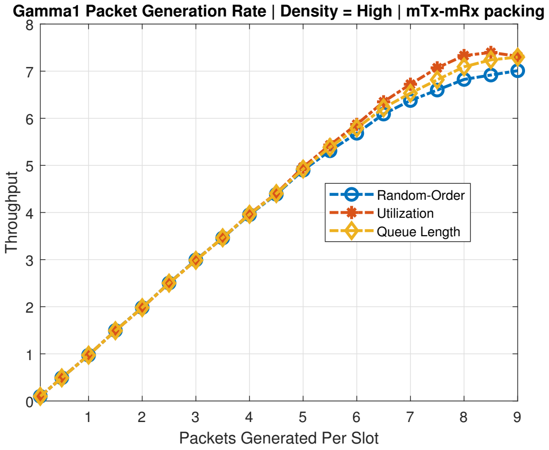
Figure A.9: Effect of Ordering the Auxiliary Nodes for Networks With Medium Density and Gamma1 Packet Generation Model Using mTx-mRx Slot-packing

Figure A.10 shows supplemental results for Section 7.2. See page number 92 for the reference to Figure A.10 in Chapter 7.



(a) End-to-end Completion Rate

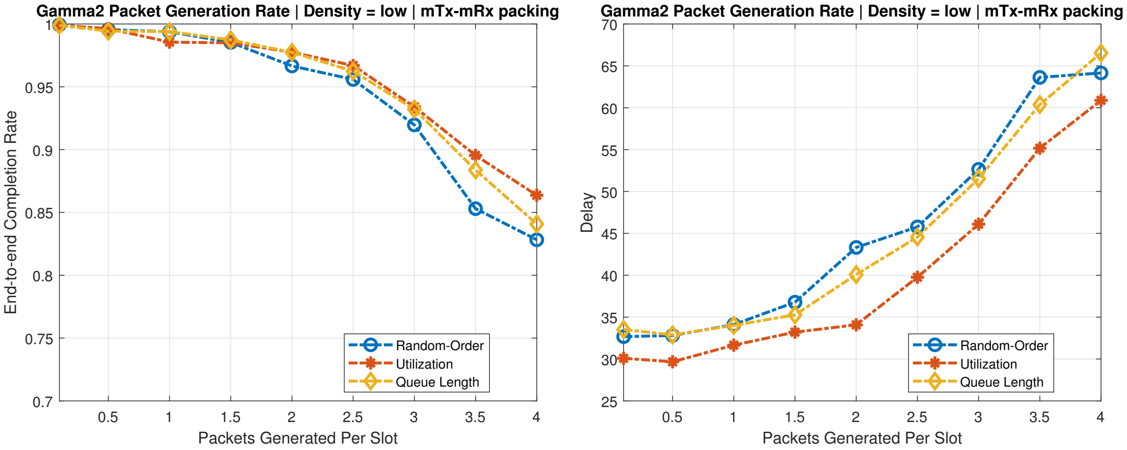
(b) Delay



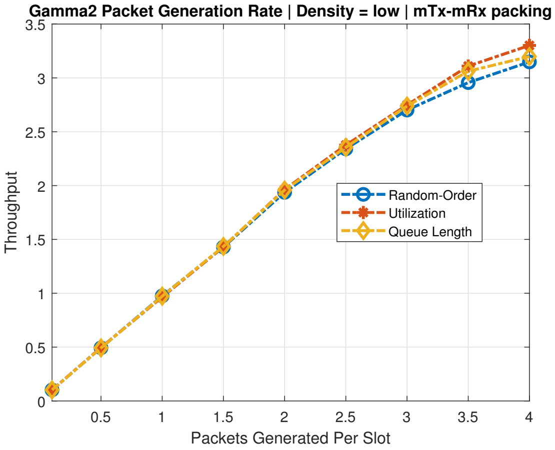
(c) Throughput

Figure A.10: Effect of Ordering the Auxiliary Nodes for Networks With High Density and Gamma1 Packet Generation Model Using mTx-mRx Slot-packing

Figure A.11 shows supplemental results for Section 7.2. See page number 92 for the reference to Figure A.11 in Chapter 7.



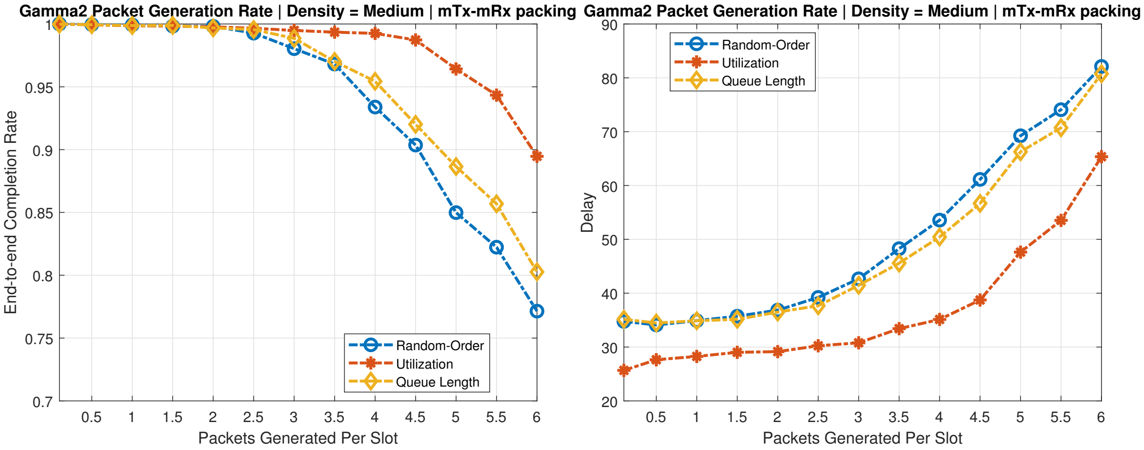
(a) End-to-end Completion Rate (b) Delay



