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Design of a Channel-Access Protocol for a Wireless Ad Hoc Network with MIMO and Adaptive Transmission

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Abstract

An ad hoc network is a wireless network that does not depend on a pre-configured infrastructure but instead creates network connectivity by utilizing the available nodes to relay packets. In this thesis, we focus on the media access control layer that has a cross-layer design and exploits features of the physical layer. The radios all utilize direct-sequence spread-spectrum (DSSS) modulation and a multiple-input multiple-output (MIMO) antenna system. The channel-access protocol uses transmission scheduling to ensure collision free and fair access to the channel for all nodes. However, a limitation of transmission scheduling is poor utilization of high-quality links. We investigate two methods to achieve higher data rates on those links that have very high signal-to-noise ratios. The first approach builds upon prior work in adapting the spreading factor of DSSS modulation to allow multiple packets to be bundled into a single transmission using an approach called slot-packing. The other approach exploits MIMO for well-conditioned links that allows multiple packets to be multiplexed with a single transmission by using multiple pairs of transmit and receive antennas. Finally, we develop a new protocol that permits both slot-packing and MIMO to be utilized for very high-quality links. We use simulations to investigate the performance of each approach, and show that substantial gains in network performance are achieved when both can be employed. Integration of our new protocol also requires careful design of the routing metrics and queueing strategies.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

An ad hoc network is a kind of decentralized wireless network in which each node is equipped with a radio that has one or more transceivers. In an ad hoc network, all nodes take part in forwarding and routing packets, and it does not depends on the existence of a fixed infrastructure, such as routers or access points. Because of this particular feature, an ad hoc network is well suited to supporting communications in situations where it is not feasible to pre-establish a prepared infrastructure, or where the common infrastructure is damaged. This type of network is often used to support military operations, temporary events, or emergency responders for disaster relief.

A multiple-input and multiple-output(MIMO) system is a technology that allows a radio to use multiple sending and receiving antennas, and therefore two nodes both employing MIMO system can utilize all antennas simultaneously in the same frequency band though careful signal processing at both sides [11]. As a result, the MIMO systems can multiply the capacity of the link. This leads to the popularity of MIMO systems in wireless networks. It is being widely used in different communication systems, particularly systems in which at least one of the nodes is stationary and has sufficient power to support the MIMO system [3]. Adaption of MIMO system in ad hoc networks has been slower, in part due to less structure in the location of nodes as compared to infrastructure-fixed networks. However, the usage of multiple antennas offers prospect of increase in capacity.

Our research for ad hoc networks focuses on networks with a dense deployment of nodes. The channel can be shared by more than ten neighbors, and in this type of scenario, the medium access control(MAC) layer plays a very important role in the system, especially for maintaining performance at high packet generation rates.

There are two typical types of MAC designs in ad hoc networks [6]. One type is contention based type, like ALOHA. This type of MAC control performs well when the traffic load is comparably low. But the system performance can collapse once the rates that nodes attempt to access the channel is increased beyond a certain level [2]. This problem is particularly sensitive to the traffic rate in dense wireless network, because if nodes attempt to transmit frequently, there will be many collisions. Another challenge faced by ad hoc networks is all nodes are part of the forwarding structure. Each node does not only send its own packets but also forwards other's packets as well. So as the generation rate rises, the traffic in the network would increase quickly. In this scenario, MAC layer design based on random access is often not a good choice.

The other type of channel access is contention-free type [6]. It can be scheduled or based on reservations. For this kind of MAC layer, time is divided into periods with fixed duration, and each period is called a slot. Each node will be assigned to several time slots, and it can only transmit in those assigned slots. The time slot assignment will repeat periodically, and one period is called a frame. Neighboring nodes are scheduled to avoid collisions so that channel access performance does not degrade at high traffic levels.

Direct-sequence spread-spectrum(DSSS) modulation is a method to spread the signal over a wider band of frequencies [8]. By modulating signals with certain sequences, called pseudo noise codes, signals will be spread into a wider frequency band. This spreading makes the signal more noise-like, and as a result, the receiver gains more ability to resist noise and interference. Furthermore, it becomes harder to detect or intercept. This technology has been applied in various wireless communication systems, such as GPS, DS-CDMA and IEEE 802.11b [9].

In combination with DSSS, we use slot packing [10]. The channel access protocol adapts the spreading factor to the channel quality. For example, if the spreading factor is halved when the channel quality allows, this doubles the data rate. This thesis presents a comparison between slot packing and MIMO, and discusses how the two methods can be combined.

1.1 Thesis Statement

In this thesis we investigate how to incorporate a MIMO system into a dense ad hoc network. In such networks, most packets must be relayed to reach their destination. We also assume that the nodes have very limited mobility. With the high level of traffic, the schedule-based MAC protocol is preferable in these types of networks.

Our approach builds upon previous work of Lyui's algorithm [7]. Lyui's algorithm is a transmission scheduling protocol that limits inference among neighboring nodes. This algorithm has a very limited throughput and one of the methods to improve this is adapting the spreading factors. A link with a high signal-to-noise ratio can have much higher capacity. This can enhance the overall performance of the whole network. The essential idea of this method is to divide the spreading factor by halves to pack multiple packets into each slot for high quality links.

However, in practice, the spreading factor must stay above some minimum value, not only to achieve direct-sequence spread spectrum, but also to prevent interference [8]. Also due to the nature of spreading factor, it is limited to powers of two. We show that a MIMO system can be a good alternative, because it can also achieve the goal of transferring multiple packets within one slot. By computer program simulations, we show that under the same conditions, where the maximum number of packets can be transmitted in a single slot is the same for both algorithm, MIMO provides similar network performance compared to slot-packing. We also identify a few situations where a system with MIMO can outperform an equivalent system that employs slot packing only.

Furthermore, since MIMO and slot-packing enhance the capacity from different aspects, both can be utilized. We develop a protocol utilizing both MIMO and slot-packing. This allows some of the links to have an even higher data rate. By computer simulations, we see considerable improvement in the network performance. We will also look into some of the details that affects the performance of the network. For example, queue size and routing metrics with utilization rate.

The following chapters contain the details. Chapter 2 provides the basics about the system design. A description of slot-packing and MIMO is given in Chapter 3, as well as a joint protocol that allows utilization of both systems. Results of simulation investigations are discussed in Chapter 4. Investigation of the network performance when utilizing slot-packing, MIMO, and the joint protocol are presented. In addition, trade offs in the routing metric and queue size are considered. Final conclusions and future work are described in Chapter 5.

Chapter 2

System Design

In this chapter, we explain the model for our system design, which involves the physical, link, and network layers. We introduce the channel model we use at the physical layer, including a brief description about our MIMO model. The details about MIMO will be provided in following chapters.

As stated in the introduction, the channel-access protocol utilizes transmission scheduling algorithm instead of ALOHA. Our system design does not depend on a specific scheduling algorithm, and for the investigations, we use Lyui's algorithm.

For the network layer, packets are stored and relayed to their destinations. We do not implement a distributed routing protocol, but assume routing information is up-to-date. We investigate routing metrics that account for physical and link layer features including data rate, MIMO capabilities, transmission opportunities, and node utilization.

2.1 Channel model

Given a transmitter node i, and receiver node j, suppose the locations of i and j are (x_i, y_i) and (x_j, y_j) respectively. If the transmit power of node i is $P_{s(i,j)}$, the received power at j is [9],

$$P_{r(i,j)} = P_{s(i,j)}(\frac{\lambda}{4\pi d_{i,j}})^{\alpha} \tag{2.1}$$

where λ is the wavelength, α is the path-loss exponent, and $d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ is the distance between node i and node j.

Spread spectrum modulation is a widely used technology in telecommunication. The core of this technique is to modulate the signals with a noise-like sequence, so that the signal can be spread over a wider frequency band. By doing so, the telecommunication system will obtain higher resistance to multiple-access interference.

We use direct-sequence spread-spectrum (DSSS) modulation, one of the most common spread spectrum methods, in our system. This technique modulates the signal with a binary chipping sequence. Each bit in the chipping sequence is called a chip, while a bit in the information message signal is called a symbol. The ratio of the symbol length to the chip length is the spreading factor. It is usually a power of two. A larger spreading factor means that we use more chips to represent a symbol. Because the chip rate is fixed, the information rate is reduced in this situation. A larger spreading factor also increases the signal's resistance against noise. [8]

After direct-sequence spread-spectrum modulation is applied, for node i and node j, we use the signal-to-interference-and-noise ratio (SINR) to decide for each transmission whether it will succeed or fail. SINR is calculated as: [4]

$$\mathrm{SINR}_{i,j} = \frac{P_{r(i,j)} N_{i,j} T_c}{N_0 + \Sigma P_{r(k,j)} T_c} \tag{2.2}$$

where $P_{r(i,j)}$, as mentioned above, is the signal power from node i received at node j; $N_{i,j}$ is the spreading factor used on link i to j; N_0 is the background noise; and T_c is the chip rate.

The interference from node k at node j is $P_{r(k,j)}$, where node k is some node which is active transmitting at the same time as node i. So, $\Sigma P_{r(k,j)} T_c$ is the total interference energy affecting this transmission.

If the SINR is greater than a threshold, β, then it is successful; otherwise, this transmission is considered a failure. [1]

2.2 Lyui's Algorithm

For ad hoc radio networks, ALOHA algorithms suffer from collisions and perform poorly at high traffic levels. Transmission scheduling protocols avoid collisions and can maintain high link utilization at heavy traffic loads.

The design of our system does not depend on a specific scheduling. For the investigation reported in this thesis, we use Lyui's algorithm to schedule neighboring nodes and therefore prevent interference among them. [5]

To apply Lyui's algorithm, each node is assigned a color number. To color a new node n, build a set of the color numbers of all its neighbors, and denote this set as C_1. Each of these neighboring nodes has its own neighbors, and denote the set of color numbers of those second neighbors as C_2. Then the color assigned to the new node n is:

$$c_n = \min\{x | x \notin C_1 \cup C_2,\ x \in Z^+\} \tag{2.3}$$

That is, c_n is the smallest color number that is not used by its first and second neighbors. In this manner, every node in the network is assigned a unique color number among its first and second neighbors. Suppose the maximum color number among its first and second number is c_{max}, the frame size of this node will be P_c, where P_c the smallest power of 2 that is greater or equal to c_{max}.

We assume that the nodes have a method to establishing slot synchronization, so that all the slot boundaries are synchronous. In each slot, node n uses the slot number i_s, its color number c_n, and its frame size P_c to decide whether it should transmit or not. First, node n will become a candidate for slots if:

$$(i_s - c) \bmod P_c = 0 \tag{2.4}$$

The following table gives an example of candidates among nodes with color number 1 to 8 in 16 slots: Then, this node checks the color number of the candidates among its first and second

Table 2.1: Lyui's Algorithm Example

Color\Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
2		O		O		O		O		O		O		O		O
3			O				O				O				O	
4				O				O				O				O
5					O								O			
6						O								O		
7							O								O	
8								O								O

neighbors. If node n has the largest color number in neighboring candidates, then this node will transmit in this slot. Since all frame lengths are powers of two, even if two nodes have different frame sizes, one of the frame lengths will be a multiple of the other, and thus their cycles can fit into each other.

2.3 Link Cost and Routing

When routing, a node will choose the path with the lowest cost for each packet. We use the worst-case SINR to decide the cost of a link. Here the worst-case SINR is the resulting SINR of the maximum possible interference. That is to say, the SINR when assuming all the nodes assigned to the same slot will transmit. When the level of the total traffic is high enough, this rate is easily achieved or at least approached, because most nodes will transmit in their assigned slots. On the other hand, as long as the path loss and environmental noise is not under-estimated, the SINR will never be below this rate, because nodes will not be allowed to transmit unless the slot is assigned to them. In practice, it is not realistic to calculate this ratio, for the fact that a node will not be able to obtain the information of all the other nodes who are assigned to the same slots due to the nature of ad hoc networks. But they can keep records of the lowest SINR they received to estimate the theoretical worst-case SINR,and as stated above, under high level of traffic, these two SINRs are very close to each other. What is more, if in reality, the SINR can always stay above the theoretical worst-case SINR, then the minimum SINR recorded will work as well as the theoretical value. The benefit of using this ratio is that the system will not have packets lost due to low SINR, since the SINR always stays above the minimum threshold. Meanwhile, this might lose some of the utility of the network when traffic level is not as high.

