Store and Haul: Improving Mobile Ad-Hoc Network Connectivity through Repeated Controlled Flooding

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Abstract

This work investigates the benefits and drawbacks of repeating controlled flooding at different intervals in mobile ad hoc networks (MANETs) to overcome episodic connectivity. Specifically, the thesis examines the efficiencies in repeating transmissions by quantifying the packet delivery ratio (PDR) and recording the resulting delays in different types of MANET scenarios. These scenarios mainly focus on partitions within the simulated networks by varying node density and mobility. The nodes store transmitted data and haul it across the MANET in the hope that it will come in range of a node that leads to the destination. A customized version of the Network Simulator 2 (ns-2) is used to create the simulations. A qualitative analysis follows and shows the cost and benefits of increased transmissions at varied time intervals.

Acknowledgment

The work in this thesis is supported by and large through the ResiliNets Research Group in ITTC at the University of Kansas. Abdul Jabbar was integral throughout the entire process and Sarvesh Varatharajan was instrumental in getting the ns-2 source code modified to perform S&H+RCF. Dr. James P.G. Sterbenz provided the direction, scope, and tutelage to bring it all to a successful end. A very special thanks to Abdul and Dr. Sterbenz as they have both spent many hours coaching and mentoring me even before the thesis began. It was only under their auspices that this project was possible. Finally, I'd like to thank my family for their patience and support throughout the MS program. They are my greatest love and most powerful inspiration (especially my Elise and Stephanie).

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Chapter 1

Introduction and Motivation

Communication is an integral part of any industry or society; as they inextricably link more and more electronic devices into their systems, they increasingly rely on communication networks. In every facet of life, from warfare to car pooling, communication mechanisms are ubiquitous. While great progress has been made in advancing the state of the art in communication networks, the challenges of modern day networks have increased in number and complexity.

Mobile ad hoc networks (MANETs) are a type of mobile, wireless network that does not rely on infrastructure. These networks contain freely-moving nodes that result in dynamic and frequently changing topologies [1]. Their design incorporates all network functionalities within the MANET nodes, including routing, forwarding, error control, connectivity, and security [2]. MANETs are often characterized by their more pronounced challenges, the most notable of which are dynamic topologies, bandwidth constraints, power constraints, and limited physical security [1]. While these challenges are somewhat daunting, the potential benefits MANETs can offer communication networks make them attractive to research and hold great promise for future networks.

These benefits of MANETs motivate novel ideas and innovative strategies. For example, dynamic topologies have been met with new types of routing protocols; proactive, reactive, adaptive, geographical, and power-aware routing protocols have been developed to help combat some of the challenges described and are outlined in Chapter 2. Most pertinent to this work is the *Store-and-Haul* (S&H) paradigm [3], which uses the mobility of the nodes to carry transmitted data across an episodically connected network.

1.1 Motivation

Traditional MANET research does not consider partitioned networks. Only recently have potential solutions been proposed – most of which consider some form of storing received data and hauling it to segregated areas of the network for retransmission [4, 5, 6, 7]. However the majority of those S&H algorithm and protocols have taken complex or memory intensive approaches; e.g. assigning "ferry" nodes [5], connection-oriented approaches, or storing every message sent in the MANET [4].

The goal of this thesis is to explore a new approach, that is easy to implement, systematically disseminates data throughout the network, requires minimal memory, and yields notable packet delivery improvements over standard MANETs protocols.

1.2 Thesis Methodology and Goals

The ultimate goal of this research is to determine the improvements possible by implementing S&H in conjunction with other MANET routing protocols. The goals of this thesis were limited to investigating S&H in conjunction with repeated controlled flooding (explained further in Section 2.1), *S&H+RCF* (store-and-haul with repeated controlled flooding):

1. Modify the ns-2 simulator so that network nodes will hold transmissions for a specified time. The customized ns-2 software is also further modified to repeat specified transmissions a specified number of times.

2. Construct reasonable scenarios of MANETs in which to run this new S&H+RCF mechanism. Run the scenarios systematically and record the results for analysis.

3. Run baseline control simulations with conventional, controlled forwarding – using the same MANET scenarios as used for the S&H+RCF simulations.

4. Analyze the results and compare control simulations with the S&H+RCF simulations.

5. Characterize the S&H+RCF performance and draw conclusions.

1.3 Contributions

This thesis contributes the following:

- Offers and explores a new communication paradigm by combining store-and-haul with repeated and controlled flooding

- Developed a new model in ns-2 to implement S&H+RCF

- Performs analysis on new communication paradigm to determine benefits and tradeoffs for S&H+RCF and shows that S&H+RCF provides better communication capabilities in disconnected networks

1.4 Thesis Organization

The rest of the thesis is organized as follows: the background of MANETs, S&H, and RCF, as well as related work in the subject area are discussed in Chapter 2. Chapter 3 explains the S&H+RCF mechanism in detail. Chapter 4 describes the simulations: network parameters, MANET characteristics, and S&H settings for the different sets of simulations. Performance results of the simulations and analysis of the benefits are outlined and discussed in Chapter 5. The thesis conclusions and comments on future work to be done on S&H are discussed in Chapter 6.

Chapter 2

Background and Related Work

MANETs vary greatly in their design, purpose, and operation. The factors that affect and impact the success of MANETs are often as dynamic as the MANETs themselves. Naturally, success greatly depends on the design objectives and the challenges or constraints that might apply to a given scenario. To better understand the basis of S&H+RCF, the different types of relevant MANET methodologies and protocols are examined and studied. RCF (repeated controlled flooding) was adapted from controlled flooding in MANETs – controlled flooding has been common in communication networks for many years. S&H (store and haul) has not been around as long and is a little more complicated. Some of the first MANET protocols and methodologies that exploited the S&H concept had slightly different objectives in mind than S&H+RCF, such as energy conservation and lossless packet delivery, but most are similar enough that made their data apt and applicable.

This chapter is organized as follows: the background and related work starts by covering the oldest and more simplistic relevant research: controlled flooding. It then delves deep into MANETs and the most popular MANET protocols. The chapter then wraps up with a description of delay tolerant networking.

2.1 Controlled Flooding

Controlled flooding (CF) is one the simplest MANET routing algorithms in network communications, much older than the concept of MANETs. CF begins with the transmission of a packet by a source to all known neighbors. If the neighbor is the packet's destination then the packet is sent to the application. If the neighbor is not the destination, the node repeats it to all known neighbors again – except to the node from which the packet came [8]. CF is neither classified as a reactive or proactive routing algorithm as it does not keep routing tables. What matters most in the routing process is the identity of the source and destination nodes [9]. The most important feature to note about CF is packets are only transmitted to nodes that have not already received the packet [10]; this is the difference between uncontrolled and controlled flooding. With this in mind, it should also be noted that CF is a little more difficult in MANETs, because paths are dynamic and frequently changing. Therefore, CF in MANETs may actually begin to transmit the packet toward the node from whence it came. If the receiving node realizes it has already seen and transmitted the packet, the packet is dropped immediately. Finally, it is not uncommon for CF to set limitations on how many times a packet may be forwarded. Most often this is done with a Time To Live (TTL) mechanism.

While it is more complex and advanced, Tiny Ad-Hoc Routing Protocol (TARP) is based on CF [11]. TARP first inspects a packet to see if that particular node is the packet's destination. If it is, the packet is passed up to the transport layer and the transmissions cease for that packet in that node. Otherwise, the packet is then subjugated to three rules. The first, duplicate discard (DD), drops packets when multiple copies have been previously seen and forwarded by the receiving node. The second rule is suboptimal path discard (SPD), which drops packets that have taken an "unreasonable" path between source and destination nodes. The final rule is load balancing (LB), which explores alternative paths through diversification. It accounts for possible congestion and works in tandem with SPD by responding to mobility and calculating more "reasonable" routes. The three rules are executed sequentially and are restrictive in nature. Their decisions are based on packet characteristics that are embedded by the TARP protocol within each packet header [11].

The header includes the source and destination addresses, the session identifier, the sequence number of the session, the packet's count, the maximum path length the packet may travel in hops, and the number of hops the packet has traveled so far. These characteristics are the *packet signature* that determines which packets are acceptable to retransmit and which are not [11].

While the results of TARP ns-2 simulations varied depending on how the rules were configured, it was outperformed by DSDV, AODV, and DSR. However, the authors contend that it is still comparable to "serious routing protocols" with relatively complex route discovery and maintenance techniques (DSDV, AODV, DSR, etc.) [9]. TARP is designed as a *maintenance free* protocol for MANETs that efficiently uses network resources. It may be best suited for MANETs that employ small and inexpensive hardware [9] [11].

2.2 Mobile Ad Hoc Networks

MANETs are defined as a network with mobile nodes that can communicate without any existing infrastructure. In other words, there is no need for towers, satellites, or any kind of stationary, wired support system [1]. Arguably, there has always been a need for MANETs but the real research for this type of network did not begin until the late 1990s. MANETs are the progeny of research programs such as Survivable, Adaptive Networks (SURAN) [1] and Survivable Communication Networks (SCN) [1]. MANETs have been developed largely through the efforts of DARPA and ONR (Office of Naval Research), which recognized the need for communication networks in areas where existing infrastructure was not available, too expensive, or impossible to deploy.

Not only have military and explorative organizations have noticed the possible benefits, MANETs have attracted the attention of commercial organizations as well, particularly the need to communicate through harsh and remote environments. From the rugged and threatening battlefields of future wars, to space exploration, to remote scientific locations such as underground exploration or polar research – MANETs provide the prospect of providing network connectivity where the luxury of infrastructure is not practical [12].

These hopes and expectations placed on MANETs are often overshadowed by the aforementioned challenges inherent to their design and function. Mobility is the physical movement of a node or nodes which dynamically changes its points of attachment to the rest of the nodes [13]. This results in the dynamic topologies in which nodes move in and out communication range as shown in Figure 2.1. Dynamic topologies are extremely problematic in network engineering because of the difficulty involved in delivering the right information or packet of information to the correct node. If nodes are moving they are often difficult to find and sometimes out of reach for a period of time.

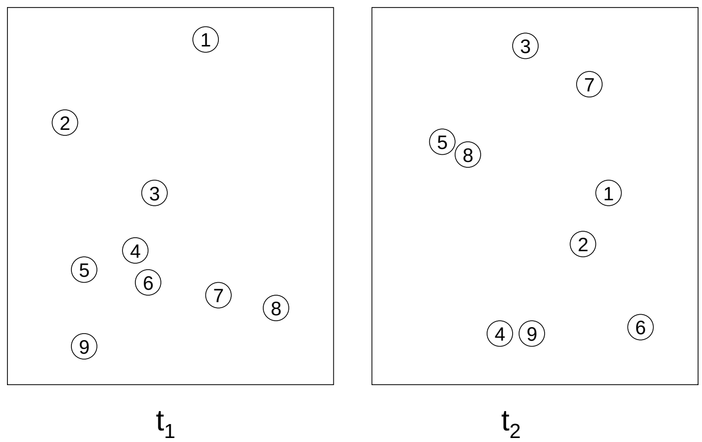

Figure 2.1. Nodes moving inside of a MANET

The next two challenges are bandwidth and power constraints. They are tightly interconnected as they often limit or exist because of each other. The bandwidth constraints are due to a number of reasons. The wireless medium is unreliable with greater limitations on bandwidth when compared to wired links. While advances have been made in wireless technology to produce higher bandwidth, the nodes are self-contained and have limited energy. Furthermore, the nodes share the same medium, which results in sharing of the limited capacity and the need for a MAC (medium access control) for arbitration [14]. As previously mentioned, the power constraints are mostly due to their self containment and need for mobility. Typically powered by batteries, nodes in a MANET have a limited amount of energy [15]. Another challenge is security; the wireless medium has proven difficult to secure since its inception. Attempts to encrypt and secure the wireless channels are often unsuccessful, as seen in WEP and now seen in WPA [16]. The added complexity of dynamic topology makes security even more difficult. The additional overhead incurred with trying to secure MANETs weighs heavy on the extremely limited resources of power and bandwidth.

Network engineers meet all of these challenges in a variety of ways. The routing protocol is integral to the success of a MANET. Just as there are many different kinds of MANET configurations, constraints, obstacles, and limitations there are many different kinds of MANET routing protocols that provide a potential solution to each scenario.

The most common and well known MANET routing protocols are classified as proactive or reactive. Proactive routing protocols keep a table of all possible paths in the MANET at all times. This is sometimes referred to as “table driven” routing and is accomplished with control messaging that monitors the paths. Reactive or “on demand” routing is where nodes only learn paths when there is data to send.

Like many aspects of engineering, no one protocol is necessarily better than another. Instead they are regarded as more suitable than another for a particular scenario. The next four sections give brief backgrounds on some of the most popular MANET protocols.

2.2.1 DSDV

DSDV (Destination-Sequenced Distance-Vector Routing) was developed for mobile networks in 1994 by Perkins and Bhagwat [17]. Based on the Distributed Bellman-Ford algorithm, DSDV has each node maintain a table that tracks all the possible paths within a mobile network making it a proactive routing protocol [17]. These tables are created from routing information that is shared between nodes through updates. The updates are at first dumped to a node entering the range of a mobile network with incremental updates to follow. The route selection is performed using age and metric of the entries in the table.

As one of the earliest MANET protocols, DSDV has some significant drawbacks – namely performance and energy consumption. However it did provide guarantees of a loop-free path to each possible destination in the MANET and is the basis for many modern MANET protocols.

2.2.2 AODV

As a successor to DSDV, AODV (Ad hoc On-Demand Vector routing) improved on a number of aspects. Using reactive routing instead of proactive routing, AODV reduced signaling overhead, collisions, and energy consumption. Performance was also increased by the way AODV finds a desired route [18].

AODV finds a route by first broadcasting a request for the destination node. This request is forwarded through the network keeping track of the path the request takes. If the request reaches the destination node, a reply traverses the same path back to the originating node. Assuming paths exist, the originating node will receive one or more ways to the destination node. The originating node will usually choose the path with the fewest hops and send the transmissions down said path. If a link fails and the path is lost the process is repeated. [18]

2.2.3 DSR

Designed specifically for MANETs in 1994, DSR (Dynamic Source Routing) is a reactive form of routing that attempts to improve route development and selection within a MANET's nodes. DSR is essentially comprised of Route Discovery and Route Maintenance. [19]

Route Discovery is performed by a sending node to find all the available paths to a destination. It floods a route request throughout the MANET. If no destination is found the route request is re-flooded until a timeout is reached. If the timeout is reached the data is either either queued for later route discovery attempts or dropped. Route Maintenance is performed when a path is lost between a source and destination. Essentially, Route Maintenance selects an alternate path or reinvokes Route Discovery.

2.2.4 OLSR

As one of the modern proactive MANET routing protocols, OLSR (Optimized Link State Routing Protocol) [20] is a canonical example of proactive and link-state routing in MANETs. This protocol is table driven and begins by controlling the topology. Topology control is established through a system of hello messages multi-point relays (MPRs). MPRs are responsible for forwarding traffic and act as a mechanism of control transmissions reduction. Each node selects a set of neighboring nodes as MPRs and the MPRs declare all the link state information to the rest of the network. These declarations provide shortest path routes to all network nodes (and potential routes for redundancy).

2.3 Disruption Tolerant Networks

Delay tolerant networks (DTNs) attempt to facilitate communications when connectivity is sporadic or discrete. This means that DTNs take a store-and-forward approach [21, 22] based on the interplanetary network (IPN) framework [23]. While the storing of data in DTNs has significant performance implications, its primary objective is to bring communication to systems in which there previously was none. [24]

Disruption tolerant networks (DTNs[1]), is a generalization of delay tolerant networking, encompassing network interruptions other than just delays. MANETs share the property of episodic connectivity with DTNs. Furthermore, S&H in MANETs is often sparsely connected or highly dynamic and can benefit from S&H. The following sections describe different different S&H methodologies employed by MANETs, presented in chronological order from when they were first described in research.

2.3.1 Epidemic Routing

One of the first researched implementations of S&H is *epidemic routing*. The protocol eventually achieves the optimal packet delivery ratio (PDR), given enough time, described by the following formula:

$$\lim_{t \to \infty} \text{PDR} = 100\%$$

Assuming that partitions do not persist indefinitely, all packets will be delivered to their destinations in MANETs [4].

2.3.1.1 Epidemic Design

The main goal of epidemic routing is to transmit every packet to every node once, and only once. Eventually, every transmitted packet should reside on every node within the MANET. Epidemic achieves this by having the node keep an array

[1]The acronym DTN is used for both delay tolerant networking and disruption tolerant networking

of all packets it generates and all the packet it receives. Each packet transmitted throughout the network must have a unique packet identifier and the array is indexed by that packet identifier. In addition to the packet identifier, the epidemic design calls for a *hop count*, and an optional acknowledgment request [4].

Epidemic is designed to only transmit each packet once to every node in the network, achieved through a simple exchange between two nodes as they come within range of one another. It starts by first establishing which node will receive first and which node will send. This is negotiated such that the node with more messages usually goes first. A small cache is maintained of recent associations to avoid redundant connections. All of this is part of the discovery process [4].

The transmitting node starts by sending a *summary vector* (bit vector) to the receiving node (SV_A in Figure 2.1), which is a hash table that is keyed by the unique identifier and is $[1 \times P]$ in size (where P is the number of packets transmitted by any node). This summary vector describes to the receiving node which packets the transmitting node is ready to send. The receiving node takes the summary vector and performs the logical AND ($\wedge$) operation on the inverse of its own summary vector ($\neg SV_B$ in Figure 2.1), which informs the receiving node of the packets that are available and not previously been transferred. The receiving node then generates a request, which is answered by the the transmitting node. This process is then repeated vice versa or as long as the nodes are in range.

Similar to the TTL field in IP, the *hop count* determines how many hops a packet will travel before it is dropped. This value is set according to how much node memory can be allocated for packet storage; the higher the hop count the better the performance.