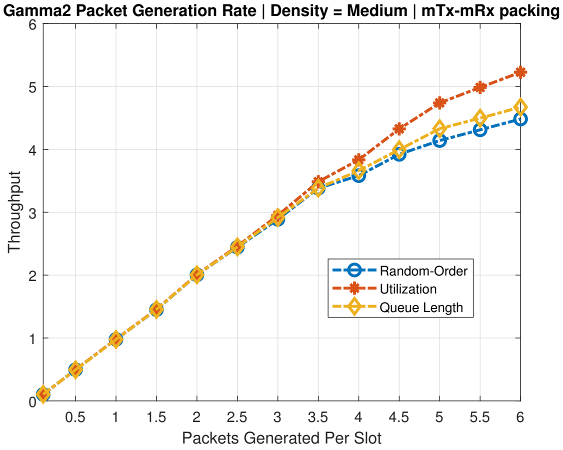
(c) Throughput

Figure A.11: Effect of Ordering the Auxiliary Nodes for Networks With Low Density and gamma2 Packet Generation Model Using mTx-mRx Slot-packing

Figure A.12 shows supplemental results for Section 7.2. See page number 92 for the reference to Figure A.12 in Chapter 7.



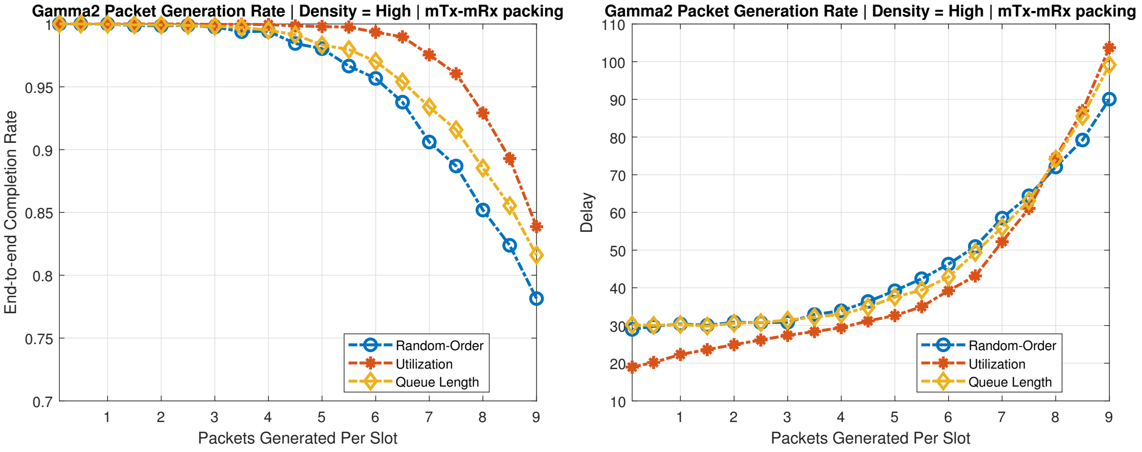
(a) End-to-end Completion Rate (b) Delay



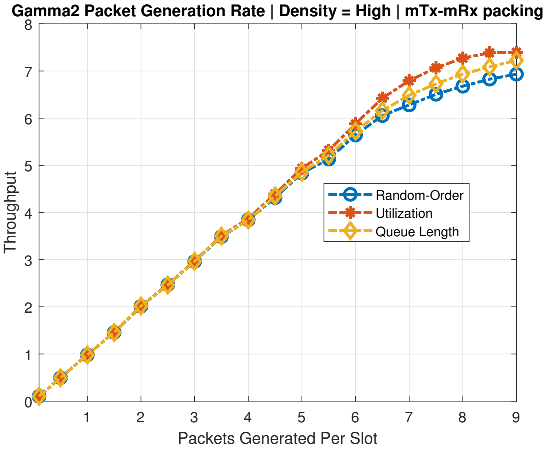
(c) Throughput

Figure A.12: Effect of Ordering the Auxiliary Nodes for Networks With Medium Density and gamma2 Packet Generation Model Using mTx-mRx Slot-packing

Figure A.13 shows supplemental results for Section 7.2. See page number 92 for the reference to Figure A.13 in Chapter 7.