The cost of each link is defined by the following formula:

$$\text{Cost}_{i,j} = \frac{\epsilon(\text{SINR}_{i,j})P_c}{n_{a|i}n_{p|i,j}}(1 + \alpha u_{i,j}) \tag{2.5}$$

where P_c is the cycle size mention in Section 2.2, n_a is the number of active slots for this node within one cycle, and n_p is the maximum number of packets that can be transmitted on this link in one slot. We will describe how n_p is decided in the next chapter. To remove poor links from routes, ϵ serves as a simple cut off function: if the input is greater than β, it returns 1. Otherwise, it returns infinity. And u is the utilization factor, which is updated after each transmission in the following way:

$$u = 0.95u' + 0.05u'' \tag{2.6}$$

where u' is the previous utilization factor and u'' is the current utilization rate: the ratio of the number of packets sent in this transmission to the maximum number of packets allowed in one slot on this link. The initial value of utilization rate is 0. This update happens every 500 slots in our tests. Each time after updating the utilization rate, all nodes will also recalculate their routes. We tried a few different design of u'', but there is no obvious difference among them. However, the usage of utilization factor shows contributions to the performance of the system. The parameter α is a weighting factor of the utilization factor. Our suggested value for α is 0.4, because this value shows good results for various situations. We investigate values for α in the chapter with simulation results.

Chapter 3

Protocol

In this chapter, we explain the details of our protocols to utilize the multiple-input multiple-output(MIMO) systems and slot-packing. Both of our protocols take advantage of high-quality links to transmit multiple packets in one slot.

3.1 MIMO

A MIMO system uses multiple antennas at both the transmitter and receiver. The extra antennas can be used to multiplex different data simultaneously, or combined together to enhance the strength of the same signal using the beam-forming method.

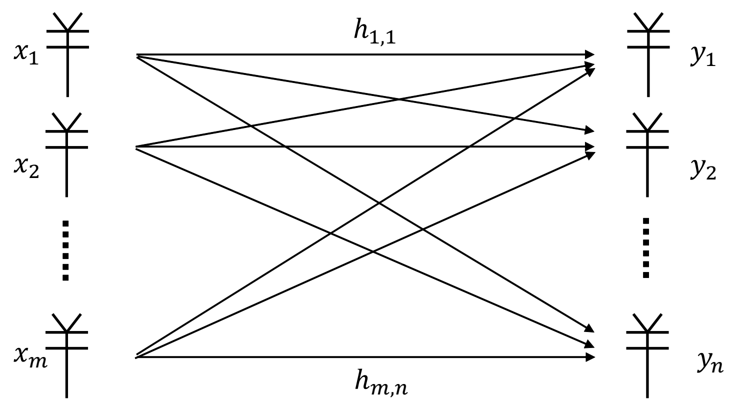

Figure 3.1: MIMO antennas

As shown above in Figure 3.1, suppose that the input signal of each transmitting antenna i is x_i; for each antenna j that receives i's signal, the channel gain between i and j is h_{ij}; and the noise at the receiving antenna j is n_j, then the final signals received by the receiving antennas can be represented by the following model:

$$\begin{bmatrix} y_1 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} h_{1,1} & \cdots & h_{1,n} \\ \vdots & \ddots & \vdots \\ h_{m,1} & \cdots & h_{m,n} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_m \end{bmatrix} \tag{3.1}$$

Or $x = Hp + N$. The channel gain matrix H can be factorized using single value decomposition:

$$H = U\Sigma V^H \tag{3.2}$$

where Σ is a diagonal matrix. The values on the diagonal of Σ are th singular values, σ, of the gain matrix H. Singular values are non-negative, and the number of non-zero singular values equals the rank of the matrix. Then by transmit pre-coding the input $\tilde{x}$ with $\tilde{x} = Vx$, and receiver shaping the $\tilde{y}$ with $\tilde{y} = U^H y$, we have:

$$\tilde{y} = \Sigma\tilde{x} + U^H n \tag{3.3}$$

This transforms a MIMO channel into single-input single-output sub-channels with input $\tilde{x}$, output $\tilde{y}$, channel gain σ and noise $U^H n$. In this singular value decomposition, U^H is a unitary matrix.

And as a unitary matrix, U^H does not change the distribution of noise n.

When there is no reflectors or scatters, only the direct signal path exits between each pair of transmitting and receiving antennas. In this type of situation, the signals received at the receiver will only differ in delay. Thus, MIMO system can only provide power gain but not multiplexing gain.

In a rich scattering environment, the reflectors and scatters will create different paths other than the direct signal path. These paths will grant H full rank. A full rank H matrix means that all its singular values are non-zero. According to the singular decomposition, a n by n MIMO channel with a full rank H matrix can have n linearly independent sub-channels.

The capacity of those sub-channels depends on H's singular values, σ. When the channel has a high SNR, the highest total capacity is achieved when each sub-channel has equal power gain, which means all singular values are equal.

However, equal power gain can not always be achieved. The ratio of the maximum singular value against the minimum one is defined as the conditional number of the gain matrix H. The conditional number has the value 1 when all singular values are equal and the channel achieves highest capacity is possible for conditional number 1. A matrix H with a conditional number close to 1 is said to be well-conditioned, and this means the MIMO channel has good capacity. In order to investigate the possible potential of MIMO systems, we assume that all H matrix are well-conditioned.

With our assumption of a well-conditioned H matrix, a MIMO channel with n transmitting and n receiving antennas has n independent parallel sub-channels with equal power gain. Each node has a fixed transmit power level. The power allocated to each sub-channel is the total power divided by the number of sub-channels. This ensures that the total transmission energy expended by a node during one transmission is the same regardless of the number of transmitting antennas that are employed. Reducing the power on a sub-channel reduces the SINR for this channel, as seen from Equations 2.1 and 2.2. Thus, the number of antennas that can be selected for a particular link is limited so that the SINR on each sub-channel is still greater than β. Furthermore, for the channel model employed in this thesis, the resulting multiple-access interference created by the node is the same regardless of the number of active sub-channels in a transmission. Because the interference environment is unchanged, there is no need to adjust the transmission schedule.

For each transmission, the number of possible sub-channels is calculated based on the link

SINR. Because the our simulation model builds the transmission schedule using the worst-case interference environment created by the schedule, the number of sub-channels for each link is fixed during the simulation. However, during a particular transmission not all of the channels are utilized if the number of packets that are routed on this link is less than the number of sub-channels. In this situation, we simply employ on the number of sub-channels required. The sub-channels that are utilized still meet the minimum SINR requirement and the multiple-access interference is also reduced. However, the transmission scheduling algorithm is not modified.

3.2 Slot Packing

The initial and maximum spreading factor is a fixed number(128 in our simulation). But when the SINR of a link is high enough, we allow the sender to reduce the spreading factor according to the link quality and send multiple packets within one slot.

For a link with initial SINR greater than β, the sender will try to half the spreading factor. By calculation, if the worst-case SINR(WSR) is still above the threshold β, the sender will use the halved spreading factor and double the number of packets it can transmit on this link. The WSR is defined by the following:

$$\mathrm{WSR}_{i,j,f} = \frac{P_{r(i,j)} N_{i,j} T_c}{N_0 + \sum\limits_{l \in \mathrm{A}_f} P_{r(l,j)} T_c} \tag{3.4}$$

where i and j are the transmitting and receiving nodes, f is the number of the slot when this transmission is arranged in a frame, and A_f is the set of the nodes that are assigned to slot f in the whole network. It is simply the SINR of node i and j in the situation where all the nodes assigned to the same slot, f, have some packets to transmit. The interference reaches the highest in such scenarios, so this corresponding SINR is the lowest SINR that can be achieved. In practice, this value can be estimated by recording the lowest SINR at the receiving node.

The transmitting node will keeps trying to half the spreading factor until the WSR falls below β and return to the previous SINR and packet number; or use the minimum spreading factor allowed if the WSR is still greater than β. Since WSR is the worst-possible SINR for a transmission, this guarantees that the receiving SINR is greater than the threshold β. In our model, it means that this transmission will be successful and no packet will be discarded because of poor signals.

3.3 Combined mode

In this mode, we allow the nodes to utilize both slot packing and MIMO.

Both slot packing and MIMO system can provide a multiplex gain. However, the gain that is possible is different for each approach due to characteristics of the channel, multiple-access interference environment, and hardware constraints. The maximum multiplexing gain of a MIMO system depends on the number of the transmitting and receiving antennas and a channel that provides a well-conditioned H matrix. For a m by n MIMO system, the maximum number of independent sub-channels is limited to $\min\{m, n\}$. For our system model, the number of transmit and receive antennas at each node is the same, that is, $m = n$. The possible gain is also limited by the physical environment. If there are not enough reflections nor scattering, then the MIMO system can only provide a diversity gain. Our simulation model assumes a rich scattering environment so that all sub-channels are available if the SINR is sufficiently large. As described in Section 3.1, a node determines the number of sub-channels based on the SINR and the constraint on the total power. However, a node may not use all the sub-channels if it does not have enough packets for the transmission.

Slot packing increases the number of packets that one link can transmit by decreasing this link's spreading factor. The maximum multiplex gain for slot packing is $\frac{N_{max}}{N_{min}}$, where N_{max} is the maximum spreading factor and N_{min} is the minimum. The minimum should not be too small because in DSSS modulation, if the length of the pseudo noise code is too short, then it is not as effective in protecting against interference. What is more, the length of the pseudo noise code is power of 2, this also limits the multiplexing gain for slot packing.

The multiplexing gain of MIMO and slot packing is restricted by the nature of each system. In a dense ad hoc network, some nodes will have links with a very high SINR. To exploit these high quality links, we allow both the spreading factor to be reduced and the power to be divided among multiple MIMO sub-channels. This provides a considerable increase in the multiplexing gain and the number of packets that can be included in a transmission. Based on the SINR, a node calculates the maximum number of packets that can be bundled in a transmission using both MIMO and a reduction in the spreading factor. Because our channel model results in an equal SINR for each sub-channel, we limit all sub-channels to the same spreading factor. With n_c antennas and a spreading factor of N, the maximum number of packets that it can transmit is $\frac{N_m n_c}{N}$. After calculating the number of packets allowed for each combination, the node picks the spreading factor and antenna number that can transmit the most packets in one slot. If there is a tie, according to the results of the simulation, the choice of this tie does not have much influence on the system. In our tests, we use the one with larger sub-channel count.

For example, suppose a link has the capacity of transmitting at most 6 packets in one time slot. Suppose the characteristics of the system are such that at most an 8-by-8 MIMO system can be employed, or the spreading factor can be reduced by up to a factor of 8, or any combination of these options. Then for this specific link, the spreading factor can be N_m, $\frac{N_m}{2}$, or $\frac{N_m}{4}$, but $\frac{N_m}{8}$ cannot be supported due to the SINR. That is, $\frac{N_m}{N}$ can take on values 1, 2, or 4. However, the MIMO system can select any subset of the 8 antennas, and for this specific link the possible n_c values are 1, 2, 3, 4, 5, 6. Table 3.1 below shows the possible combinations that can be selected, and the number of packets that can be included in the transmission for these combinations. Values in the table with an $\times$ are not possible for this link. The bold numbers are the ties for the maximizing combinations. That is, the system can select 3 sub-channels and reduce the spreading factor in half, or select 6 sub-channels and make no change to the spreading factor. Either choice results in the same SINR on each sub-channel, and in our model there is no advantage between these two choices.

