ABSTRACT

PRABHU, MANJUNATH M. Power Adaptive, Spatial Distributed MAC (PowSD-MAC): A Long Distance Media Access Control (MAC) Protocol For Air-to-Air (A2A) Communication. (Under the direction of Associate Professor Mihail L. Sichitiu.)

This thesis focuses on an *Airplane-to-Airplane (A2A) communication* system. We propose an *airplane black box data replication* application that aims to replicate all black box data to nearby airplanes, thereby avoiding the use of expensive black boxes. We review existing MAC protocols for long distance communication involving high-mobility nodes. In these conditions, it has been shown that contention based protocols are inefficient due to increased packet collisions. In this thesis, we propose a media access protocol called Spatial Distributed MAC (SD-MAC) based on Time Division Multiple Access (TDMA). This protocol allocates slots for packet transmission and provides acknowledgments for reliable communication. SD-MAC also provides adaptive power control for increased spatial re-use, which significantly improves the performance of the protocol. The protocol with adaptive power control is called PowSD-MAC. We compare SD-MAC and PowSD-MAC with tuned-up versions of IEEE 802.11 [1] for varying topologies using different airplane cruise speeds, airplane density, offered load conditions and packet sizes. We evaluate the performance of the proposed protocol in terms of efficiency, reliability and scalability by implementing these protocols in OMNeT++ [2], an event-based network simulator. The results show that PowSD-MAC outperforms IEEE802.11 for a large range of parameters and performance metrics. This material is based upon work supported by the National Science Foundation under Grant No. 0553247.

Power Adaptive, Spatial Distributed MAC (PowSD-MAC): A Long Distance Media Access Control (MAC) Protocol For Air-to-Air (A2A) Communication

by

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Dedication

To my family . . .

Biography

Manjunath M. Prabhu was born on February 9, 1982 in Mangalore, Karnataka, India. He earned a Bachelor of Engineering (B.E) degree in Electronics and Communication from Rashtreeya Vidyalaya College of Engineering (RVCE), Bangalore in July, 2003. He developed a keen interest in computer networks while working at the Center for Electronic Design and Technology (CEDT), The Indian Institute of Science, Bangalore. He worked as a project assistant with the Telematics groups at CEDT, researching in wireless ad hoc networks for over a year. His association with students and faculty at CEDT convinced him to seek a formal degree in computer networks. In Fall 2005, he joined North Carolina State University for graduate studies in Computer Networking, and became a member of the Wireless and Local Area Networks (WALAN) research group.

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Chapter 1

Introduction

1.1 Motivation

Air traffic density all over the world is experiencing a steep rise with increase in the number of passenger and cargo airplanes. The Federal Aviation Administration's (FAA) annual forecast predicts that passenger boarding will rise 3.8% in 2007 to 768.4 million. The boarding is expected to surpass 1 billion by 2015 [4]. The forecast also expects 62.5 million take-offs and landings at towered airports (in USA) in 2007. By 2020, that number is predicted to reach 81.1 million operations, growing by an average of 1.4 million per year during the forecast period. The statistics in [5, 6, 7] show that on an average 750-850 airplanes take-off and land every day in a busy international airport. The FAA also suggests that, as part of a wide-ranging transformation of the entire airspace system, their reform proposal will ensure that there is a move away from ground-based technologies into more dynamic satellite-based operations. Airplane to airplane (A2A) communication will play a significant role in this transformation.

Similar to vehicle-to-vehicle ad-hoc networks (VANETs), airplane-to-airplane (A2A) communications may significantly improve travel safety and comfort. We propose an *airplane black box data replication* system, which is useful in case of airplane disasters, where, data from the black boxes is often crucial in determining the cause of the accident and preventing future tragedies. In some cases black boxes are destroyed in the accident or are never found. Furthermore, many small airplanes do not have black boxes (due to price constraints). We propose to use airplane-to-airplane (A2A) data communication system to replicate all the data that is currently recorded on the black boxes to nearby airplanes. In the proposed system, every airplane will act as a data source and, possibly as a destination for one or more airplanes. Each airplane, for the duration of its flight, will find a nearby destination airplane (within wireless range) and proceed to upload the black box data to this destination. In the adaptive power control mechanism, before the link between the two airplanes breaks, the transmission power is increased to maintain a reliable communication link. Each source continuously searches for the closest airplane to send data to. Thus, during its flight, the data from one source airplane may be uploaded to several other destination airplanes. In the event of an accident of the source airplane, data from all those destination airplanes can be collected at a centralized location and all black box data of the source airplane can be reconstructed. This strategy will allow for inexpensive black box devices to be installed in practically all airplanes, as, in this scenario, it is not necessary for the black box to be overly reliable and survive fires and tremendous G forces.

A2A communication systems face the same problems as other mobile ad-hoc networks (MANETs): link reliability, mobility, lack of centralized coordination, etc. Link reliability is a major issue because current protocols do not consider the stability of the established links, resulting in frequent link breakages. The link breakage results from changes in topology caused by mobility, and changes in the environment affecting the transmission channel. Initiating a new link-connection after the current link breakage often results in large delays, overhead and possibly, loss of information. The reliability can be increased if stable (long-lived) links are established before the current link is broken. However, additional considerations differentiate A2A systems from general-purpose MANETs:

- In A2A systems, the distance between neighboring airplanes varies from a few kilometers to hundreds of kilometers; for a high-speed communication system this results in very large propagation delays (comparable with packet length).

- In A2A systems, the evolution of the airplane (node) trajectory can be predicted with a high probability;

- In A2A systems, the communication between neighboring airplanes is usually unobstructed, resulting in a far more predictable formation and breakage of wireless link as a function of the physical distance than in other MANETs that have to contend with slow- and fast-fading effects.

- In A2A systems, with non-negligible propagation delay, carrier-sense/contention based media access protocols are known to be ineffective.

- In A2A systems, using long-range communication links provides better mobility support but reduces spatial re-use. To increase the network capacity, there is a need to provide high spatial reuse, allowing multiple nodes to communicate simultaneously.

Given the importance of the A2A applications, the focus is on developing protocols to provide *reliable* and *efficient* data transfer in MANETs. We expect that, due to the high airplane density and the predictability of airplane trajectories, all data will be successfully replicated. We aim to maximize the network capacity providing reliable point to point communication. In addition, a very interesting problem for this application is determining the transmission power that will maximize the network capacity (long range communications will be comparatively long lived but will interfere with many other communications). We propose adaptive power control schemes to localize communication and expect that this application will be highly scalable.

1.2 Contribution

This thesis proposes SD-MAC, a media access protocol designed for long-range A2A communication. We identify the following three critical components in our system model. A logical block diagram of the system model is shown in Fig 1.1.

- *Link Maintenance (LM)*
  The Link Maintenance module on every mobile node establishes and maintains the wireless link. This module stores updated location information of all single-hop and two-hop neighbors of the airplane in a table called the *Neighbor Table (NT).* Link quality information could also be stored and used to predict link breakage. This module invokes the adaptive power control scheme to maintain connectivity before the existing link breaks.

- *Neighbor Selection (NS)*
  The LM module maintains information also used by the NS module. The NS module

accesses information from the NT in selecting the best neighbor. The neighbor selection could be based on distance, link-quality, mobility etc. The goal of this module is to choose neighbors which result in long-lived links.

- *Medium Access Control (MAC) Protocol*
  The MAC protocol coordinates the media/channel access considering the node mobility and the propagation delay introduced by the long-range wireless links. The MAC protocol provides reliable data transfer over wireless links for black box data replication.

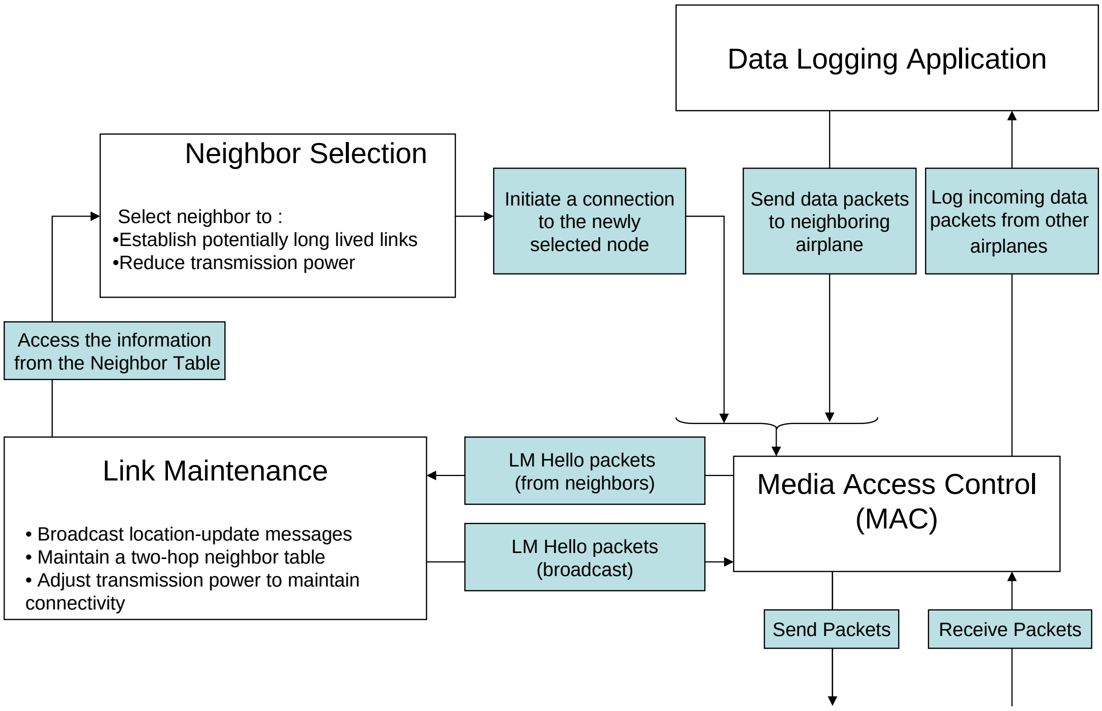


Figure 1.1: Block diagram of the system model.

The main goal of this thesis is the development of the MAC protocol in conjunction with the *Link Maintenance* and *Neighbor Selection* modules. We propose a link maintenance module to collect and update location information of all two-hop neighbors. An established link is maintained through adaptive power control. The location information is exchanged through periodic broadcasts of *LM Hello Messages*. We also propose a location-based neighbor selection scheme that chooses a neighbor from the information maintained by the LM module. When a new neighbor is chosen as its destination, the current link is broken to establish a new link. In the mean time, data packets are buffered to avoid loss of information. Also, this scheme allows isolated nodes to join their nearest cluster, thus avoiding loss of information for long intervals of time.

The main contribution of this paper is the development of the SD-MAC, a long-distance TDMA based MAC protocol, suitable for A2A communication. SD-MAC is based on TDMA with time divided into frames. Each frame contains slots and all messages are sent over one or several slots. The LM-Hello packets are used to exchange information of all one-hop neighbors and slot availability in the frame. SD-MAC uses the basic mechanism of RR-ALOHA [8] to broadcast control information; however, in contrast to RR-ALOHA, SD-MAC explicitly accounts for propagation delays in the reservation scheme (by appropriately shifting reservation slots). Additionally, to increase spatial reuse and to avoid link breakages due to high mobility, we augment SD-MAC with an adaptive power control mechanism, resulting in PowSD-MAC, a joint scheduling and adaptive power control MAC protocol. We show that PowSD-MAC provides an efficient and reliable MAC protocol suitable for the proposed black-box replication system. The protocol performance is evaluated and compared with tuned-up versions of IEEE 802.11.

Owing to its scheduling mechanism, PowSD-MAC can provide reliable QoS for long-lived flows with constant bandwidth needs (such as an uncompressed VoIP or a periodic monitoring application). Although we developed and evaluated the performance of PowSD-MAC specifically for the A2A communication system, we believe that it would also be suitable for other applications with large propagation delays (e.g., an ultrasound-based under-water wireless sensor network).

We introduce a *destination-based* slot allocation mechanism to reserve slots for sending Data. Once, a neighbor is selected as destination, the source requests the destination to allocate slots for DATA/Acknowledgement (ACK) exchanges. The destination allocates slots for the source to send data and allocates slots for itself to send the ACKs.

The proposed scheme with dynamic slot allocation accommodates long-range links and high mobility nodes. It provides reliability by acknowledging data information received. With adaptive transmission power adjustment, the scheme increases the average link duration and provides high spatial re-use achieving high network throughput.

1.3 Thesis Organization

This thesis is organized as follows: Chapter 2 describes the related work. Chapter 3 discusses the need for dynamic time-division multiple access protocols for long distance communication. It describes the proposed media access protocol including the enhancement for an adaptive power control mechanism. Chapter 4 describes the simulation model used and compares the performance of the proposed protocol with IEEE 802.11. Finally, Chapter 5 summarizes the results of our work and discusses future work.

Chapter 2

Related Work

The literature related to long range communication systems can be classified based on the components identified in Section 1.2. In Section 2.1 we review link-maintenance protocols that aim to establish links with uninterrupted connectivity. These protocols maintain information of link availability. Existing work consists of statistical methods, reactive schemes and proactive schemes to determine link availability. Once a link breakage is detected, these protocols invoke schemes to choose a suitable neighbor. A new neighbor can be selected to establish long-lived links based on location information, link-quality information or other parameters. In Section 2.2 we discuss existing MAC protocols and their variants to accommodate large propagation delay. We also review protocols that have been designed for long distances between communicating nodes.

2.1 Link Maintenance and Neighbor Selection Protocols

Existing literature in the area of link-availability for wireless mobile ad-hoc networks, focuses on statistical methods to estimate the stability of paths. Gerharz et al. [9] develop metrics to identify stable links relying on online statistical evaluation of the observed link durations. They use the current link duration to determine its expected residual lifetime. In [10], the authors extend their previous work and analyze details of specific mobility scenarios and their influence on link stability metrics like the transmission range and shape of the area over which the nodes are distributed. The statistical methods have the advantage of reducing the number of hello or discovery messages required when establishing a new link. They fail to provide mechanisms for adapting to dynamically changing scenarios. Also, these metrics have been designed mainly for city-based MANETs and mobility-sensitive environments. However, many researchers have recognized the drawbacks of purely stochastic models for determining MANET performance in real world environments.

Link Maintenance schemes have also been developed as part location-based routing algorithms. The implementation of location-based routing algorithms is further justified by the increasing availability of small and inexpensive low-power Global Positioning System (GPS) receivers. Location based routing have been presented in several algorithms like the Location-Aided Routing (LRA) [11], the Distance Routing Effect Algorithms for Mobility (DREAM) [12], and the Geographical Routing Algorithm (GRA) [13]. These protocols aim to reduce the control overhead and do not evaluate the stability of the links.

Link-prediction schemes focus on predicting link breakages well in advance. A new link is then established just in time to avoid the delay and loss of packets involved during link failures. The predictive location-based routing protocol in [14], introduces location-delay prediction and location-resource update schemes. The location-delay prediction is accurate because it predicts the location of the destination accounting for the propagation delay of the packet. Apart from the location update, resource availability information is also broadcasted in order to select a path along which all nodes satisfy certain QoS requirements. The update information is flooded throughout the network. In [15], the authors propose a more efficient location-update algorithm with a reduced number of broadcast packets. The location update packets are only broadcasted to single-hop neighbors. The goal is to reduce the overhead introduced by the schemes that flood location information. Other resource information can be used to establish stable links. With variations in the channel conditions, determining neighbors based on geographical proximity will not be sufficient for determining connectivity. However, with stable channel conditions and reliable broadcast, these protocols show improved performance.

The wireless channel plays a significant role in determining the connectivity between wireless nodes. Two factors affecting link quality are signal strength (RSSI) and signal to noise ratio (SNR). A channel-aware link prediction scheme for selecting reliable links using signal strength information has been presented in [16]. It classifies the channel as strong or weak and selects nodes with strong channels while determining the route to the destination. In [17] the authors propose using differentiated signal strength (DSS) as a parameter. DSS indicates if the signal strength is becoming stronger or weaker. This scheme helps in choosing links that would have longer lifetime. A path is proactively established when the quality of an existing path in use becomes too low. In [18], when a path is likely to be broken, a warning is sent to the source indicating the likelihood of a disconnection. With this early warning, the source can initiate route discovery early and switch to a more stable path potentially avoiding the path break altogether. This paper suggests using a predetermined threshold for selecting the new links, but has not evaluated the threshold theoretically or experimentally. The SNR used to predict hand offs in conventional cellular technology has also been proposed for ad hoc networks in [19].

Most link maintenance schemes have been developed as part of routing protocols. In routing algorithms, the route from source to destination consists of several links. Each node maintains neighbor information to establish a new connection if the current link fails. Once, the link breakage occurs or is predicted, the nodes initiate a new discovery process to choose a new link/neighbor. Most schemes select new links to minimize the number of hops, thereby not considering the stability of the links. The link prediction schemes in [14, 16, 17, 18] propose methods to select a new neighbor, but have not fully evaluated them considering node mobility. A neighbor selection scheme has been experimentally determined in [19], where a node with average SNR greater than 1.2 times the average SNR of the current neighbor is chosen as a new neighbor. The suitability of the value of 1.2 has been tested for one particular scenario.