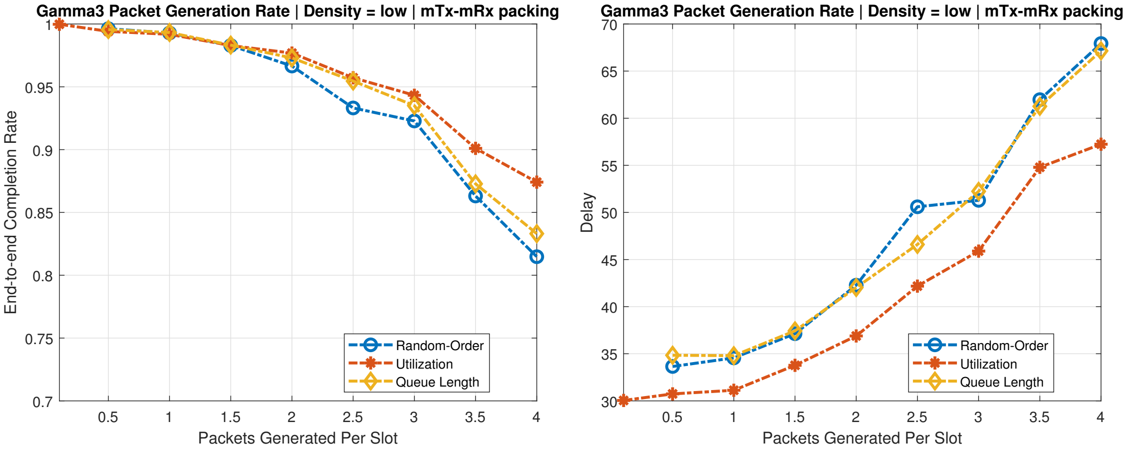
(a) End-to-end Completion Rate (b) Delay



(c) Throughput

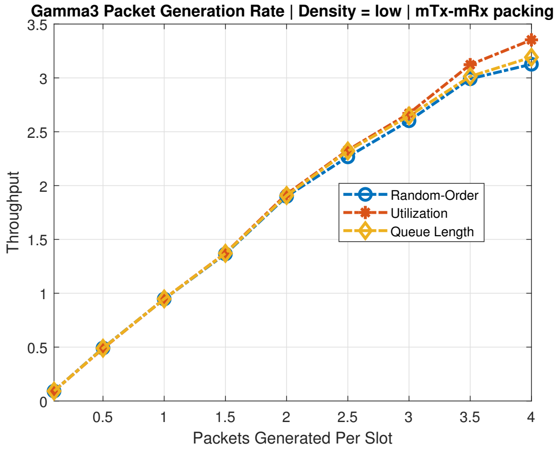
Figure A.13: Effect of Ordering the Auxiliary Nodes for Networks With High Density and gamma2 Packet Generation Model Using mTx-mRx Slot-packing

Figure A.14 shows supplemental results for Section 7.2. See page number 92 for the reference to Figure A.14 in Chapter 7.



(a) End-to-end Completion Rate

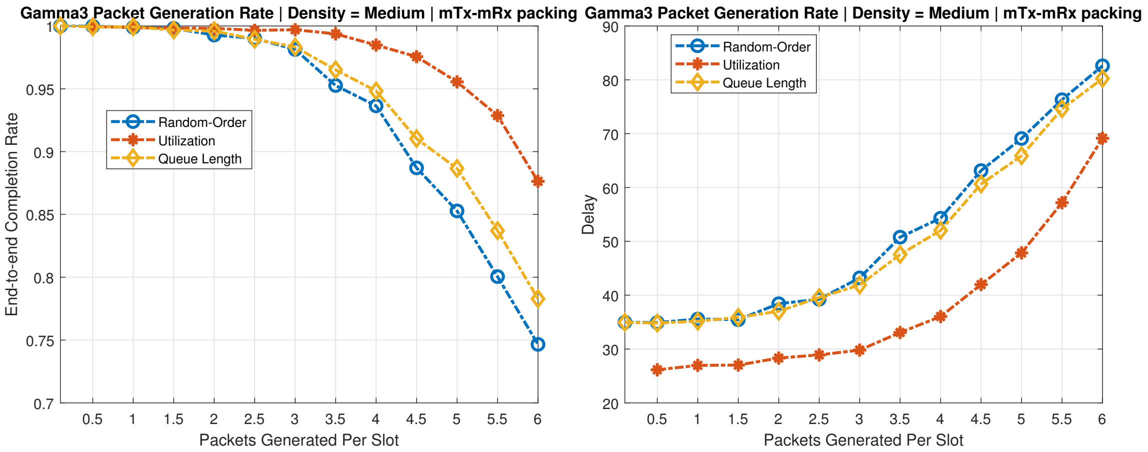
(b) Delay



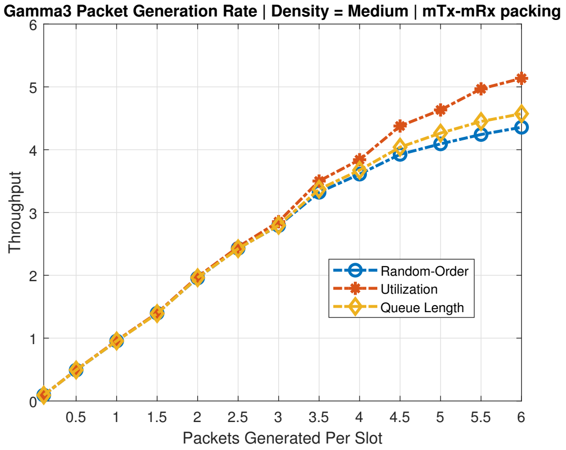
(c) Throughput

Figure A.14: Effect of Ordering the Auxiliary Nodes for Networks With Low Density and gamma3 Packet Generation Model Using mTx-mRx Slot-packing

Figure A.15 shows supplemental results for Section 7.2. See page number 92 for the reference to Figure A.15 in Chapter 7.