Table 3.1: Example of Selecting Combination

n_c \ $\frac{N_m}{N}$	1	2	4
1	1	2	4
2	2	4	$\times$
3	3	**6**	$\times$
4	4	$\times$	$\times$
5	5	$\times$	$\times$
6	**6**	$\times$	$\times$

For each transmission, a node picks the first packet in its queue and looks up the next hop for this packet in its routing table. Then the node checks the link between itself and the next hop neighbor and decides the n_c and $\frac{N_m n_c}{N}$ combination according to the link conditions. This also decides the maximum number of packets it can transmit, n_{pm}. Then the nodes checks the other packets in its queue and picks the first n_{pm} routed to the same neighbor. If there are fewer than n_{pm} packets that can be forwarded to this neighbor, it could be possible to reduce the number of sub-channels or increase the spreading factor. However, in our investigations this is not implemented because the improvement in the interference environment cannot be taken advantage of using the scheduling algorithm that is employed. We also do not measure performance in terms of potential energy savings, so possible reductions in power also do not change the network performance.

Chapter 4

Results

We use a computer simulation program to investigate the performance of the MIMO system and the adaptive spreading protocol, both individually and when jointly applied. The investigations are organized into three sections, and the key conclusions are highlighted. In the first section, we examine the combinations of MIMO and slot packing for different system limitations and network densities. For these investigations the other simulation parameters are fixed. In the second section the choice of routing metric is examined. It is obvious that the routing metric must identify high quality links so the multiplexing gain can be exploited. However, it is possible that a small number of links become bottlenecks, so we investigate how including the utilization factor helps reduce the traffic load at key nodes. In the final section the effect of queue size on the network performance is investigated. The queue size needs to be large enough so there is the possibility of exploiting high quality links. However, a very large queue size does not improve network throughput but just increases the delay.We have selected representative results to include in this chapter to support the main conclusions. Additional simulation results confirming similar performance in different network settings are included in the Appendix. Table 4.1 lists the parameter values we used in our tests.

4.1 Combinations

We test different combinations of MIMO and slot-packing limits. These combinations can be divided into four groups. In each group, all combinations share the same maximum possible link capacity. This capacity is the maximum number of packets that can be transmitted on a single link

Table 4.1: Simulation Parameters

Parameter	Value
Area Length	1414 m / 1060 m / 795 m
Number of Nodes	200
Re-route Interval	500 slots
Maximum Spreading Factor	128
β	8
α	3.5
n_0	4.0×10^{-21}
λ	0.125
T_c	2.9×10^{-7}
Total number of time slots	10^5

within one slot. It depends on the product of the number of MIMO antennas used on this link and the maximum number of packets allowed to be packed in each transmission using slot packing.

For example, if the maximum spreading factor is 128, and we limit the spreading factor to be not less than 16, then there can be at most $128 \div 16 = 8$ packets in one slot on each link. If we apply a 4 by 4 MIMO onto this, then the maximum number of packets becomes $8 \times 4 = 32$. So 32 is the maximum possible capacity of this S8M4 combination. Additional combinations with the same maximum possible link capacity include S4M8, S2M16, S16M2, S1M32 and S32M1.

In our simulations, we use combinations up to S8M8. The first group is the 8 capacity group, including S1M8, S8M1, S2M4, and S4M2. The second group consist of S2M8, S8M2 and S4M4 combinations, with a capacity of 16. The third group is the 32-capacity group of combinations of S4M8 and S8M4. The last group contains only the S8M8 combination.

4.2 Densities

In our simulations, the performance of each group varies when the density of the network changes. We use three different densities. The number of the nodes is 200 for all three densities. We change the area from 1414×1414, 1060×1060 to 795×795 meters to adjust the density. Table 4.2 gives the average number of neighbors of one node in these three densities.

For each set of simulation results, we show the end-to-end completion rate, the average hop count and the end-to-end delay versus the total packet generation rate. We generate 1000 random

Table 4.2: Average Number of Detectable Neighbors

Area Length/m	Average Number of Neighbors
1414	12.51
1060	22.26
795	39.57

networks for each section and take the average of the results of the 1000 networks. In a slot the network generates p packets on average($p \ll n$, where n is the number of the nodes), so each node generates a packet with a probability $\frac{p}{200}$. The destination for a packet is selected with a uniform distribution over all the other nodes in the network. In each simulation, after an initial period to allow the system to approach steady-state performance (i.e., a warm-up phase), we begin to count the number of packets generated, delivered, and dropped until the end of the simulation. We set the warm-up phase to be 1500 slots. The total number of packets found in the network at the end of the warm-up phrase is approximately the same as at the end of the simulation. The completion rate is the ratio of the number of the packets delivered to generated. The average hop count is the average number of hops a successfully delivered packets experienced when it reaches its destination and delay is the number of time slots counted from when this packet is generated to when it arrives at its destination.

4.2.1 795 Density

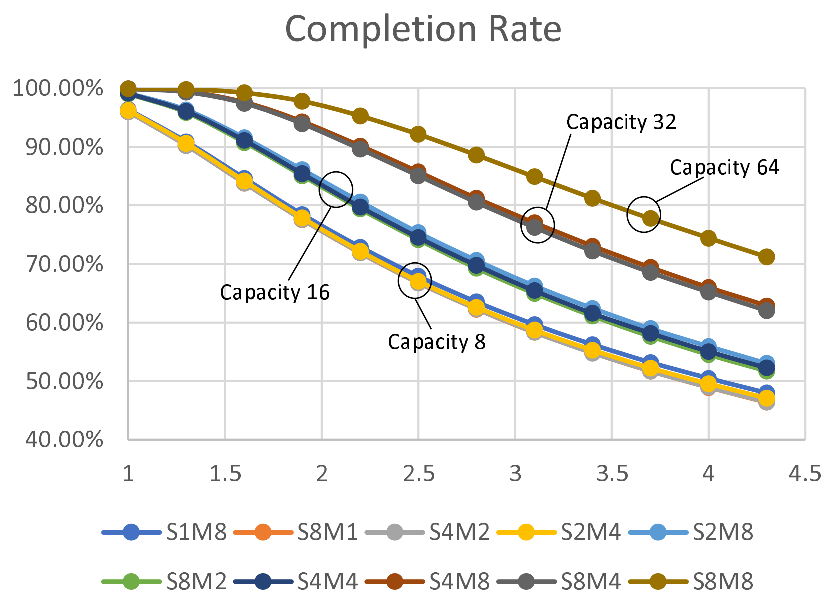

Figure 4.1: 795 Density Completion Rate

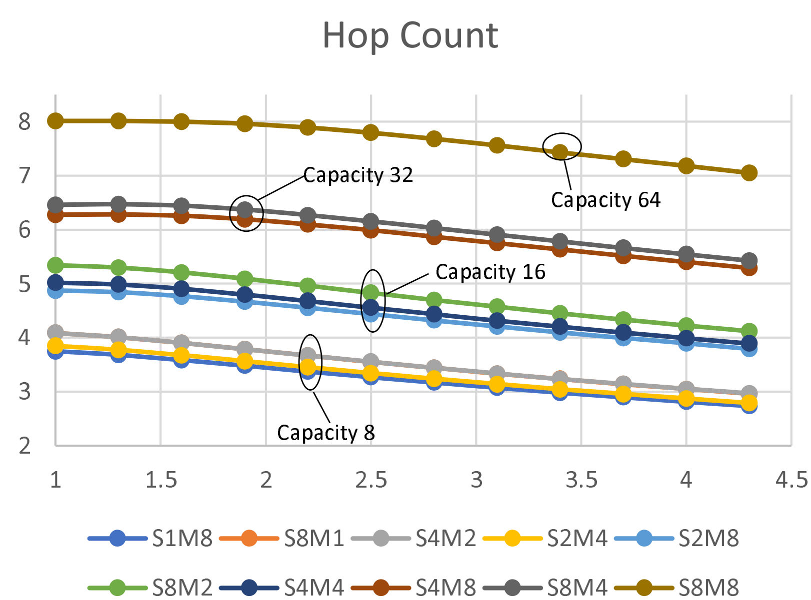

Figure 4.2: 795 Density Hop Count

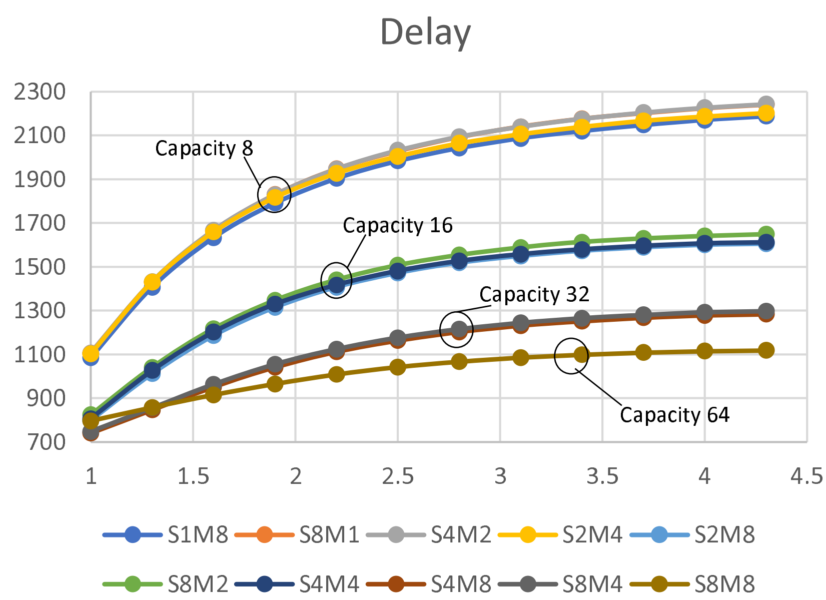

Figure 4.3: 795 Density Delay

For the network with the highest node density, different combinations in the same group overlap heavily with each other in terms of completion rate, as shown in Figure 4.1. With this node density, there are many high-quality links that can be utilized. Systems that can support a larger number of antennas or lower spreading factors have a significant increase in network throughput. Figure 4.2 shows that the average hop count also increases significantly if the maximum link capacity that the system supports is increased. This is because the routing metric assigns a high capacity (but short) link much lower weight using Equation 2.5. Note that the hop count decreases slightly as higher packet generation rates. This is simply due to the fact that packets that must be relayed along a longer route have a higher probably of being dropped due to buffer overflow. The delay is also dramatically reduced for systems that support a higher link capacity, in large part due to reduced queueing delay, as shown in Figure 4.3. However, at the lowest packet generation rate of 1, the delay for the systems with maximum link capacity of 64 is greater than that for the systems with maximum capacity of 32. This reflects that increase in delay due to additional relays since the queueing delay is typically small at this generation rate.

Consider the network performance for various system configurations that result in the same maximum link capacity. We had expected that the additional combinations possible with a system with a larger number of sub-channels compared to one with the ability to decrease the spreading factor would result in improved network performance. For example, a system with the maximum link capacity of 8 packets per slot can support all combinations from 1 to 8 with a S1M8 configuration. But with a S8M1 configuration, only 1, 2, 4, or 8 packets can be packed into a single transmission. However, the option of 3, 5, 6, or 7 sub-channels on sufficiently good links does not provide enough additional flexibility to provide an increase in throughput or a decrease in delay. A small decrease in hop count can be observed in Figure 4.2 due to the presence of a few additional routes, but the difference is so minor as to not significantly impact overall network performance.