2.2 Wireless MAC Protocols

MANETs allow a group of communicating nodes to self configure and maintain a network without the support of a base station or a central controller. In the absence of a centralized controller, MANETs require an efficient and distributed MAC protocol. However, there are several constraints like mobility and unpredictable wireless channel which pose greater challenges to MANETs. Literature survey [20, 21, 3] for MANETs lists several design parameters that can be used to classify wireless MAC protocols. Romaszko et al. [3] classify MAC protocols as shown in Figure 2.1.

For A2A communication, we need to choose MAC protocols designed for long

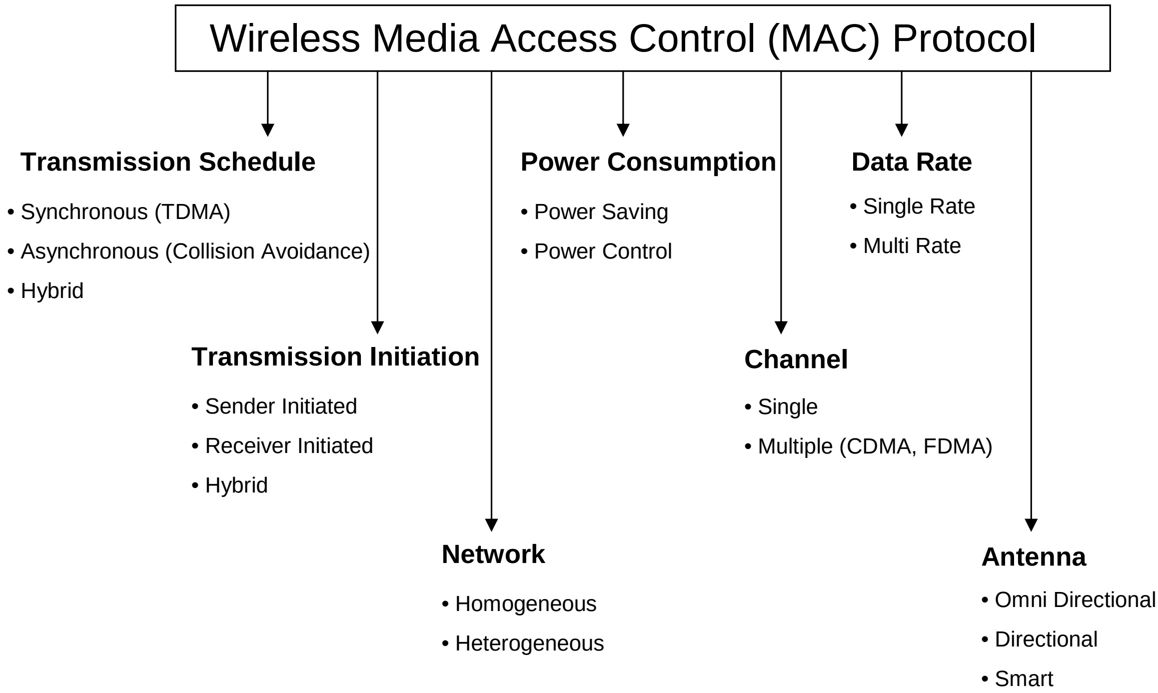


Figure 2.1: Classification of MAC protocols for MANETs [3].

distance links. The authors in [20] discuss the challenges that long range MAC protocols face considering that the transmitted signal will have to propagate to nodes that are tens or hundreds of kilometers away. Control and management of the network, becomes more difficult in a wider coverage area, due to increased propagation delays and potential near-far problems that could arise when inter-node distances vary widely for the signal to be carrier-sensed. The carrier-sense time cannot be fixed as distances between the nodes are constantly changing. If the carrier-sense time is too small, the nodes may end up sending at the same time. If it is too big, the throughput considerably reduces. The increase in transmission range results in lower spatial capacity. However, long-range links relax some of the mobility constraints that apply for short-range and medium-range links.

2.2.1 Asynchronous MAC Protocols

We review asynchronous MAC protocols based on carrier-sense multiple access with collision avoidance (CSMA/CA), which need to be modified to accommodate the variable propagation delay between neighboring links. IEEE 802.11 [1], based on CSMA/CA requires contention window slot-time adaptation for long distance links and the values used for timeouts need to be changed. In long-range link scenarios these protocols suffer from unnecessary contention resolution due to large propagation delay and round trip time. RTS/CTS can be used to reduce the number of collisions between the data packets. Again, due to non-negligible propagation delay, the probability of RTS/CTS packets colliding increases drastically. Hence, using RTS/CTS for every data packet transmission is very inefficient.

Floor acquisition multiple access (FAMA) [22] protocol consists of both carrier sensing and a collision avoidance dialogue between a source and the intended receiver of a packet. The minimum length needed in control packets to acquire the floor is specified as a function of the channel propagation time. The floor is acquired using an Request-to-Send and Clear-to-Send (RTS-CTS) exchange multiplexed together with the data packets in such a way that, although multiple RTSs and CTSs may collide, data packets are always sent free of collisions. To increase the efficiency of the channel, a station that has successfully acquired the floor can dynamically send multiple packets together in a train, bounded by an upper limit. Since the transmission time of data packets is usually much longer than control packets, the channel resource is considerably wasted. The problem becomes more severe as network load increases and RTS collisions happen more frequently.

The receiver oriented approach of MACA-BI [23] evenly arbitrates the transmission among competing senders achieving a higher throughput. A node ready to transmit, instead of using the RTS signal, waits for an invitation by the intended receiver in the form of an Ready to Receive (RTR) control packet. A node is allowed to send a data packet only if it has previously received an RTR, whereas a node that receives an RTR that is destined to a different node has to back off long enough for a packet to be sent in the clear. A receiver-initiated collision avoidance strategy is attractive because it can, at least in principle, reduce the number of control packets needed to avoid collisions. The authors in [24] show scenarios in a network with hidden terminals where the MACA-BI fails. They propose Receiver Initiated Protocols with Dual Polling (RIMA-DP), where receivers can request for data from the polled node, and a transmission request for the polling node to send data. This causes all neighbors of the interacting nodes to back-off. Comparative analysis of throughput of receiver-initiated multiple access protocols shows that a receiver-initiated collision avoidance strategy can be made more efficient than any of the sender-initiated strategies. However, as the node density and network load increases, these protocols scale poorly since delay increases exponentially and this results in a considerable drop in throughput.

2.2.2 Synchronous MAC Protocols

Synchronous MAC protocols based on Time Division Multiple Access (TDMA) and other scheduled/reservation-based protocols are more appropriate for networks with large link delays. Time Division Multiple Access (TDMA) shares the medium by dividing the time into several fixed time frames that are subdivided into slots. In these protocols, only one station may transmit during a particular time slot. To ensure that nodes keep track of time frames and slots, TDMA protocols maintain time synchronization among the nodes. There are techniques [25] to apply additional corrections to compensate residual time and frequency drifts.

The Five-Phase Reservation Protocol (FPRP) [26] is a contention-based protocol which uses a five-phase reservation process to establish TDMA slot assignments that are non-conflicting with high probability. In this protocol, each slot has an information slot and reservation slot. FPRP allows nodes to make reservations within TDMA broadcast schedules. A sender that wants to reserve an information slot must contend for it during its reservation slot. The reservation slot consists of five phases that resolve conflicts among all nodes that are also contending for the information slot within a two-hop radius. A node that reserves an information slot can transmit with a low chance of collision during that slot. In FPRP, it is assumed that nodes maintain perfect synchronization through GPS.

In [27] the authors survey protocols specific to Inter Vehicular Communication. Many proposals suggest using Reservation ALOHA (R-ALOHA) [28] for distributed channel assignment. R-ALOHA has higher throughput than slotted-ALOHA, since a node that reserves a slots can use it in subsequent frames as long as it has packets to send. However, R-ALOHA has a potential risk of instability in the case of many participating nodes and frequent reservation attempts due to short packet trains. Lott et al. [29] solve this problem by allowing every node to reserve a small part of transmit capacity permanently even if it has no packets to send. This results in a circuit-switched broadcast connection primarily used for signaling purposes. The time synchronization is built upon the information from GPS and additional synchronization sequence in parallel to data transmission. Further system evaluation under high node mobility can be found in [30]. On the other hand, traditional R-ALOHA needs a single-hop environment for all nodes to receive all the transmitted signals and, most important, to receive the status information of slots. Since ad hoc networks suffer from the hidden terminal problem, destructive interference with already established channels can occur.

Borgonovo et al. [8] have developed a new protocol, named Reliable R-ALOHA (or RR-ALOHA) to overcome the problems associated with R-ALOHA. This protocol transmits additional information to let all nodes be aware of the status of each slot, thus safely allows the reservation procedure of R-ALOHA. The two-hop relaying that propagates the status information is very similar to what is used in ad hoc routing to let a node know the neighbor information of its neighbors. The authors also propose the ADHOC-MAC [31] protocol based on a dynamic TDMA mechanism that is able to provide prompt access and the variable-bandwidth, reliable channels, needed for QoS delivery. ADHOC-MAC provides the terminals with up-to-date connectivity information, which makes the protocol highly dynamic, avoiding the hidden terminal problem, and highly reactive to changes in topology. However, the authors provide minimal simulation results of the performance of the protocol.

Although these protocols have not been designed for long-range communication, TDMA inherently has mechanisms to accommodate propagation delay. In order to reduce cross-talk between channels/slots, a *guard time* interval is introduced between two slots. The guard time between time slots also accommodates time inaccuracies due to clock instability, delay spread of transmitted symbols and transmission time delay. This guard time duration takes into account the maximum propagation delay between communicating nodes. However, these guard times are directly proportional to the propagation delay and quickly become a significant source of inefficiency, especially for high-speed communication systems: a guard time equal to the round trip propagation delay for a distance of 300km represents 20000 bits for a 10Mb/s system.

2.2.3 Power-Control MAC Protocols

Power control in MANETs has been extensively studied for controlling network topologies, channel conditions and node mobility. The objectives of transmit power control are to reduce the total energy consumed (for energy-conservative applications) and increase network throughput by increasing the channel spatial reuse (for throughput-sensitive applications). In most cases the advantage will be two-fold as both energy-savings and increase in network throughput can be achieved by choosing an optimal transmission power. Transmission power control benefits dense or highly loaded networks, where a large number of nodes need to efficiently share the wireless medium with minimal interference. If the transmission power is dynamically adjusted, it is possible for the neighboring nodes to transmit with acceptable interference at the receiving nodes. We limit our survey to schemes which focus on increasing the throughput and classify the Transmission Power Control (TPC) protocols as surveyed in [32].

Protocols use TPC as a means of controlling network topology (e.g., reducing node degree while maintaining a connected network). In [33] the authors design an asynchronous, distributed, and adaptive algorithm which finds the smallest common power (COMmon POWer) level at which the network is connected. They maintain multiple routing tables in user space, one for each of the transmit power levels available. The optimum power level selected for the node is the smallest power level whose routing table has the same number of entries as that of the routing table at the maximum power level. However, Park et al. [34] show that using the minimal transmission range might not always results in optimal throughput performance. Using both throughput and throughput per unit energy as the optimization criteria, they demonstrate that the optimal transmission power is generally a function of the number of stations, the network topology, and the traffic load. They suggest that transmission range be changed adaptively to achieve maximum throughput. They propose two transmission power control algorithms called Common Power Control (CPC), and Independent Power Control (IPC) that adjust the transmission power adaptively, based on the network conditions to optimize throughput performance. In CPC, all nodes are forced to use the same transmission power. Hence, such an approach can be easily adopted in tandem with existing ad hoc network protocols that assume common power usage. IPC operates in a purely distributed fashion and requires no global coordination to synchronize the transmission powers as in CPC.

Topology control protocols may lack a proper channel reservation mechanism (e.g., RTS/CTS like), which negatively impacts the achievable throughput under these protocols. Appropriate transmission power level can be computed by the intended receiver, which is in a better position to determine the potential interferers in its neighborhood than the transmitter. A node is allowed to proceed with its transmission if the transmission power will not disturb the ongoing receptions in the receivers neighborhood beyond the allowed interference margin. The authors in [35] implement a power controlled multiple access (PCMA) protocol in an ad-hoc network in which the source-destination pairs can be more tightly packed into the network allowing a greater number of simultaneous transmissions (spectral reuse). They achieve power controlled transmission while still preserving the collision avoidance property of multiple access protocols.

The power management scheme in [36], divides the entire network into clusters. Each mobile node is assigned a dedicated signaling time slot of a global signaling channel for broadcasting a beacon. Every node that receives this packets keeps a record of the average RSSI. The nodes then choose their direct N neighbors to form clusters and transmit at a power level bounded by $[P_{max},P_{min}]$. The authors assume the availability of a reliable reverse channel that operates in a different frequency band for sending the ACK/NACK to the source. A joint clustering/TPC protocol was proposed in [37], where each node runs several routing-layer agents that correspond to different power levels. These agents build their own routing tables by communicating with their peer routing agents at other nodes. Each node along the packet route determines the lowest-power routing table in which the destination is reachable.

2.3 Summary

For A2A communication we use a simplified mobility model (Section 4.1.1) and assume that the channel conditions at high altitudes are not highly variant. In our proposed application all destinations are a single hop away, and thus we do not require a highly probabilistic approach in determining link availability. We conclude that location information of neighbors is sufficient in establishing long-lived links for long range communication systems. However, we suggest that the transmission power be adaptively varied to maintain connectivity until a stable link (with a new neighbor) is established.

For long-distance communication with varying propagation delay among neighboring nodes, it is important to know the transmission schedule of all the neighbors of the receiver. Scheduled transmissions can avoid frequent collisions at the receiver. However, we also aim to localize communication to make the application highly scalable. This poses the challenge of determining an optimal transmission power to minimize interference. For high mobility nodes, dynamically changing transmission power can remove isolated nodes, increase the spatial reuse and maximize the network capacity. We propose a joint scheduling and power control mechanism which uses the RR-ALOHA [8] to broadcast control information. The protocol is completely distributed and uses adaptive slot-adjustment and power control to maximize spatial reuse.

Chapter 3

Power Adaptive, Spatial Distributed MAC: PowSD-MAC

In this chapter, we identify issues and challenges facing A2A communication systems. The components of the system model discussed in Section 1.2 are modified to address these challenges. We propose PowSD-MAC, a scalable and reliable media access protocol for long distance A2A communication.

An A2A communication environment is shown in Figure 3.1. We list key design requirements generic to a MAC layer for A2A communications and specific to a black box data replication application:

- *Single-hop broadcast:* Black box data replication requires airplanes to find a suitable destination to transfer black box data. Every airplane needs to maintain the current location information of its neighbors. Control information has to be exchanged between nodes[1] to coordinate channel access. A reliable channel is required to maintain current neighbor information and exchange control information.

- *Single-hop reliable unicast:* The black box data is critical information and should be reliably transferred to the destination airplane. Reliable communication is established by *acknowledging* received data.

[1] We use nodes and airplanes interchangeably

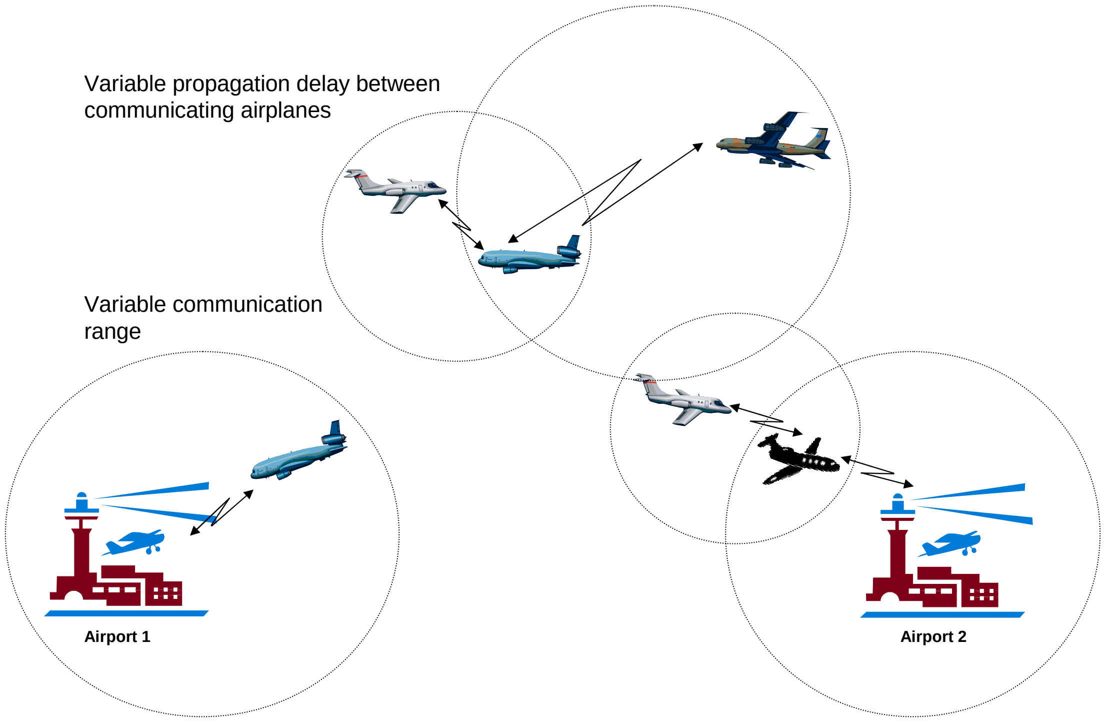


Figure 3.1: A2A communication environment for black box data replication.