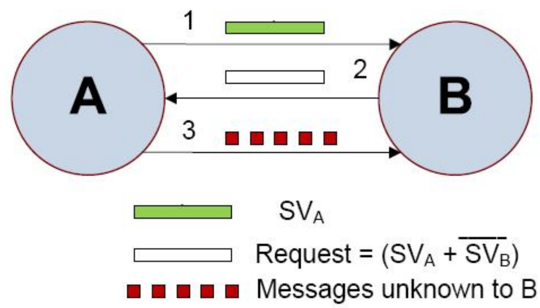

Figure 2.2. Epidemic Routing Packet Exchange (adapted from [4])

2.3.1.2 Epidemic Performance

As a resource conscience, S&H transmission scheme for segregated MANETs, Epidemic is a possible alternative to scenarios deemed appropriate for S&H+RCF. As with S&H+RCF the protocol can transport data to segregated regions of networks that might not have ever received transmissions. The two areas where the two protocols can differ most is in energy consumption and performance. Consideration of energy consumption is beyond the scope of this thesis and is addressed in future work (Chapter 6), but performance can be examined. Unfortunately a direct comparison to S&H+RCF is unavailable because ns-2 does not currently possess a working Epidemic package. Therefore a qualitative discussion and comparisons of the protocols' characteristics are made.

Using stochastic modeling of traffic and nodes, multiple mobility models have been examined with the Epidemic routing protocol [25]: Random Waypoint, Random Direction, and Random Walk. The protocol itself has been examined in two forms: two-hop multicopy Epidemic and unrestricted multicopy Epidemic. In the unrestricted multicopy Epidemic the hop count is set to infinity.

The Laplace-Stieltjes Transform (LST) of message delay is defined to help normalize the results. In addition to the mathematical analysis, simulations were run; both sets of results matched "very closely" [25]. Results differed based on the form (unrestricted multicopy or two-hop multicopy) and mobility models comparing one another and determining the ponits of which performance was greatly affected. Transmission range and the number of MANET nodes can be used to describe performance in the network:

$$\lambda = O(r(N))$$

where λ is the inter-meeting time intensity and $r(N)$ is the transmission range of a network with N nodes [25].

Performance metrics of Epidemic routing have been examined: *delivery delay*, *loss probability*, and *power consumption* [26]. MANETs consisting of $N + 1$ mobile nodes using unrestricted multicopy Epidemic were in a closed area following the random-waypoint and random-direction mobility models, with traffic generated according to a Poisson process. This analysis ascertains the basic network characteristics of delay and loss, as well as captures the number of retransmissions (used for calculating energy use) and storage requirements. Further analysis was then done to extended models that included two-hop Epidemic, probablistic forwarding, and limited-time forwarding. Finally, performance under limited buffer size was analyzed with two drop schemes: drophead and droptail. The analysis shows that Epidemic is intrinsically predictable and Markovian models can lead to quite accurate performance predictions [26].

Epidemic routing under contention has also been examined [27]. Noting that MANETs are often deployed in hostile environments, this research puts constraints on bandwidth and scheduling while introducing signal interference.

2.3.2 Store and Haul

Store and Haul (S&H) is a paradigm that uses node mobility to physically carry data across regions of MANETs where communication is not possible due to connectivity limitations, interference, or eavesdropping. This label was first coined in 2002 [3] and was first published in the Epidemic routing protocol two years earlier [4]. S&H has been explored in a variety of ways and is sometimes referred to as store and carry forward (SCF) or message ferrying [4], [7], [28], [5]. The interesting concept behind S&H is that it uses mobility to overcome some of the challenges created by mobility itself. This essentially turns a potential challenge into a potential strength and uniquely applicable to MANETs in need of DTN architectures.

2.3.3 Message Ferrying and Store-Carry-Forward

Message Ferrying (MF) is a store-and-haul variant in which only predetermined nodes can use their mobility to physically transport data through the MANET, unlike Epidemic in which any node can carry data across the network [6]. There are a wide variety of implementations, each with varying characteristics, objectives, and results.

The intial implementation designates *message ferries* that have a deterministic mobility model while the rest of the *regular nodes* may have stochastic node mobility [5]. Ferries are classified as *task-oriented* or *message-oriented*. Task-oriented ferries' path is designed for other non-messaging reasons such as a bus on a campus or planes patroling a battlefield. Message-oriented ferries follow trajectories designed to enhance communications. Four message ferrying categories are crisis-driven, geography-driven, cost-driven, and service-driven. Crisis-driven applications include battlefield or disaster area communication, when infrastructure is unavailable due to environmental conditions. The ferries enable the segregated areas to communicate with one another by transporting data between them. Geography-driven types of network nodes are often densely deployed within clusters but are inherently sparse due to larger geographic distances between the clusters. In the cost-driven category, ferries can be used where it would be expensive to create network infrastructure between clusters. This category includes city buses that could transport non-critical or best-effort traffic to other networks. The service-driven category is an opportunity for MF to provide a service not already available in the existing network infrastructure, such as anonymous communication within a network [5].

Node-Initiated Message Ferrying (NIMF) is a scheme in which the ferry moves along a predetermined route known by the regular nodes. Nodes are then responsible for traveling to meet the ferry when needed. Conversely, the node needs to periodically check to see if messages are waiting for delivery from the ferry. Ferry-Initiated Message Ferrying (FIMF) uses the opposite initiation in which the ferry travels to the nodes for communication. This can be accomplished either by ferry nodes periodically traveling to all the regular nodes or by some sort of signal or beacon the regular nodes produce when they are ready to communicate.

Node buffer sizes, both in the ferries and regular nodes, as well as the impacts of node mobility and transmissions range affect performance. Multiple ferries can work in tandem alleviating contention, with coordination of regular nodes and ferries. The research is regarded as an in depth analysis of message ferrying uses and concerns [5].

Other MF research goes delves deeper into different strategies, potential uses, performance, and characteristics, including differentiated services [29], optimizing ferry routes, scheduling ferries, and ferry buffer management [30, 6, 31]. There are also have been proposals for more efficient or effective strategies [32, 30].

Store-Carry-Forward (SCF) is another term used for S&H and also been referred to as *mobility-assisted routing* [33] and *store and foward* [29]. Several protocols have been labeled as SCF. The following sections cover three of the most common.

2.3.3.1 MeDeHa

An example of limited use of SCF can be found in the Message Delivery in Heterogeneous, Disruption-prone Networks (MeDeHa) protocol [34]. The primary objective of MeDeHa is establish a framework for data delivery in heterogeneous DTNs. It establishes this with four functional components: *message relaying*, *buffering*, *topology and content information exchange*, and *traffic differentiation*.

The first component, *message relaying*, is the SCF piece, that is a system in which all nodes can store and haul data. It is referred to as simpler and more opportunistic than other SCF systems: simple in that scheduling, beaconing, or summoning systems are not needed and more opportunistic in that the nodes can take advantage of more network types. *Buffering* is directly addressed for two reasons. First in heterogeneous networks the Access Points (AP) or other gateways between the varying kinds of networks are of great strategic value, and should be used as a temporary repository for undelivered messages due to their high availability of resources. This can be enhanced by buffering at the data link layer [34].

The *topology and content information exchange* portion consists of nodes periodically exchanging a few key pieces of information: topology, routing table, and message buffer information, as well as available resources and performance metrics. The overhead in this is more than offset with the improvements in relay selection. The last component of MeDeHa is *traffic differentiation*. Here MeDeHa attempts to satisfy application-specific requirements, by using message priority, TTL, scope, and message tags to provide quality-of-service (QoS) [34].

The basics of the node operation is shown in Figure 2.2. Each node has one of four states: idle, receive, forward, and buffer. The nodes start in the idle state and will switch to the forward state if it has a message to send, or will switch to the receive state upon the reception of a message. After receiving a message the node will either recognize itself as the destination and return to idle state or switch to the forwarding state if it is not the destination. Once in the forwarding state it will forward the message if an acceptable path or suitable relay is found. If not, it switches to the buffered state. Here the node decides whether or not to drop the message or store the message in the buffer for later attempts at transmission. In either case, the node will return to the idle state.

In summary, MeDeHa uses a combination of networks to efficiently buffer messages and carry them through areas where there is no network infrastructure [34].

2.3.3.2 Efficient Adaptive Routing

Another example of the use of SCF is the Efficient Adaptive Routing (EAR) protocol for DTN [35]. EAR is characterized as a bandwidth efficient solution that achieves its efficiency by dynamically allocating available bandwidth according to the current state of the DTN. The two components by which EAR conserves

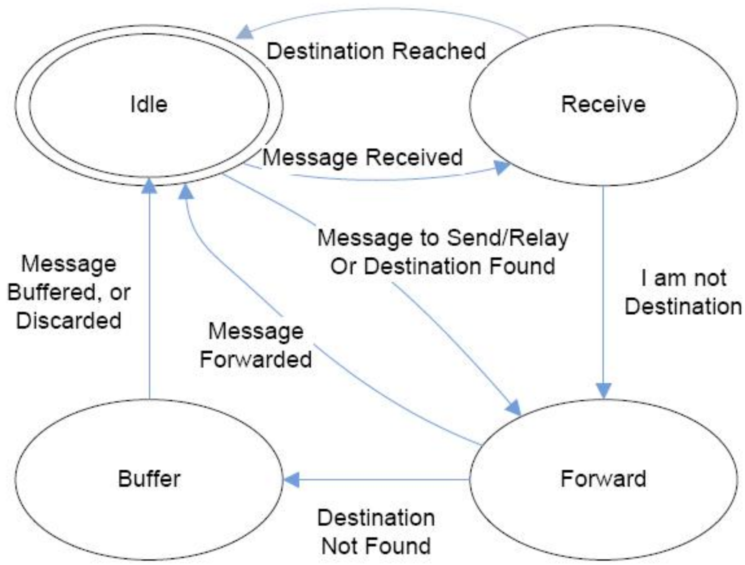

Figure 2.3. MeDeHa State Diagram. Adapted from [34]

bandwidth are through multi-hop routing and mobility-assisted routing. The EAR protocol uses multi-hop routing when it can to transmit data as it usually provides the best performance. However if the network is congested or a path is not known, EAR can limit the number of hops or switch to the second component: mobility-assisted routing. Here the node carries the message to be delivered to a more centralized location, one that is more likely to know the path or a location with less congestion. EAR out performs DSDV in most scenarios, in both bandwidth and PDR [35].

2.3.3.3 Store-and-Carry Forward Routing

Store-and-Carry Forward Routing (SCFR) spans the spectrum from connection-based MANETs (networks lacking the capability of carrying data) to “mobility-assisted” MANETs (such as S&H and SCF) [36]. SCFR is a complex MF protocol that can be seen in the summation of the four main components of the strategy:

- design of ferry trajectory and rendezvous points
- movement scheduling for ferry and message
- role changing abilities amongst network nodes (as needed)
- node redistribution through ferry movement

One of the more notable characteristics of SCFR is the ability to effectively and efficiently redistribute nodes throughout a geographic space. As seen in Figure 2.4, the nodes are spread out through the physical constraints of network while keeping connectivity amongst all nodes. This is achieved through node adaptation (switching back and forth from ferry to non-ferry) and dynamic reorganization.

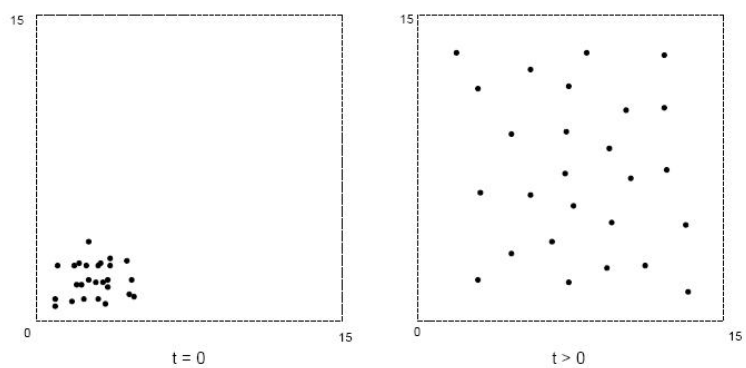

Figure 2.4. Node Redistribution by SCFR. Adapted from [36]

The *dual-control plane* system divides node control into two planes for heterogeneous networks [37]: the Stationary-plane (S-plane) for message routing among stationary nodes and the Mobility-plane (M-plane) for trajectory control of the mobile nodes. In this system, all mobile nodes can act as ferries and transport data, and nodes may change roles when it is necessary. Figure 2.5 shows the logical separation between the planes. Through this system the network can efficiently control node movement to keep partitioned networks connected [37].

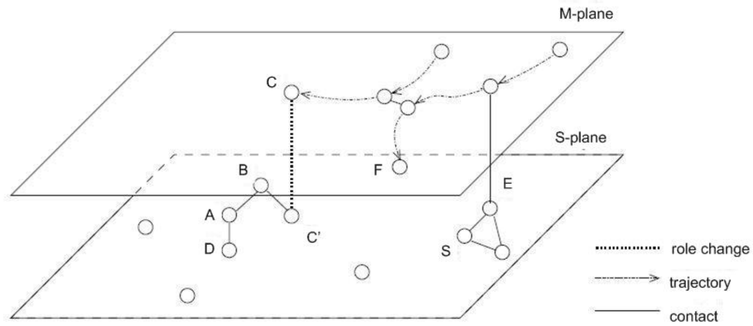

Figure 2.5. Dual Control Planes for SCF. Adapted from [37]

2.3.4 VANETs

Vehicale Ad-Hoc Networks (VANETs) are a type of MANET that classifies their nodes as "vehicles", such as automobiles, trains, and buses. This implies that the nodes are not only mobile but have ample power resources, transmission range, and speed. This is in stark contrast to other types of MANETs, such as wireless sensor networks and Personal Area Networks (PANs).

VANET research often uses the SCF mechanism and nomenclature and is applicable to SCF due to the ample resources [38]. SCF has been proposed in conjunction with vehicle navigation systems to connect sparsely communicated VANETs. The routing methodology analyzes the vehicles vectors from tuples that are shared amongst the vehicles to determine to which vehicle to forward data or which direction data should be forwarded. The tuples contain vehicle destination, waypoints, and street paths. In its simplest form this system can provide information such as weather, road conditions, and traffic conditions. However, this methodology could also be used to for inter-vehicle, end-to-end communication such as messaging, sharing data, finding locations, and Internet access. These services are described as Vehicle-to-Vehicle (V2V) or Vehicle-to-Roadside (V2R), for which geography based routing can be used [38, 39].

Other work investigating the benefits of SCF and VANETs has evaluated performance, using Markov chain models to evaluate SCF procedure in VANETs [39] under varying network conditions with dynamically changing vehicle densities. Markov chain modeling is especially applicable for analyzing mobility at an intersection, which is central to VANETs. It is important to the correct hop count to increase the availability of information, while trying to keep traffic and congestion to a minimum [39].

Chapter 3

Store-and-Haul with Repeated Controlled Flooding

Store-and-Haul with Repeated Controlled Flooding (S&H+RCF) is an attempt to alleviate some of the challenges inherent in a sparsely connected MANETs. The protocol is described in this chapter first with a basic overview and impetus behind the protocol in Section 3.1. The chapter then closes with a detailed description of the protocol in Section 3.2.

3.1 Overview of S&H+RCF

S&H+RCF research began by evaluating basic kinds of connectionless communication, namely controlled flooding – one of the most simple kinds of connectionless communication. As previously mentioned, controlled flooding is defined as transmitting data to all known communication paths regardless of whether or not the recipient can be reached on a particular link [8]. Each node receiving that transmission continues to forward the packet in the same manner except back to the path from whence it came (Chapter 2.1). Controlled flooding was deemed preferable for this research due its increased efficiency over regular flooding. Furthermore, controlled flooding seemed suitable not only for its simplicity but the potential synergy when shared with S&H. All the strategy lacked was the repetition of the transmissions and delay for the topologies to change.

In most networks repeating flooded transmissions is a waste of bandwidth as recipients have already received the flooded data due to static, contiguous topologies. But the dynamic topologies inherent in MANETs produce new links as time changes. Additionally, partitions often arise and create pockets of unreachable nodes. It is the characteristic of node mobility intrinsic to MANETs that makes repeating floods advantageous. Naturally, the S&H movement is the linchpin that augments the effectiveness of the controlled flooding and dynamic topologies by bringing the transmissions to the unreachable nodes.

This repeated, controlled flooding (RCF) augmented with S&H is a novel, yet simple solution for many different kinds of MANETs. From Personal Area Networks (PANs) to sensor networks, this strategy could increase packet delivery ratios (PDRs) and extend communication coverage where normal MANETs without S&H would not have communicated. Additionally, this strategy could be modified for different kinds of MANETs. Performance could be enhanced simply by increasing or decreasing the number of repeats. It could also be enhanced by modifying the interval between repeats, depending upon the characteristics of the MANETs in question. These modifications could even be made in real time depending on the requirements of a particular scenario.

3.2 Mechanism Description

S&H+RCF communication operates in the following manner: when a node has a message to send, it floods the message to all surrounding neighbors. The neighbors then relay the message immediately to their neighbors, to achieve the best possible performance equivalent to controlled flooding. The node then waits a specified interval and then repeats the transmission. The node repeats this process (waiting and retransmitting) until a specified number of transmissions is met, as outlined in the flowchart found in Figure 3.1.

There is significant potential in the S&H methodology when combined with RCF. The improvements chronicle which MANET characteristics combined with which S&H+RCF settings yield desirable results. Improvement in packet delivery is the main goal of the strategy.

Expectedly, the improvements do not come without a cost. The tradeoffs for improved packet delivery ratio (PDR) through S&H+RCF are increased delays and increased consumption of energy through additional retransmissions. Challenges the S&H+RCF mechanism would add to securing transmissions are outside the scope of this research. The additional drains in energy are also mentioned in Section 6.2.