4.2.2 1060 Density

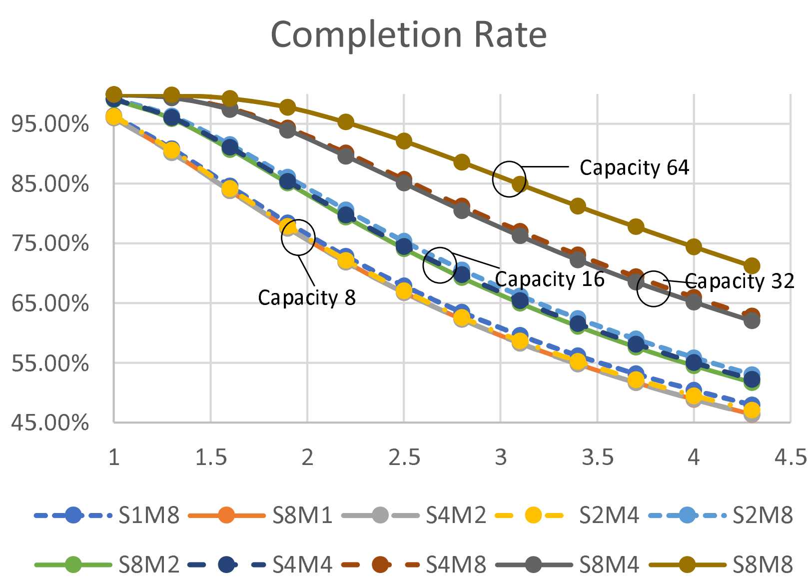

Figure 4.4: 1060 Density Completion Rate

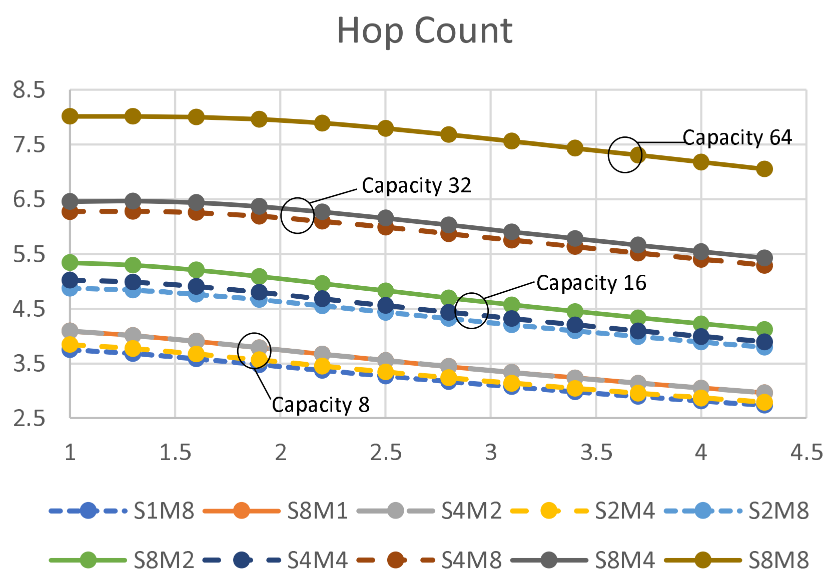

Figure 4.5: 1060 Density Hop Count

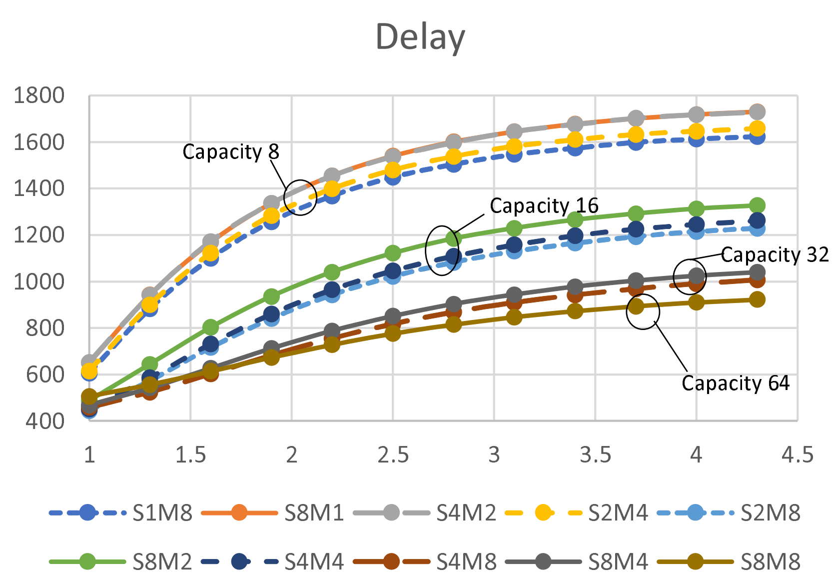

Figure 4.6: 1060 Density Delay

Under this density, combinations in the same groups begin to show difference. Combinations with higher MIMO number perform slightly better than those having higher slot-packing rate. The most likely reason is that MIMO allows numbers like 3, 5, 6 while slot-packing only doubles. Under the previous density, the network is dense enough that each packet will have more choices of routes, and therefore the traffic is more spread. So these minor changes of some links will not show. The difference also shows in the slot and hop count. Those with higher MIMO number has a lower average in both slot count and hop count.

4.2.3 1414 Density

The networks with the medium level of node density show similar trends in performance compared to the high density scenarios. Figures 4.4, 4.5, and 4.6 show the performance results for these experiments. We do observe that there is a small decrease in hop count compared to the previous section. Because the average number of neighbors is smaller with this node density, there are a smaller number of high-quality links that are available compared to the dense network scenarios. So, even though the average distance between a pair of nodes increases, the number of relays decreases. For a given maximum link capacity, the hop count and delay decrease as the system supports an increased number of sub-channels (and a corresponding decrease in number of choices for the spreading factor). However, the difference is small and is not significant when the completion rate is considered, as shown in Figure 4.4.

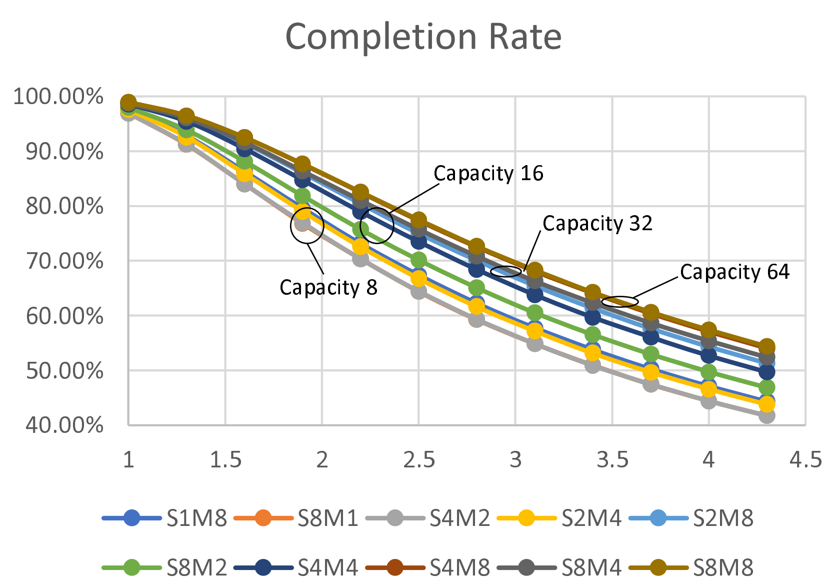

Figure 4.7: 1414 Density Completion Rate

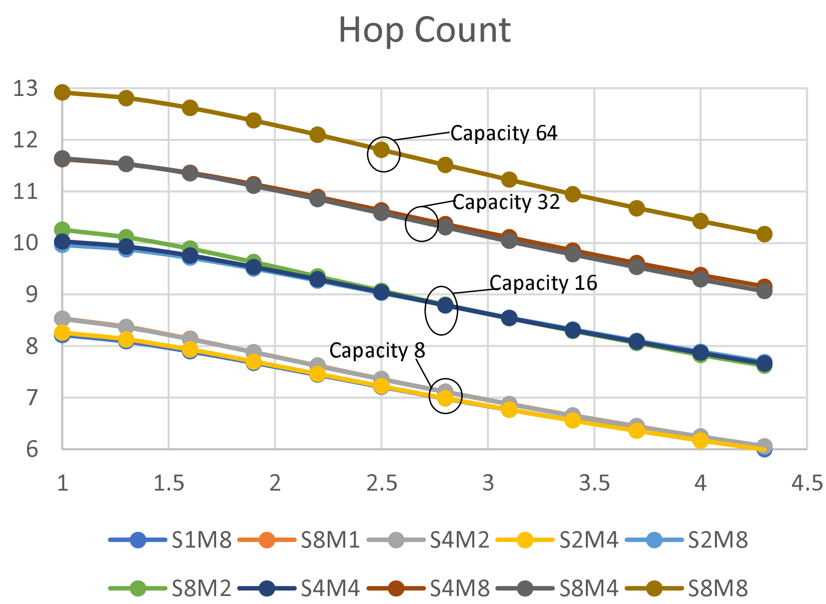

Figure 4.8: 1414 Density Hop Count

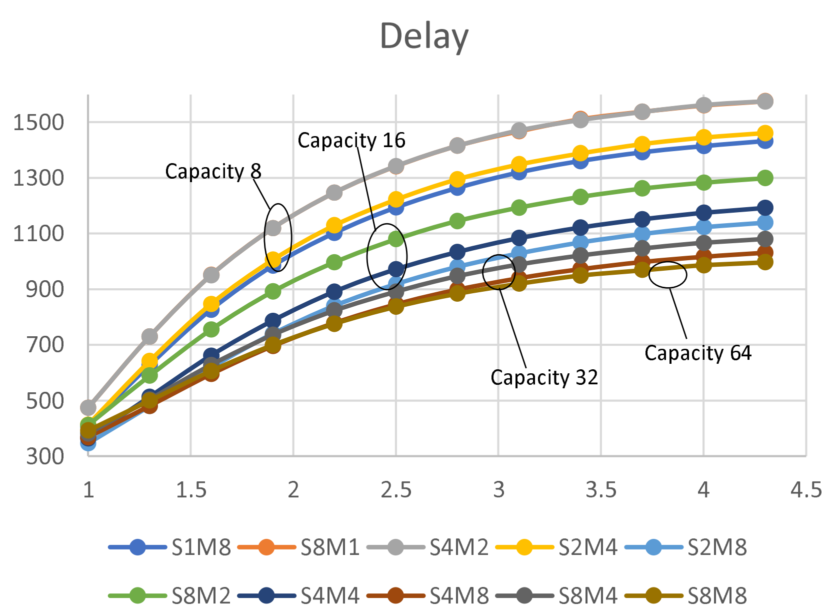

Figure 4.9: 1414 Density Delay

When the area becomes even larger, the difference becomes more distinct with in the same group. For example, in Figure 4.7, the S1M8 and S2M4 combination result lines lies right between the S8M1, S4M2 lines and S8M2 line. The difference within the group(S8M1 and S1M8) is close to some inter-group combinations(S8M1 and S8M2). Each group seems to share a similar hop count, but the delay shows similar tendency as the completion rate. One possible reason is that larger delay indicates the on average a packet stays longer in the network, thus causing more traffic when the generation rate is the same.

4.3 Utilization Weight

For the model employed in this study, packets are dropped due to either buffer overflow or time out. In either event, most packets are dropped at a small number of bottle neck nodes. In some cases, one or two nodes can drop more 90 percent of the total dropped packets. To amend this, we use utilization rate to spread the traffic.

We test a few different formulas. The best choice depends on a variety of parameters of the network. For the sets of parameters we have tested, (1 + 0.4 × Utilization Rate) gives good performance for most of the situations. Below is an example of this.