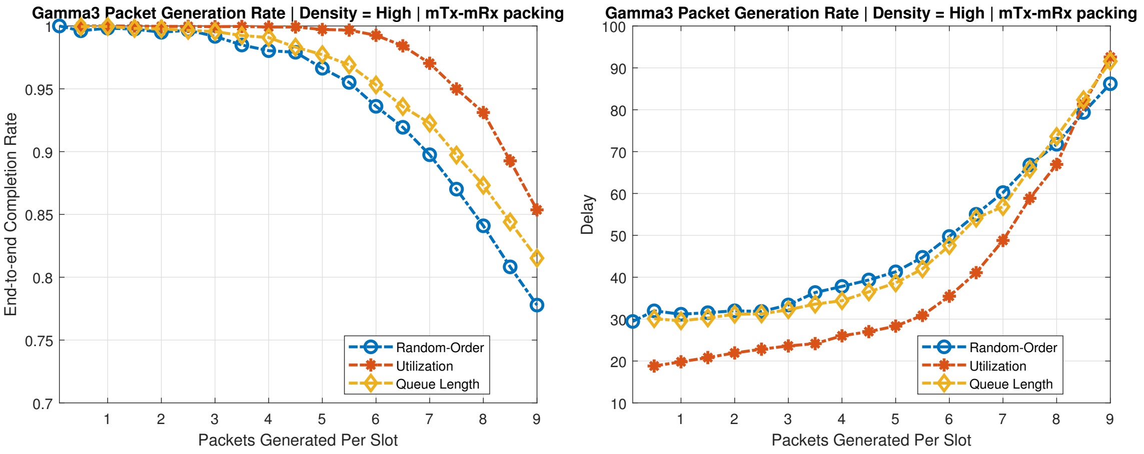
(a) End-to-end Completion Rate (b) Delay



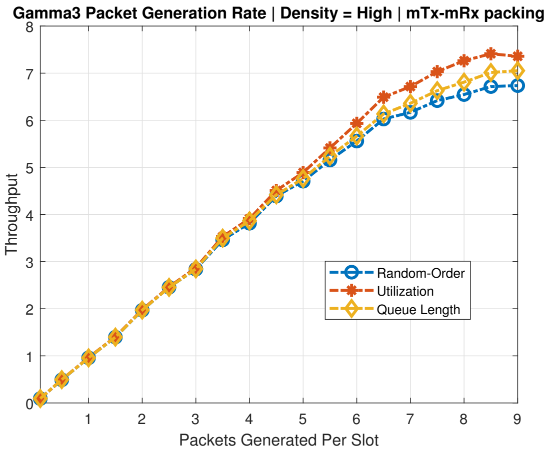
(c) Throughput

Figure A.15: Effect of Ordering the Auxiliary Nodes for Networks With Medium Density and gamma3 Packet Generation Model Using mTx-mRx Slot-packing

Figure A.16 shows supplemental results for Section 7.2. See page number 92 for the reference to Figure A.16 in Chapter 7.



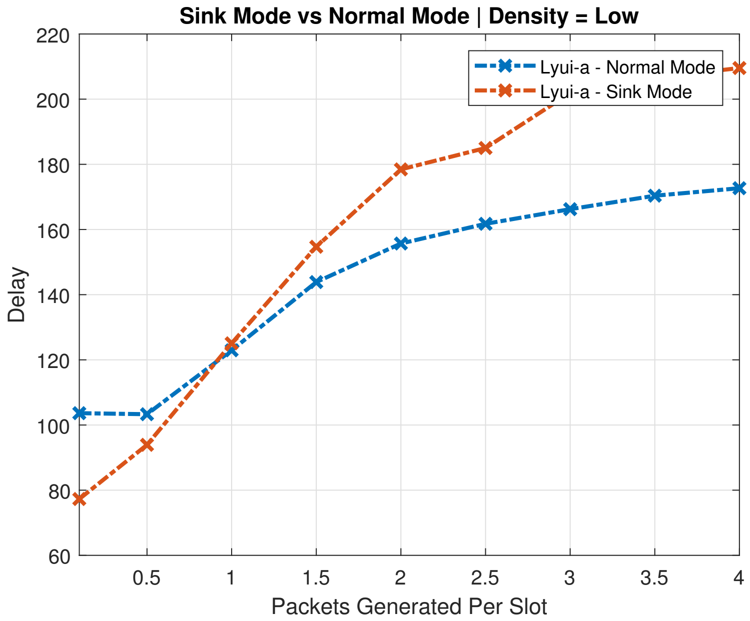
(a) End-to-end Completion Rate (b) Delay