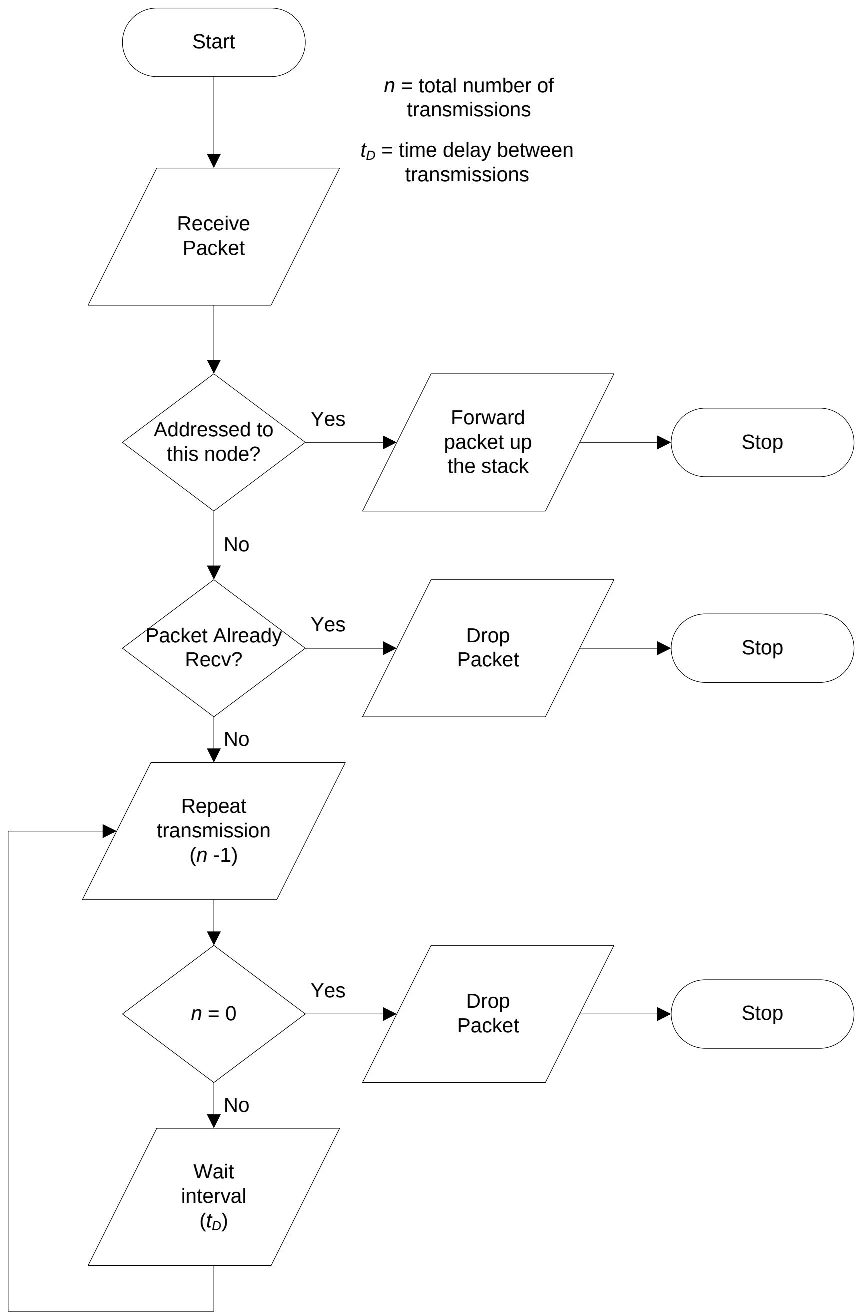

Figure 3.1. Flowchart of S&H+RCF

Chapter 4

Simulations

Due to the expense and difficulty of building and running actual MANETs, simulations are the source of all data gathered in this thesis. The simulations are run on the network simulator ns-2, a discrete event network simulator. Each network event (e.g. node movement, transmission, error, collision) is chronologically recorded into a *trace file*, as the simulation progresses. Calculations were made from the data collected and conclusions were then drawn from those calculations.

The standard ns-2 distribution does not have the capability to simulate S&H networks. The simulation software had to be customized so that the simulated nodes would carry data and transmit that data at the appropriate time. After the ns-2 software was modified, it had to be tested thoroughly. Starting first with simple examples and working to complex simulations, the modified version was always checked for inconsistencies and mistakes. Once the modified version was verified through extensive testing, the network models were designed. The goal of the model design was to be as realistic as possible. Furthermore, the scenarios in which those models were simulated were also designed based on realistic network conditions and realistic node capabilities. Finally, some of the limitations of the software and hardware resource constraints were overcome through design refinement and adjustments in both the models and scenarios.

The chapter is organized as follows: Section 4.1 describes the changes made to the ns-2 software, Section 4.2 outlines the static network parameters found in all the simulations, Section 4.3 explains the network scenarios in which the simulations were run, and Section 4.4 ends the chapter by explaining how results were verified.

4.1 Modifications to ns-2

An ns-2 distribution can be modified by editing the C++ source code. The modified code is then recompiled after editing and executed for the desired simulation. As with many software suites programmed in C++, editing source code can be a very complex process; there are many C++ source and header files and finding the right files to modify can be quite challenging.

The most current version of ns-2 at the time this thesis was started was ns-2.31. This distribution provided all files that were modified and generated all the simulations. After close inspection of the available files, modifying an existing routing protocol would be the best way to produced the desired effect. The closest standard routing protocol included in ns-2.31 is the *flooding protocol* – used to produce uncontrolled flooding [40]. Each routing protocol had a header file and a source file. These two files were used as a template to create the ResiliNets Flooding protocol.

The first modifications were designed to make the flooding *controlled*. In the native ns-2 *flooding protocol* all packets were passed up through the layers once they were received. To make the flooding *controlled*, packets already received by the node should be dropped as soon as possible. This means that all the packets received must be tracked in some kind of data structure. This is accomplished by taking the packet ID and asserting a bit in a bit array indexed by the packet ID, such that every received packet would first check an array for a previous instance. If the bit in the array with the value of the packet ID had been asserted, then the node had seen the packet before and the packet should immediately be dropped; the drop occurs at layer 2 [41].

After *controlled* flooding was established the next step was to create *repeated controlled* flooding. C++ structures were created to hold the packet ID, destination IP addresses, number times to be repeated, and interval time. From this a separate scheduling method creates the appropriate packets and schedules them for transmission within the node, producing RCF [42].

When the new packets are created so they can be repeated, they are created with the same packet ID and destination IP address. The payload is simply filler information and irrelevant to the experiment (except for the size needed for performance analysis). The process of creating RCF also provides the desired S&H mechanism, since packets are held while the nodes are moving.

4.2 Simulation Model

Once ns-2 was modified to incorporate S&H+RCF, the simulation models were designed. First, the physical topology was established, with randomly placed nodes in a 1000 meter square. All the nodes are mobile and able to S&H data. The antenna transmitted omni-directionally and the IEEE 802.11 wireless protocol is chosen for its familiarity and popularity. Thirty nodes are used in all simulations and the queue length is set to 50 packets for each node. The simulations run for

1000 seconds. Finally, the bandwidth on every node is set to 54 Mb/s and the random-waypoint (RWP) mobility model is used for node movement with speeds randomly selected between 10 and 20 m/s. All of these settings remained consistent throughout all simulations. The static parameters used in the simulations are shown in Table 4.1.

Table 4.1. Simulation Parameters

Parameter	Value
Routing	S&H+RCF
Area	1000×1000
Number of nodes	30
Simulation time	1000 [s]
Link layer	LL
MAC type	802.11
Mobility model	Random Waypoint
Bandwidth	54 Mb/s
Antenna	Omni
Queue length	50 packets
Channel type	Wireless
Radio propagation	TwoRayGround
Node speed	10 m/s - 20 m/s

Speed and paths are set parameters of the simulation movement files. The movement files instruct the nodes when to move, where to move to, and how fast to travel. Partitions are created when node density is low enough that adjusting the transmission range causes parts of the network to become disconnected. Using Perl scripts, the number of partitions is calculated by finding the running average from the movement files. The movement files are repeatedly generated until the desired running average is achieved.

Traffic is created through Constant Bit Rate (CBR) generators on ten randomly selected nodes. Ten other randomly selected nodes are chosen to receive the traffic generated. The total amount of packets created in each scenario was

50,000. The packets are 1 KB in size. Five packets are transmitted every second, per transmitting node, which results in a bandwidth of 40 Kb/s.

4.3 Simulation Scenarios

Several different scenarios involving S&H+RCF are examined, with the number of transmissions and the intervals between those transmissions varied in different combinations. Three options for the number of transmissions are used: one, two, three, and five total transmissions (by a node for each packet received).

Initially, the intervals between transmissions were only three values: one second, three seconds, and five seconds, however, longer intervals were needed to explore performance tradeoffs – resulting in scenarios with 10, 20, 40, and 60 second intervals. Unfortunately, when intervals were longer than ten seconds the server ran out of available memory. Solutions were sought to create simulated scenarios with intervals larger than ten seconds. It was determined that larger intervals could be *artificially* created within memory constraints by increasing the node speed, the premise being that nodes would move faster, essentially speeding up time, and creating a larger, *artificial* interval. Testing began with two sets of scenarios created with ten second intervals: one set at ten seconds and nodes moving at normal speeds and one scenario set with five seconds and nodes moving twice as fast; everything being exactly the same, except the interval between transmissions and the node speed. Comparatively, the *artificially* created interval of ten seconds produces results within ± 7% of the PDR values created by simulations with natively set intervals of ten seconds, as illustrated in Figure 4.1. Unfortunately, the delay values are several degrees of magnitude off from the natively created ones. The delay is much smaller in the artifically created intervals

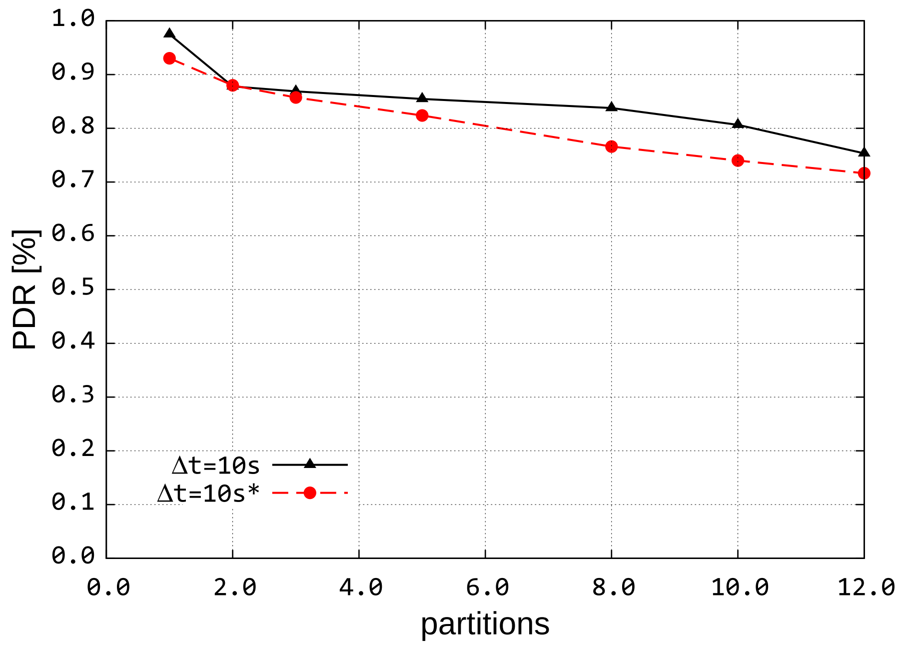

Figure 4.1. Difference between natively set and artificially set intervals (Δt)

than the natively created intervals because the nodes are moving much faster and disseminating the messages with less delay.

While artificially creating intervals is not preferred, there is still value and insight to be gained from examining those results. Table 3.2 shows all the combinations used in number of transmissions and interval between transmissions. All interval values marked with an asterisk signify artificial creation by increasing node speed.

The final network factor simulated is the number of partitions. This is necessary to test the efficacy of S&H+RCF in partitioned networks. Partitions result from sparse connectivity by reducing the transmission range of the networks nodes. All 30 nodes in the simulations have the same transmission ranges. The average number of partitions are calculated from the movement files, as previously described.

Table 4.2. Simulation Scenarios

Interval	Num of Tx	Interval	Num of Tx
1s	2tx	10s*	2tx
1s	3tx	10s*	3tx
1s	5tx	10s*	5tx
3s	2tx	20s*	2tx
3s	3tx	20s*	2tx
3s	5tx	20s*	3tx
5s	2tx	20s*	5tx
5s	3tx	40s*	2tx
5s	5tx	40s*	3tx
10s	2tx	40s*	5tx
10s	3tx	60s*	2tx
10s	5tx	60s*	3tx
		60s*	5tx

Finally, each scenario was run at least three times each to increase confidence in the results.

4.4 Functional Verification

The results of the simulations are repeatedly verified for accuracy. The verification initially began by creating test simulations that are very small. Two packets are transmitted in a network of only three nodes. Each discrete event is then examined for functional accuracy from within the simulation trace files. The tests are then increased in size and complexity, each test ending with an examination for functional accuracy. Once the tests reached ten nodes with 100 transmitted packets and functional accuracy is maintained, the simulations show they reliably scale to larger networks.

There are also internal verification processes within the analysis of all the trace files. Perl scripts are run on all the trace files to look for unexplained anomalies.

The Perl scripts count how many packets are sent and how many packets are received to ensure that there are never any instances of more received packets than packets sent. The Perl scripts also check received times to ensure no packets are received before they are sent. Finally, there are random audits of the trace files to provide additional quality assurance; random snippets of randomly chosen trace files were examined to verify functional accuracy.

Chapter 5

Analysis

This chapter presents the analysis of the S&H+RCF simulations runs. Each scenario is run three times using ns-2 and all the trace files are collected for parsing and data extraction. Perl scripts are used to analyze these trace files. The Perl scripts not only extract the necessary data, they calculate the desired values and averages, while looking for potential errors by doing consistency checks on the data (as discussed in Section 4.4). Many of these values are considered pertinent and recorded in a spreadsheet, the most noteworthy of which are the number of packets successfully received by the nodes and the delay incurred by each successful reception. Those packets successfully received are used to calculate the scenario's packet delivery ratio (PDR). The delay incurred by each successful reception is used to calculate the average end-to-end (E2E) delay in the scenario. The other noteworthy values extracted from the ns-2 files are the average node degree, average number of partitions, and average goodput.

The simulations have three variable parameters: average number of partitions in the scenario (or *network density*), number of transmissions for each packet, and the time interval each node waits between transmissions. These three variables change from scenario to scenario while all other network parameters remained static. These variables are listed in Table 5.1 along with their possible values.

Table 5.1. Possible Dynamic Variable Values

Variable	Description	Possible Values
n	Number of transmissions (total)	2 tx, 3 tx, 5 tx
Δt	Interval between transmissions	1 s, 3 s, 5 s, 10 s, 20 s, 40 s, 60 s
P	Avg. number of partitions	Contiguous network (1 part), 2 part, 3 part, 5 part, 8 part, 10 part, 12 part

From all these values recorded in a spreadsheet, tables are created and plotted using Gnuplot to help provide for the analysis of S&H+RCF.

This chapter is organized to examine the results in three different ways: with respect to network density (Section 5.1), the interval between transmissions (Section 5.2), and the quantity of repeats (5.3). Each section has two subsections: one subsection examines the PDR (packet delivery ratio) results while the other subsection focuses on the delay results.

5.1 Analysis of Network Density

The first part of the analysis focuses on average network density or average number of partitions – network density is simply the concentration of nodes in a given area and the number or partitions is the number or segregated groups of nodes such that they are out range and unable to communicate with each other. Density is examined in relation to the other two dynamic variables, with network density values plotted along the x-axis. Thus there is a set of plots where the interval between transmissions is changed and the quantity of transmissions are held constant, and a second set of plots keep the interval between transmissions held constant while the quantity of transmissions are changed. This is done for both PDR and delay.

5.1.1 Effect of Network Density on PDR

This section analyzes the effect of varying the network density on PDR, as measured by the number of partitions. This is done for a variety of transmission repeat parameters. The first three plots, Figure 5.1, Figure 5.2, and Figure 5.3 have similar, consistent traits. Most notable is how the PDR decreases as the network becomes more partitioned. This is to be expected and it can be further asserted that as partitions reach the number of nodes in the network for all scenarios, PDR is reduced to zero – expressed by the following equation:

$$\lim_{P \to n} \text{PDR} \to 0$$

In these three plots the control data from ordinary controlled flooding (as opposed to RCF) can be seen where n=1 tx. Those control simulations only transmit once and thus the interval value is meaningless. Controlled flooding (CF) had higher PDR values in very dense simulations, but performed poorly when the networks were less dense. The real benefits of repetitions can be seen as the network density decreases (as $P \to 12$). Figures 5.2 and 5.3 show how increasing the interval between transmissions (Δt) increases the PDR dramatically.

Another characteristic seen in these figures is how $\Delta t = 5$ s (Figure 5.3) scenarios outperform the $\Delta t = 2$ s plots (Figure 5.2) in overall aggregate PDR and the $\Delta t = 3$ s plots outperform the $\Delta t = 1$ s (Figure 5.1) plots in overall aggregate PDR. The longer the interval between transmissions, the higher the PDR when the number of transmissions is the same.