- *Variable length packets:* The protocol design should allow variable length data or control information without reducing the efficiency or performance. Varying the length of the packets should not result in a large increase in overhead or inefficient utilization of channel bandwidth.

- *Variable transmission range:* For long-distance links, using a constant transmission power control results in poor scalability. Airplanes must be able to adjust their transmission power to reach their nearest neighbor. Adaptive transmission power control results in high spatial reuse.

These issues are addressed by identifying three components that are required for an efficient A2A communication system. In the following sections, we provide a detailed discussion of each of the components of the system model. An overview of the system model was provided in Section 1.2.

3.1 Link Maintenance (LM)

The goal of the Link Maintenance module on every airplane is to establish and maintain wireless links. The NS (Neighbor Selection) module (Section 3.2) requires location information of neighboring nodes in order to choose a suitable neighbor. To provide this information, the LM module periodically broadcasts *LM Hello packets* at constant power. Each hello packet contains the *NodeID, x-coordinate, y-coordinate* (could be trivially augmented to include the z-coordinate) fields that provide the sender's current location information. We assume that all the nodes are able to obtain information about their location from a GPS (or other similar) system.

All nodes transmit their hello packet at a constant power. The LM module on every node stores the updated location information of all single-hop neighbors of the airplane in a table called the *Neighbor Table (NT)*. In A2A communication systems, we assume the topology does not change considerably over short intervals of time. Hence, the direction and speed at which an airplane travels can be derived from any two recently received hello packets. The location, speed and direction of an airplane is sufficient to find the current location of the airplane.

The NS module periodically accesses the NT to choose the closest neighbor. Hence, the LM module needs to maintain updated information in its NT. If hello packets are not received from a node for N_{Bcast} number of frames, the node is considered to be out of range and its entry is removed from the NT. If the value of N_{Bcast} is very small, the entries in the NT are flushed too fast causing unnecessary and frequent changes in the destination. When using a synchronous media access scheme, this repeatedly changes the transmission schedule and decreases the performance of the protocol. Choosing a large value of N_{Bcast} could provide stale or out of date values to the NS. An empirical value for N_{Bcast} has been determined in Section 4.4.3.

The other objective of the LM module is to avoid large overhead costs by reducing the number of update messages. LM generates the hello packets with constant frequency. Immediate response (emergency broadcasts) to hello packets proposed for city-based MANETs (Section 2.1) are not necessary for A2A communication. However, the frequency at which hello packets are sent is a parameter of the MAC protocol and based on reliability of the broadcast channel it provides. LM broadcasts hello packets only to single-hop neighbors, thus avoiding the overhead involved in flooding the packets in the network. Also, with constant transmission power, only the sender's location information is sent in the hello packets.

In Section 3.4, an additional functionality is added to the LM module to adaptively adjust the transmission power. With adaptive transmission power, location information of all single-hop neighbors of the sender also has to be sent. Hence, every node has location information of all its two-hop neighbors.

3.2 Neighbor Selection (NS)

Airplanes travel at high speeds and mobility is an important factor that determines the stability of the links. The current link could be broken because of unpredictable channel conditions or when the communicating nodes go out of range. In A2A systems, the communication between neighboring airplanes is usually unobstructed, resulting in a far more predictable formation and breakage of wireless link as a function of the physical distance than in other MANETs that have to contend with slow- and fast-fading effects. Every neighbor's departure or failure is indicated by absence of hello packets from this neighbor. During the entire journey there could be several link breakages. This leads to a high number of lost packets as well as increased delay in finding a new neighbor.

The goal of the NS module on an airplane is to choose a new suitable destination neighbor, to which to transfer the black box data. The new link can be established even before the current link is broken to avoid the delay in data transfer or loss of packets when setting up a new link connection. The NS module replaces the current link with a more reliable and long-lived connection, if such a neighbor exists. It should provide an efficient communication channel, avoiding frequent retransmissions, thus, reducing the waiting time of the critical data at the source.

The NS-module uses a location-based selection scheme in which the nearest neighbor is chosen as the destination. The NS-module is invoked every time a new entry is updated/refreshed in the NT by the LM module. It checks if the new entry is closer than the existing destination to choose/retain its destination. However, fixed transmission power results in isolated nodes, a problem common to A2A communication systems. Movement induced disconnections can be avoided by adaptive transmission power control until a new destination is selected (Section 3.4.1).

3.3 SD-MAC: A MAC protocol for A2A Communication

The design requirements listed above can be met by using a synchronous/scheduled mechanism like time division multiple access (TDMA). A *TDMA-based* approach has the following characteristics:

- Each node is allowed to transmit only in its assigned set of slots. The slots can be assigned by a central controller or by nodes themselves in an distributed manner by exchanging schedules of interacting nodes.
- Collisions can occur only if the node happens to use the same time slot for transmission as a neighboring node. Collision among the nodes can be avoided with high probability through effective slot assignment schemes. Also, nodes retain the assigned schedule for some duration in time during which the transmissions will be relatively collision free.
- Assigned slots can be used to broadcast control information or send data. However, packets containing slot assignments (control information) can get corrupted and dropped. Based on the application, reliability can be provided explicitly.
- Multiple contiguous slots can be reserved based on the availability in the time frame. Hence, packets of variable length can be used without increasing unused channel space.
- The transmission schedule can provide information to nodes to dynamically change their transmission power. Nodes tune their transmission power to reach the destination nodes. This increases the spatial reuse and, hence, the capacity of the network.
- Global clock synchronization can be provided using GPS.

From Section 2.3 and the above mentioned advantages, we choose to design and develop a time division multiple access (TDMA) based MAC protocol where slots are assigned in a distributed manner.

3.3.1 Principle and Basic Operation

SD-MAC is based on Time Division Multiple Access (TDMA) dividing time into fixed-length frames. Frames are further divided into slots and nodes reserve slots to transfer data without having to contend for the medium. The principle of SD-MAC is based on RR-ALOHA [8]. In RR-ALOHA, nodes contend to reserve a slot in the frame. This slot, called the Basic Channel (BC), is used to transmit information of all the slots in the frame. Since, all nodes in the one-hop transmission range are aware of the schedules of all its one-hop and two-hop neighbors, future reservations are over non-overlapping slots. However, RR-ALOHA assumes negligible link-propagation delay and constant transmission power. For long-distance links, the slots reserved by the sender might not be the same for any of its neighbors. With RR-ALOHA, the number of reserved slots for every packet or duration of each reserved slot could be increased to accommodate propagation delay. This is equivalent to providing guard time for every packet or every slot irrespective of the propagation delay between the communicating nodes. If the number of slots in a frame increases, a large number of slots remain unused for long distance links. If the duration of each slot is increased, large part of the slot remains unused for nodes that are short distances apart. In both cases, a large part of the reserved channel remains unused.

SD-MAC has an adaptive-slot adjustment mechanism to accommodate variable length links (from a few meters to hundreds of kilometers). The mechanism is well suited for long-lived flows (that offset the scheduling overhead) like the ones needed to upload black-box information to nearby airplanes. To facilitate the presentation, we assume that the duration of each slot is smaller than the transmission time of the smallest packet. We call a group of slots over which the packet (or a group of packets from the same transmitter) is sent a *mini-frame (MF)*. A MF can begin at the end of a frame and extend into the next frame. The frame length and slot-duration are implementation specific and are evaluated in Section 4.4.2. An example of the frame structure is shown in Fig. 3.2.

SD-MAC reservation process has two phases. In the first phase, nodes use slotted ALOHA to *check* and then *reserve* a MF. An attempt to reserve the MF is called *checking* the MF. If all the neighbors have successfully received this MF, the MF is considered to be *reserved*[1]. This initial mini-frame, called *Bcast-MF*, establishes a reliable broadcast channel to exchange neighbor location information (from the Neighbor Table maintained by LM) and control information with all single-hop neighbors. Nodes update their NT from the neighbor location information present in the mini-frame. The control information, called *Neighbor Occupancy List (NOL)* contains information of all the MFs sent or directly received by this

[1]The terminology is similar to the BUSY and RESERVE used in RR-ALOHA

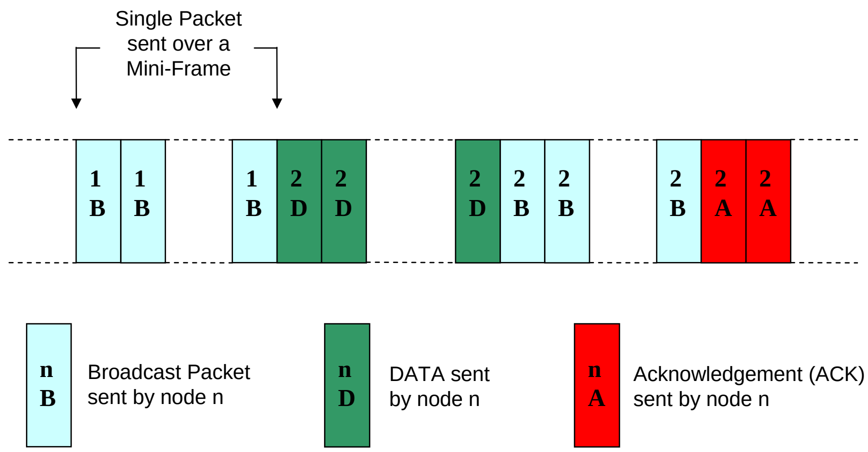


Figure 3.2: Frame structure showing mini-frames.

node. From the NOLs received, nodes build a two-level table called *Occupancy Table (OT)*. The first level (OT-1) occupancy list contain entries in which the node sends or receives from its single-hop neighbors. This list also includes entries that are not destined to this node. The second-level (OT-2) entries form a list of slots in which the node is not allowed to send. Thus, nodes receiving NOLs, have knowledge of the transmission schedules of their one-hop and two-hop neighbors. Nodes are allowed to update the occupancy of the slots (its OT entries) every time it receives a hello packet. Nodes do not update entries when they send or receive unicast packets. In this section, we assume the NOL contains Bcast-MFs from other nodes and Data/ACK has not been allocated. In the second phase, the reliable broadcast channel is used to reserve MFs for Data and ACK.

The hello packet format is shown in Fig. 3.3. The *Location Information* field is a list of the single-hop neighbor entries from the node's NT. The *Slot Occupancy Information* field contains the OT-1 entries. Each entry contains source and destination id's of nodes to which the MF belongs. It also contains the slot numbers at which the MF begins and ends. In Section 3.4.2, we show that the slots blocked by the OT-2 entries can be reused to increase spatial capacity. These slots have a *power-cap*, the upper-limit on the maximum transmission power to send a packet over these slots. The *Allowed Transmission Information* contains the *power-cap* on the slots. In Section 3.5, we explain how the hello packet is used by nodes to request and reserve slots to send their black-box information.

The *Data Reservation Request* field contains the number of new MFs the requesting node requires to send its Data. This request is intended to the node with node-id marked in the *Destination Id* field. An isolated node will not have chosen a destination and has this field marked with -1. The destination node reserves MFs for Data and ACK. The *New Reservation List* contains the newly reserved MFs for each of the requesting nodes.

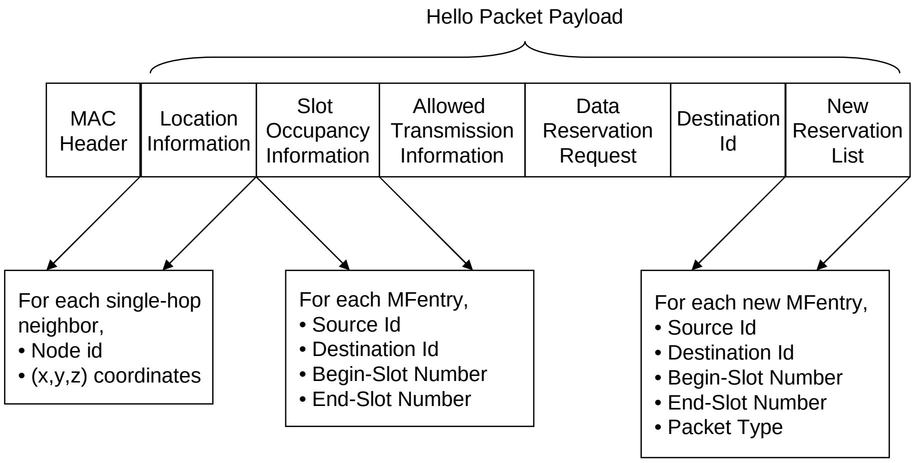


Figure 3.3: Hello packet format.

Each airplane *checks* a Bcast-MF by randomly selecting a contiguous set of unused slots from its OT to send its NOL and location. Consider node i chooses a random set of slots for its Bcast-MF and sends its hello packet in this MF. The sender's NOL will contain entries for MFs it has received and now, its Bcast-MF. All the single-hop neighbors that receive this hello packet update their OT with any new entry in the received NOL. Node i's entry is updated in all of its single-hop neighbors. This reservation is successful, if the MF does not overlap with any of the existing entries in the OT-1's on any of its single-hop neighbors. Node i confirms that its Bcast-MF is successfully reserved, only if all the received NOLs from all its single-hop neighbors indicate a successful reservation. Several nodes may simultaneously attempt to reserve MFs. If a new MF entry from node j overlaps with a reserved entry from node i in the OT-1 of any common neighbor, node k, the MFs collide and the newer MF from node j is dropped.

In SD-MAC, an entry for a mini-frame in a NOL that extends over slots [x,y] are not marked with an entry over slots [x, y] on the receiver. To accommodate the propagation delay, SD-MAC calculates the propagation delay between the sender and the concerned receiver (itself or its single-hop neighbor). The propagation delay, p_d, is calculated in terms of the slot-width w using,

$$p_d = \frac{D(i,j)}{c * w}, \tag{3.1}$$

where $D(i,j)$ is the distance between nodes i and j in meters, and c is the speed of light.

For a MF of length L beginning at slot x, the MF occupies slots $[x,\ x + L - 1]$ on the sender. If a Bcast-MF entry belongs to a single-hop neighbor p_d slots apart, the OT-1 will be updated with an entry over slots $[x + floor(p_d),\ x + L - 1 + ceil(p_d)]$, where $floor(p_d)$ is the function that returns the greatest integer less than p_d and $ceil(p_d)$ is the function that returns the smallest integer not less than p_d. The OT-2 will be blocked with an entry with slots $[x - ceil(p_d),\ x + floor(p_d) - 1]$. The OT-2 entries are blocked as the nodes are prevented from sending in these slots. However, if the MF belongs to a two-hop neighbor, the OT-2 will be blocked with an entry over slots $(x' - ceil(p'_d),\ y' - floor(p'_d))$. The MF occupies slots (x', y') on the actual receiver. This receiver re-broadcasts the information in its NOL, which is heard by the two-hop neighbors of the actual sender. The propagation delay between the actual receiver and the two-hop neighbor is p'_d.

For example, consider the scenario shown in Figure 3.4 with the link availability shown in Table 3.1. The table consists of entries for directly connected nodes and the propagation delay between the nodes is calculated using (3.1). A snapshot of the occupancy tables on each of the nodes is shown in Figure 3.5.

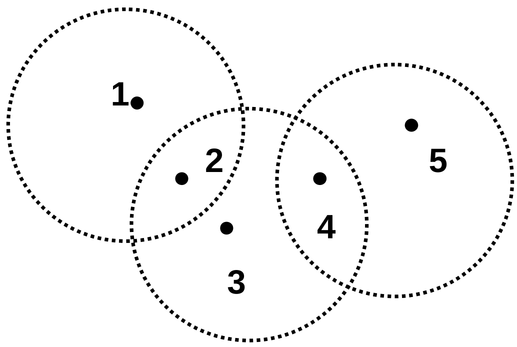


Figure 3.4: Example scenario showing connectivity between nodes.

Nodes 1, 2, 3 etc., (represented as N1, N2, N3 etc.,) periodically broadcast hello

Table 3.1: Node connectivity and propagation delay between nodes in SD-MAC

Direct Links	**Propagation Delay (Number of Slots)**
$1-2$	2.5
$2-3$	2.2
$2-4$	4.3
$3-4$	3.7
$4-5$	3.7

packets. The figure shows a frame of 100 slots with a Bcast-MF spread over 10 slots. For simplicity, the Bcast-MF for node N5 has not been shown in the figure. Consider that node N1 randomly picks 10 contiguous slots, 40-49, as its Bcast-MF, adds the entry in its OT-1 and broadcasts the hello packet. Node N2 is the only node that is in the transmission range of node N1. This hello packet is received by node N2 after a propagation delay of over 2 slots as shown in the Table 3.1. Node N2 adds a new entry in its OT-1, shifting slots to accommodate the propagation delay. It marks slots 42-52 as *checked* by node N1. This MF is *reserved* and can be reused by the sender in subsequent frames, if this entry does not overlap with the other entries already present on all its neighbors. In this example, the hello packets from node N2, will have NOL acknowledging the presence of an entry for node N1. Hence, node N1 *reserves* the Bcast-MF once the NOL from its only neighbor confirms node N1's successful transmission. All other single-hop neighbors of node N2 are also informed about the reservation by node N1. These neighbors of node N2 must avoid sending in slots that will interfere with the reception of a Bcast-MF from node N1 at node N2. Nodes N3 and N4 *block* slots 39-50 and 37-48 respectively.