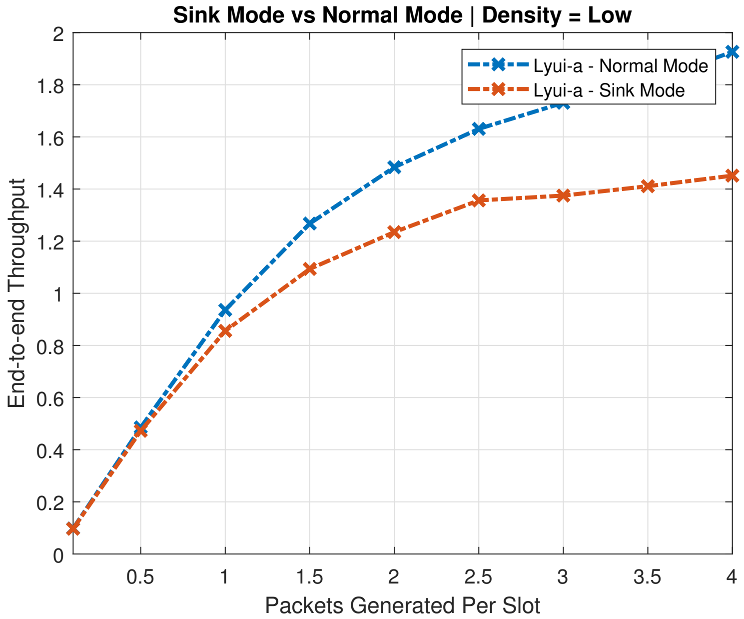
(c) Throughput

Figure A.16: Effect of Ordering the Auxiliary Nodes for Networks With High Density and gamma3 Packet Generation Model Using mTx-mRx Slot-packing

Figure A.17 shows supplemental results for Section 7.3. See page number 97 for the reference to Figure A.17 in Chapter 7.



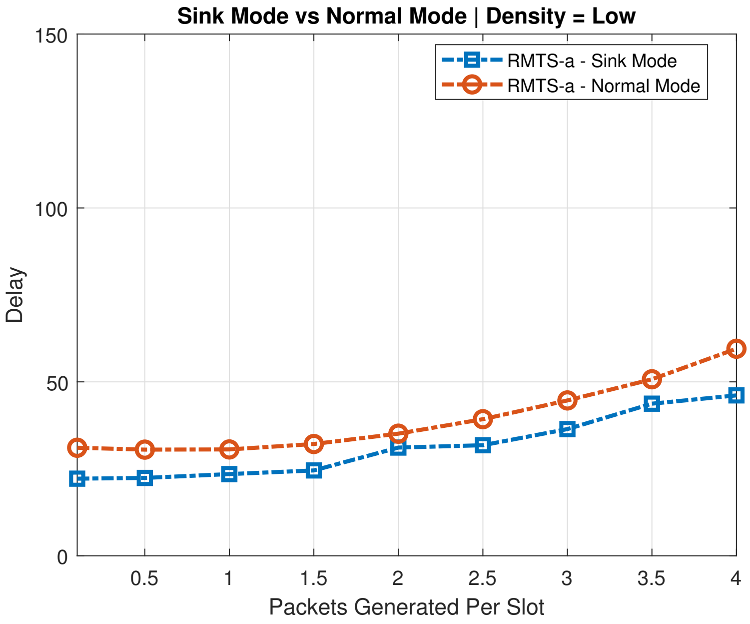
(a) Delay



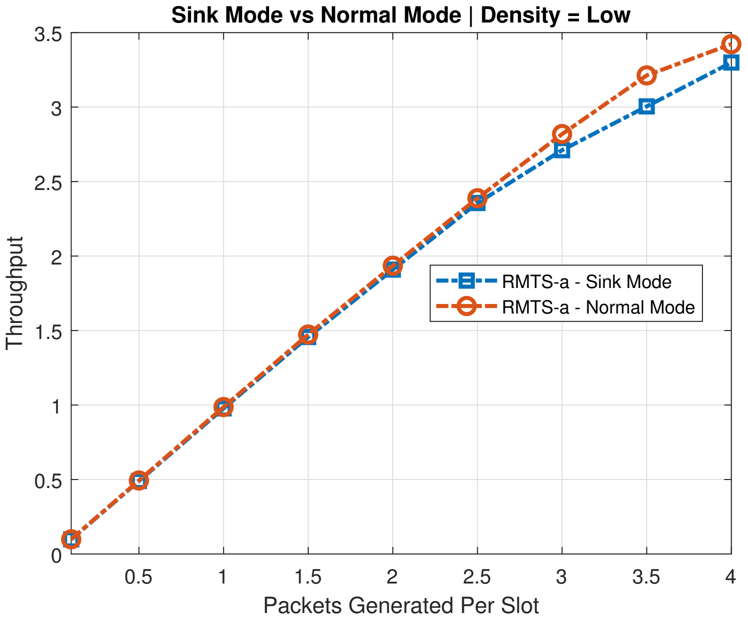
(b) Throughput

Figure A.17: Comparison of Performance of Lyui's Algorithm Between Normal Mode and Sink Mode for Networks With Low Density

Figure A.18 shows supplemental results for Section 7.3. See page number 98 for the reference to Figure A.18 in Chapter 7.