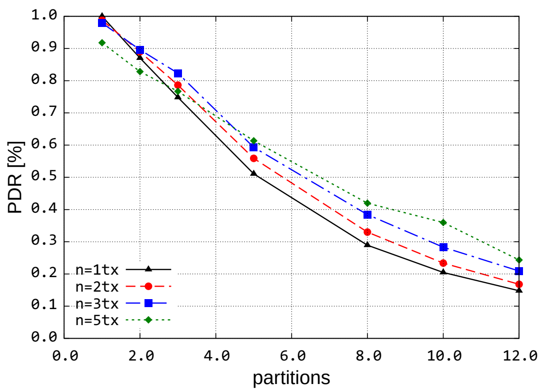

Figure 5.1. Avg PDR; Δt=1 s

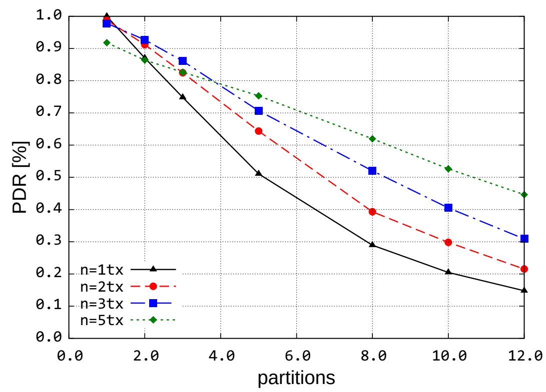

Figure 5.2. Avg PDR; Δt=3 s

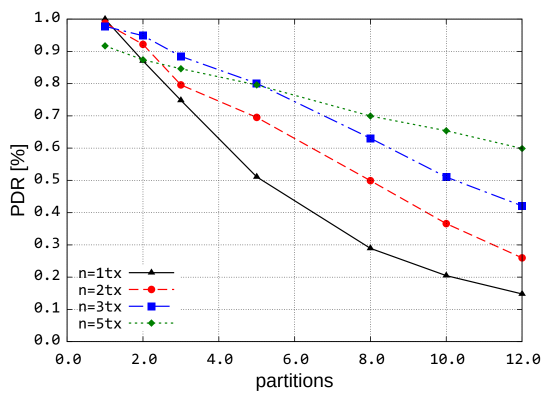

Figure 5.3. Avg PDR; Δt=5 s

While the PDR increase from increased interval between transmissions (Δt) is notable, a more intriguing observation is where the plots in each figure intersect. This shows when the benefit of the increased transmissions begins to take effect as a network is further segregated. It also shows that when a network is very dense, the extra transmissions are superfluous and result in more interference. Consequently, this decreases PDR for scenarios in which the network is very dense and the number of transmissions is high. However, the more partitioned networks show increases in PDR when transmissions and intervals are increase (e.g. the n= 5 tx start to significantly outperform the n= 2 tx and n= 3 tx scenarios in which

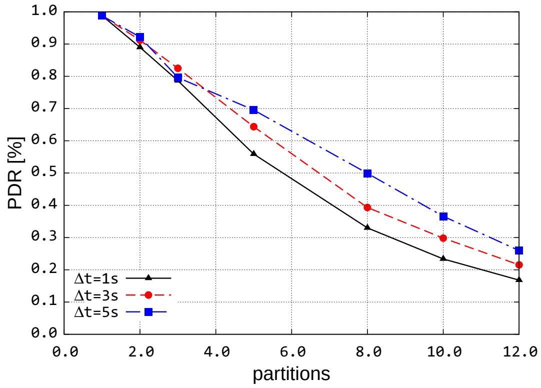

Figure 5.4. Avg PDR; n=2 tx

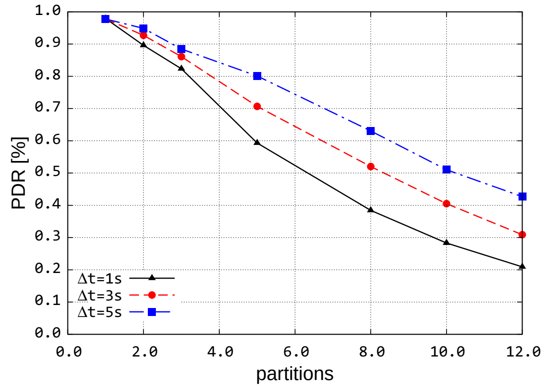

Figure 5.5. Avg PDR; n=3 tx

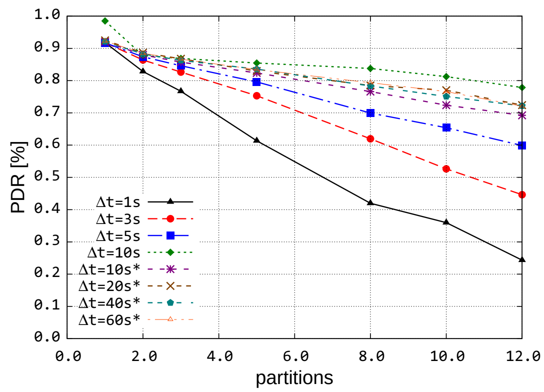

Figure 5.6. Avg PDR; n=5 tx

$P \geq 5$). The more partitioned the network, the better it is for PDR to repeat the transmission often.

The final and more insightful observation is noticing the trend in all three plots. As the interval increases from 1 s to 3 s to 5 s, the benefit in repeating transmissions linearly increases in scenarios in which network density is less ($P \geq 5$). In other words, these figures show that as a network becomes increasingly partitioned, the benefits of repeating transmissions and increasing intervals between partitions has a greater effect on PDR. Conversely, the increase in intervals can actually hurt PDR when networks are more very dense.

The second set of scenarios analyzed are those in which the number of transmissions remains static while the intervals between transmissions vary. As with the first family of plots, these have similar and consistent traits. The PDR decreases as the network becomes more and more partitioned. The deficiency in which too many transmissions can have negative affect on PDR is shown again in Figures 5.4, 5.5, and 5.6. However because Figure 5.6 shows extended intervals between transmissions (some of which are artificially created)[1], it has additional information to offer.

Figure 5.6 shows that as the interval between transmissions becomes large enough, the loss in PDR in dense networks can be mitigated. The congestion and collisions experienced from heavy transmissions can be offset with large intervals between transmissions. It also shows a diminishing return in PDR from increasing the interval past a certain value. In these experiments that value was Δt =10 s. The cause of this diminishing return is from nodes moving out of range before other nodes actually transmit the data, essentially missing their opportunity, or "window" to transmit. In other words, nodes move in and out of range all before a transmitting node has a chance to repeat the transmission.

5.1.2 Effect of Network Density on Delay

Along with PDR, delay is a very important network characteristic. E2E (End to End) delay is defined as the amount of time it takes for a packet to reach its destination after transmission. All of delay values are summed together to provide the average E2E delay of each scenario. This delay in communication is often the

[1]Some experimental scenarios with increases of interval between transmissions were tried. They only make it into select figures because only PDR values were accurately given and often do not relate to other scenarios, as discussed in Section 4.3

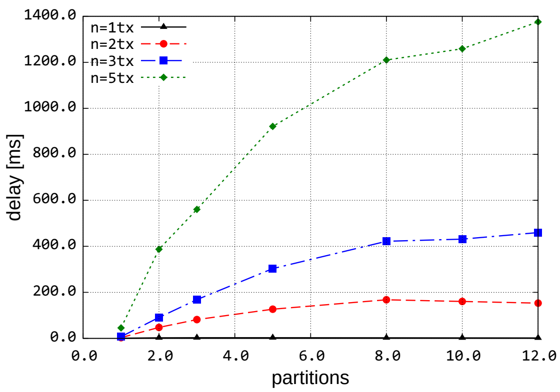

Figure 5.7. Avg E2E Delay; Δt=1 s

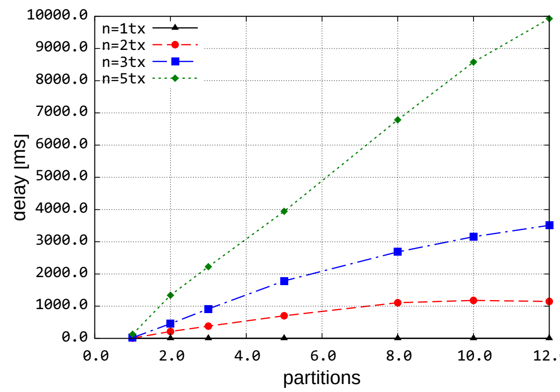

Figure 5.8. Avg E2E Delay; Δt=3 s

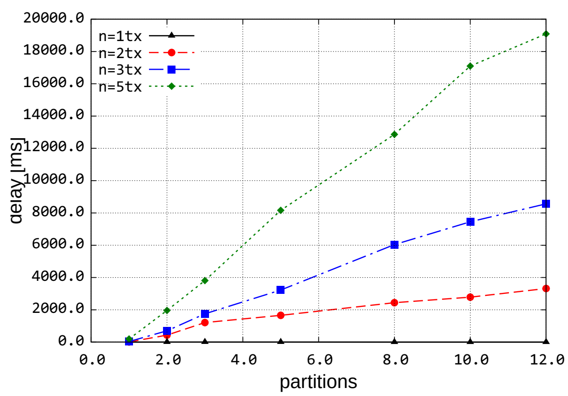

Figure 5.9. Avg E2E Delay; Δt=5 s

trade off for increased PDR in MANETs. There are many cases where delay is the by-product of increasing successfully received transmissions ([4], [5], [6], [29], [11]). S&H+RCF also experiences delays as a cost of increasing PDR. However, those delays are increased only for the packets that would not have been received in regular CF; E2E delays are never worse in S&H+RCF than CF. S&H+RCF subscribes to the philosophy in DTNs – a successful, albeit delayed, transmission is "better late than never".

The first set of scenarios analyzed are those in which the interval between transmission remains static while the number of partitions and transmissions are

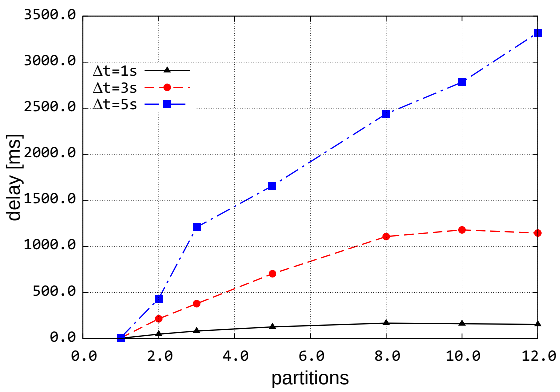

Figure 5.10. Avg E2E Delay; n=2 tx

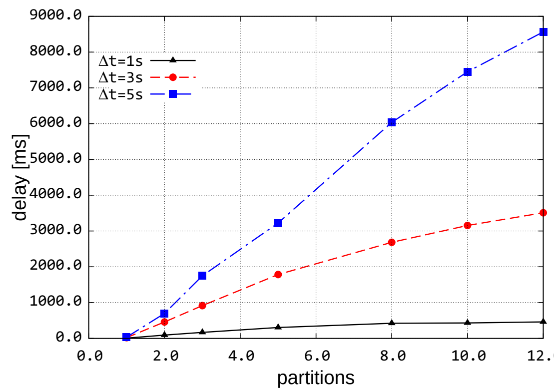

Figure 5.11. Avg E2E Delay; n=3 tx

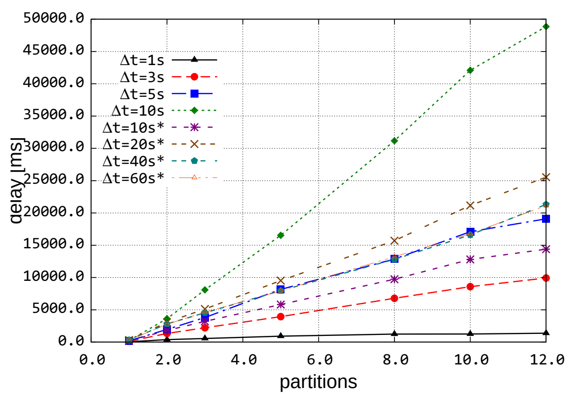

Figure 5.12. Average E2E Delay; n=5 tx

varied. Here it can be seen in Figures 5.7, 5.8, and 5.9 that the delay increases as the networks are more partitioned. It can also be seen how delay increases as the number of transmissions increase. Additionally, the three plots show how the CF simulations have a delay nearly equal 0 ms. This is due to the immediate transmission of packets upon reception. While the delay is extremely low and plateaus around 2.5 ms, it offset by extremely low PDR levels for highly partitioned networks.

The quantity of the delay between the different figures is very pertinent. The maximum amount of delay is a product of how many hops are taken before reaching a destination – how many times it has to be repeated to make the next hop, and how long of interval between each repeat. The maximum amount of delay, or D_{Max}, is

$$D_{\text{Max}} = N \times \Delta t \times n$$

where N is the total number of nodes in the network, d is the E2E delay, and n is the number of transmissions.

The maximum delay seen in the graphs varies depending on which value is set in the interval between transmissions. In Figure 5.7 the delay never exceeds over 1400 ms. In Figure 5.8 the delay peaks at 10,000 ms and around 20,000 ms in Figure 5.9. It is an exponential increase as the networks decrease in density and increase in intervals between transmissions.

The second set of scenarios analyzed are those in which the number of transmissions remains static and the intervals between transmission are varied. As with the earlier delay figures, Figures 5.10, 5.11, 5.12 demonstrate how delay increases as the partitions increase and as the interval between transmissions increases. It is notable to show how the maximum delay seen in Figures 5.10, 5.11, 5.12 is consistent with those found in Figures 5.7, 5.8, 5.9 respectively. Variations in intervals between transmission have about the same effect on delay as the variations in the number of transmissions, which is consistent with

$$O(d) = N \times \Delta t \times n$$

It is also seen in Figure 5.9 in which the artificially created intervals do not give accurate results in delay; most pronounced and clear when comparing Δt =10 s and Δt =10 s*.

5.2 Analysis of Transmission Interval

The second part of the analysis examines the scenarios with respect to the interval between transmissions, or Δt. The figures place Δt on the x-axis for a variety of network densities and numbers of transmissions. The first subsection pertains to the effect these variables have on PDR, while the following subsection focuses on the effect they have on delay.

5.2.1 Effect of Repeat Interval on PDR

When examining the effect network density and transmission quantity have on the interval between transmission, trends are established. The first set of Figures 5.13, 5.14, 5.15 show how PDR is more drastically and positively affected in the more heavily partitioned networks. It is in those scenarios ($P \geq 5$) in which PDR is positively and greatly effected by an increase in the interval between transmissions.

In Figures 5.16, 5.17, 5.18, 5.19, the PDR showing the greatest improvement in increasing the number of transmissions is when the network is less dense. This can be seen when comparing the more heavily partitioned scenarios (Figures 5.18 and 5.19) with the less partitioned, more dense scenarios (Figures 5.16 and 5.17). In that direct comparison, the increased affect the number of transmissions has on the interval between transmission has when the number of partitions are higher.

An interesting observation is seen in Figure 5.16. The n=3 tx plot begins to outperform the n= 2 tx plot as the interval between transmissions increases. This supports the assertion that congestion and collisions experienced when transmissions are high and the network is dense can be mitigated with increased intervals between transmissions. This does come at the cost of additional delay, as ex-

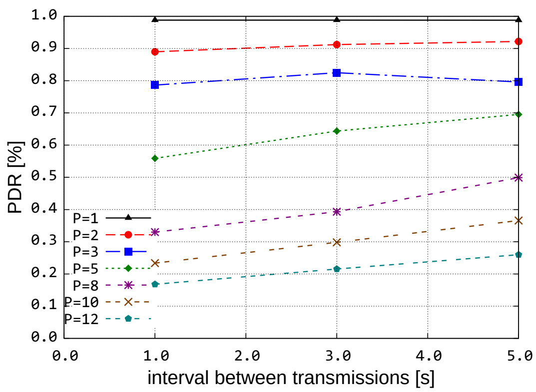

Figure 5.13. Avg PDR; n=2 tx

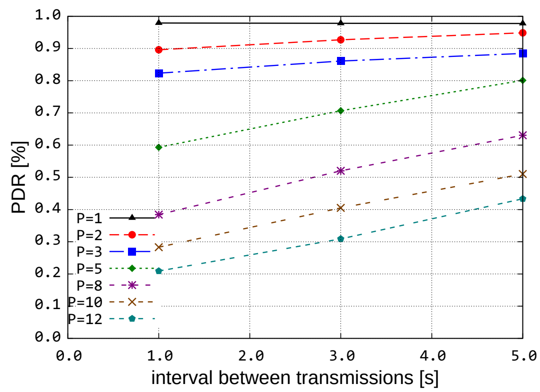

Figure 5.14. Avg PDR; n=3 tx

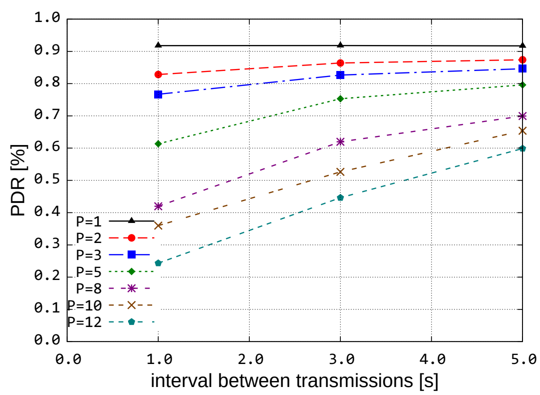

Figure 5.15. Avg PDR; n=5 tx

plained further in the following section.

5.2.2 Effect of Repeat Interval on Delay

The effect of network density and transmission quantity, with respect to the interval between transmissions, is shown in two sets of figures.