In the next frame, consider that node N4 chooses its Bcast-MF over slots 27-36. The hello packet from N4 is received by nodes N2, N3 and N5. All nodes mark an entry in their OT-1 for node N4. For example, node N2 receives the hello packet after a $PD > 4w$. Node N2 adds an entry in its OT-1 over slots 31-41, shifting slots based on the propagation delay. In the subsequent frames, if the NOLs from nodes N2, N3 and N5 show an entry for node N4, this Bcast-MF is successfully reserved. If due to node mobility, the propagation delay between nodes N4 and N2 increases by one slot-width, node N2 will shift the entry for node N4 from slots 31-41 to slots 32-42. In this case, from the OT-1 of node N2, the newly changed MF now collides with an entry from node N1. The common neighbor N2, resolves the collision retaining the older entry from node N1. The NOL in the next hello packet

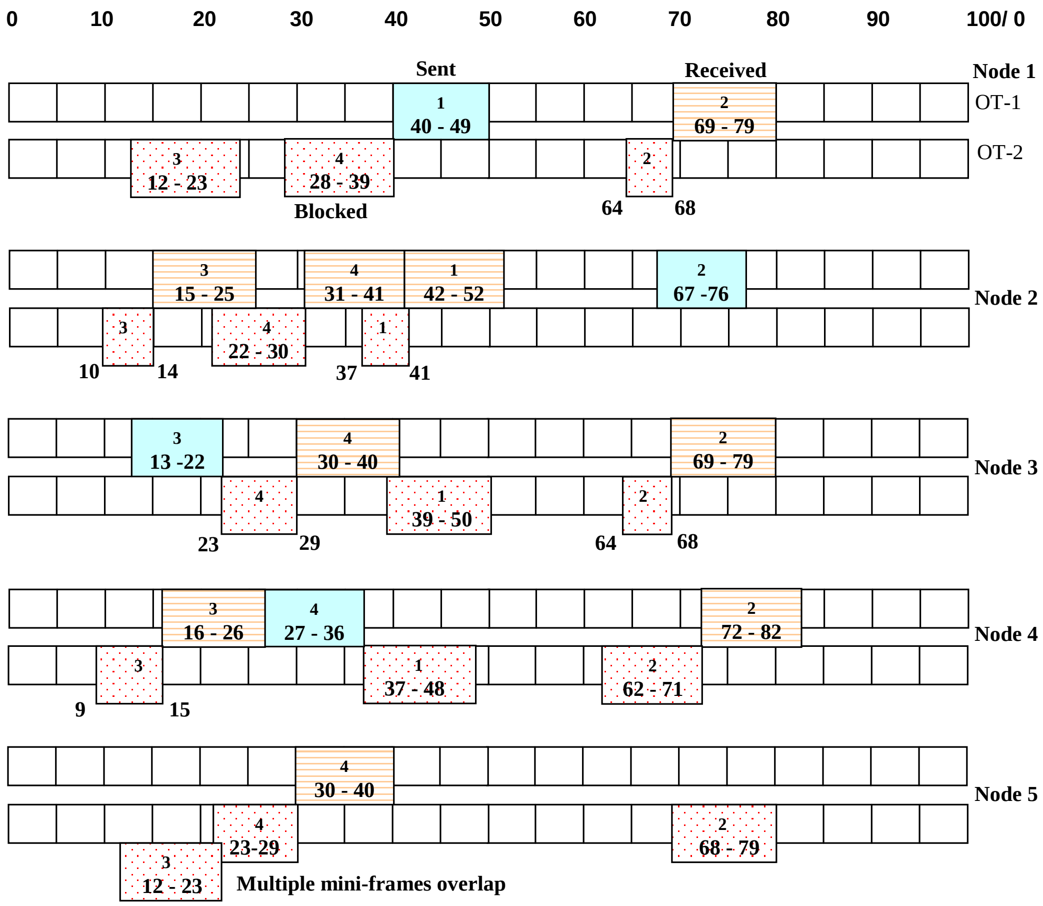


Figure 3.5: Basic Operation of SD-MAC. Each MF represented by slots $x - y$, occupy slots over the interval [x,y].

from node N2 informs node N4 of the collision. This prompts node N4 to choose another Bcast-MF. Nodes N1 and N4 are two-hop neighbors and should avoid sending in slots that would result in a collision at their common neighbor node N2. Hence, a Bcast-MF from node N2 ensures that node N1 blocks slots 28-39 and avoids sending in slots that would interfere with node N4's transmission at node N2.

Overlapping Bcast-MF entries in OT-1 indicate collision at the receiver, but overlapping entries in OT-2 is just an indication of the total number of slots marked by overlapping entries in which the node is not allowed to transmit. In this example, the overlapping entries in the OT-2 of node N5 blocks slots 12-29, preventing a transmission from N5 colliding with the hello packets transmitted by nodes N3 and N4 respectively.

We determine the number of slots that need to be blocked by neighbors that directly receive Bcast-MFs. In this example, the hello packet from node N2 is heard by nodes N1, N3 and N4. Node N3 blocks slots 64-68 and node N4 blocks slots 62-71. If node N4 was allowed to send a packet, for example over slots 58-67, this packet would be received by node N3 in slots 61-71 and would interfere with node N3's ongoing reception of Bcast-MF from node N2. Similarly, there could have been another node, node N6 close to node N2 such that the propagation delay between them is less than one slot duration. To avoid interfering with node N6's reception of Bcast-MF from node N2, we need to block slots 62-71 on node N4.

Once a MF has been reserved by a node, neighboring nodes need to maintain coherent information about that transmission. Nodes maintain a counter for every MF to update current information. Every time the NOL confirms the occupancy of an existing entry in the receiver's OT-1, its counter is reset. If the NOL is not received for N_{Bcast} consecutive frame lengths, those entries are flushed from OT-1 and OT-2. The NOLs could get corrupted due to the wireless path loss or lost because of overlapping MFs due to mobility. Dropping the lost MFs from the schedule within one frame duration makes the protocol too sensitive and unstable. An empirical value for N_{Bcast} is determined in Section 4.4.3.

In the above scenario, the sender is informed of an unsuccessful transmission, prompting it to change or renegotiate its transmission schedule to accommodate the dropped MF. Consider a situation where an increase in the propagation delay between nodes N4 and N2 coincides with a loss of Bcast-MF from node N1 due to the transmission errors on the wireless channel. The Bcast-MF from node N4 is successfully received at node N2. However, when updating the entry for node N4 in OT-1, node N2 observes that this new entry collides with an existing entry for node N1. Node N2 is forced to retain the older MF occupied by node N1. If this situation had occurred when node N2 had not heard from node N1 for N_{Bcast} frames, node N2 will drop the reservations for node N1 and update an entry for node N4. For this reason, all nodes have to maintain counters for every mini-frame entry in their OT-1/OT-2. Every time a NOL confirms the occupancy of the entry already marked in the receiver's OT-1, the counter is reset.

If the sender discards its Bcast-MF and chooses a new set of random slots for its Bcast-MF, its neighbors do not wait for N_{Bcast} consecutive frame lengths to remove the entry for the discarded Bcast-MF. The neighbors remove the previous entry and add the new entry once they receive a NOL from the sender without the old entry. In this example, node N2 can inform node N4 that it has not received a hello packet from node N4 for N_{Bcast} consecutive frames. This informs node N4 that it has to discard the current Bcast-MF and choose a new Bcast-MF. Node N4 does not explicitly inform its other neighbors, nodes N2 and N5, which continue to retain an entry for the older Bcast-MF. However, the next NOL from node N4 will inform all its neighbors to update the current information.

The scheme allows nodes that are more than two-hops apart to reuse the slots. In this example, nodes N1 and N5 can reuse slots as their transmission ranges do not overlap. With adaptive transmission power control, this property further enhances the performance of the protocol.

3.3.2 Modifying RR-ALOHA for A2A Communication

Current long-range MAC protocols use guard time to account for the propagation delay. In RR-ALOHA, consider the case where the size of the Bcast-MF is increased to accommodate the propagation delay (see Table 3.1). Node N1 has to send its Bcast-MF in slots 40-52. Node N2 will also reserve slots 40-52 for node N1 in its OT-1. Slots 50-52 on node N1 and 40-41 on node N2 are wasted. Using RR-ALOHA, for every link, the time amounting to the propagation delay between the nodes is wasted.

Previously, node N4 had checked slots 27-36 to send its Bcast-MF. To accommodate for the propagation delay, node N4 needs to be changed to 27-41. However, node N4 cannot send over these slots as its entry on node N2's OT-1 will collide with the existing entry from node N1. The best node N4 can do is check slots from 25-39. Another approach could be to increase the slot duration to accommodate the propagation delay. However, increasing the slot duration will increase unused channel space if the nodes are close to each other. In A2A communication, where the distance between two airplanes often vary between a few tens to hundreds of kilometers this results in non-negligible part of the channel being unused.

3.4 PowSD-MAC: SD-MAC with Adaptive Power Control

For the black box data replication application, the A2A communication system does not require a fully connected network. However, the airplanes need to remain connected to a suitable destination in their neighborhood. The connectivity depends on the number of nodes per unit area (node density) and their radio transmission range. In RR-ALOHA, all nodes transmit with constant power. In an ad hoc network, if the transmission power of a node is increased, it will typically achieve a higher transmission range and possibly reach more nodes. For long-range communication, the nodes are sometimes a few hundred kilometers apart. In SD-MAC, the transmission power of all the nodes will have to be increased irrespective of the current distance between the nodes. With increased density, a large number of nodes compete for limited channel access and nodes take longer time to schedule transmissions. This results in increased delay in transferring black box data. Higher transmission range will increase the overhead and the interference with other nodes. This reduces the overall capacity of the network. With an increase in offered load, unfairness between transmitting airplanes is observed. On the other hand, if we reduce the transmission power of a node, the node may be isolated without any link to other nodes. Isolated nodes are undesirable in A2A communication systems.

In Section 4.4.4, we show that even with an adaptive slot adjustment, SD-MAC has poor scalability because of common transmission power. The protocol performance is affected to the extent that IEEE 802.11 outperforms SD-MAC. In a non-homogenous network, with long-range links, determining an optimal common transmission power is not an optimum solution. We propose PowSD-MAC, which incorporates an adaptive transmission power control scheme with SD-MAC. The proposed components in the previous sections have to be modified for adaptive transmission power control.

3.4.1 Modifications to LM and NS Module

The LM module has the additional functionality of dynamically adjusting the power at which the LM hello packets are transmitted. Every node that has black box data to be transferred, *checks/reserves* a Bcast-MF. The transmission power is changed to increase/decrease the range by step-size, ΔD, distance units. Since, the distance between the airplanes is tens to hundreds of kilometers, the minimum step-size, ΔD, is set to one kilometer and is represented in terms of power-distance units.

Node i transmits its LM hello packets at P_{Bcast} power-distance units. The transmission power, P_{Bcast}, is calculated in terms of the slot-width w using,

$$P_{Bcast} = p_d * c * w \tag{3.2}$$

where p_d is the propagation delay between the nodes and c is the speed of light.

Consider that node i has chosen its Bcast-MF; the node adjusts its transmission power to ensure that its hello packet reaches its download destination. When the NS module chooses a new destination, the P_{Bcast} is automatically adjusted to reach this node. If the sender has an empty NT, it transmits its hello packet with an initial power value, P_{Init}, with its *destination* field marked unknown. If no response is heard for N_{Bcast} frames, it chooses a new Bcast-MF, otherwise, it transmits its next hello packet at 1.5 times its P_{Bcast}. An additive increase in power-distance units results in a slow response for isolated nodes. An exponential increase causes a large number of neighbors to increase their transmission power.

There could be several source nodes that choose a common destination, node j. Node j adjusts its P_{Bcast} to reach the furthest node, node i, that has node j as its destination. This mechanism avoids isolated nodes as long as the transmission power can be increased sufficiently to reach a neighbor. Consider that node j receives a hello packet from a node i that has no neighbor/destination i.e., node i has its *Destination Id* field marked with -1 (see packet format in Fig. 3.3). Node j checks its neighbor table for another node k that is closer to node i than itself. If node j itself is not the closest node, it discards the received hello packet without updating its OT. If it is the closest node, it increases its P_{Bcast} to reach node i only for one frame duration as there could be several nodes hidden from one another replying to node i. If node j is indeed the nearest node, future hello packets from node i will have its destination marked as node j.

With adaptive transmission power control, nodes require location information of their two-hop neighbors. When all the nodes are only exchanging the hello packets, and no data is being transferred, LM can maintain single-hop neighbor information to avoid collision due to hidden terminals. When additional slots are allocated for transferring data, optimizations can be made with the increased overhead of exchanging hello packets with information of all single-hop neighbors. The LM module updates location information of all single-hop and two-hop neighbors of the airplane in the NT. This is further explained in

Section 3.5.

The functionality of the NS-module remains the same i.e., it chooses the nearest neighbor as its destination. The nearest neighbor selection, allows the LM module to maintain a link that communicates at minimum transmission power. This also increases the spatial re-use and reduces the scalability issues seen with SD-MAC. Adaptive power control also eliminates isolated nodes.

3.4.2 Basic Operation of PowSD-MAC

Adaptive transmission power adjustment by the LM, will result in asymmetric wireless links. The LM modifies the earlier example scenario to the one shown in Fig. 3.6. Table 3.2 show the asymmetric transmission links and link propagation delays. The basic operation of PowSD-MAC is similar to SD-MAC, where nodes with black box data, randomly pick slots to broadcast their hello packets at the transmission power calculated by LM module. We assume that NOL contains Bcast-MFs from other nodes and DATA/ACK has not yet been allocated. We show the basic operation of PowSD-MAC in Figure 3.7.

The propagation delay is proportional to the distance between the nodes, and nodes choose nearest neighbors as their destination. Nodes N1 and N5 transmit their Bcast-MF to reach their destination (their only neighbor). Similarly, nodes N3 and N4 adjust their maximum transmission power to reach their closest neighbors. Node N2 has node N3 as its closer neighbor. However, node N2 must increase its transmission range to reach nodes N1 and N3 as both these nodes choose node N2 as their destination.

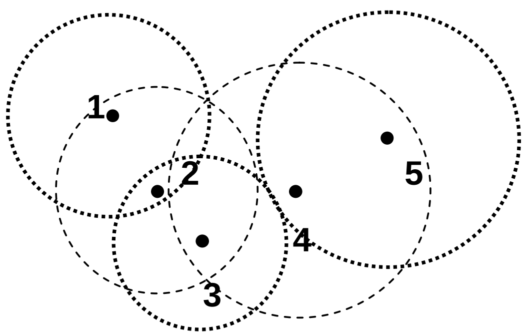


Figure 3.6: Example scenario showing connectivity between nodes and asymmetric links

Table 3.2: Node connectivity and propagation delay between nodes in PowSD-MAC

Node-Id	**Destination**	**Propagation Delay (Number of Slots)**	**Transmission Range (power-distance units)**
1	2	2.5	38
2	3	2.2	Max(38,33)
3	2	2.2	33
4	5	3.7	56
5	4	3.7	56

In this example, adaptive transmission power modifies the topology and, nodes that were previously two-hops apart are now three-hops apart. This increases the slot reuse as shown by the *empty* slots. We observe that nodes N1 and N4 can send in the same slots with collision-free receptions. Node N5, which is yet to reserve slots for sending hello packets has more empty slots to choose from before sending its hello packets. The slots that were occupied in SD-MAC are *cross-marked* to show that they are empty and can now be used to send DATA from node N1 to node N2.

In PowSD-MAC, the transmission of a Bcast-MF is considered successful, if all the received NOLs from its direct-hop, not single-hop, neighbors indicate its occupancy. Direct-hop neighbors of node i are the set of nodes that directly receive the hello packets transmitted by node i. Single-hop neighbors of node i are nodes from which this node hears hello packets. In SD-MAC, the symmetric links ensure that single-hop neighbors are direct-hop neighbors. In this example, node N3 has nodes N2 and N4 as its single-hop neighbors. Node N3's only direct-hop neighbor is node N2. Node N3 does not drop its Bcast-MF although the NOL from node N4 will not have an OT-1 entry for node N3's Bcast-MF.