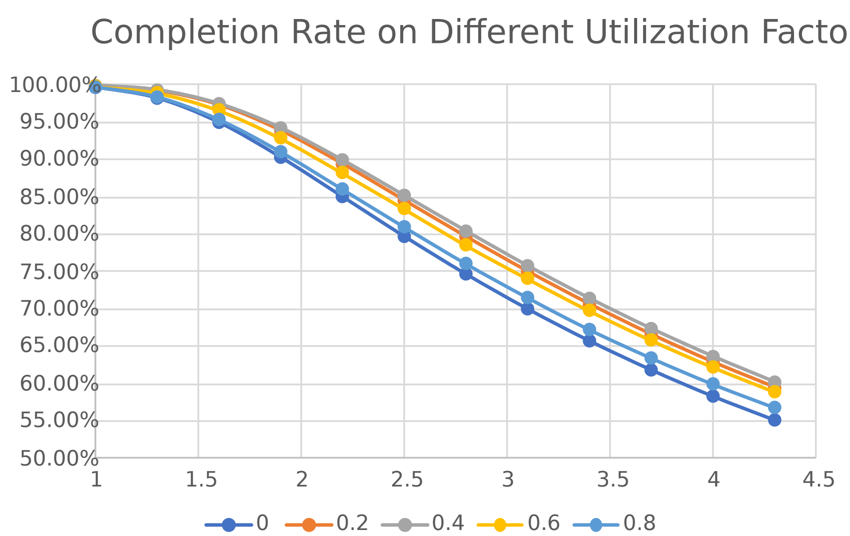

Figure 4.10: Completion Rate for Different Utilization Weight

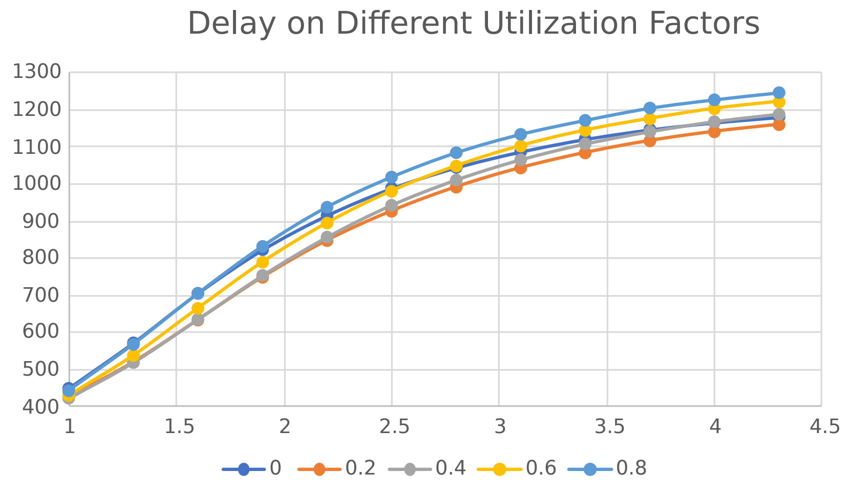

Figure 4.11: Delay for Different Utilization Weight

This test has a 1060 density and a maximum link capacity of 32. From Figure 4.10 and 4.11, we can see that 0.4 utilization weight gives a higher end-to-end completion rate and lower delay.

The details of more utilization weight tests can be found in Appendix A.

4.4 Queue Size

Larger link capacity requires larger queue size. For example, if the link can transfer 64 packets at one time, and the queue size is limited to 50, then the nodes can never provide enough packets to fill the link, wasting the 64 link capacity.

On the other hand, larger queue size may lead to longer packet delivery delay. In order to avoid extremely long delays, we set a time to live of each packet to 5000 slots. If a packets stays in the network for more than 5000 slots, it will be discarded immediately. It is 10 times of the normal packets delivery delay when the network maintains a good condition. For a network with a queue size as larger as 1000, it will hold more packets in the queue. As a result, packets are more likely to stay in the queue until it reaches 5000 slots. Then more packets will be dropped due to time out when the queue size is larger than a proper value.

Figure 4.12 shows how the queue size changes affect the network performance for a S4M8 network at 1060 density. We can see in this case, a queue size of 1000 does not lead to better performance than 150.

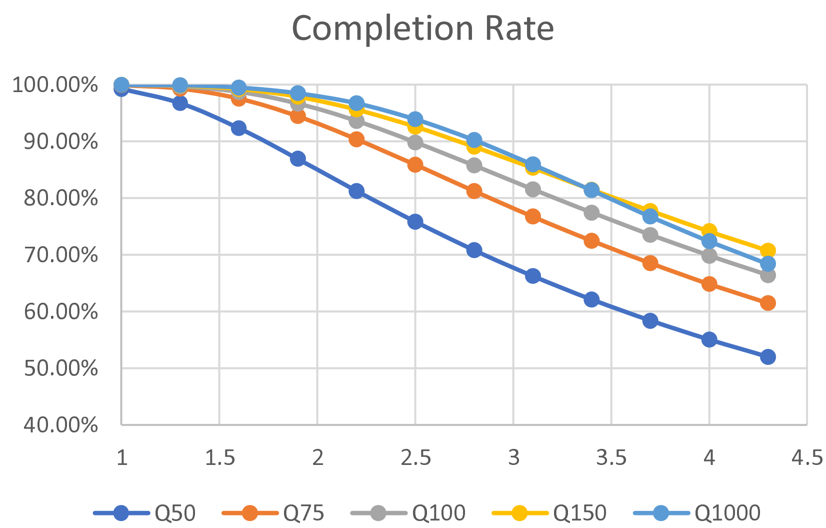

Figure 4.12: Completion Rate for Different Queue Size

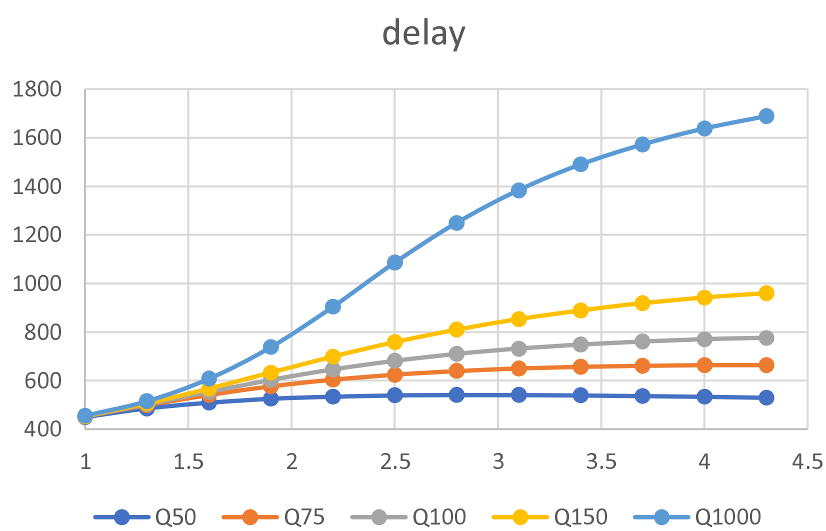

Figure 4.13: Delay for Different Queue Size

However, in Figure 4.13, the average delay in a network with large queue sizes like 1000 is extreme. Sufficient queue size is needed according the possible maximum link capacity, but queue size should not be too large. For more results about queue size, please see Appendix B.

Chapter 5

Conclusions

A scheduled channel-access protocol for an ad hoc network provides reliable opportunities to access the channel and can avoid collisions and delays associated with a contention-based channel-access protocol. However, utilization of the transmission opportunities can be very poor, especially for traffic that has random inter-arrival times or requires multiple relays to reach its destinations. Two mechanisms that can improve the efficiency of the channel access are to adapt the spreading factor or to employ a MIMO system. Both of these mechanisms can improve the data rate for a link with a high SINR. Each of these approaches is limited due to system characteristics. For example, reducing the spreading factor increases the data rate but also reduces the protection against multiple-access interference. A MIMO system depends on having a channel that is well-conditioned as well as additional limits on hardware and processing power. In this thesis we have assumed an idealized model of these systems and examined the trade-off between the two approaches. We show that while the MIMO system has the potential to exploit a larger number of options for utilizing a specific link compared to changes in the spreading factor, the number of situations in which this leads to an improvement is limited. For the scenarios we have examined, the two approaches result in similar network performance in all situations.

It is also possible to employ both systems simultaneously, subject to a limit on the total transmission power. The MIMO system with n transmit and receive antennas can establish up to n independent channels limited only by the SINR requirement. Then each sub-channel can also adapt the spreading factor, again subject to maintaining an acceptable SINR. Exploiting both possibilities provides a significant improvement in network performance in scenarios in which there are links with a high SINR. In many situations there are multiple configurations of sub-channels and spreading factors that result in the same link capacity. Based on the initial study, for our model there is no advantage to maximizing the gains utilizing one system over the other. Instead the combination that leads to the largest capacity is all that is required, and when there are multiple choices they have equal performance in our model.

In order for the ad hoc network to take advantage of the high-capacity links created by these systems, it is critical that other aspects of the protocol design account for this behavior. We show the design of the routing metric is critical so that high-capacity links are identified and traffic is routed on these links. Because the network performance is often limited by a few bottleneck nodes, including a measure of utilization in the routing metric is helpful to force some traffic to be routed around the bottlenecks. However, to be effective there have to be a large number of alternative routes, and increasing the weight of links to a bottleneck node by too large a value increases congestion in the network.

Providing sufficient queue size is also an important parameter in exploiting this system. In the investigations included in this thesis, we consider parameter options that allow up to 64 packets to be bundled into a single transmission opportunity. Thus, it is important that the queue size is large enough so that there is an opportunity to utilize the link capacity. However, very large queue sizes result in excessive queueing delay, especially at nodes that do not have the ability to utilize high-capacity links. It is clear that the queue size needs to be larger than the maximum link capacity. We show that further increases in the queue size result in very limited improvements to end-to-end completion rate or throughput but result in very large delays. However, there is not a clear heuristic for selecting the best queue size.

Future work will consider multiple receivers in our systems. Both MIMO and slot-packing can allow one to node transmit packets to multiple neighbors in one time slot. This can better utilize the links and requires less queue size than single receiver system. Also, it will be important to investigate how MIMO performs when the environment is not ideal: how the network will change if the channel gain matrix is not well-conditioned. Another issue is the bottle neck nodes. In our tests, sometimes one or two nodes can drop up to 90% of the packets. If we can design a protocol that spreads the traffic from these bottle neck nodes, there is a good chance that the network will be able to deliver more packets.

Appendices

Appendix A Utilization factor

We tried a few different utilization factor mentioned in Chapter 4. Here are the test results.

A.1 795 desity

We first start from utilization factor 1, then find out that fractional utilization factor work better. For this density, we first try with the largest maximum link capacity(32).