Figures 5.20, 5.21, 5.22 show the increase in delay interval between transmissions increase and network density decreases. The plots are less linear when n= 2 tx (Figure 5.20) and more linear in scenarios with more transmissions, as seen in Figure 5.22. This suggests the exponential increase in delay as the interval

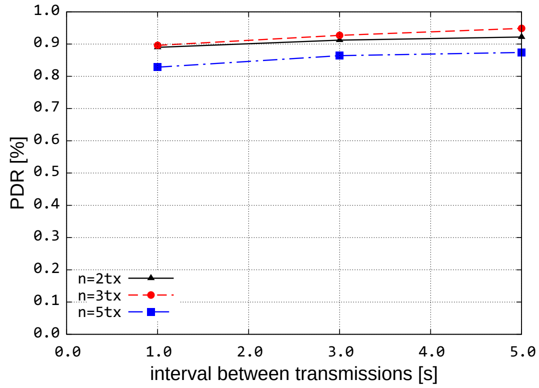

Figure 5.16. Avg PDR; P=2

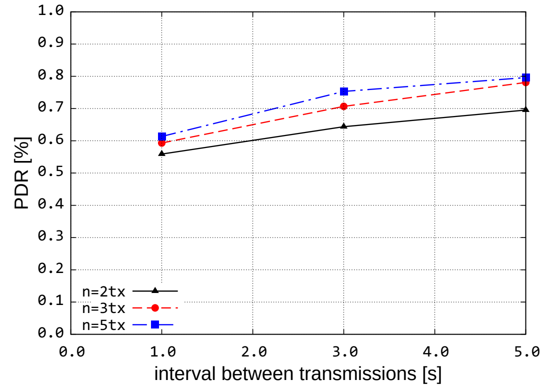

Figure 5.17. Avg PDR; P=5

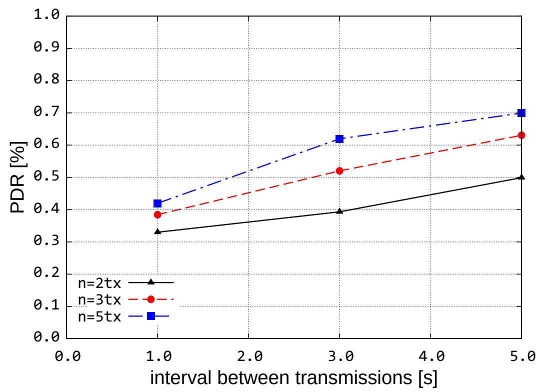

Figure 5.18. Avg PDR; P=8

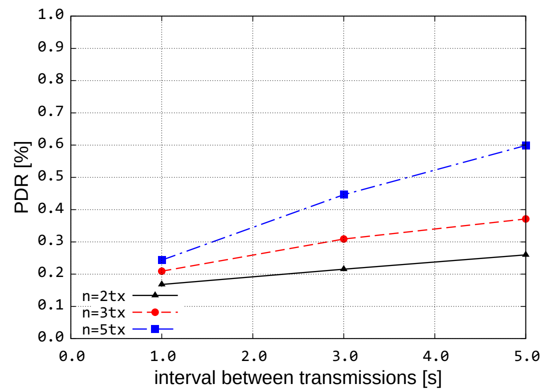

Figure 5.19. Avg PDR; P=12

between transmissions and number of transmissions increase.

The trends established in the second set of figures once again show a similar maximum in *actual* delay and show the exponential increase when both the interval between transmissions are increased and network density decreased. These characteristics are seen in Figures 5.23, 5.24, 5.25, 5.26.

5.3 Analysis of Transmission Quantity

The last part of the analysis examines the effect transmission quantity (the number of transmissions n) has when varying the other two dynamic variables.

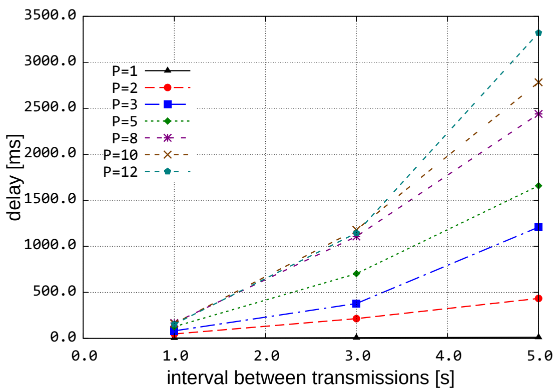

Figure 5.20. Avg E2E Delay; n=2 tx

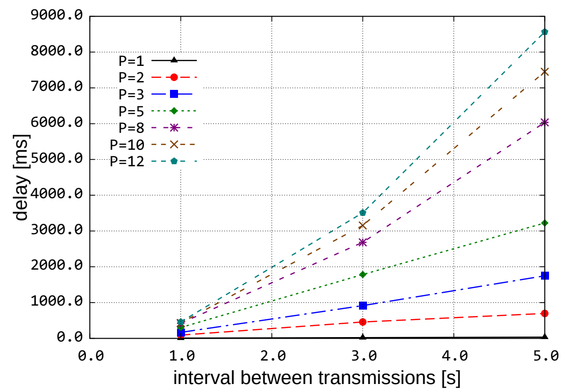

Figure 5.21. Avg E2E Delay; n=3 tx

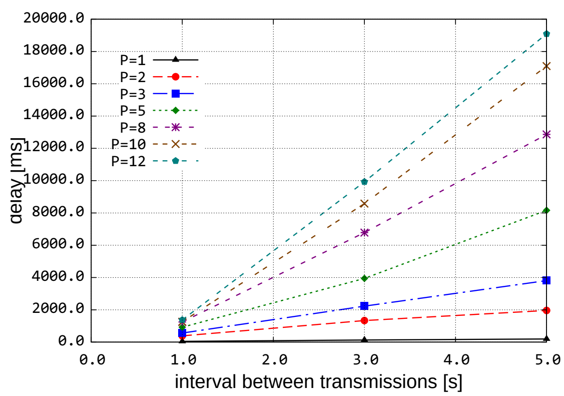

Figure 5.22. Avg E2E Delay; n=5 tx

In these sets of figures, the number of transmissions is displayed on the x-axis. Two sets of figures are displayed: one set showing how network density affects the characteristics of transmission quantity n and the other showing how interval between transmissions Δt affects transmission quantity. This is done for both PDR and delay.

5.3.1 Effect of Transmission Repeats on PDR

In Figures 5.27, 5.28, 5.29 the number of transmissions affects the PDR in one of two ways depending on what level of network density is examined. When

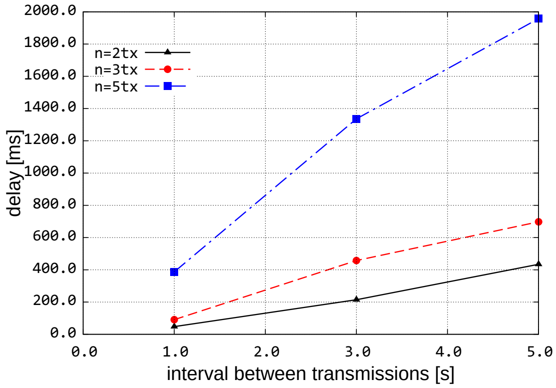

Figure 5.23. Avg E2E Delay; P=2

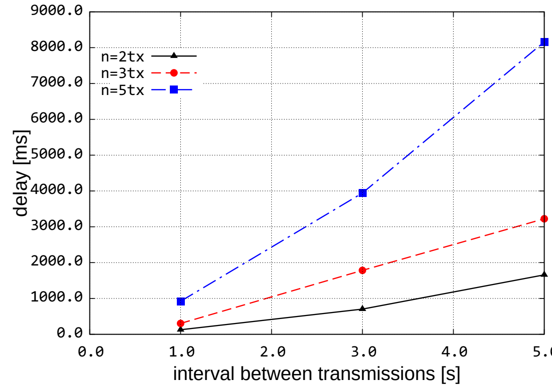

Figure 5.24. Avg E2E Delay; P=5

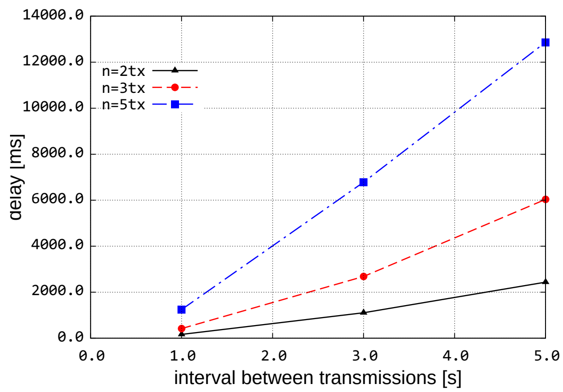

Figure 5.25. Avg E2E Delay; P=8

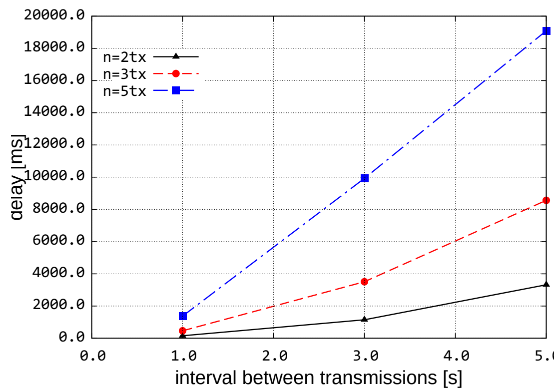

Figure 5.26. Avg E2E Delay; P=12

the network is relatively dense (P $<$ 5), the increase in transmissions brings the PDR down. Again, this is due to the congestion and collisions. However, as the network becomes less dense ($P \geq 5$), the increase in repeated transmissions actually increases the PDR. This is seen across all three figures for all three values of Δt. Also seen across all three figures is how the increase in Δt helps mitigate the congestion and collisions in more dense networks. This can be seen in how the plots converge at higher and higher levels of PDR as Δt is increased.

The plots do not show the control data (CF simulations), for when n=1 tx, because CF does not have a value for Δt and could not be plotted. The plots

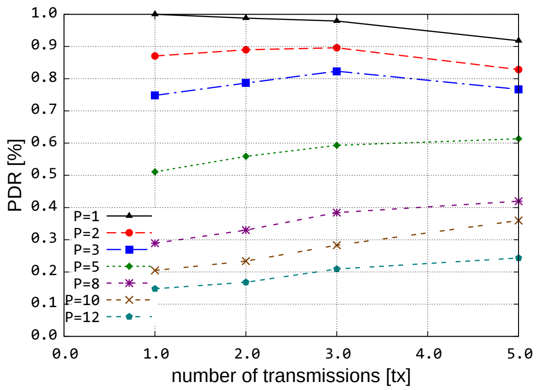

Figure 5.27. Avg PDR; Δt=1 s

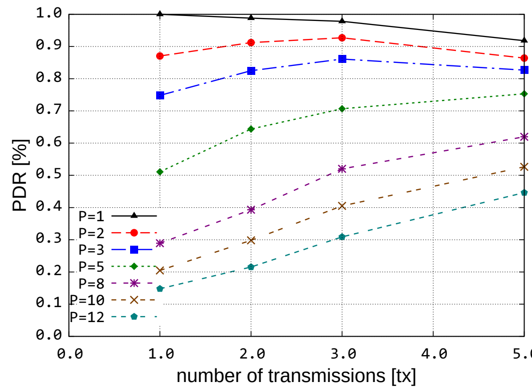

Figure 5.28. Avg PDR; Δt=3 s

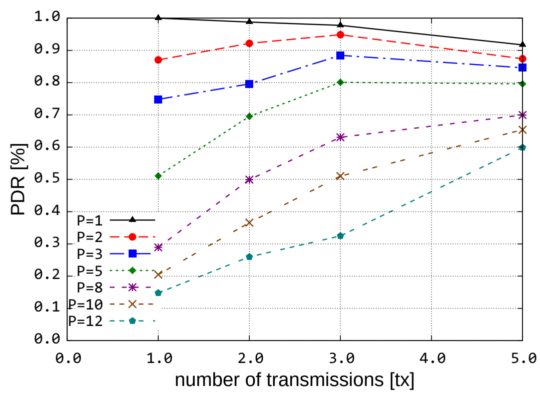

Figure 5.29. Avg PDR; Δt=5 s

once again show how PDR increases immediately after the first partition or $P \geq 2$. This can be seen in the positive slopes between n= 1 and n= 2 for all plots where $P \geq 2$.

The second set of PDR plots shows four plots (selected from a family of seven plots) that characterize PDR when partitions are kept static and interval between transmissions are evaluated. They are shown in Figures 5.30, 5.31, 5.32, 5.33. In this set of plots, the PDR is increasingly affected as the networks become more and more partitioned – there is more of a disparity in the results of changing the interval between transmissions as the networks become less dense. Most notably,

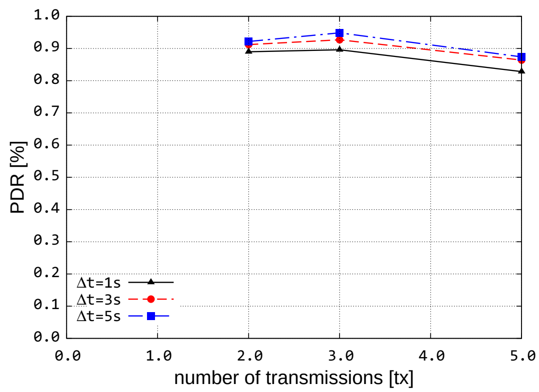

Figure 5.30. Avg PDR; P=2

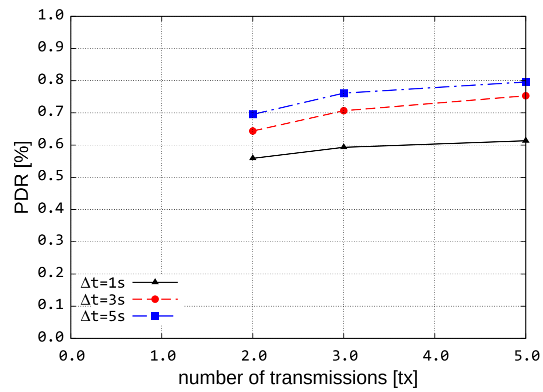

Figure 5.31. Avg PDR; P=5

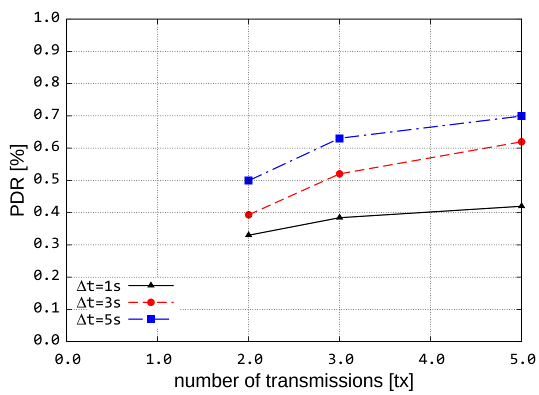

Figure 5.32. Avg PDR; P=8

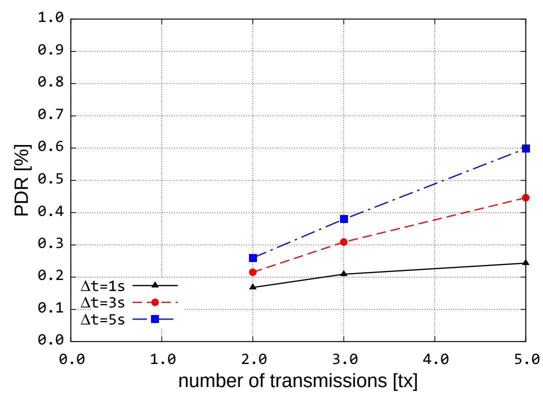

Figure 5.33. Avg PDR; P=12

this can be seen when comparing Figure 5.30 to Figures 5.32 and 5.33. In this comparison, it can be seen how the PDR values are very close to one another when the network is more dense (Figure 5.30) and there is more of an effect on PDR, when varying the interval between transmissions, in less dense networks (Figures 5.32 and 5.33).

5.3.2 Effect of Transmission Repeats on Delay

The figures showing the effect network density has on delay, when examining the number of transmissions, stay consistent with previous observations. In Fig-

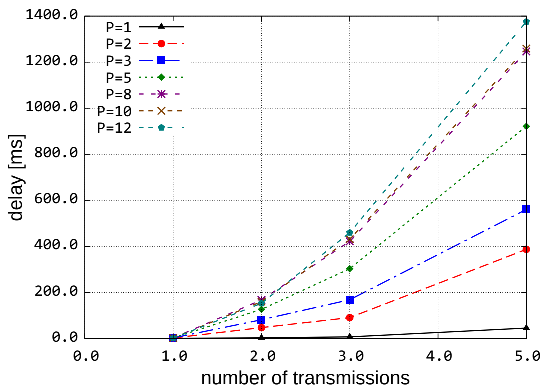

Figure 5.34. Avg E2E Delay; Δt=1 s

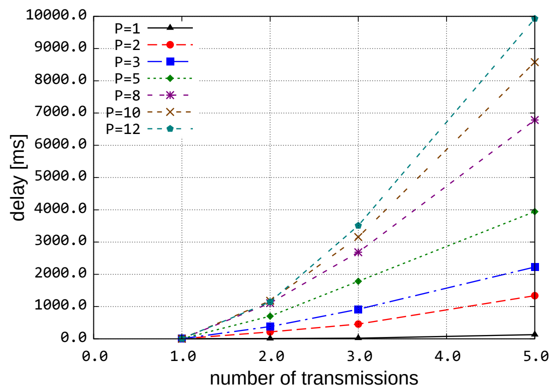

Figure 5.35. Avg E2E Delay; Δt=3 s

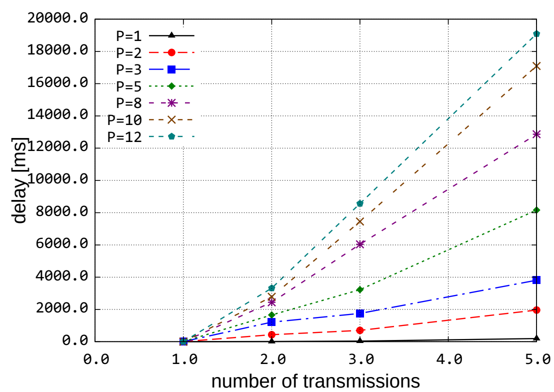

Figure 5.36. Avg E2E Delay; Δt=5 s

ures 5.34, 5.35, 5.36 increases in delay are relative to network density. The *actual* maximum delay observed is consistent with previous delay figures (as seen in Section 5.2.2). Figures 5.10, 5.11, 5.12 show delay ceilings of 1400 ms, 10,000 ms, and 20,000 ms, respectively. CF data can also be seen where n= 1 tx. However the delay for all the CF simulations was less than 2.5 ms, due to the fact that if the transmission did not immediately reach its destination it was dropped rather than repeated.