Collisions are resolved giving priority to interfering, unreachable nodes. If a new MF from node j overlaps with an existing entry from node i on any of their common neighbors, node k, the MFs collide. In PowSD-MAC, the MF from node j is dropped only if hello packets from node k reach node j, otherwise, MF from node i is dropped. From Figure 3.6, the transmission power of nodes N3 and N2 is not sufficiently high to send hello packets to node N4. Node N2 has *checked* and *reserved* slots 67-76 to send its hello packets. If node N4 were to choose slots such that the Bcast-MFs from nodes N2 and N4 collide at node N3, the collision is detected after N_{Bcast} frames. Although the hello packets from nodes N2 and N4 collide, node N3 assumes N2's transmission was unsuccessful because of the wireless path loss. Node N3 incorrectly informs node N2 of its successful transmission

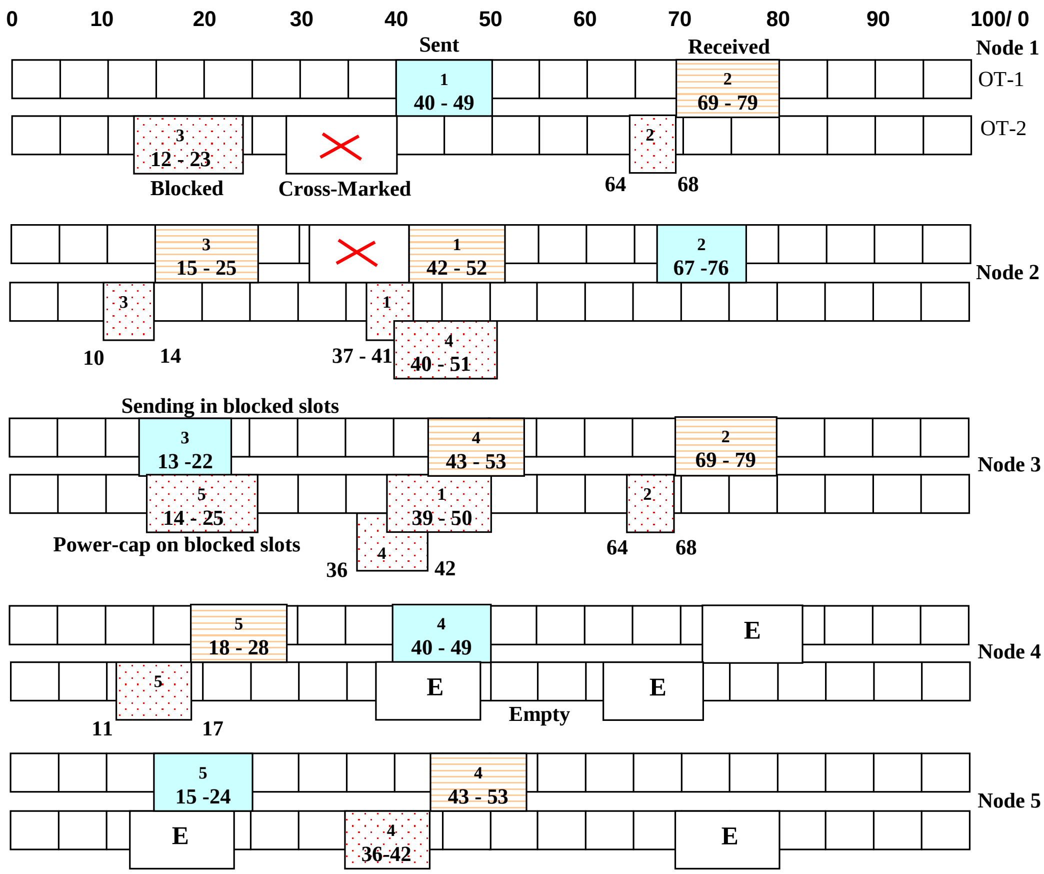


Figure 3.7: Basic Operation of PowSD-MAC.

for N_{Bcast} frames, until the counter expires. Node N4 is unaware of the collision as hello packets from node N3 do not reach it. Node N3 drops the entry for node N2 after N_{Bcast} attempts. However, even after N_{Bcast} frames, node N4 uses the same slots for sending its hello packets. In SD-MAC, the collision would be resolved within one frame duration. In PowSD-MAC, although the nodes are two-hops apart, the collision is resolved after a delay of N_{Bcast} frames.

With adaptive power control, each node has reduced number of single-hop neighbors. The probability of two nodes picking overlapping slots for Bcast-MFs is low and does not affect the performance of the protocol. The results in Chapter 4 shows that the network throughput increases with increased offered loads. We can infer that the increase in spatial bandwidth reuse is sufficient to outweigh the inefficiencies resulting due to the delay in resolving these collisions. However, there is a high-probability of a Bcast-MF colliding with a Data/ACK mini-frame. In the next section, we show that collisions due to overlapping Bcast-MF and Data/ACK mini-frames are resolved in less than N_{Bcast} frames.

PowSD-MAC increases the slot re-use by introducing *power-cap* on *blocked* slots. The power-cap is a power level below which the nodes are allowed to transmit packets. Consider node N5 chooses slots 15-24 for its Bcast-MF. In SD-MAC, these slots were blocked, as sending in these slots would interfere with node N3's reception at node N4. In PowSD-MAC, node N5 reuses these to send its hello packets. Subsequently, node N3 blocks slots 14-25 to avoid transmitting in these slots. PowSD-MAC places a *power-cap* on node N3, preventing it from transmitting at a power level that would reach node N4. However, Node N3's P_{Bcast} is below this power cap and the slots are reused to send hello packets to node N2.

3.5 Slot Allocation for DATA/ACK

Consistent with the black-box data replication application, we consider a *destination based reservation* approach for allocating slots for Data/ACK (unicast) packets. All airplanes have black box data to be transferred and they initiate exchange of hello packets. Each sender chooses its closest node as the destination and requests it to reserve slots for the sender. The sender sends hello packets marked with the number of slots required to be reserved and the node-id of the neighbor for which the request is directed. A particular destination might receive several requests from different neighbors (senders) in a single frame duration. Each receiving node, matches its node-id with the node-id for which the request is intended. All the requests are stored by the destination and slots are reserved just before it is scheduled to send its hello packet. Allocating slots for Data/ACK increases the overhead because a node requesting reservations needs to send information of the power-cap on the slots in which it allowed to send. This information is called the *Allowed Transmission List (ATL)*. The hello packets now contain the ATL, NOL and a single-hop NT (to maintain a two-hop neighbor list). Although this approach increases the overhead, it avoids conflicts between multiple senders reserving overlapping slots to send data.

In SD-MAC, the allowable slots for transmission must be clear for the destination to reserve the slots for sending unicast[1] packets. Alternatively, these slots should have a power-cap, a value smaller than the constant transmission power used in SD-MAC. In PowSD-MAC, nodes are allowed to transmit in slots in which its transmission power does not exceed the power-cap placed on the slots. This increases the spatial reuse, especially when slots are allocated for unicast packets.

Consider that node i requests node j to allocate slots for transmission of a single data packet. The propagation delay between the nodes is p_d slots and the transmission power at which they must transmit is P_{ij} power-distance units. The Data and ACK transmissions are considered to be over symmetric links. Hence, P_{ij}=P_{ji}. The power-cap P_{cap} on available slots in the ATL is measured in power-distance units. We assume Data Mini-Frames (Data-MFs) and ACK Mini-Frames (ACK-MFs) are of fixed length, L_D and L_A respectively.

The destination node j chooses L_D+1 contiguous slots, $[x,\ x + L_D]$, to receive from node i. It reserves a Data-MF only if slots $[x - floor(p_d),\ x - floor(p_d) + L_D - 1]$ are available for transmission on node i and these slots have $P_{ij} < P_{cap}$, where P_{cap} is the power-cap on these slots, measured in power-distance units. Node j also looks for L_A contiguous slots, $[y,\ y + L_A - 1]$, in which it is able to transmit and has $P_{ji} < P_{cap}$. Node j reserves an ACK-MF only if slots $[y + floor(p_d),\ y + L_A - 1 + ceil(p_d)]$ on node i do not overlap with existing entries.

Nodes are *blocked* from sending unicast packets in slots that interferes with the reception of its single-hop or two-hop neighbor. Consider that a certain node k has information of an ongoing transmission from node i to node j. Node k is *not allowed* to send in slots that interferes with the reception at node j. Node j could be a single-hop or two-hop neighbor of Node k. In PowSD-MAC, the single-hop neighbor information is sent in the hello packets and nodes have location information of its two-hop neighbors. Nodes transmit hello packets and unicast packets with different power-levels. All slots of any node should have a power-cap updated from information available of all unicast packets destined to its one-hop and two-hop neighbors to avoid collision at common receiving nodes. Hence, in PowSD-MAC, nodes need to maintain a two-hop neighbor table.

Nodes are allowed to reuse the slots occupied by an entry in its OT-2 whose destination is not available in its NT. The Data/ACK slot allocation mechanism is explained with an example. Consider the scenario shown in Fig. 3.8. In the current scenario, node

[1] In this section the Data/ACK packets are referred to as unicast.

N1 has moved away from the rest of the nodes and node N4 is equidistant from nodes N3 and N5. Table 3.3 has data of the transmission power and propagation delay between the nodes.

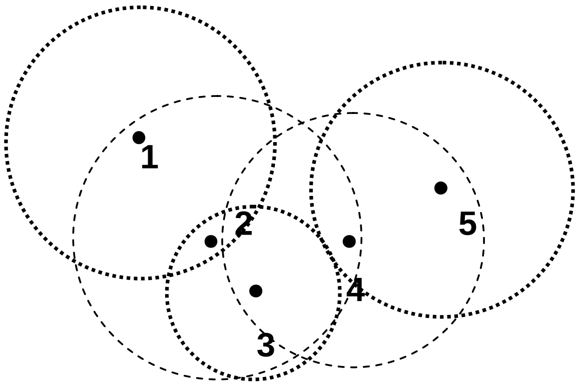


Figure 3.8: Example scenario and different types of mini-frames.

Table 3.3: Node connectivity and propagation delay between nodes for Data Allocation in PowSD-MAC

Node-Id	**Destination**	**Propagation Delay (Number of Slots)**	**Transmission Range (power-distance units)**
1	2	4.6	69
2	3	2.2	Bcast-MF at 69 Data-MF at 33
3	2	2.2	33
4	5	3.7	56
5	4	3.7	56

Each node maintains its frame information in two lists, OT-1 and OT-2. In Fig. 3.9, for convenience, we split OT-1 into OT-1a, a list with information of MFs either sent by the node or received by the destination node, and OT-1b, a list with information of MFs received although sent to a different destination. All the information is updated only from the NOL received with the hello packet. The entries in OT-1b and OT-2 maintain the power-cap for each slot. Every slot of this entry has a transmission power threshold represented by its *power-cap*. The power-cap entries for OT-1b are not separately shown. Table 3.4 lists the different type of MFs exchanged by the nodes.

Consider node N2, in its hello packet, requests node N3 to allocate a Data-MF.

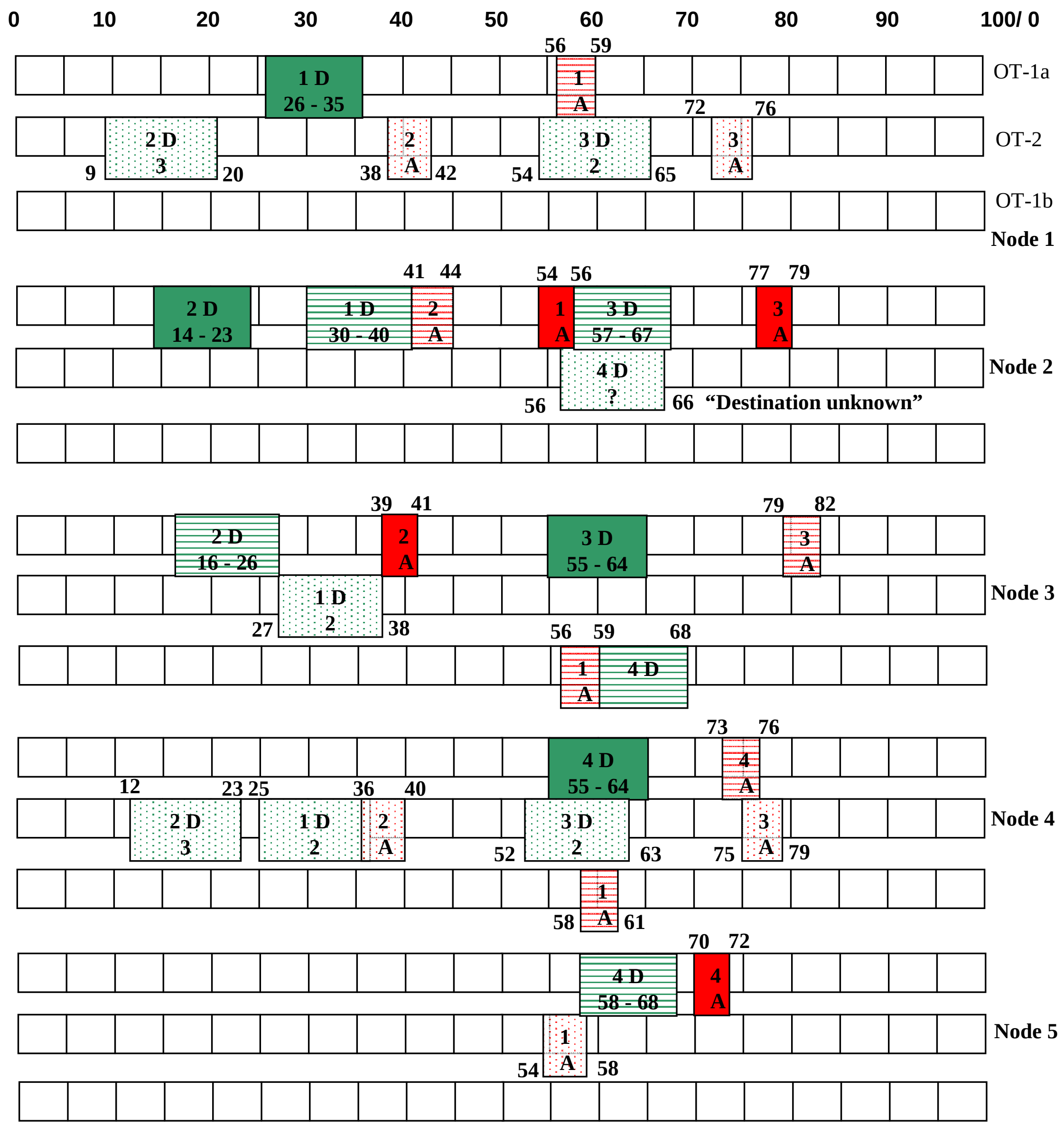
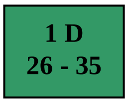
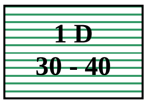
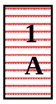
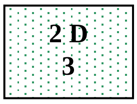
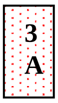


Figure 3.9: Basic operation of Data/ACK allocation.

Table 3.4: Different types of mini-frames.

Type of Mini-Frame	Description
	DATA Mini-Frame sent by node N1. 10-slots in length, transmitted from node N1 to its destination (i.e., node N2).
	ACK Mini-Frame sent by destination of node N1. 3-slots in length, transmitted by a node that received the DATA-MF from node N1.
	Received DATA-MF sent by node N1. This MF extends over slots 30 to 40. Nodes to which this MF is not destined, update a power-cap to reduce their transmission from reaching the destination.
	Received ACK-MF sent by destination of node N1. Nodes to which this MF is not destined, update a power-cap to reduce their transmission from reaching the destination.
	Blocked DATA-MF sent by node N2. This node (i.e. node N4) should avoid sending with a transmit power that affects the reception of this packet at its single-hop neighbor, node N3.
	Blocked ACK-MF sent by destination of node N3. This node (i.e. N4) should avoid sending with a transmit power that affects the reception of this packet at its single-hop neighbor, node N3.

Its destination node N3 allocates slot 16-26 for receiving Data. Every Data-MF must be acknowledged and node N3 reserves slots 39-42 for its ACK-MF to send its acknowledgement for the Data packet it receives. We observe that the ACK-MF is placed in the first set of available slots close to its Data-MF. Node N3 sends this information in the NOL of its next hello packet. Node N2 shifts the slots and reserves slots 14-23 for its Data-MF. Node N2, subsequently informs nodes N1 and N4 about the allocation along with the location of node N3. Nodes N4 and N1, block slots to avoid interfering with node N3's reception of data from node N2. In this example, an entry in OT-2 of node N4, shows that it blocks slots 12-23 because of transmission of data from node N2. For this set of slots, it updates its power-cap to a value equal to the transmission power required to reach node N3 (future transmissions in these slots should be at a transmission power less than the power-cap).

The nodes maintain counters for unicast MFs to maintain the updated information. If the unicast MF or its information from NOL is not received for N_{Ucast} consecutive frame lengths, those entries are flushed from OT-1 and OT-2. When unicast packets collide, the existing entry is retained and the new overlapping entry is dropped. Unicast packets colliding at nodes that are not the intended destination remain unresolved. In this example, a collision between an ACK-MF from node N2 and a Data-MF from node N4 at node N3 is ignored. However, the information about these mini-frames, received from hello packets is used to update entries in OT-1b and to set the power-cap over these slots. Slots 56-59 are updated with a power-cap P_{31}, the minimum transmission power required to transmit from node N3 to node N1. Slots 58-68 are updated with a power-cap P_{34}, the minimum transmission power required to transmit from node N3 to node N4. The overlapping slots 58-59 are updated with a power-cap $minimum(P_{31}, P_{34})$. PowSD-MAC provides high spatial re-use as we observe the *blocked* slots 55-64 are used to transmit a Data-MF from node N3 to node N2. Nodes N2, N3 and N4 are all single-hop neighbors and they send over the same slots 55-56. From the figure, node N2 has an entry marked *Destination Unknown*. Node N2 is aware that this MF is for a packet from node N4 destined to node N5, whose location information is not available in its NT. Node N2 discards the blocked slots 56-66 and reuses them.