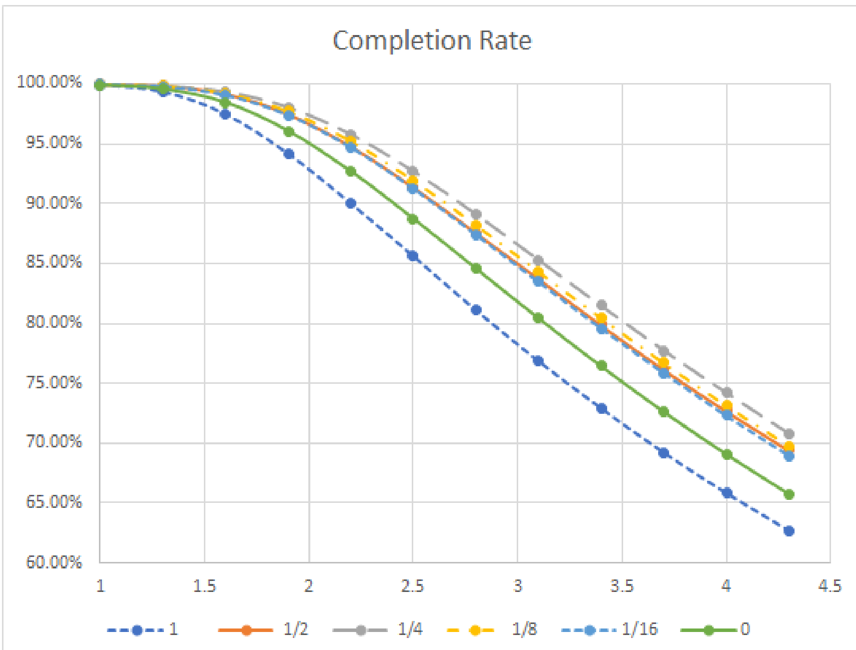

Figure 1: 795 Density Completion Rate

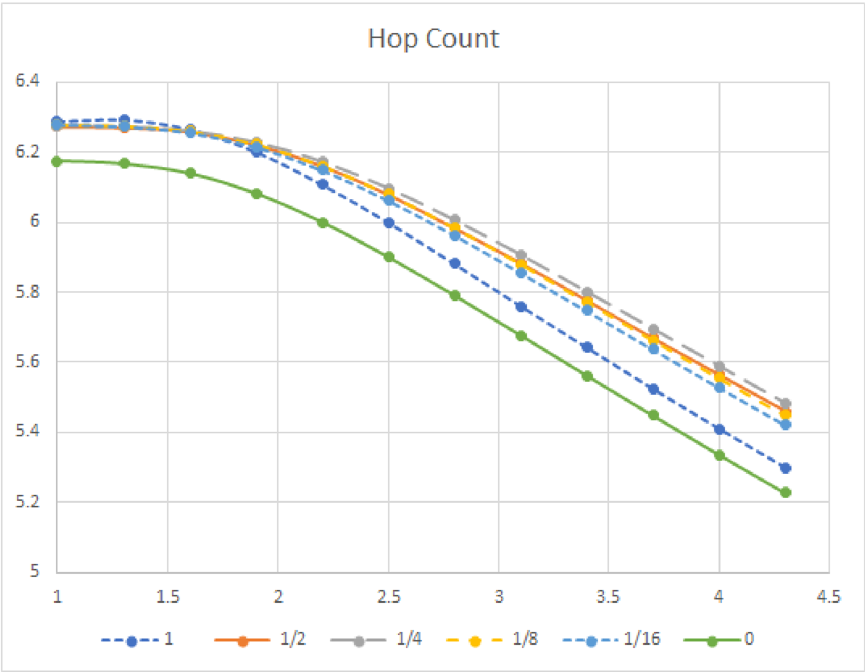

Figure 2: 795 Density Hop Count

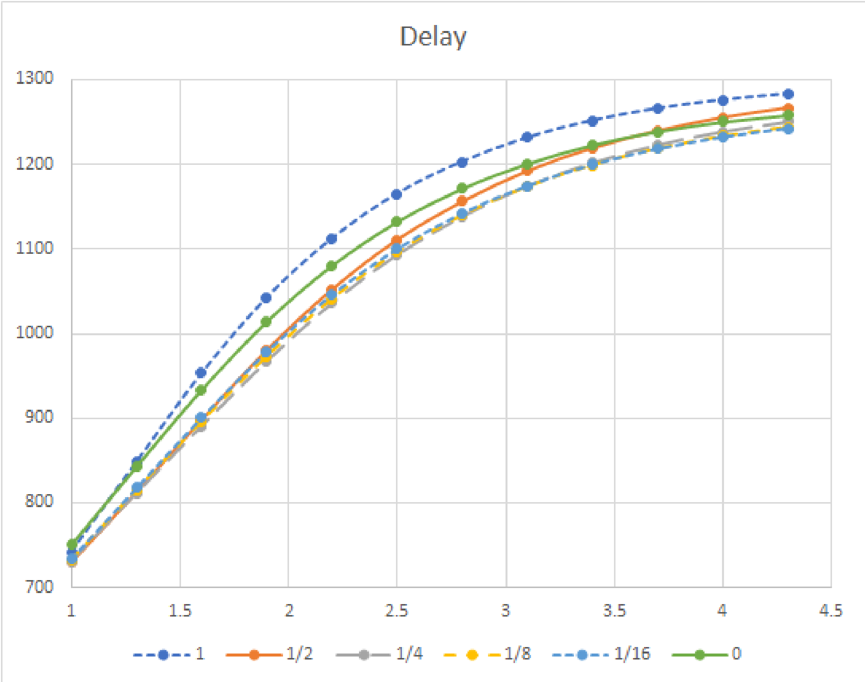

Figure 3: 795 Density Delay

The best value for this set of parameters is about 0.25.

We then try this on a few other link capacity. For example, below is the result with maximum link capacity of 8.

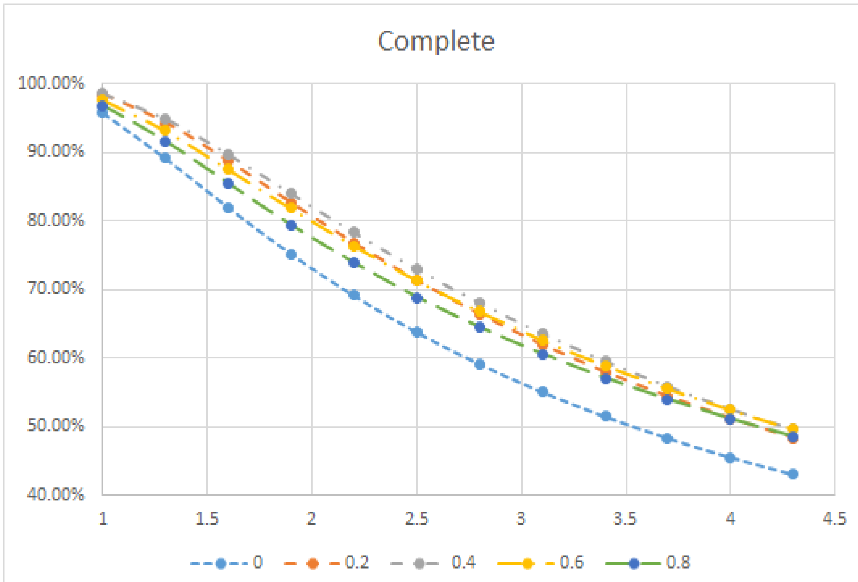

Figure 4: 795 Density Completion Rate - Capacity 8

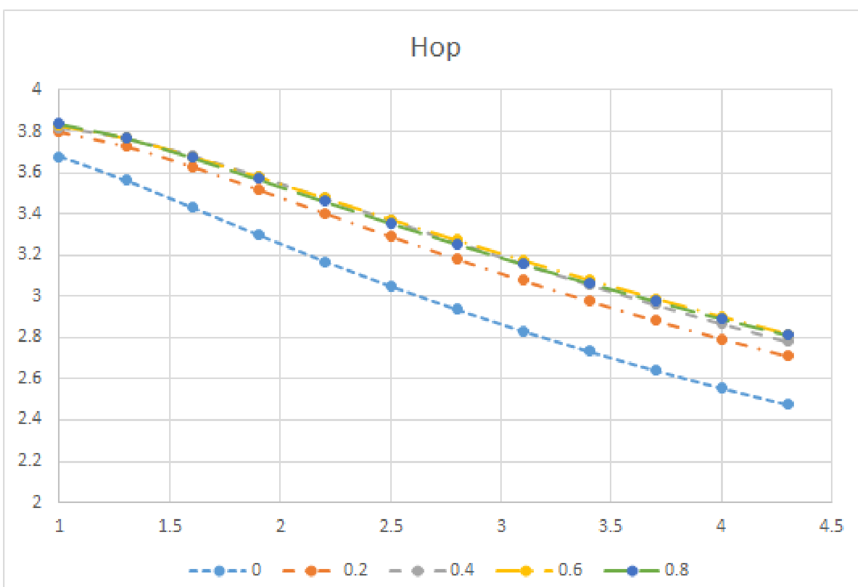

Figure 5: 795 Density Hop Count - Capacity 8

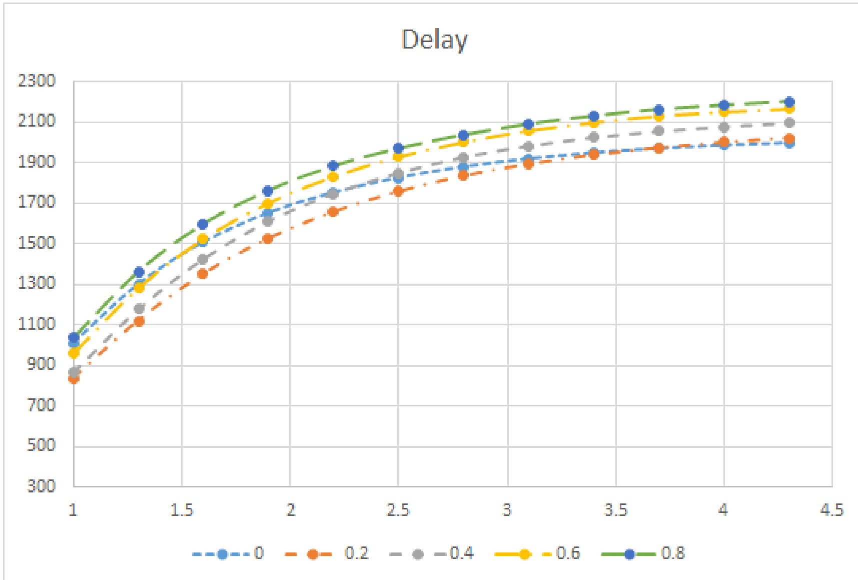

Figure 6: 795 Density Delay - Capacity 8

The best value shifts to 0.4 this time.

A.2 Other desities

We repeat the test for different densities. For simplicity, we only list the completion rate graphs here.