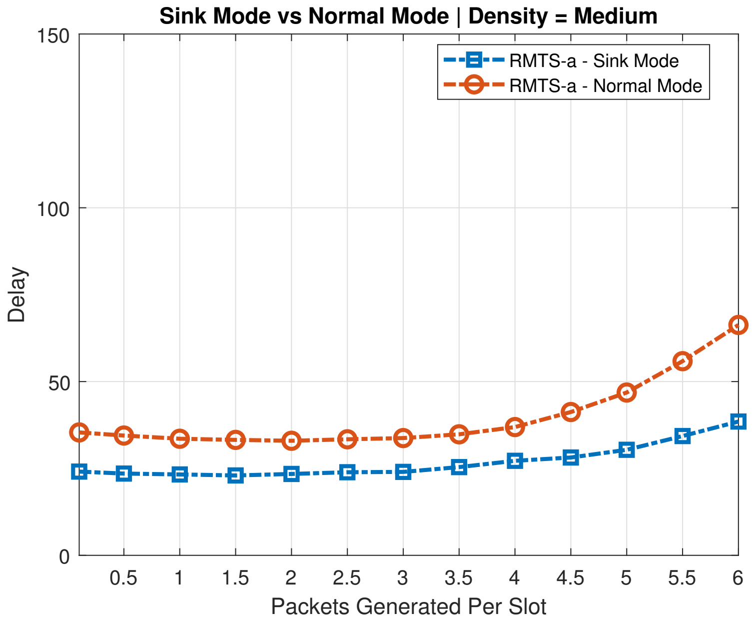
(a) Delay



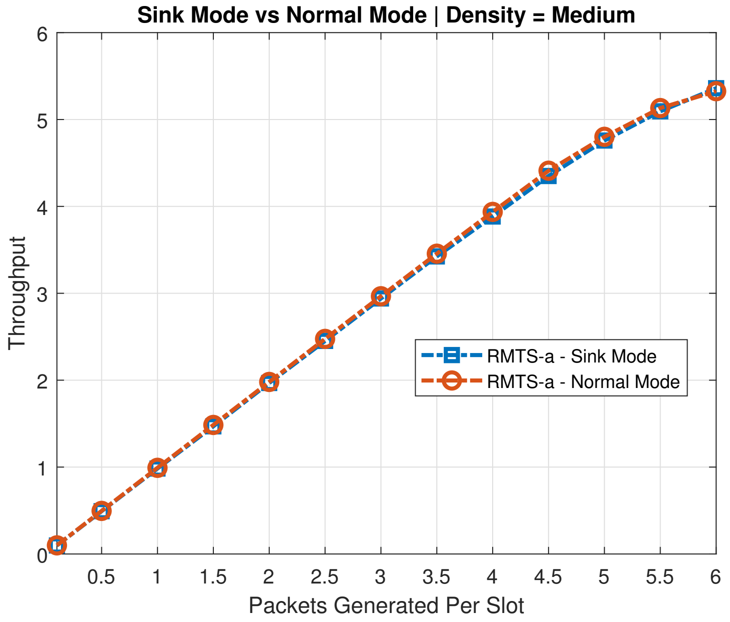
(b) Throughput

Figure A.18: Comparison of Performance Between Normal Mode and Sink Mode for Networks With Low Density

Figure A.19 shows supplemental results for Section 7.3. See page number 98 for the reference to Figure A.19 in Chapter 7.