In PowSD-MAC, collision between Bcast-MFs are resolved within N_{Bcast} frames. With large number of unicast packets in a frame, there is a higher possibility of a Unicast-MF colliding with a Bcast-MF. Since, Bcast-MF contains the control information for coordinating the schedules, it is important to make the Bcast-MF transmission robust. We resolve the collision giving the Bcast-MF a higher priority. If a unicast entry in any received NOL collides with an existing Bcast-MF entry, the unicast entry is immediately dropped.

With a tight transmission schedule, if a node loses its Bcast-MF and has no free/available slots to choose a new Bcast-MF, it randomly selects a set of slots occupied by Unicast packets. Since, this is equivalent to a overlap between an Unicast-MF and a Bcast-MF, the Unicast-MF is forcibly dropped. At several common receiving nodes, if a Unicast-MF and a Bcast-MF collide, the Data-MF counter reaches N_{Ucast} before the Bcast-MF reaches N_{Bcast} and gets dropped. Consider an example where a Bcast-MF from node N1 and a Data-MF from node N3 collide at node N2. Both packets are discarded by node N2 and the counters for both entries are incremented every frame. The Data-MF reaches $N_{Unicast}$ before the Bcast-MF reaches N_{Bcast}. The Data-MF is dropped and the Bcast-MF retains the slots. Consider that a Unicast-MF from node i collides with a Bcast-MF from node k at a common node j. The only condition when a node i's Unicast-MF receives a higher priority at node j, is when node j's Bcast-MF does not reach node i. This is because node i cannot be informed of node j's reserved slots.

Chapter 4

Performance Evaluation

In this chapter, we evaluate the performance of SD-MAC and PowSD-MAC and empirically obtain values for a few simulation parameters. The performance of these protocols is compared with tuned-up versions of IEEE 802.11 for a large range of parameters and performance metrics.

4.1 Simulation Environment

We evaluate the proposed Link Maintenance, Neighbor Selection schemes and MAC protocols using Mobility Framework (MF) extensions to OMNeT++ [2]. OMNeT++ is a public-source, component-based, modular and open-architecture network simulation environment. The MF is intended to support wireless and mobile simulations. The core framework implements the support for node mobility, dynamic connection management and a wireless channel model. All simulation models developed as part of this thesis are plug-in modules to the core framework.

4.1.1 Mobility Model

The mobility model has been designed to simulate typical air traffic movement. The mobility model has 2 modules:

- *Air Traffic Control (ATC)*: The number of airports and simulation area are the input parameters for this module. Based on these parameters the ATC randomly places several airports in the simulation area.

- *Air Mobility*: At the beginning of the simulation, all airplanes, select a random destination airport and a random delay from current simulation time to begin their journey. No two airplanes can take-off from the same airport within a span of two minutes. All airplanes fly with constant cruise speed between airports. The cruise speed is uniformly distributed between 0.15 and 0.3 kilometers per second (i.e., 540-1080 km/h), the cruise speed at which passenger aircrafts fly as per current regulations.

We assume stable channel conditions and use the free space radio propagation model. The simulation scenario consists of 10 airports in an area of 1000x1000 square kilometers with 60 airplanes unless otherwise specified.

4.2 Protocols for Comparison

SD-MAC is compared with a tuned-up version of IEEE 802.11. The LM and NS modules used in SD-MAC are also used in the tuned-up version of IEEE 802.11. The modified LM and NS modules used in PowSD-MAC are also used with the tuned-up version of IEEE 802.11 for fair evaluation. In this section, we refer to the two tuned-up versions of IEEE 802.11 protocol as *802.11* and *pow802.11*.

The Data timeout values for 802.11 are modified to accommodate the maximum propagation delay and to avoid packet time-outs. We do not use RTS/CTS when evaluating IEEE 802.11 due to the significant overhead. For 802.11 and Pow802.11, the MAC/PHY parameters are set according to IEEE 802.11g [38]. IEEE 802.11 *aSlotTime* is a physical (PHY) layer specific parameter that defines the slot length. The value of *aSlotTime* should include the transceiver time and the propagation delay. Setting the *aSlotTime* to accommodate the maximum propagation delay between two communicating nodes in A2A communication system results in large queuing delays and loss of information. The *retry-limit* is the number of transmission attempts per Data packet at the source, before the packet is dropped. Since, we do not use RTS/CTS, the *retry-limit* is set to 7 as in the standards. We use the same retry-limit value for PowSD-MAC. We choose two sets of traffic loads: 20kbit packets at 400 packets/s and 80kbit packets at 160 packets/s ensuring a fully occupied transmission schedule.

To simulate hubs and different size airports, each airport determines its air traffic density as an exponentially distributed random number. Airports act as fixed sink nodes with a fixed transmission radius of 15 km. If an airport is closer than any other airplane, the airport becomes the preferred destination for data upload. Airport nodes do not send data packets, but are allowed to acknowledge the data packets they receive. Stationary airplanes (i.e., while in the airport) do not send hello packets, do not respond to hello packets and have no black box data to transfer.

4.3 Performance Metrics

To evaluate the performance of PowSD-MAC and compare with the modified version 802.11 for long distance, we identify the following metrics:

- *Throughput* is the number of successful transmissions or acknowledged transmission over the total transit time. The total transit time is the sum of the transit time for each airplane i.e., from the time the airplane departs from an airport, to the time it arrives at its destination airport.
- *Packet Delivery Ratio (PDR)* is calculated as the ratio of the number of successful transmissions over the total number of transmission attempts.
- *Overhead* is calculated as the average number of control information bits sent per second. The control information includes the hello packets, the network layer header sent along with the Data packet, and the MAC and PHY (Physical Layer) headers.
- *Average link duration* determines the amount of time a node retains one neighbor as its destination. Frequent link breakages will require nodes to buffer the information until a new destination is chosen. This results in delaying the transmission of critical data. In extreme scenarios, the buffer overflows resulting in loss of information.
- *MAC delay* is the delay from the time the MAC layer at the source node attempts to send a Data packet to the time this packet is received by the MAC layer at the destination node. This delay also includes the transmission and propagation delays.

- *End-to-End delay* is the delay between the time a Data packet is sent by the application at the source node to the time the application at the destination node receives the packet. This delay includes the processing, queueing and the MAC delays between the communicating nodes.

4.4 Evaluation of the Protocol Parameters

We use PowSD-MAC to determine the optimal value of each parameter that will be used for comparison and evaluation of the proposed protocols.

4.4.1 Calculating the Length of a Broadcast Mini-Frame

The optimal hello packet length, *Blength*, varies with node density, payload size and offered load. With high mobility nodes, *Blength* remains constant for less than 2-3 seconds. Although the Bcast-MF has higher priority compared to a Unicast-MF, dynamically varying its length will result in frequent collisions and changes in transmission schedule. We use a simple approximation condition shown in Algorithm 1 to maintain constant *Blength* over longer duration of time.

Algorithm 1: Hello packet length approximation

if $Blength_{Avg} \leq \alpha * Blength_{Set}$ **then**
  $Blength_{Set} = \beta * Blength_{Set}$

if $Blength_{CF} > Blength_{Set}$ **then**
  $Blength_{Set} = \gamma * Blength_{CF}$

$Blength_{Avg}$ is the average number slots occupied by the Bcast-MF over the previous 10 slots. The $Blength_{CF}$ is the number of slots the hello packet needs in the *current frame* to send all the control information. The $Blength_{Set}$ is the number of slots finally allocated before the hello packet is broadcasted. The approximation algorithm continuously adapts to any increase in the length of the hello packet, using γ. However, α and β ensure that its length is reduced gradually. The aim of the approximation is to increase the stability of the schedule. Empirical values of α=0.6, β=0.8 and γ=1.1, provide the best packet success ratio for varying offered loads, slots/frame and broadcast threshold, N_{Bcast}. The *Blength* inaccuracies are less than 0.1% of the frame duration per node.

4.4.2 Determining the Optimal Slot Length

The frame duration has been fixed to one second. From Fig. 4.1 (a), we observe that the channel utilization (average throughput) increases with increase in number of slots per frame, N_{Slots}.

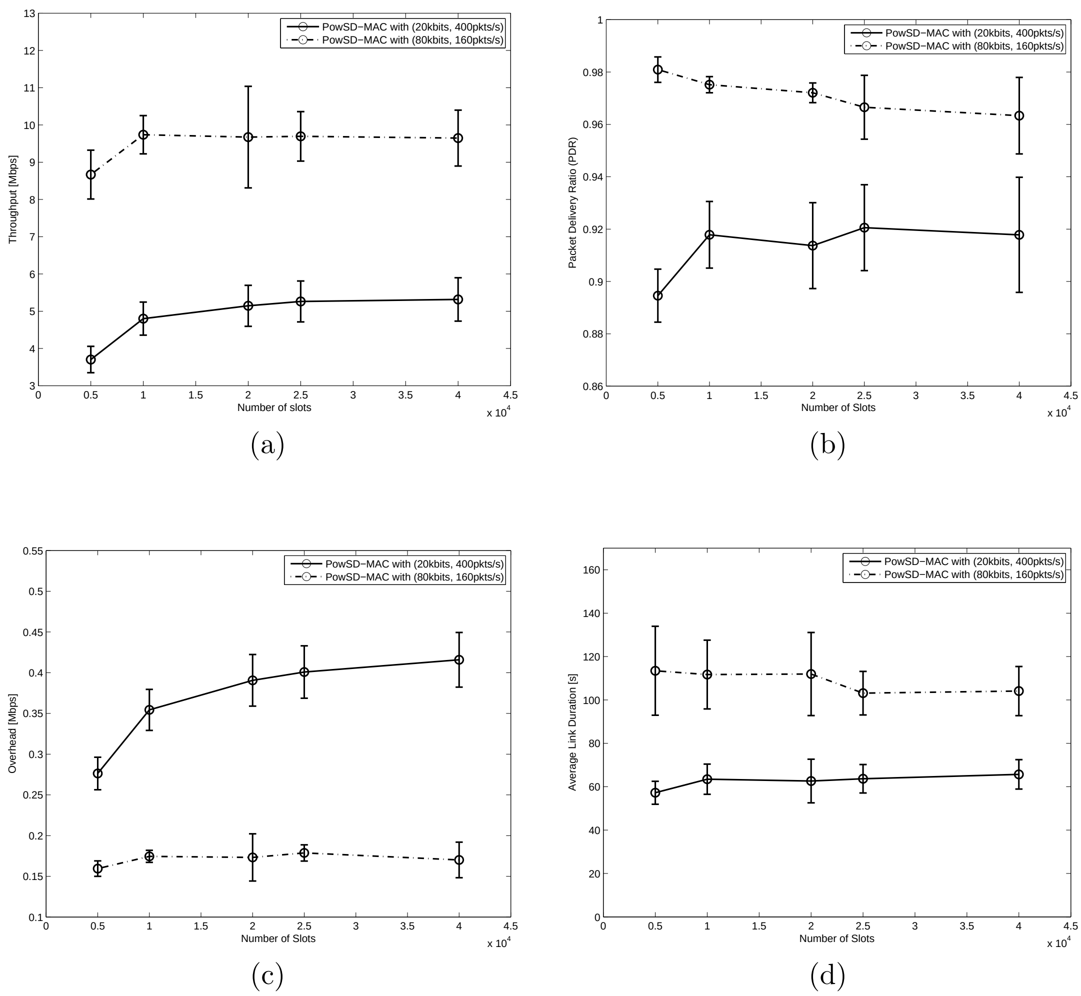


Figure 4.1: The throughput (a), PDR (b), overhead (c) and link duration (d) as a function of the number of slots.

With a small slot-length, the channel is better utilized, with a tighter transmission schedule. For small packet sizes, this will result in frequent overlapping slots and retransmissions. However, the increased channel utilization overcomes the effect of a less stable transmission schedule. The PDR increases for smaller packet sizes as shown in 4.1 (b). With large packets the reduction in PDR is not significant.

A large slot-length reduces the number of slots/frame. This also reduces the amount of slot occupancy information exchanged using hello packets. Hence, increasing the slot-length decreases the overhead as shown in 4.1 (c). However, large slot-length increases channel wastage as a packet will occupy only a small fraction of an entire slot. This is similar to the guard time introduced in TDMA. We choose N_{Slots}=25000 slots/frame. Further decrease in slot-length results in larger overhead without an increase in throughput.

4.4.3 Determining the Optimal Value of the Broadcast Threshold

The broadcast threshold, N_{Bcast}, is the number of lost packets to detect a broken-link. Its value determines the stability of the links. In SD-MAC, it prioritizes and retains the slots allocated to hello packets over Data/ACK packets, resolving collision. In 802.11 the number of retransmissions fills in the same role. Also, the location information is retained in the neighbor table for N_{Bcast} frames.

A low value of unicast threshold N_{Ucast} ensures faster collision resolution between Unicast-MFs. We choose $N_{Ucast} = 2$. In SD-MAC, low values of N_{Bcast} will result in frequent readjustments of the transmission schedule. In reactive schemes, the delay in the allocating slots results in a reduction in throughput as shown in Fig. 4.2 (a). There is a high probability of a Bcast-MF overlapping with a Unicast-MF. The Bcast-MF requires a higher priority and needs to be retained as the control information exchange is important to maintain a stable transmission schedule. Hence, we need to choose a value such that N_{Bcast} is always greater N_{Ucast}. However, higher values of N_{Bcast} result in longer delays in resolving collision. Fig. 4.2 (b) shows that the PDR stabilizes for higher values of N_{Bcast} for 802.11.

Small values of N_{Bcast} cause unnecessary changes in destination. Higher value of N_{Bcast} affects the neighbor selection scheme, retaining stale neighbor information. 802.11 has a higher collision probability and choosing a low value of N_{Bcast} results in a choosing a wrong destination (not the nearest neighbor). Hence, we determine the value of N_{Bcast} based on the average link duration. Fig. 4.2 (d) shows the average link duration for PowSD-MAC and Pow802.11 as a function of N_{Bcast}. We choose $N_{Bcast} = 5$ for PowSD-MAC and

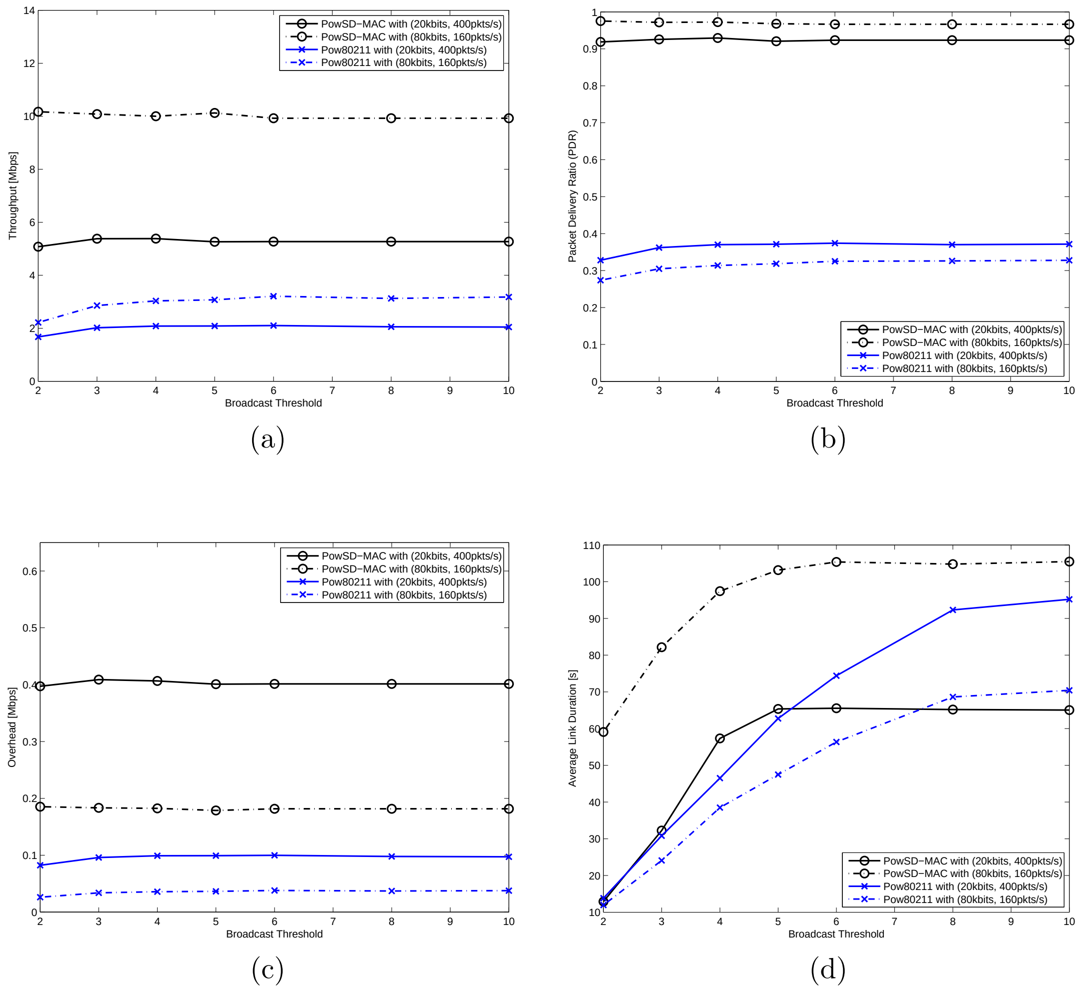


Figure 4.2: The throughput (a), PDR (b), overhead (c) and link duration (d) as a function of broadcast threshold, N_{Bcast}

$N_{Bcast} = 8$ for Pow802.11; the values for which the link duration stabilizes.