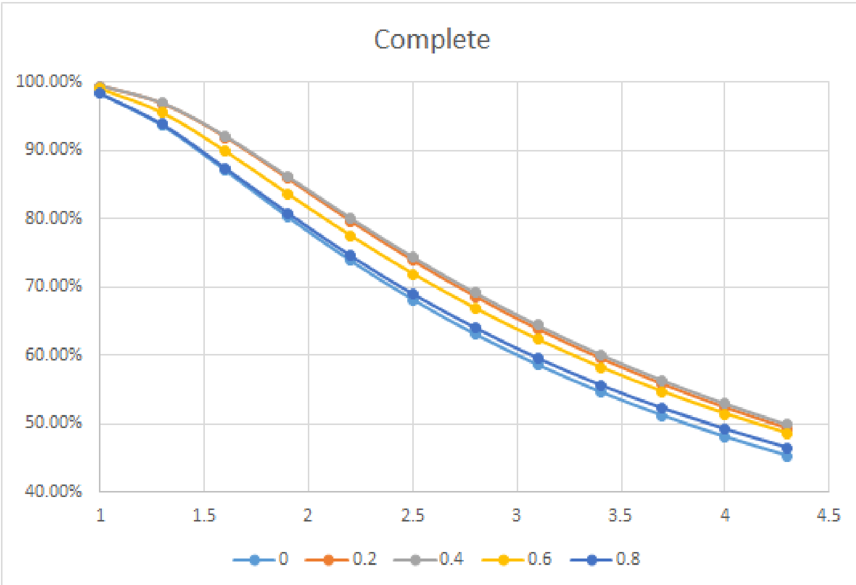

Figure 7: 1060 Density Capacity 8

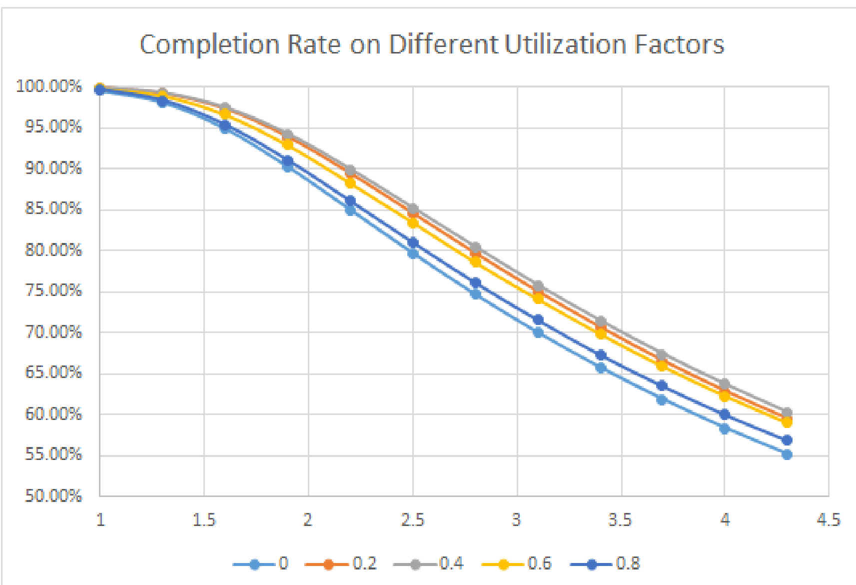

Figure 8: 1060 Density Capacity 16

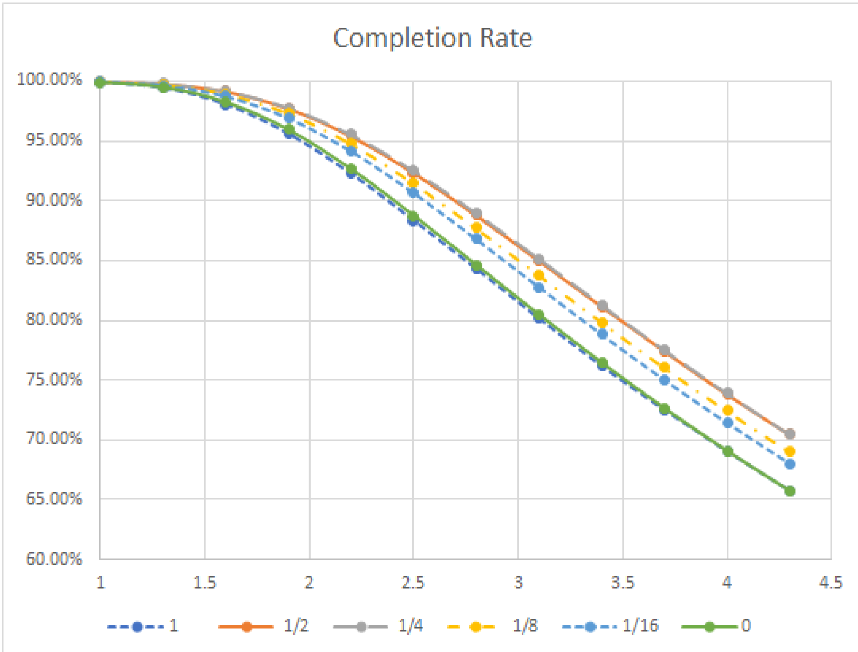

Figure 9: 1060 Density Capacity 32

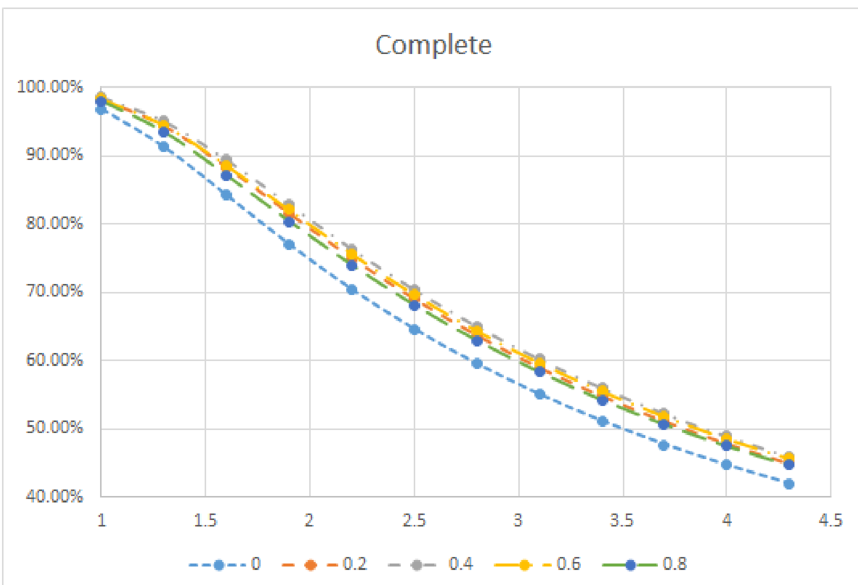

Figure 10: 1414 Density Capacity 8

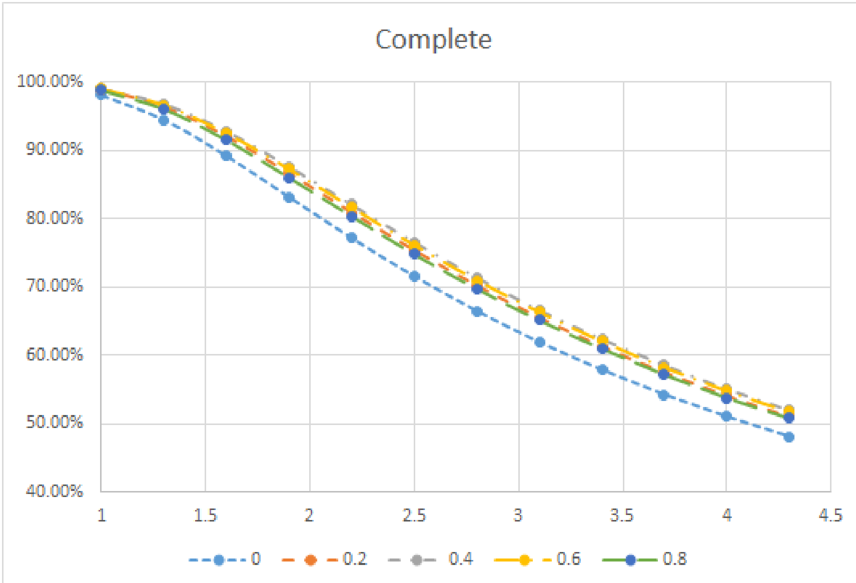

Figure 11: 1414 Density Capacity 16

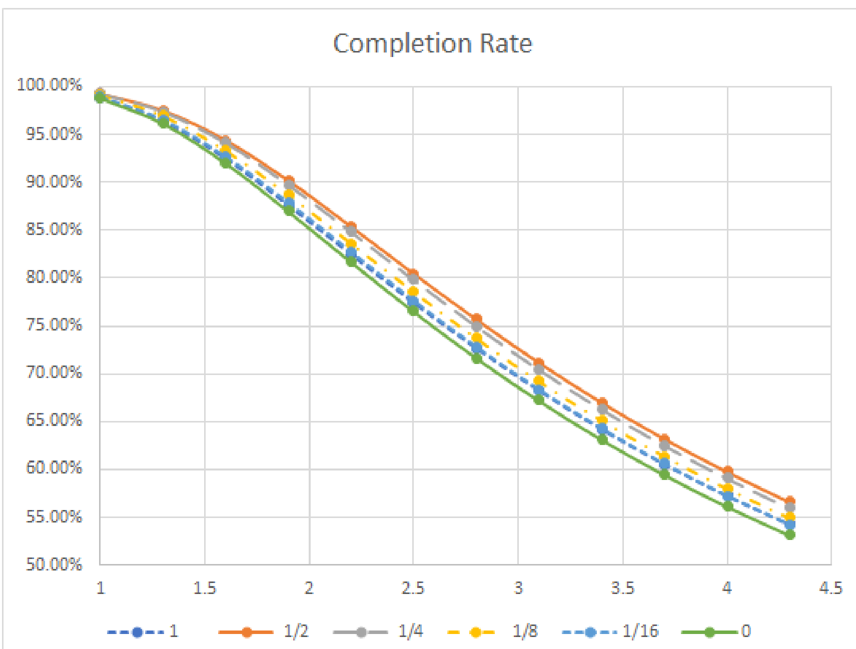

Figure 12: 1414 Density Capacity 32

For most situations, a utilization factor less than 1 improves the completion rate. Among our tests, the value 0.4 works well in different parameter settings. Thus, we choose this value to be our final utilization factor.

Appendix B Queue Size

Here are the results for different queue size in density 1060.