Another noteworthy observation from this set of figure, is the plots have more of a curve when the intervals between transmissions are lower. They increase

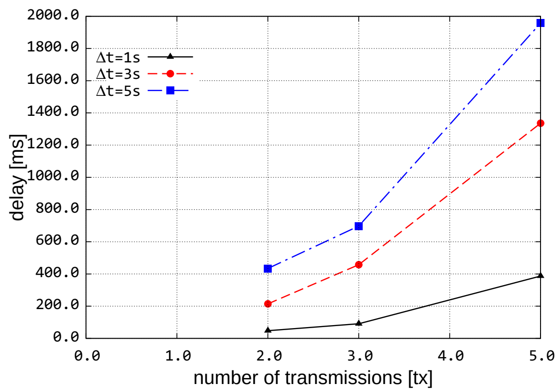

Figure 5.37. Avg E2E Delay; P=2

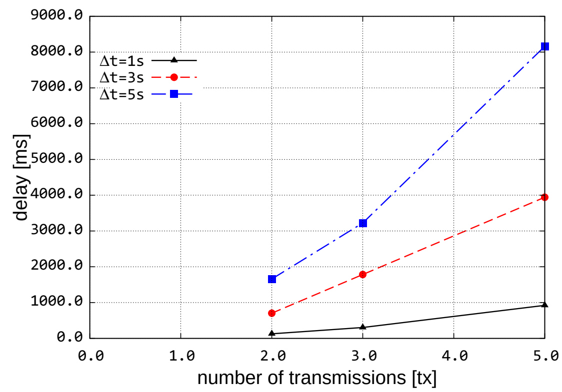

Figure 5.38. Avg E2E Delay; P=5

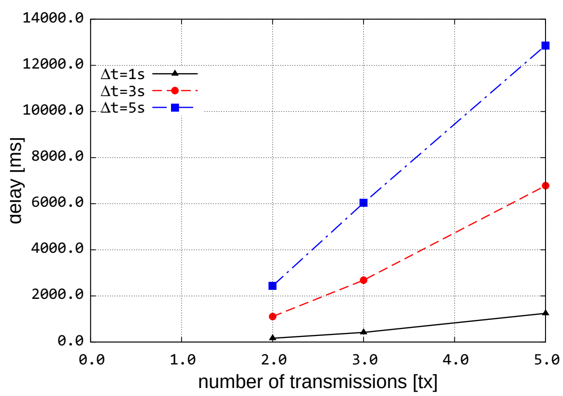

Figure 5.39. Avg E2E Delay; P=8

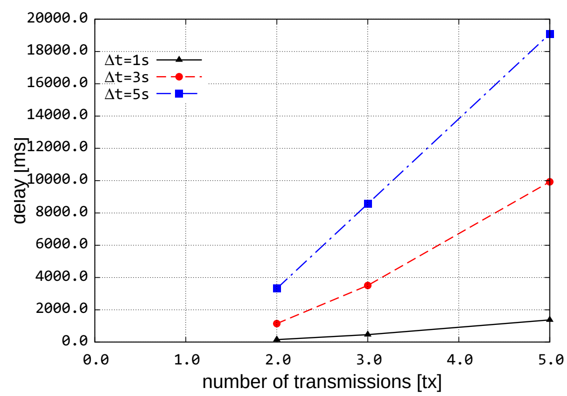

Figure 5.40. Avg E2E Delay; P=12

more sharply as the intervals between transmissions increase. This shows the aforementioned exponential increase in delay as the interval between transmissions and number of transmissions increase.

The effects of delay on the number of transmission when varying the interval between transmission show similar trends. Figures 5.37, 5.38, 5.39, 5.40 show curves similar to those seen in Figures 5.34, 5.35, 5.36. The plots are more like curves in denser networks and begin to become more linear as the networks become less dense. The rate at which delay is incurred increases exponentially as the network becomes more and more partitioned, when increasing the number of transmissions within the S&H+RCF protocol.

Chapter 6

Conclusions and Future Work

This thesis provides a working model for the newly conceived S&H+RCF (store-and-haul with repeated controlled flooding), routing for sparsely-connected mobile wireless networks. The background research suggests it is a unique and new approach to communications within a MANET. S&H+RCF exemplifies a functional, practical, and simplified way to communicate within MANETs, as shown through rigorous analysis. The analysis of S&H+RCF provides many things to consider and includes observations about the protocol's characteristics and trade-offs. The first section of Chapter 6 draws conclusions and insight from this analysis. The last section of Chapter 6 presents ideas for the next steps in the research process.

6.1 Conclusions

S&H+RCF is very simple in design and yields noteworthy results. It displays significant increases in PDR (packet delivery ratio) for MANETs (mobile ad hoc networks) that are not strongly connected. With S&H+RCF, the more partitioned the network is, the greater the increase in PDR from repeated transmissions and increased intervals between partitions. As the quantity of transmissions and interval between transmissions is increased, there is a direct, positive relationship between network density and PDR.

$$\text{PDR} \propto P \text{ when} \uparrow \Delta t \text{ or} \uparrow n$$

The more substantial increases in PDR are seen when the average number of partitions is greater than five. As the network increases in partitions (decreases in network density) S&H+RCF becomes more effective – until the network is so partitioned that $P \geq n$ and PDR is reduced to zero. Additionally, the increase in PDR eventually plateaus. This can be seen when $\Delta t \geq 10$ s in Figure 5.6.

Contiguous and less partitioned networks did not see an increase in PDR. In fact, there was slight degradation in PDR when transmissions were increased due to the contention of packets – especially when the interval between transmissions is small. Another consideration in S&H+RCF is the delay incurred when repeating multiple times and waiting before repeats. This delay can be significant and increases exponentially when intervals are increased or as more transmission attempts are needed. This could render S&H+RCF useless for real-time applications. Nevertheless, this outcome is offset by realizing that the packets would have never reached their destination without the repetition. This "better late than never" strategy classifies S&H+RCF as a DTN routing protocol.

A final but unexplored drawback is the energy consumption that is sure to come from the repeated transmissions. While more memory efficient than routing protocols like epidemic [4], S&H+RCF consumes more energy. The additional energy consumed can be calculated with the following:

$$E_{\text{S\&H+RCF}} = E_{\text{Epidemic}} \times n$$

where $E_{\text{S\&H+RCF}}$ is the energy consumed by the S&H+RCF protocol and E_{Epidemic} is the energy consumed by an Epidemic protocol. This is discussed more in Section 6.2.

In summary, the thesis contributes a new communication paradigm by combining two simple MANET concepts: S&H and RCF. The work develops a new model in ns-2 that simulates the effects this paradigm would have in typical MANETs. Finally, it performs an analysis on the new paradigm and weighs the empirical drawbacks.

6.2 Future Work

There is still much to explore with the S&H+RCF protocol. The most immediate and obvious research would start by running more simulations and testing new, possibly more extreme, values for the dynamic variables: n, P, and Δt, taking the simulations in this thesis to a more detailed and varied level. This would also include finding where the plateaus or extremes for n are located; just as was done with Δt. These simulations could even stagger the repeats and intervals making them progressively longer (1s, 3s, 5s, 10s). There could also be research done into the adjusting of dynamic variables in real time by intelligent "partition aware" networks that could adjust to the dynamic variable to achieve desired levels of PDR. In addition to the extra data, guidelines for network engineers could be formally established. These would dictate what parameter values should be used for a given scenario.

Another worthwhile direction would be directly comparing the S&H+RCF protocol to Epidemic routing by simulation. This would test how each performed in certain scenarios and should note where one outperforms the other and why. This direct comparison would require an analysis of S&H+RCF's energy consumption – as Epidemic transmits much less frequently than S&H+RCF making it more energy efficient. Energy consumption would undoubtedly be part of the considerations and tradeoffs between S&H+RCF and Epidemic routing.

Security concerns are also in need of attention – not only securing transmissions between nodes, but preventing denial of service attacks. It would also be nice to find gain factors to help make educated decisions when engineering networks with S&H+RCF. Finally, it would be extremely worthwhile to build physical or actual MANETs that employ the S&H+RCF routing protocol. These physical models would greatly add to the accuracy and validity of the data discovered in the simulated scenarios.

Appendix A

Appendix – Plots

This appendix contains a full set of the plots generated for the analysis of S&H+RCF.