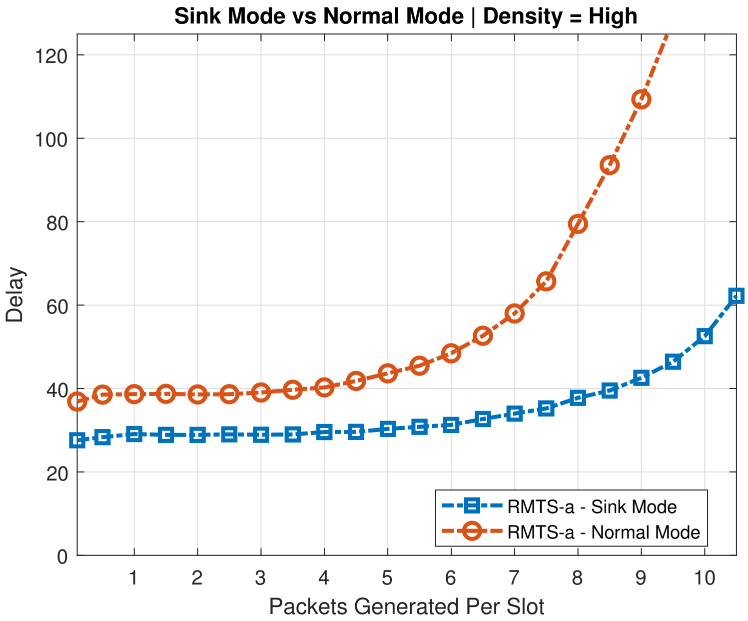
(a) Delay



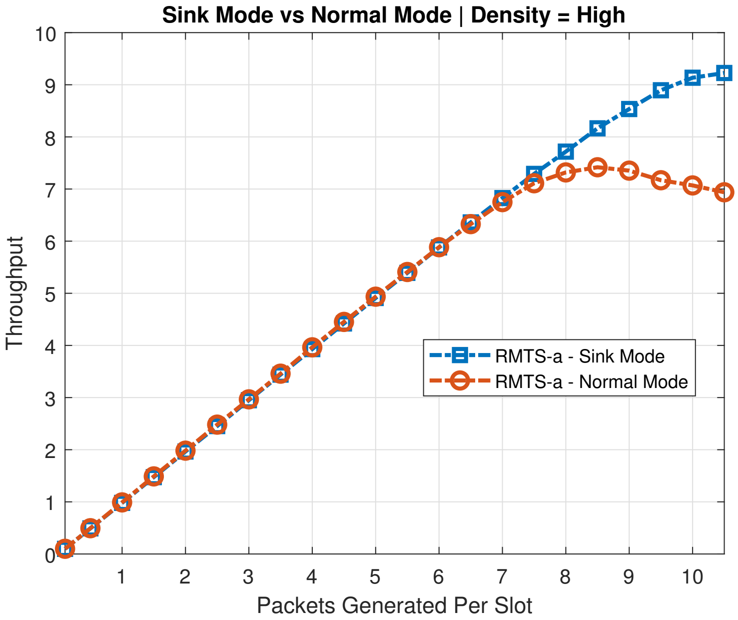
(b) Throughput

Figure A.19: Comparison of Performance Between Normal Mode and Sink Mode for Networks With Medium Density

Figure A.20 shows supplemental results for Section 7.3. See page number 98 for the reference to Figure A.20 in Chapter 7.



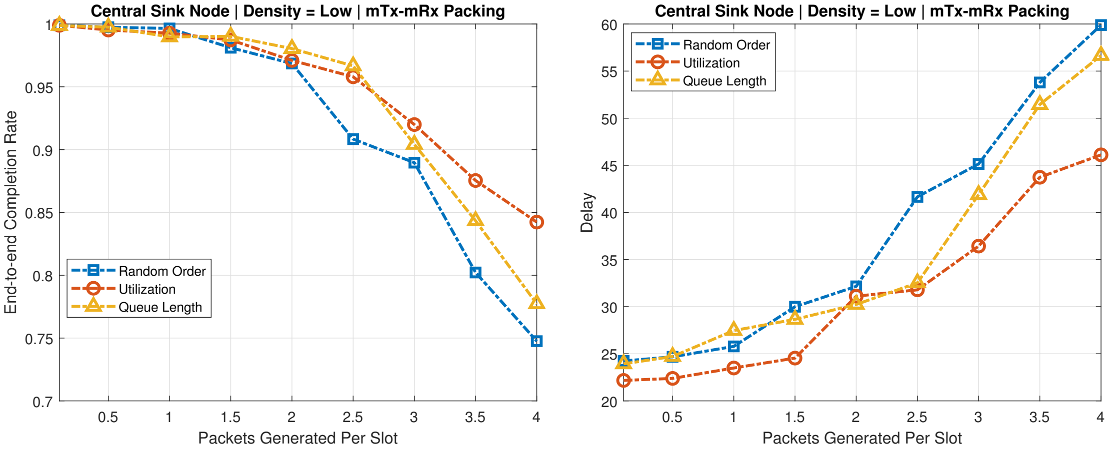
(a) Delay



(b) Throughput

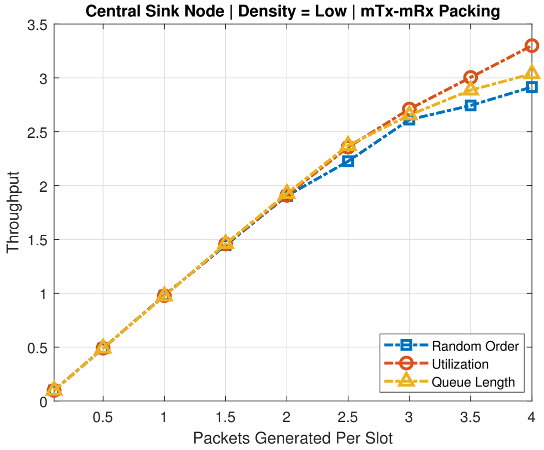
Figure A.20: Comparison of Performance Between Normal Mode and Sink Mode for Networks With High Density

Figure A.21 shows supplemental results for Section 7.3. See page number 98 for the reference to Figure A.21 in Chapter 7.