4.4.4 Protocol Performance as a Function of the Number of Airplanes

We study the performance of the proposed protocols with respect to the changes in the number of airplanes as shown in Fig. 4.3. The simulation area is changed to 200x200 square kilometers with 6 airports. The offered load is 400 packets/s for packets with 20kbits payload. The default transmission power is set to represent a single-hop network i.e., all nodes hear each other. We study the performance and scalability of the protocols for high offered loads. In this section, the network throughput is calculated as the ratio of the

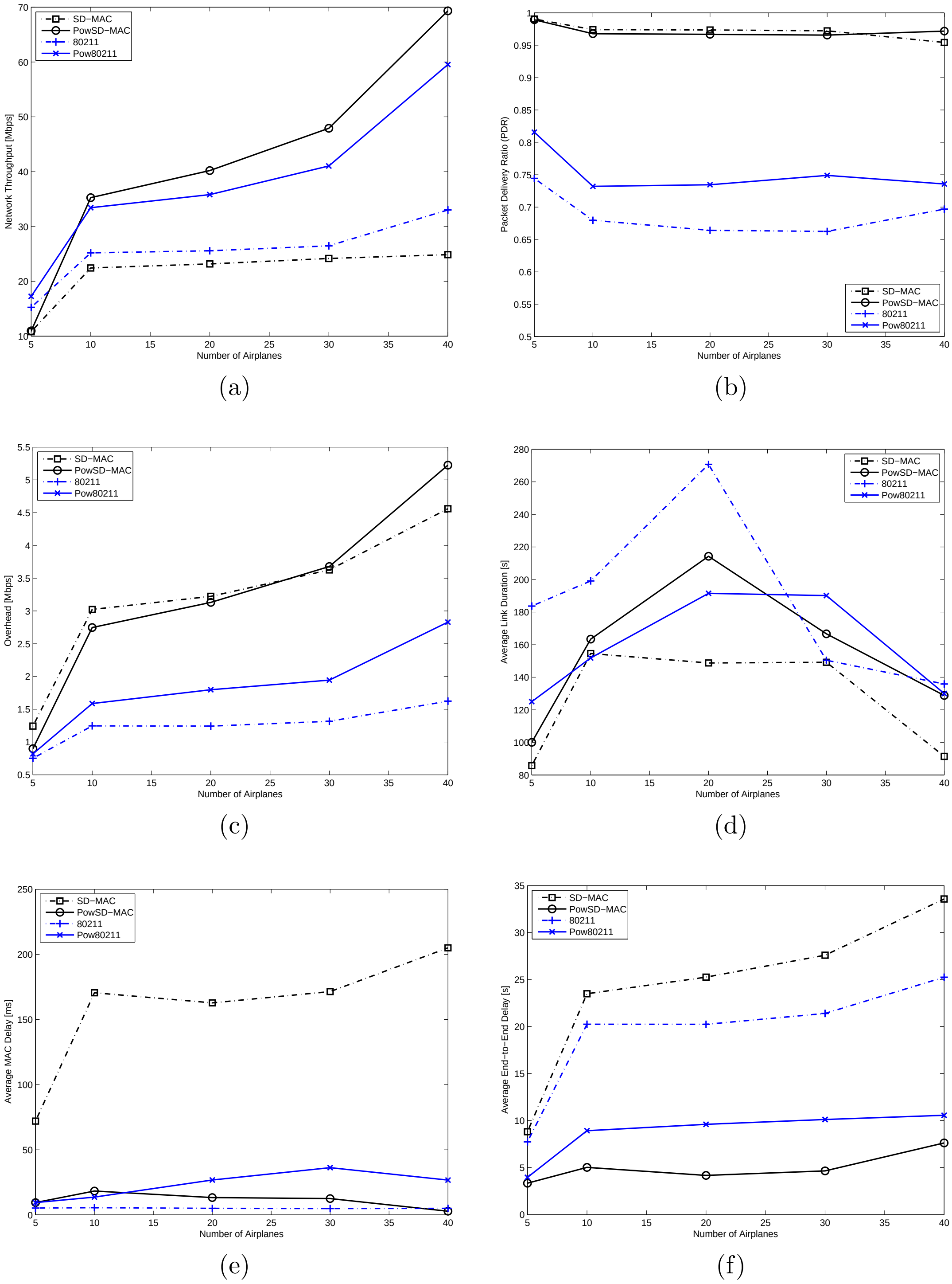


Figure 4.3: The throughput (a), PDR (b), overhead (c) and link duration (d) MAC delay (e) and end-to-end delay (f) as a function of the number of airplanes

total number of packets successfully received over the total simulation time instead of the total transit time. This clearly shows the variation in throughput with increase in number of airplanes. SD-MAC is unable to scale beyond 10 nodes as the throughput stabilizes for increased node density as shown in Fig. 4.3 (a). The scalability can be increased by choosing a lower common transmission power. However, selecting a low common transmission power can isolate nodes and choosing an optimal transmission power is not a feasible solution in a dynamic mobile environment. SD-MAC does not suffer from increased collision as its PDR is ≈ 0.97 as shown in Fig. 4.3 (b). The low throughput is due to the unavailability of free slots. In comparison, 802.11 suffers from a large number of collisions as observed from its low PDR. With 802.11, a large number of transmissions occur simultaneously due to the ineffective carrier-sensing (hidden terminal problem). This is sufficient to enhance its performance in comparison to SD-MAC. However, from the performances (throughput and PDR) of Pow802.11 and PowSD-MAC we can conclude that adaptive transmission power is necessary to increase the spatial reuse.

SD-MAC suffers from high MAC-delays. The small sized packets result in a tight transmission schedule and nodes could frequently lose MFs. Due to the poor scalability, the new reservations take more time to get assigned and are placed far apart. It also suffers from large end-to-end delays indicating that nodes are not able to reserve slots with increased offered loads and airplane density as shown in Fig. 4.3 (e) and (f). In 802.11 and Pow802.11, the packets are dropped at the source after retry-limit number of transmission attempts. These packets do not account for the MAC-delay. Pow802.11 suffers from higher MAC delays when compared to 802.11 as fewer packets are dropped at the source. Packets reach the destination after failing the first few transmission attempts. Hence, we observe that Pow802.11 has a higher PDR and throughput. 802.11 drops more packets at the source and this reflects in a large end-to-end delay. The increased spatial reuse and schedule-based approach in PowSD-MAC ensures that it suffers from minimal MAC and end-to-end delays. In the remaining sections we evaluate the performance of the power adaptive protocols for different environments.

4.4.5 Performance as a Function of the Offered Load

In Fig. 4.4, we compare the performance of PowSD-MAC with Pow802.11 for varying offered loads. With increased offered load, Pow802.11 does not show any noticeable variation in throughput as seen in Fig. 4.4 (a). Although increasing the offered load provides more transmission attempts, with contention based protocols, this also increases the collision probability. In comparison, PowSD-MAC allows greater spatial re-use as seen with the steady increase in throughput with increased offered load. Once the network capacity is reached, the transmission schedule cannot allocate slots for new MFs as no free slots are available. The protocol ensures that the assigned schedule remains stable. This is seen by the flattening of the trace with increase in load. In contrast to Pow802.11, increase in the number of transmission attempts does not increase the number of collisions.

Fig. 4.4 (b) shows that, in Pow802.11, the PDR is ≈ 0.6 indicating that a packet transmission fails once every three attempts. The increase in offered load is offset by increase in number of collisions as observed by a nearly constant PDR despite the increase in offered load. The PDR is always greater than 0.85 in PowSD-MAC. The slot allocation provides a nearly collision-free domain. For lower payload size, PowSD-MAC provides a tight transmission schedule. Increasing the offered load results in a large number of unicast-MFs contending for limited slot availability. Resolving collisions and providing a stable schedule takes a longer time. For larger payload size, the time to resolve collisions is offset by the transmission schedule remaining unchanged for longer frame durations. Hence, the PDR remains constant.

PowSD-MAC also has a far larger overhead than Pow802.11, due to the exchange of additional slot information (NOL and ATL) in the hello packets. Fig. 4.4 (c) shows the variation in the overhead for differed offered loads. In Pow802.11, the headers and neighbor information account for the minimal overhead. However, it is clear from Fig. 4.4 (b) that the extra overhead results in a far better packet delivery ratio, and, for this application, the extra information gained by NOL and ATL exchanges is effectively used to avoid collisions.

Pow802.11 has a lower PDR indicating several retransmissions for successfully sending the packets. From Fig. 4.4 (e) we observe that this increases its MAC delay in comparison to PowSD-MAC. A larger packet size increases the collision probability that further increases the delay. From the PDR, we observe that Pow802.11 suffers from large number of retransmissions. This increases the queuing delay and end-to-end delay as shown in Fig. 4.4 (f). Pow802.11 suffers from large delays as it does not have any guaranteed reservations. In PowSD-MAC with large packet sizes, consecutive Data-MFs to same destination often will not be close to each other. This results in a linear rise in MAC delay, for increased offered load. At higher offered load, MFs are placed close to each other resulting

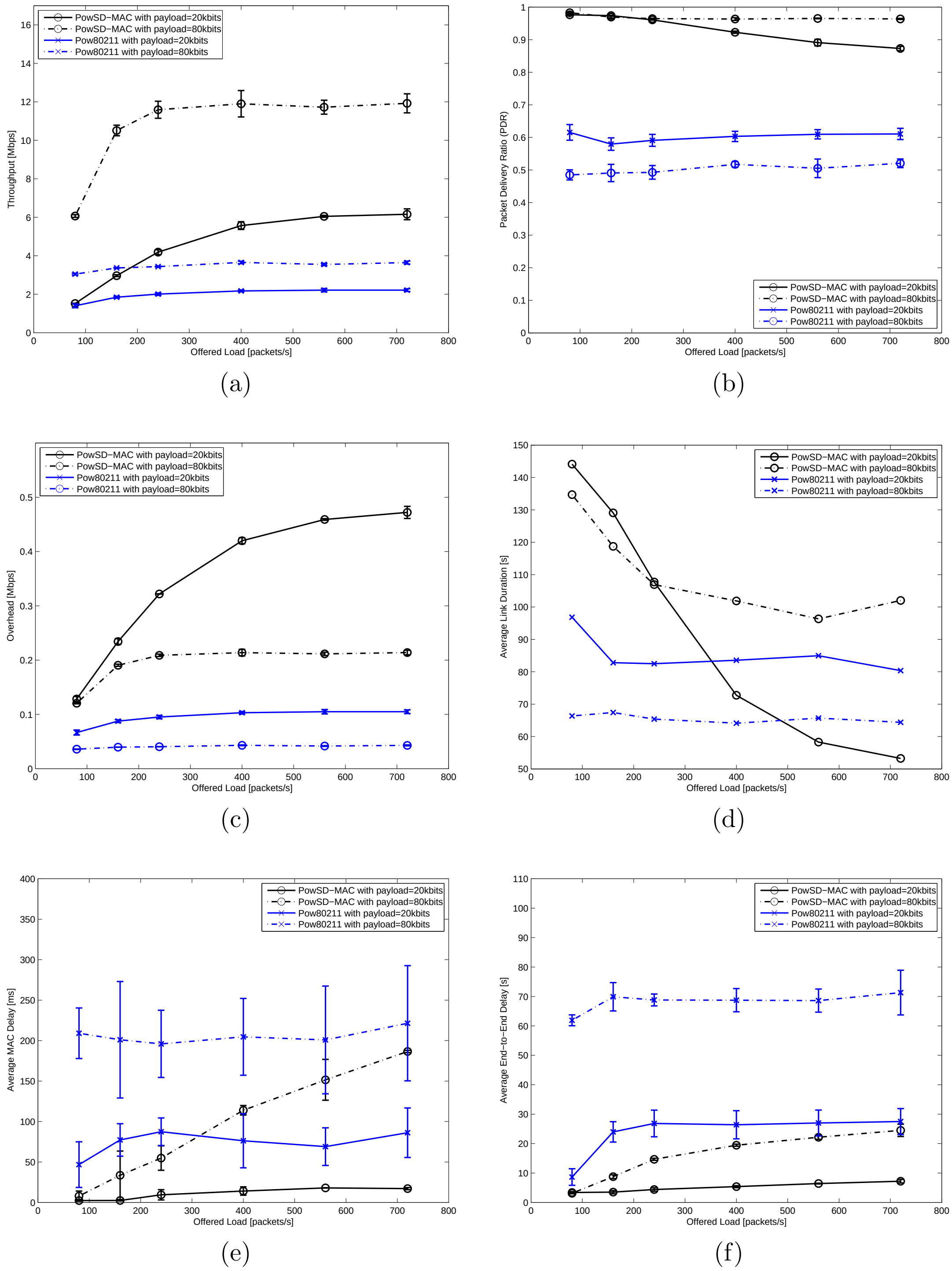


Figure 4.4: The throughput (a), PDR (b), overhead (c), link duration (d), MAC delay (e) and end-to-end delay (f) as a function of the offered load

in a tighter transmission schedule. The gradual increase in the end-to-end delay is due to the unavailability of the slots.

4.4.6 Performance as a Function of the Payload Size

The performance of the protocol is also dependent on the packet size as shown in Fig. 4.5. For varying offered loads, the packet delivery ratio (PDR) for Pow802.11 is ≈ 0.6 for 20kbits payload and ≈ 0.48 for packets with payload of 170kbits. Increasing the payload size, increase the collision probability resulting in a lower PDR. In comparison, PowSD-MAC utilizes the channel bandwidth far better, resulting in better throughput. With adaptive slot adjustment and good spatial reuse, the PDR for the lower payload sizes with 400 packets/s is ≈ 0.91 as observed in Fig. 4.5 (b). Larger payloads occupy more slots, decreasing the number of MFs in a frame. With fewer entries in the NOL, the length of the Bcast-MF (and overhead) is reduced. The probability of losing a Bcast-MF due to collision is also reduced resulting in more stable transmission schedule. Hence, in contrast to Pow802.11, the PDR increases from 0.91 to 0.97 with increase in payload.

In Pow802.11, although the PDR decreases with increase in payload size, sufficient number of transmissions are successful, ensuring a gradual increase in throughput. With PowSD-MAC, there is a substantial increase in throughput with larger payload size as shown in Fig. 4.5 (a). PowSD-MAC provides reliability through ACKs and, a Data-MF must be followed by an ACK-MF for every source-destination pair. For better efficiency and tighter transmission schedule, the Data-MF and its ACK-MF must be as close as possible. This can result in small gaps of free slots that cannot be used by any neighboring node. With larger payload packets, these gaps can be reduced resulting in a more efficient schedule. Also, from the variation in PDR, we have observed that larger payload packets increase the transmission schedule stability providing a greater throughput.

The overhead decreases with increase in packet size as fewer Data packets can be sent over a frame duration. This also decreases the number of ACK packets per frame time. From Fig. 4.5 (c), we observe the drop in overhead with increased packet size using for both protocols. In PowSD-MAC, the NOL carries information for every MF in the frame. Hence, increasing the payload size reduces the number of MFs showing a more pronounced drop in the overhead. Once the PDR stabilizes with increase in payload size, the number of packet transfers per second decreases, reducing the overhead.