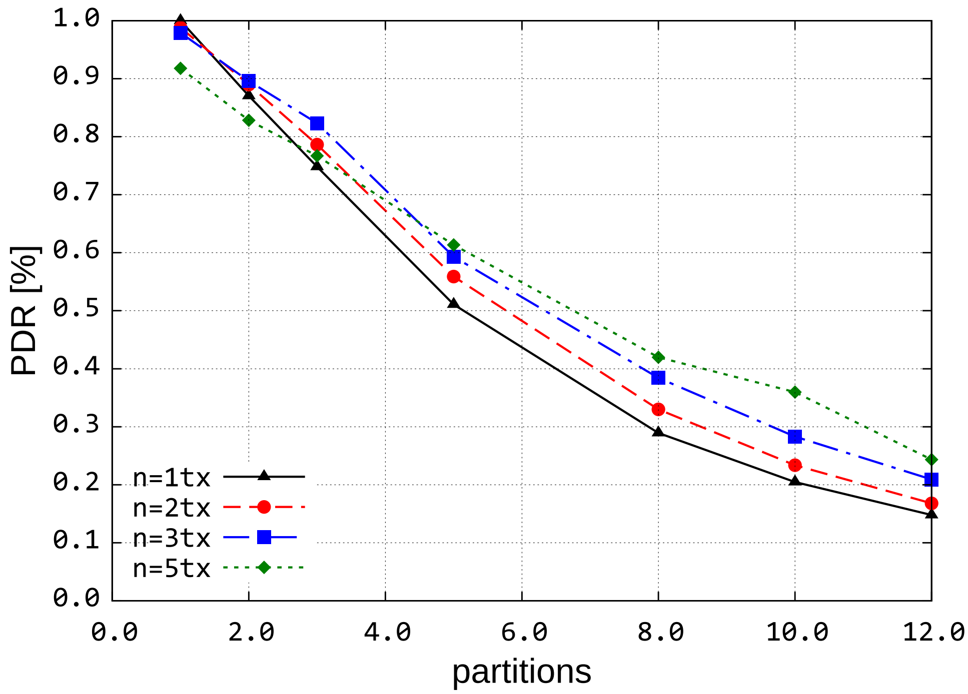

Figure A.1. PDR; Δt =1 s

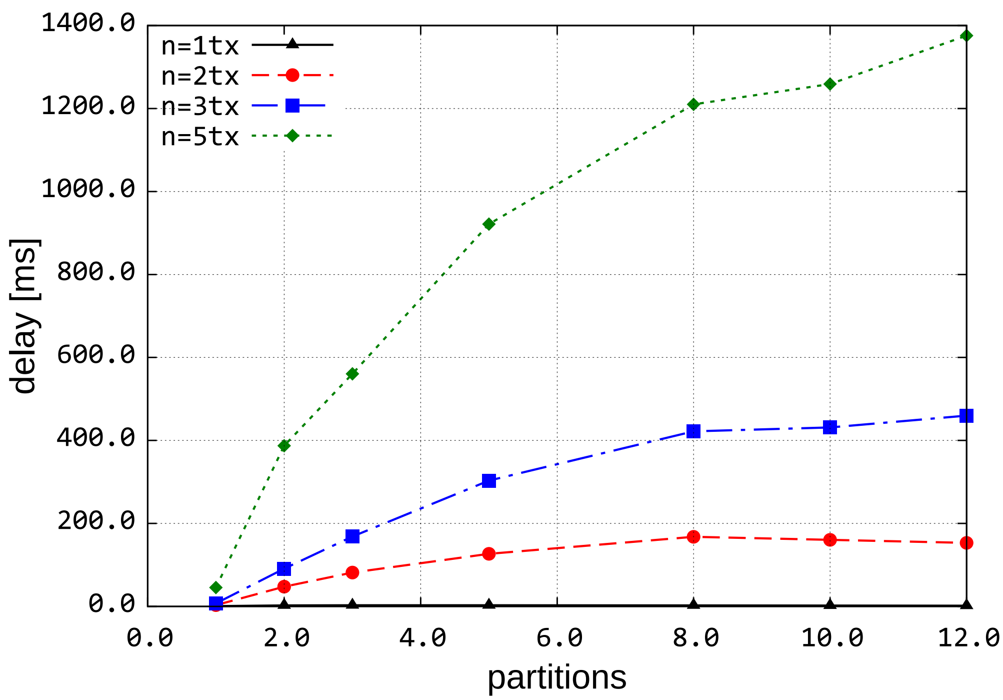

Figure A.2. Delay; Δt =1 s

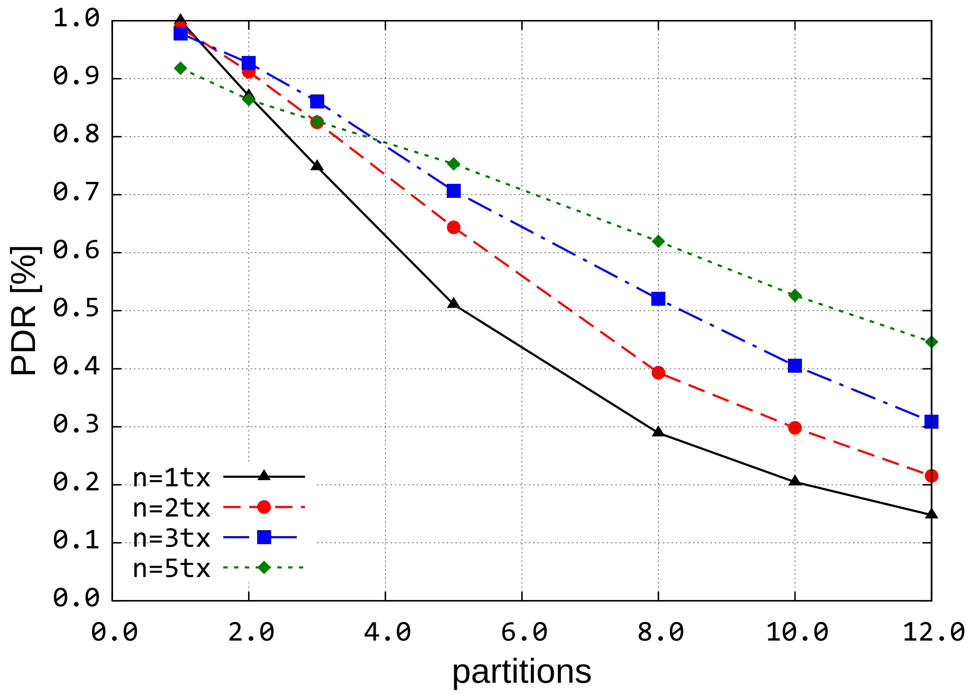

Figure A.3. PDR; Δt =3 s

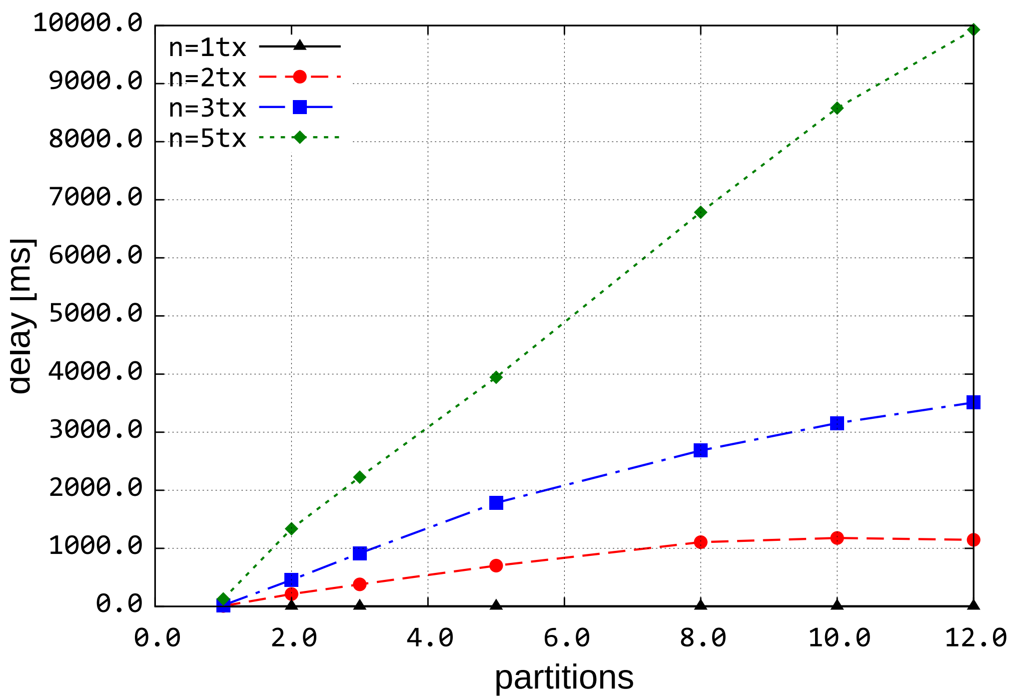

Figure A.4. Delay; Δt =3 s

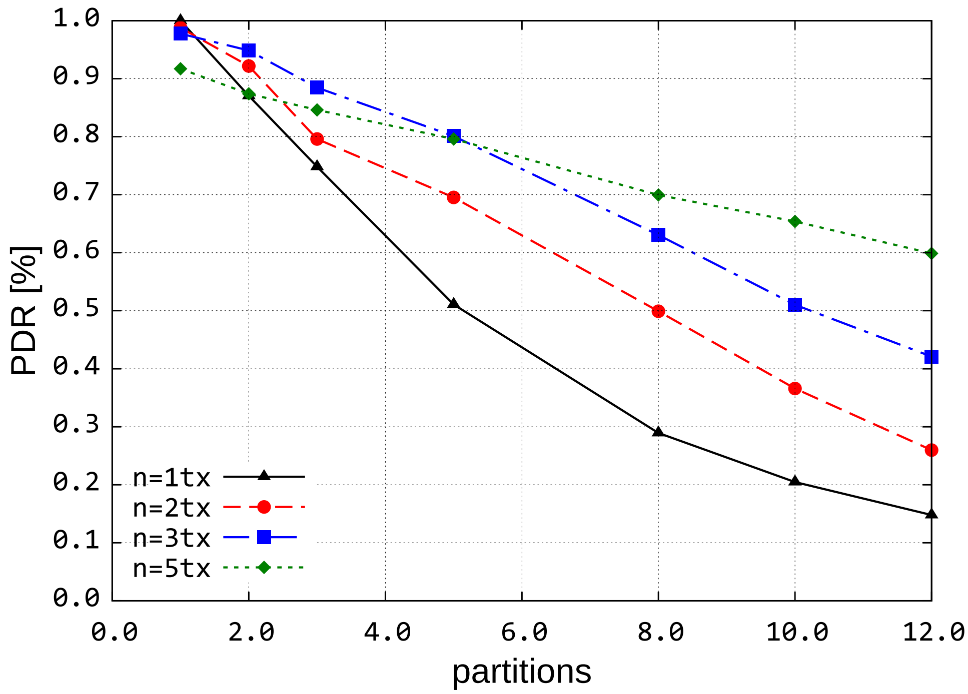

Figure A.5. PDR; Δt =5 s

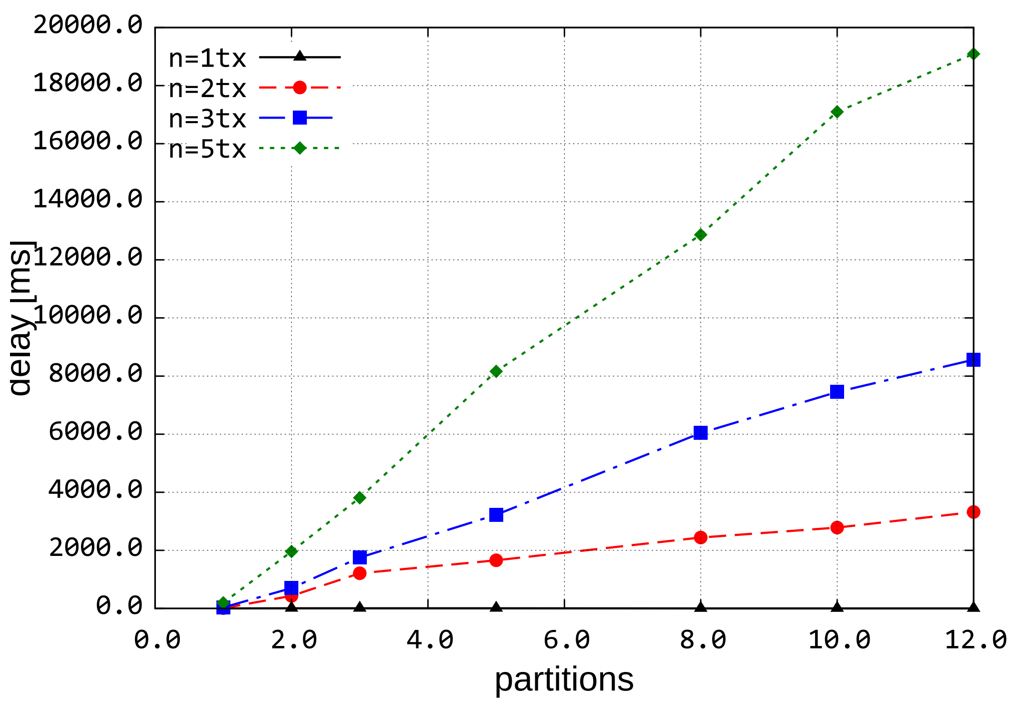

Figure A.6. Delay; Δt =5 s

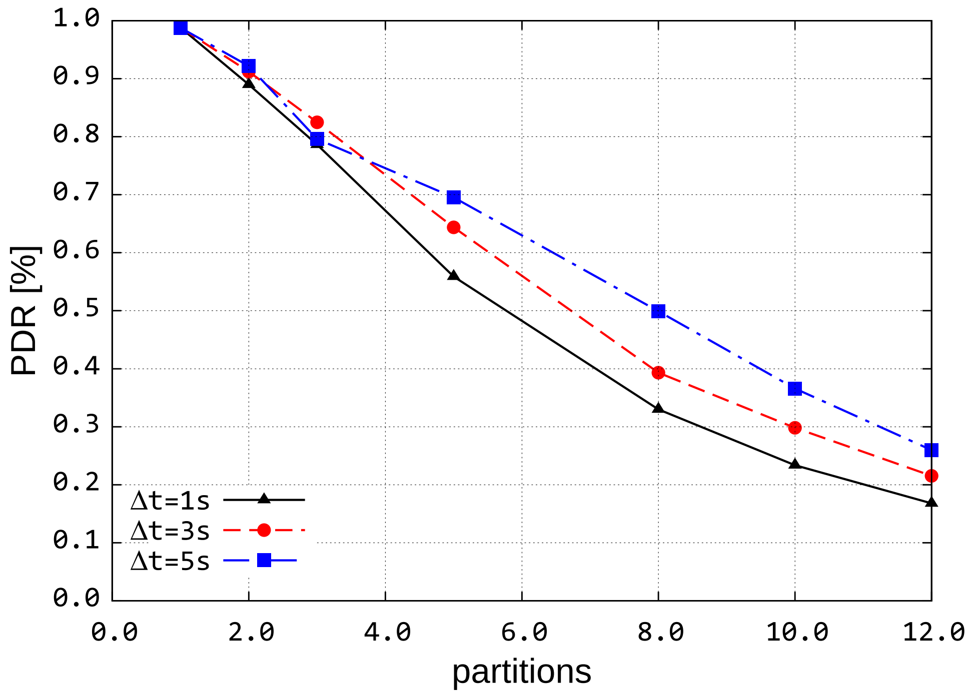

Figure A.7. PDR; n=2 tx

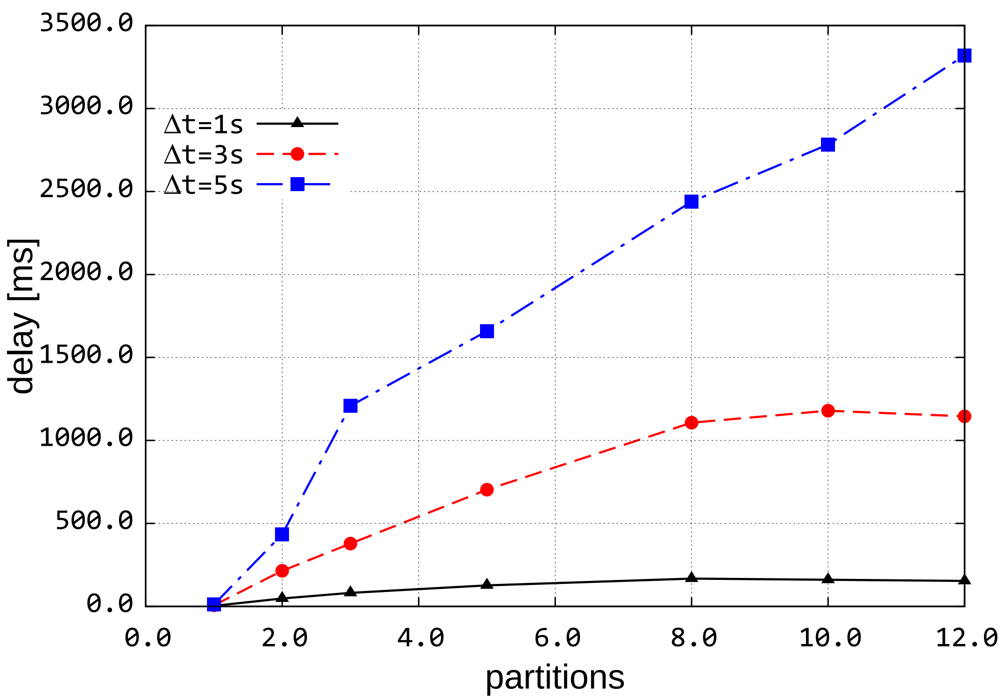

Figure A.8. Delay; n=2 tx

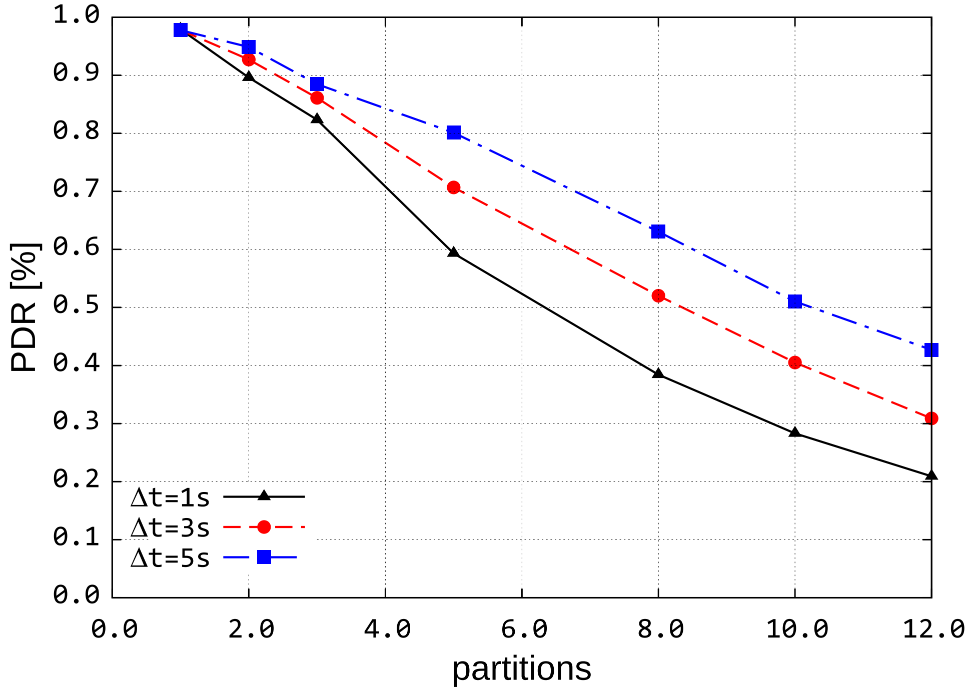

Figure A.9. PDR; n=3 tx

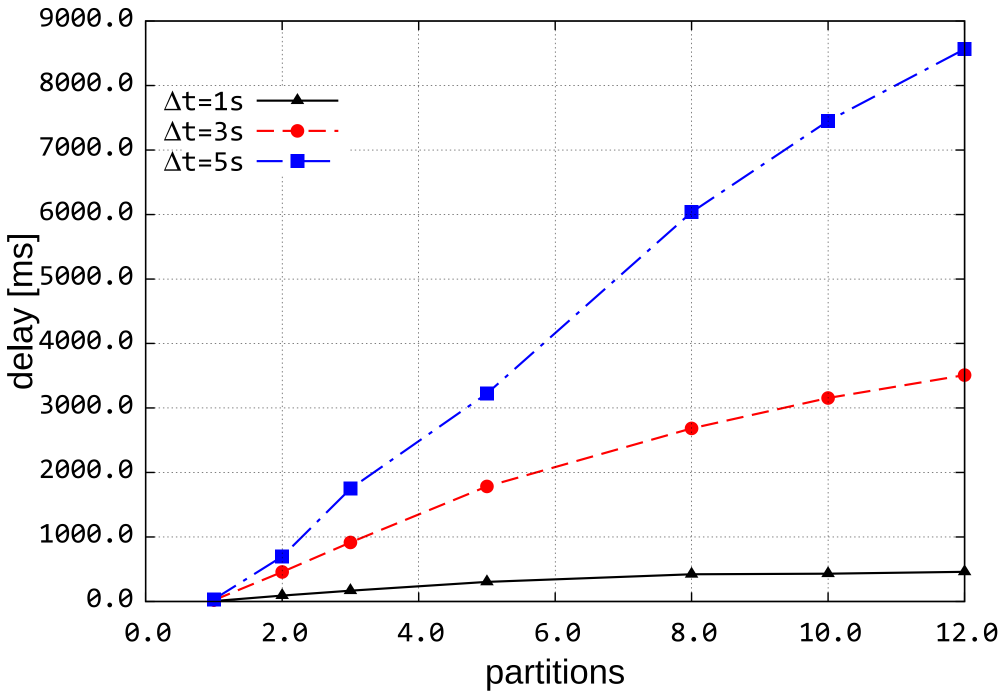

Figure A.10. Delay; n=3 tx