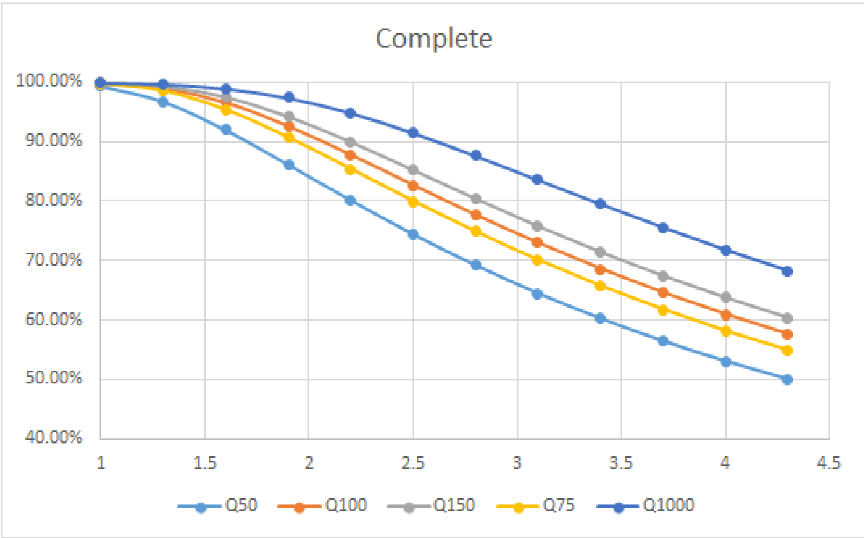

Figure 13: Capacity 16 Completion Rate

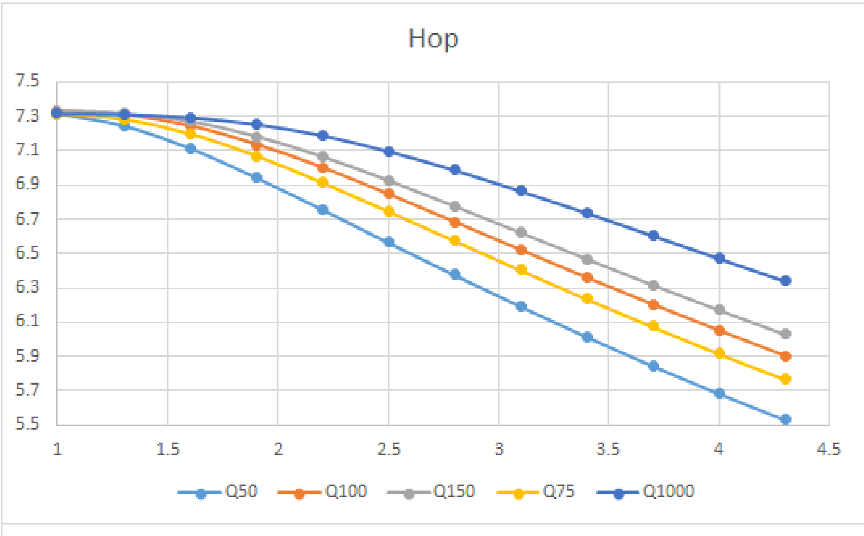

Figure 14: Capacity 16 Hop Count

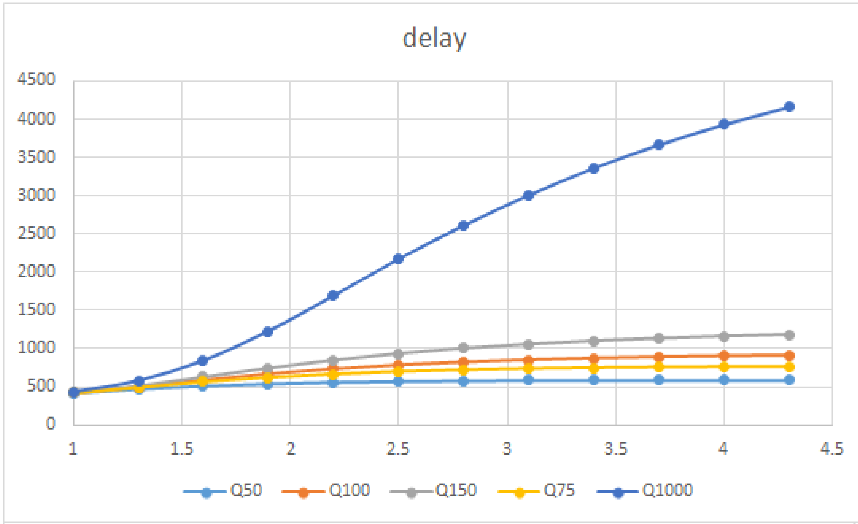

Figure 15: Capacity 16 Delay

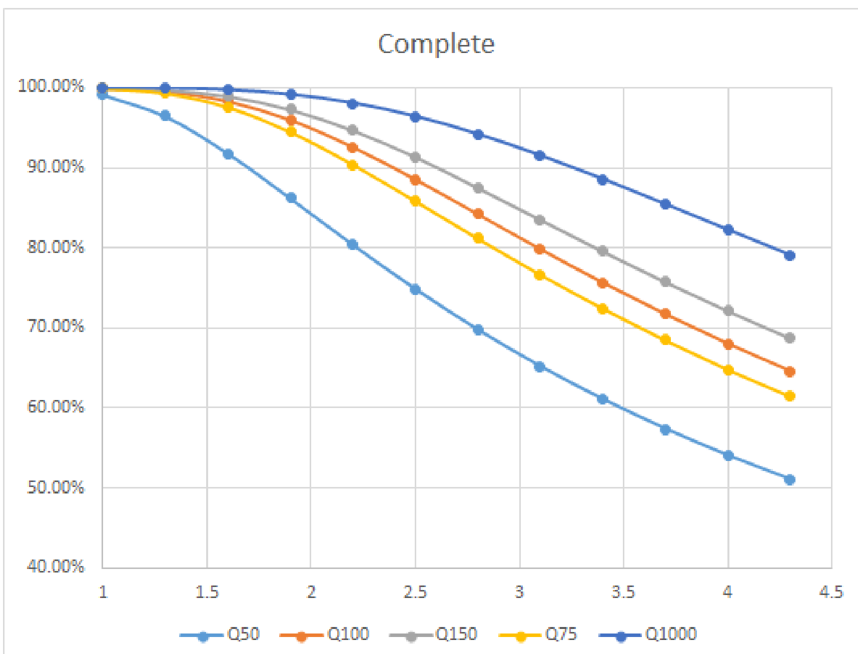

Figure 16: Capacity 32 Completion Rate

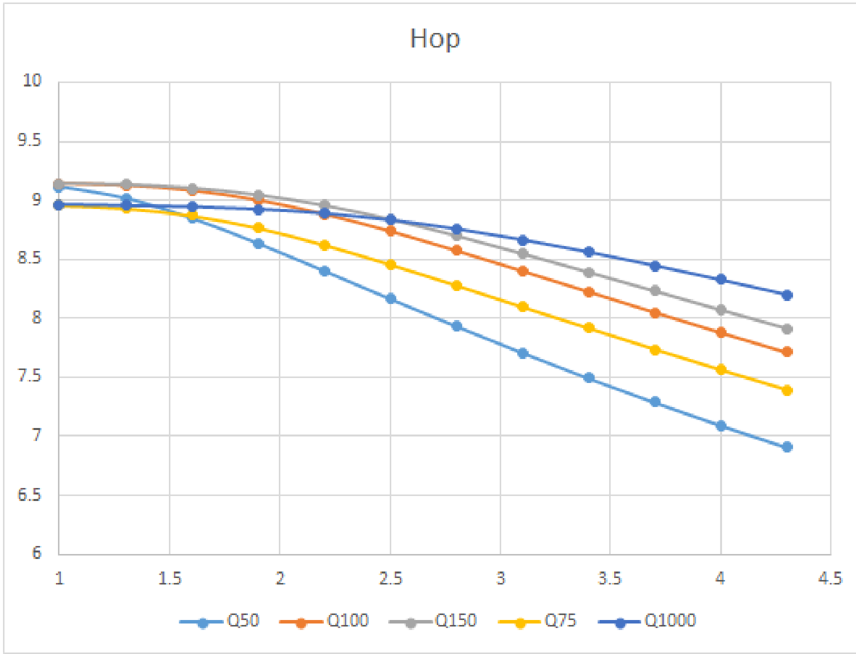

Figure 17: Capacity 32 Hop Count

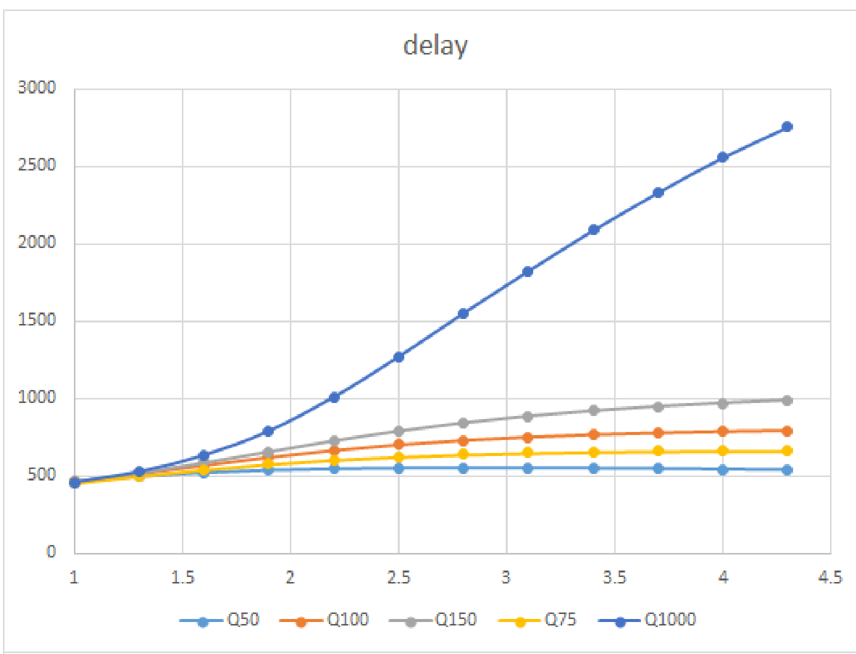

Figure 18: Capacity 32 Delay

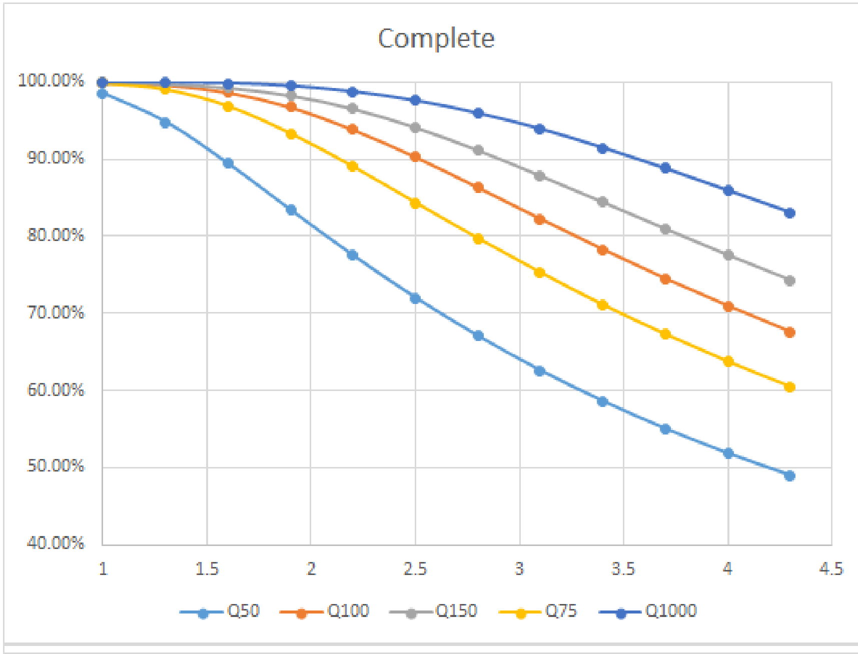

Figure 19: Capacity 64 Completion Rate

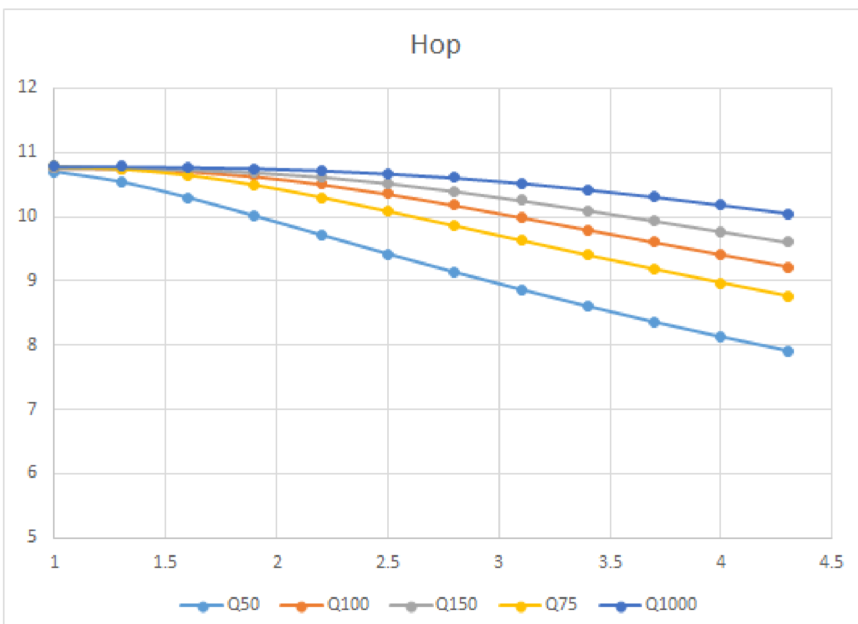

Figure 20: Capacity 64 Hop Count

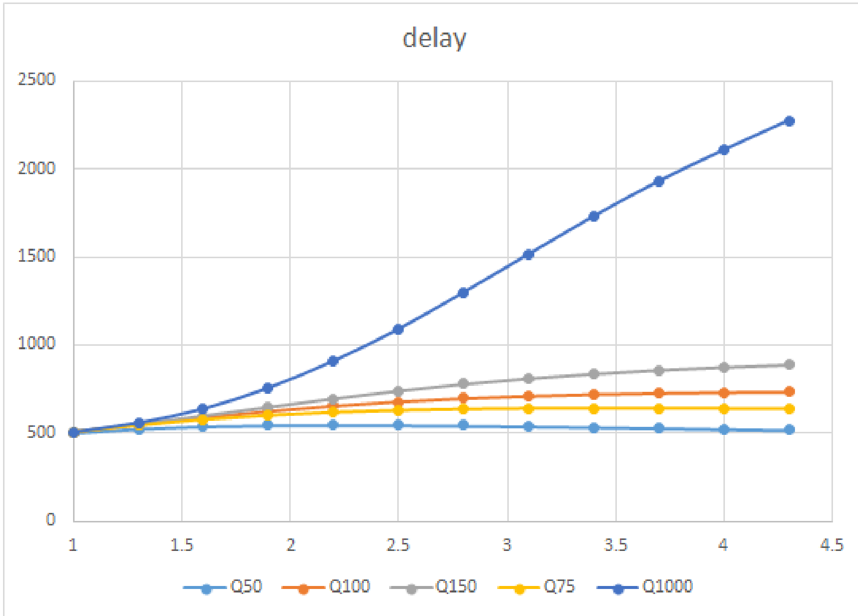

Figure 21: Capacity 64 Delay

Increasing the queue size raises the completion rate. But when the queue size grows from 150 to 1000, the improvement is similar to that from 100 to 150. Meanwhile, the delay soars. So a queue size as large as 1000 is not a reasonable choice.

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