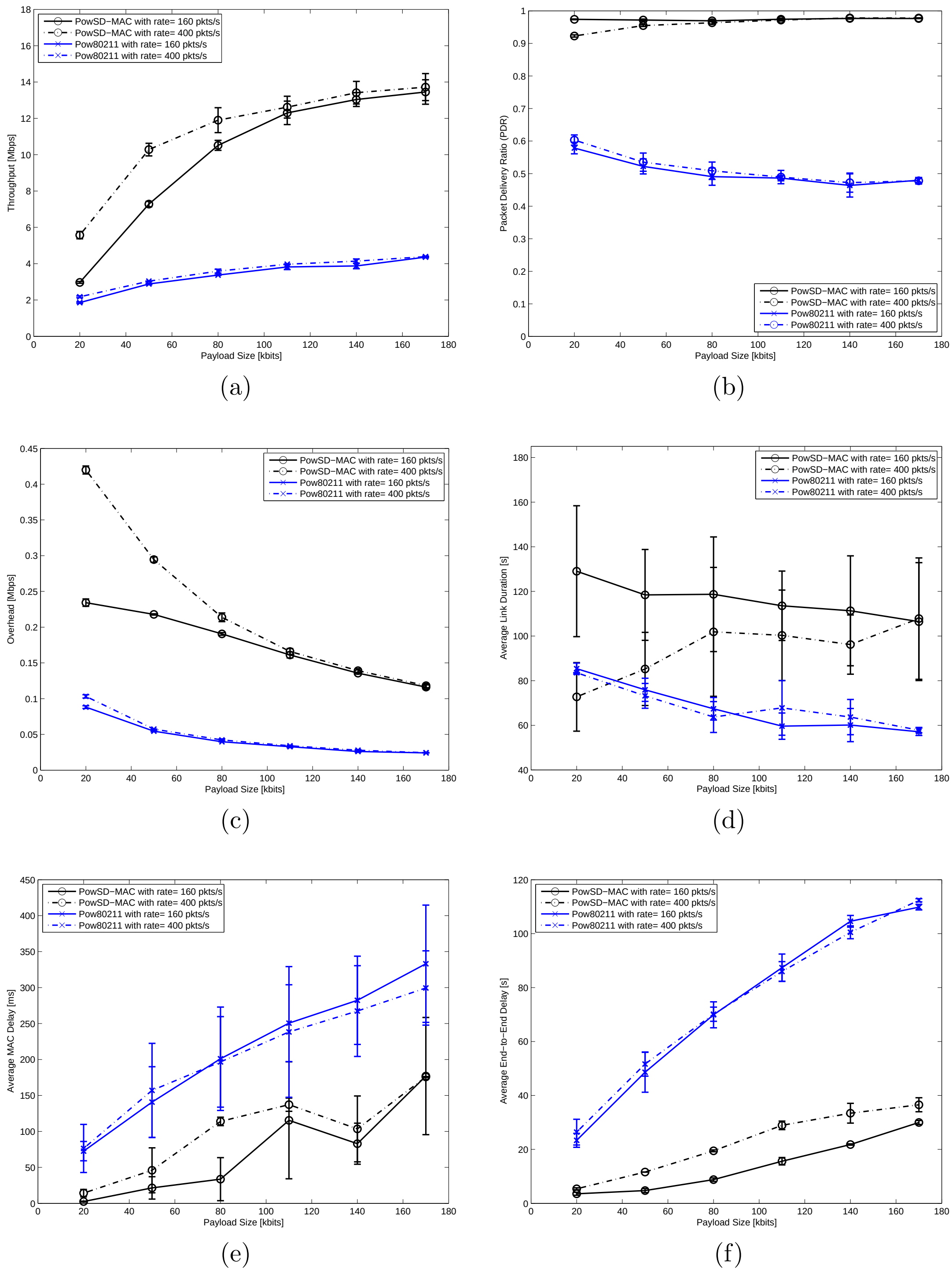


Figure 4.5: The throughput (a), PDR (b), overhead (c), link duration (d), MAC delay (e) and end-to-end delay (f) as a function of the payload size

With PowSD-MAC, the PDR remains constant and frequent retransmissions do not account for an increase in the MAC delay. When packets are retransmitted, they do not have any predefined time between two transmission attempts. The new Data-MFs are spaced further apart with increased packet size. Also, finding the required amount of slots for a new reservation will take a longer time. The linear increase in MAC delay is shown in Fig. 4.5 (e). The end-to-end delay also increases as the chosen destination may not be able to reserve MFs in the same frame duration due to the lack of available slots. New MFs are reserved only after moving freeing up unused overlapping slots over N_{Bcast} frames. The variation in end-to-end delay is shown in Fig. 4.5 (f). For Pow802.11, increasing the packet size results in higher collision probability. This is observed from the drop in PDR for large packet sizes. The large number of retransmissions results in an steeper increase in MAC and end-to-end delay when compared with PowSD-MAC.

4.4.7 Performance as a Function of the Airplane Mobility

High mobility can result in frequent changes in propagation delay and largely unstable transmission schedules. With smaller payload size, a large number of MFs occupy the frame to form a tight schedule. A small change in the topology will result in overlapping slots, requiring renegotiation of schedule. This is observed in Fig. 4.6 (a), where the average number of successful transmission per frame decreases with mobility. Increasing the payload size reduces the number of overlapping MFs, resulting in a stable schedule as seen with the 80kbit packets. Pow802.11 does not show any noticeable variation in throughput with mobility as the collision probability remains unchanged.

Collisions or overlapping MFs are reported only by the hello packet that are broadcasted once every frame duration. The time between detecting overlapping MFs and resolving them could be as large as a frame duration. With increased node mobility, the link propagation delay between the nodes changes resulting in large number of colliding unicast-MFs, retransmissions and frequent change of schedule. Fig. 4.6 (b) shows the PDR gradually decreasing for packets with 20kbits payload. The stability of the transmission schedule seen with packets with larger payloads ensures that the drop in PDR with increased node mobility is negligible. The PDR is unaffected by mobility for nodes using Pow802.11.

With small packet sizes consecutive Data-MFs are placed close to each other.

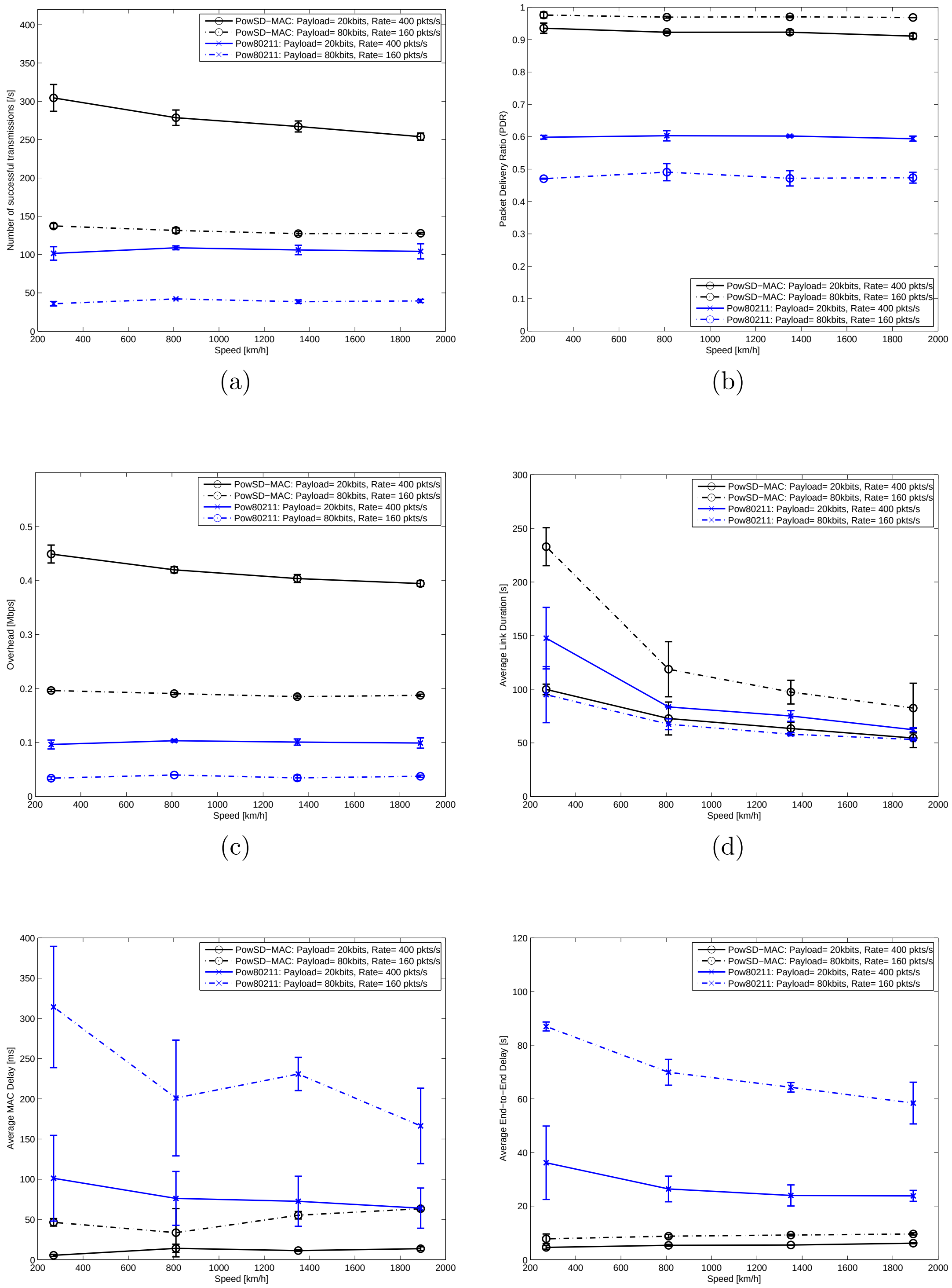


Figure 4.6: The number of successful transmissions (a), PDR (b), overhead (c) link duration (d) MAC delay (e) and end-to-end delay (f) as a function of the cruise speed

Although the transmission schedule is unstable, the effect on MAC delay is negligible when compared to the MAC delay seen with larger packet sizes. With PowSD-MAC, the PDR does not indicate the frequency with which nodes get an opportunity to transmit packets. Larger packets will require longer time to reserve MFs and their MFs are placed far apart. With increased mobility, the transmission schedule will change frequently. This results in an increase in MAC delay with increase in average cruise speeds as shown in Fig. 4.6 (e). The effect of MAC delays is insignificant in comparison to the queueing delay. Hence, we do not observe any variation in the end-to-end delay.

4.4.8 Performance as s Function of the Airplane Density

High node density results in increased contention for a constant available bandwidth. The variation in performance with node density is shown in Fig. 4.7. Using the nearest-node neighbor selection and adaptive transmission power control, a high node density decreases the average transmission power result in better scalability. With both protocols we observe an increase in network throughput with increase in number of airplanes as shown in Fig. 4.7 (a). However, there is minimal variation in average overhead as the amount of slot occupancy information exchanged per node remains the same. This is shown in Fig. 4.7 (b).

Pow802.11 shows a significant improvement in PDR with increased node density. With a large number of airplanes, the average link distance and propagation delay between the communicating nodes decreases. With smaller or negligible propagation delay, CSMA/CA based protocols carrier-sense better. This increases the probability of a successful transmission attempt as shown in the figure. The increase in PDR results in smaller delays at the source. Hence, the MAC delay and end-to-end delay decreases with node density. Using PowSD-MAC, the high node density results in a large number of nodes requesting slot-reservations. With small packet sizes and increased node density, the transmission schedule is unstable. Pow802.11 is based on CSMA/CA and inherently provides fairness. PowSD-MAC lacks a fairness scheme and this results in some nodes waiting for longer durations of time to access the channel. With these nodes failing any transmission attempt; the average delay, before their next transmission attempt, increases. This results in an increase in MAC delay as shown in Fig. 4.7 (e).

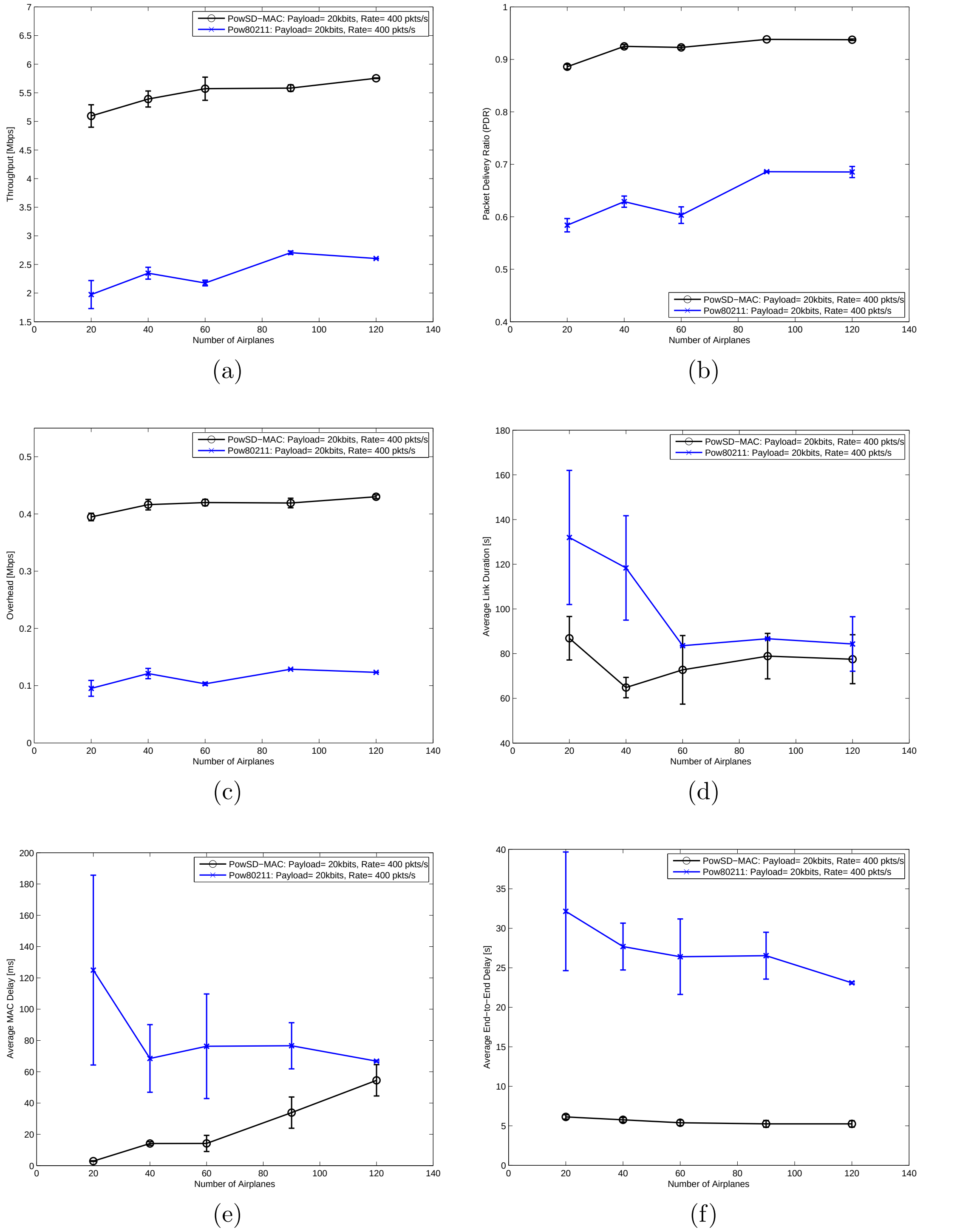


Figure 4.7: The throughput (a), PDR (b), overhead (c) and link duration (d) MAC delay (e) and end-to-end delay (f) as a function of the node density

Chapter 5

Conclusion and Future Work

5.1 Conclusion

In this thesis, we presented a new, power-adaptive, scheduled MAC protocol that, for environments with *large propagation delays* and *long-lived* flows, utilizes the wireless channel far better than existing, contention-based MAC protocols. The adaptive slot mechanism exploits the non-negligible propagation delay in long distance links when allocating slots, resulting in a tight collision free transmission schedule. The protocol provides reliable data transfer, critical to the proposed black-box data replication application. We introduce an adaptive transmission power control mechanism to increase spatial reuse and avoid isolated nodes. We have shown through simulations that PowSD-MAC has a high packet delivery ratio resulting from a stable transmission schedule. With a nearly collision free approach PowSD-MAC by far provides a better throughput when compared to tuned-up versions of IEEE 802.11. PowSD-MAC outperforms 802.11 with varying payload size packets. However, the small payload size packets result in a large overhead, reducing the stability of the schedule and decreasing the network throughput. With large payload packets and high offered load, the overhead drops significantly and improves the performance of the protocol. In scenarios with increased airplane mobility, PowSD-MAC provides a fairly stable transmission schedule. The stability decreases with decrease in payload size, degrading its performance. However, it outperforms Pow802.11 in all the scenarios. PowSD-MAC ensures high spatial reuse making it highly scalable as its performance remains unchanged with increased network size or node density. We have shown that the proposed scheme outperforms contention based protocols like IEEE 802.11 over a wide range of parameters.

5.2 Future Work

Predictive schemes need to be explored for LM and NS modules. The nodes can predict their neighbor's location from its previous location information update. With these schemes, the frequency of the location update information can be reduced. This reduces the overhead of the LM Hello packet. The neighbor selection schemes then chooses a new neighbor from the currently predicted location information.

Prediction-based slot allocation can be introduced to improve the performance of PowSD-MAC. With the available location information, we can develop techniques where nodes are able to shift slots predicting a change in the propagation delay. The source or the destination can shift slots for existing reservations, avoiding an overlap of MFs. Overlapping MFs can be predicted and resolved just before the overlap occurs. The delay caused by overlapping MFs and subsequent new reservations can be reduced. These schemes result in a more stable transmission schedule, improving the performance.

The predictive schemes reduce the delay and overhead seen in the reactive schemes. These schemes can reduce the redundancy by decreasing the frequency of LM Hello packets. The single-hop neighbor information and control information can be sent intermittently. Decreasing the overhead reduces the size of the Bcast-MF resulting in more stable broadcast domain. In the previous section, we have shown that reducing the overhead improves the performance of PowSD-MAC.

Quality of Service (QoS) could be provided for real-time applications or emergency messages. The Bcast-MF could explicitly ask neighboring nodes to drop/retain slots based on the QoS requirements. However, the main challenge would be providing a highly reliable Bcast-MF, even before regulating the reservation of slots. With increased offered load and node density, the slotted ALOHA approach results in a large delay to choose and reserve a new Bcast-MF. Better techniques to choose and prioritize Bcast-MFs need to be designed.

Currently, the fairness among contending nodes has not be evaluated. Even under high offered loads, nodes will be able to reserve a Bcast-MF. However, if all available slots for sending Data/ACK have been occupied by existing nodes in the neighborhood, a new node is delayed and has to buffer packets in its queue. This delay is unsuitable for real-time application and could lead to possible loss of information due to buffer-overflow for any application. Co-operative mechanisms to achieve fairness need to be studied.

Finally, we only evaluated the performance of the proposed MAC protocol for A2A communication. It is also well-suited for other environments with large delays, for example, under-water communication using slow propagating ultra-sounds.

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