(a) End-to-end Completion Rate

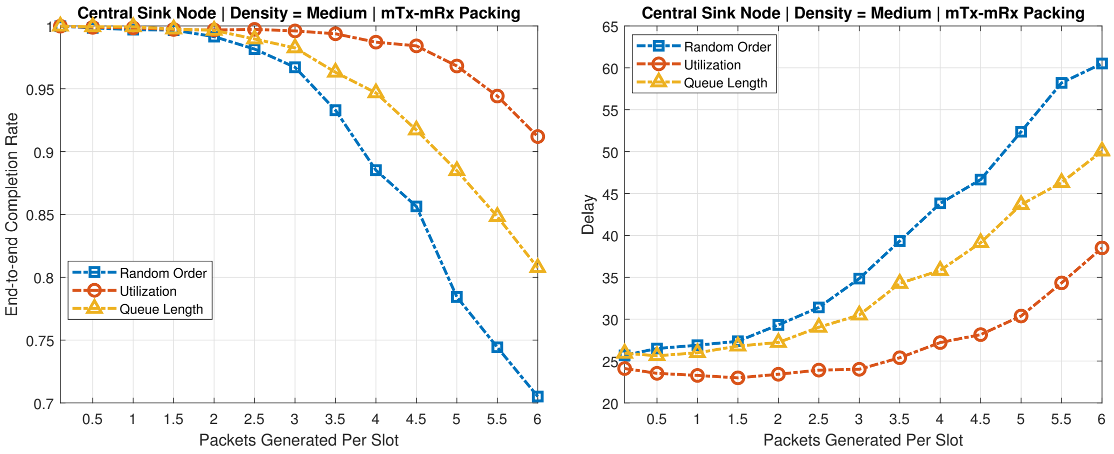
(b) Delay



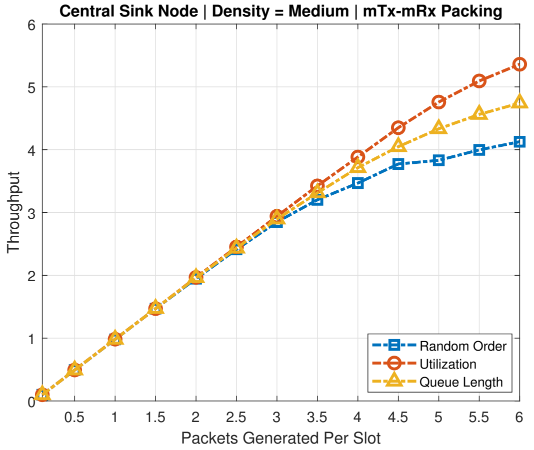
(c) Throughput

Figure A.21: Effect of Ordering the Auxiliary Nodes in Sink Mode for Networks With Low Density

Figure A.22 shows supplemental results for Section 7.3. See page number 98 for the reference to Figure A.22 in Chapter 7.



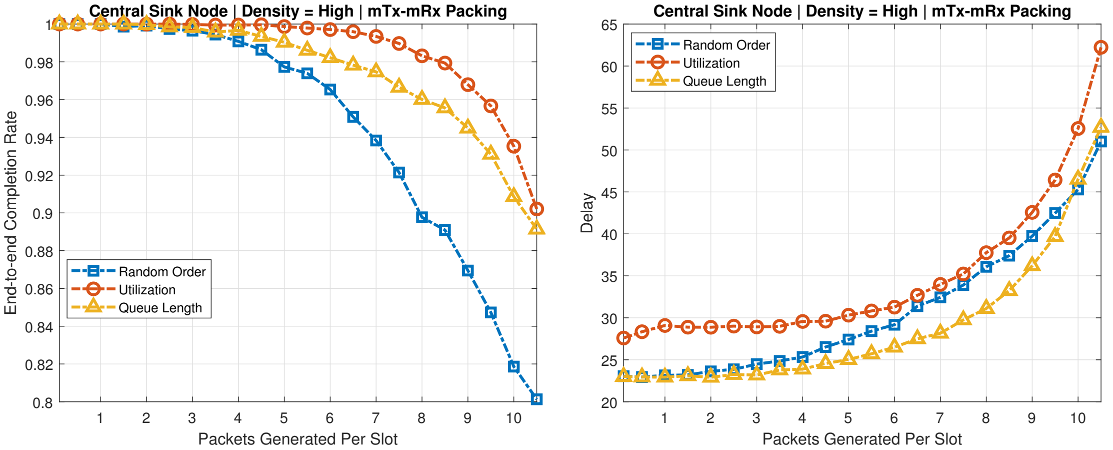
(a) End-to-end Completion Rate (b) Delay



(c) Throughput

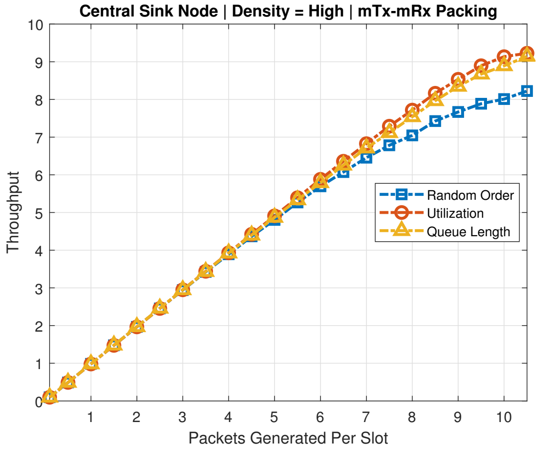
Figure A.22: Effect of Ordering the Auxiliary Nodes in Sink Mode for Networks With Medium Density

Figure A.23 shows supplemental results for Section 7.3. See page number 98 for the reference to Figure A.23 in Chapter 7.



(a) End-to-end Completion Rate

(b) Delay



(c) Throughput

Figure A.23: Effect of Ordering the Auxiliary Nodes in Sink Mode for Networks With High Density

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