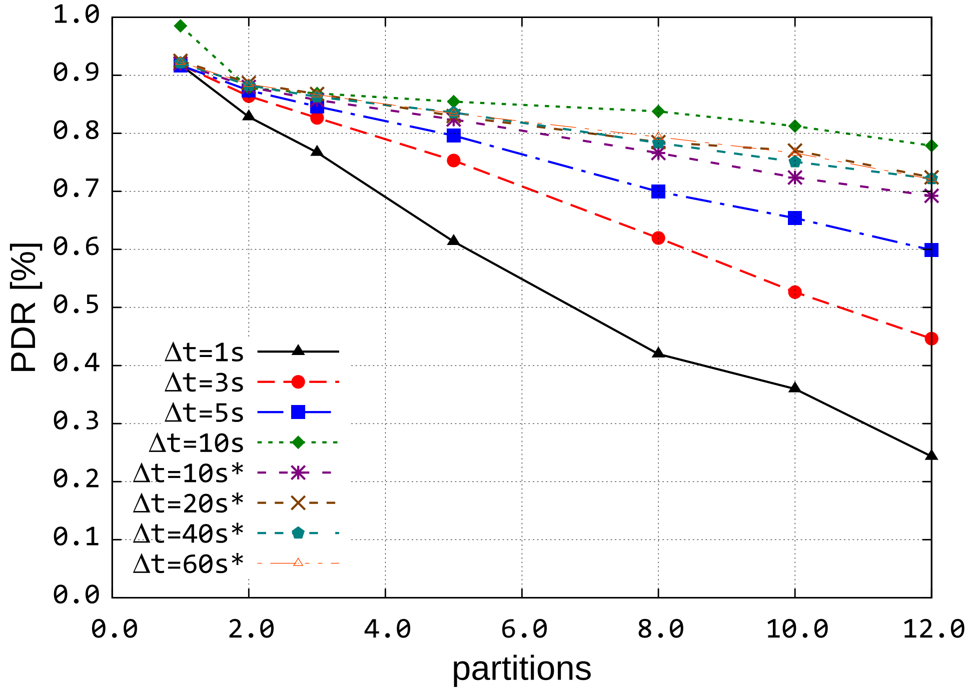

Figure A.11. PDR; n=5 tx

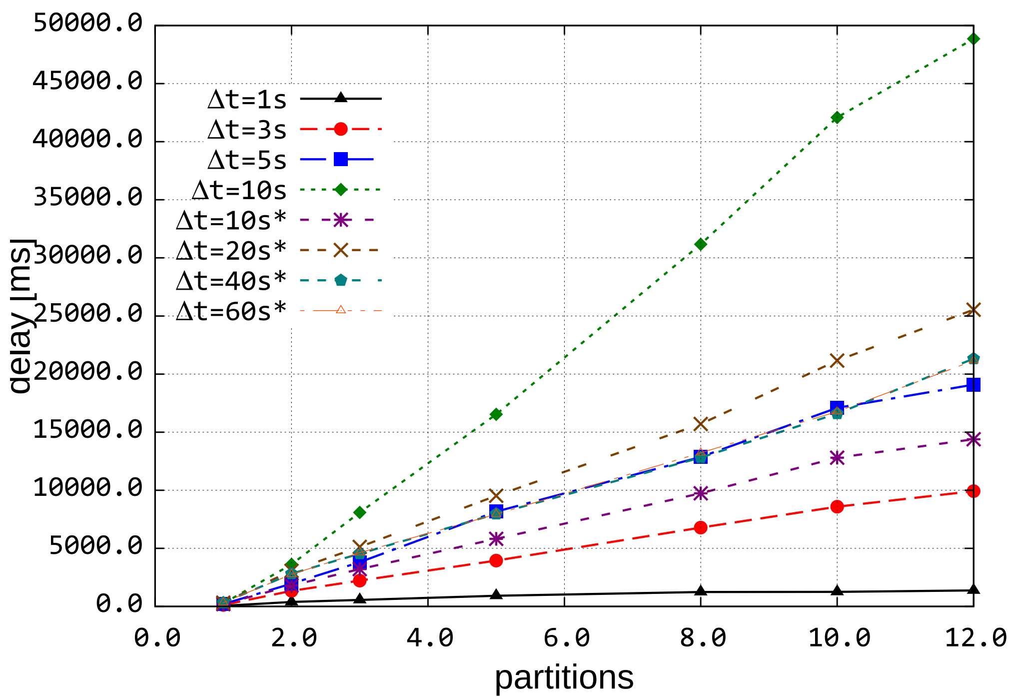

Figure A.12. Delay; n=5 tx

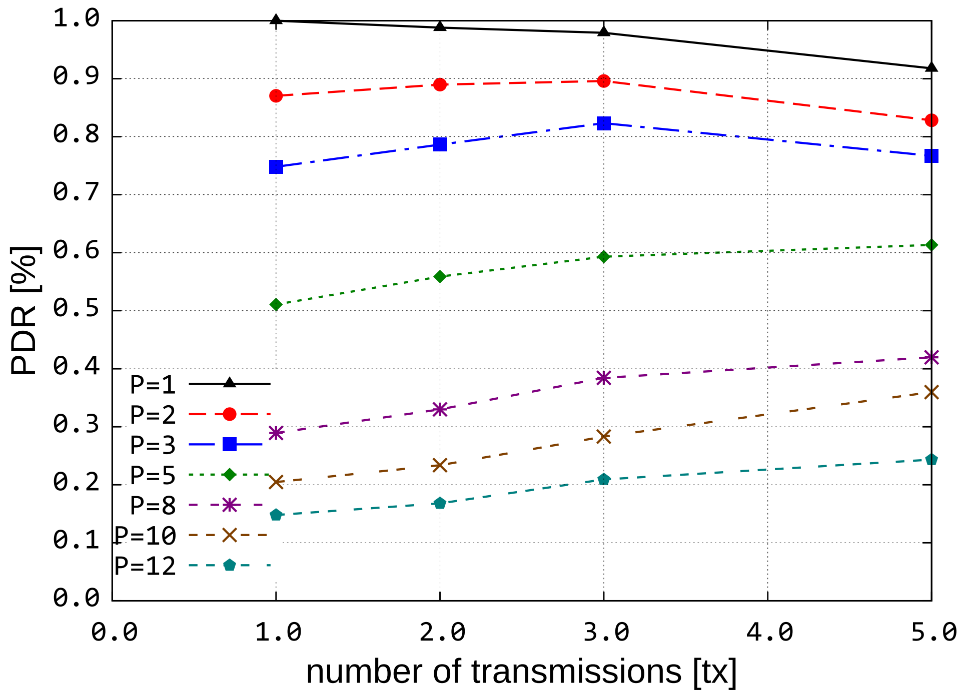

Figure A.13. PDR; Δt =1 s

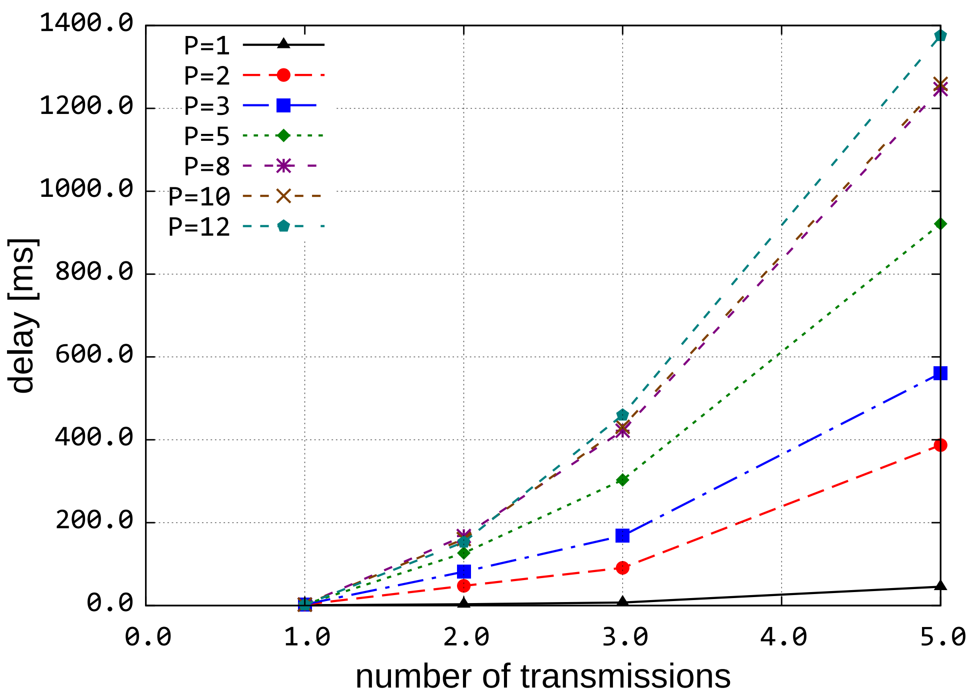

Figure A.14. Delay; Δt =1 s

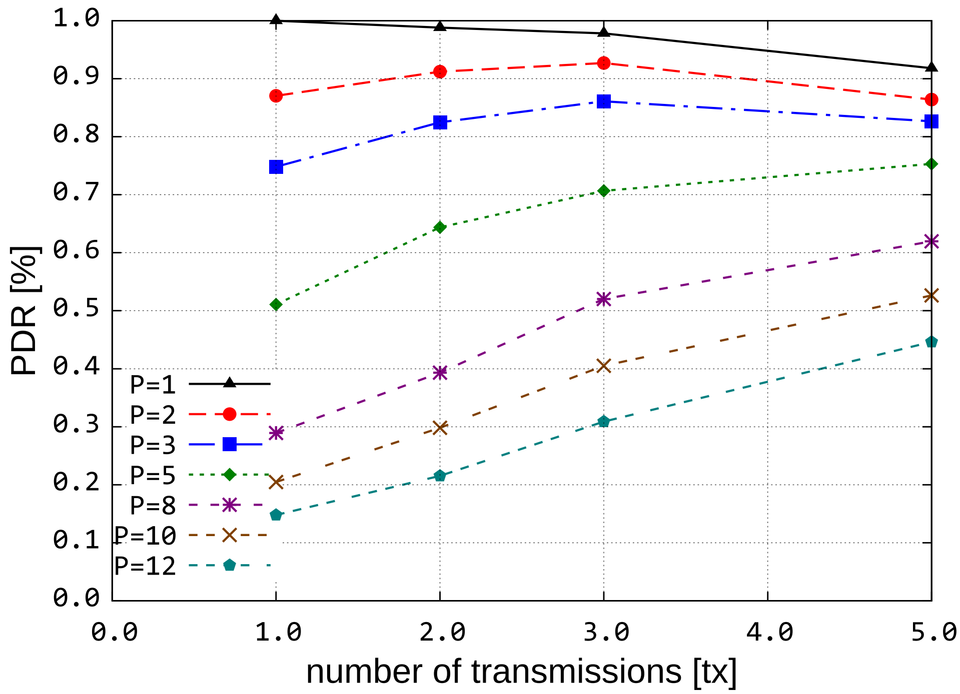

Figure A.15. PDR; Δt =3 s

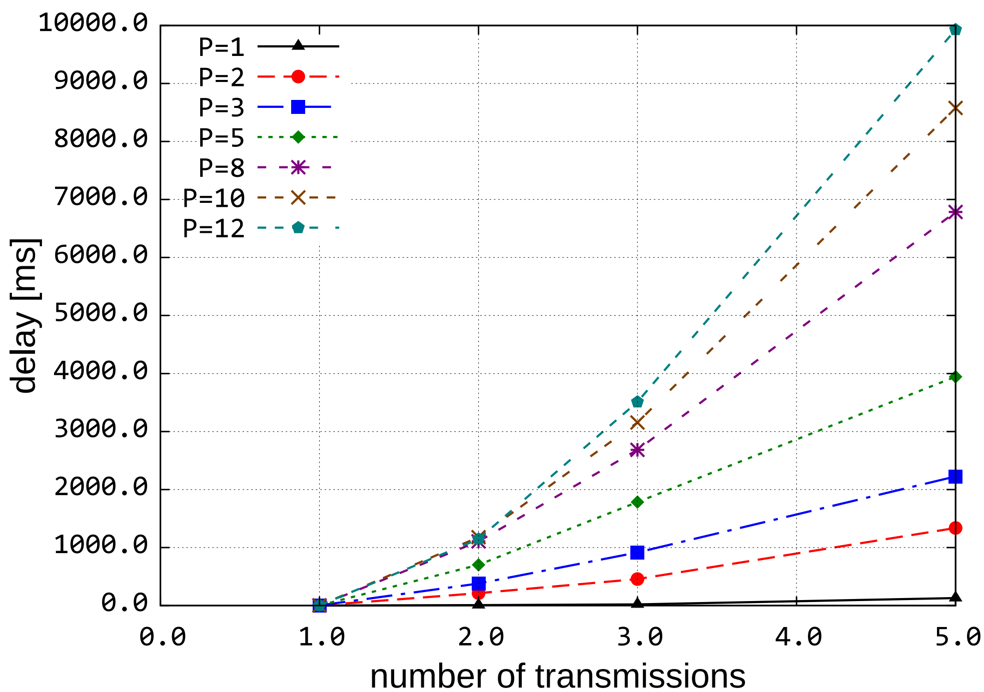

Figure A.16. Delay; Δt =3 s

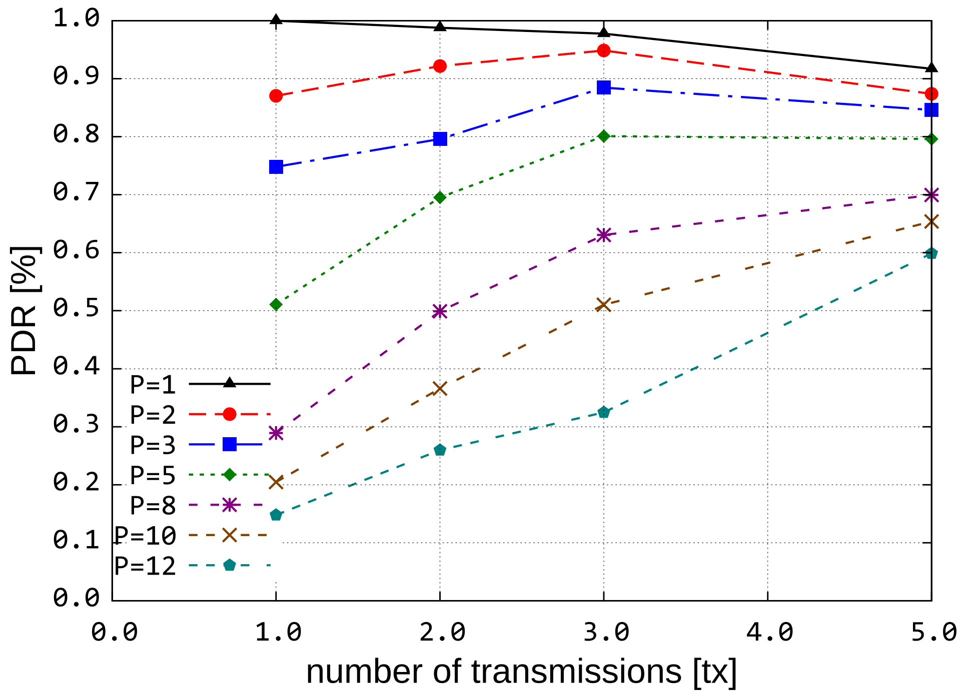

Figure A.17. PDR; Δt =5 s

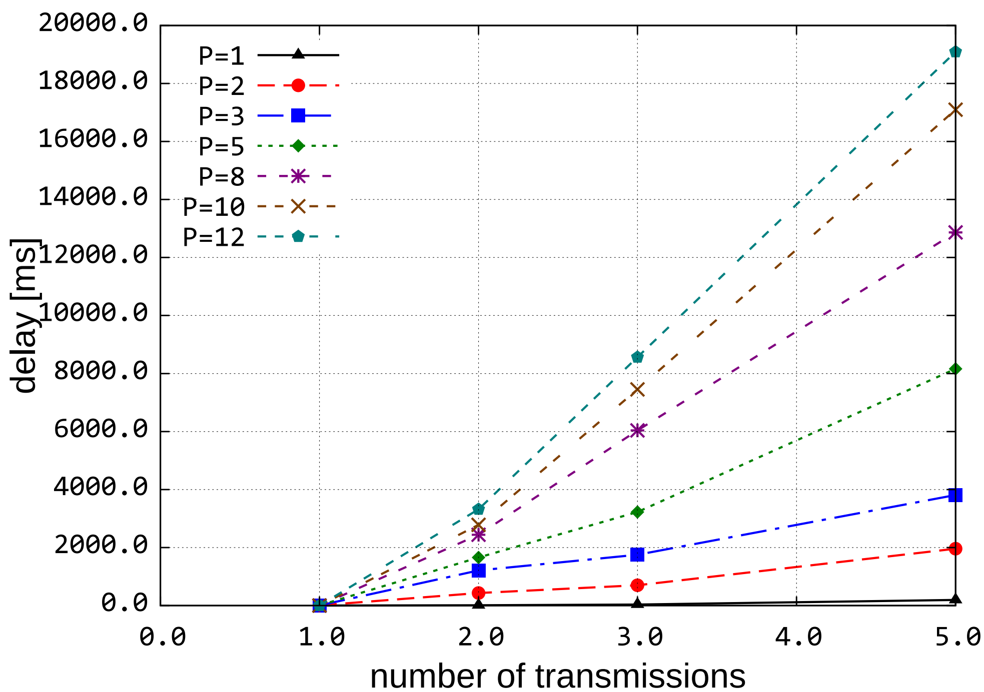

Figure A.18. Delay; Δt =5 s

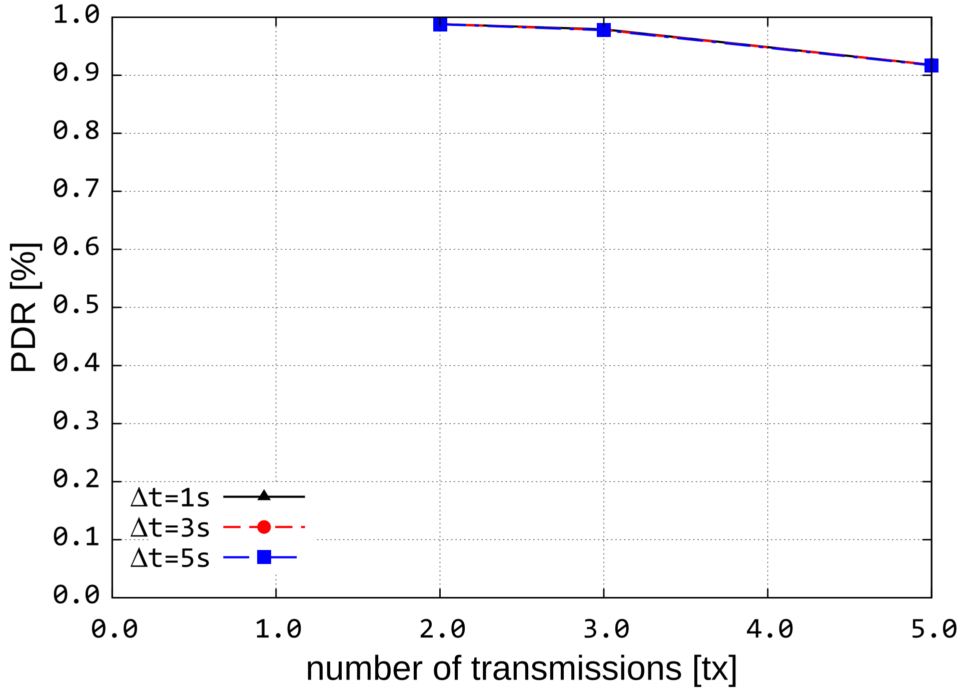

Figure A.19. PDR; P=1

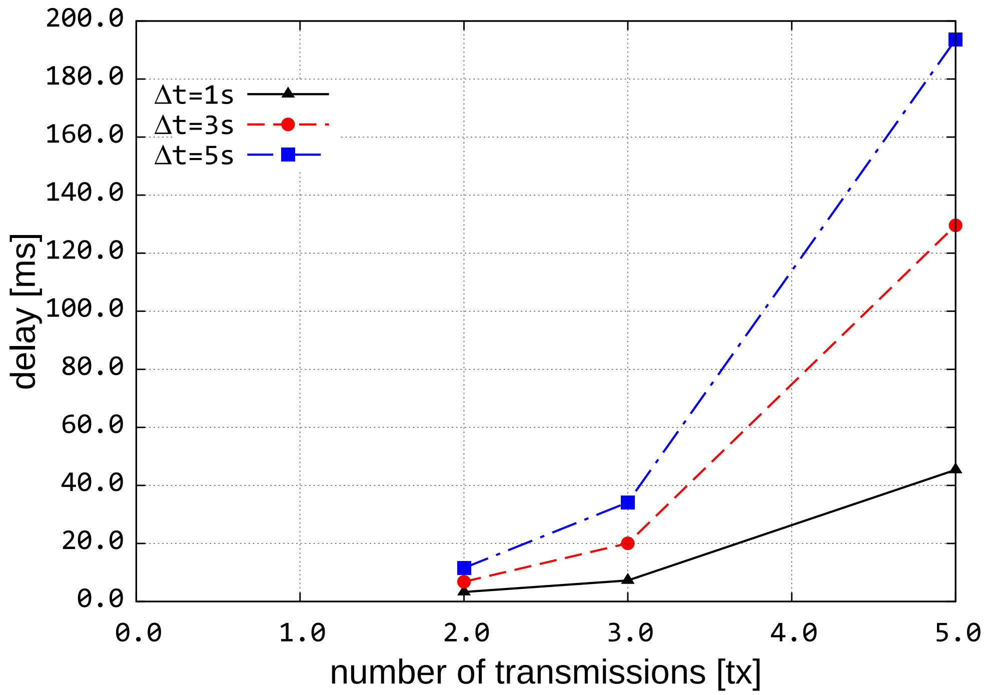

Figure A.20. Delay; P=1

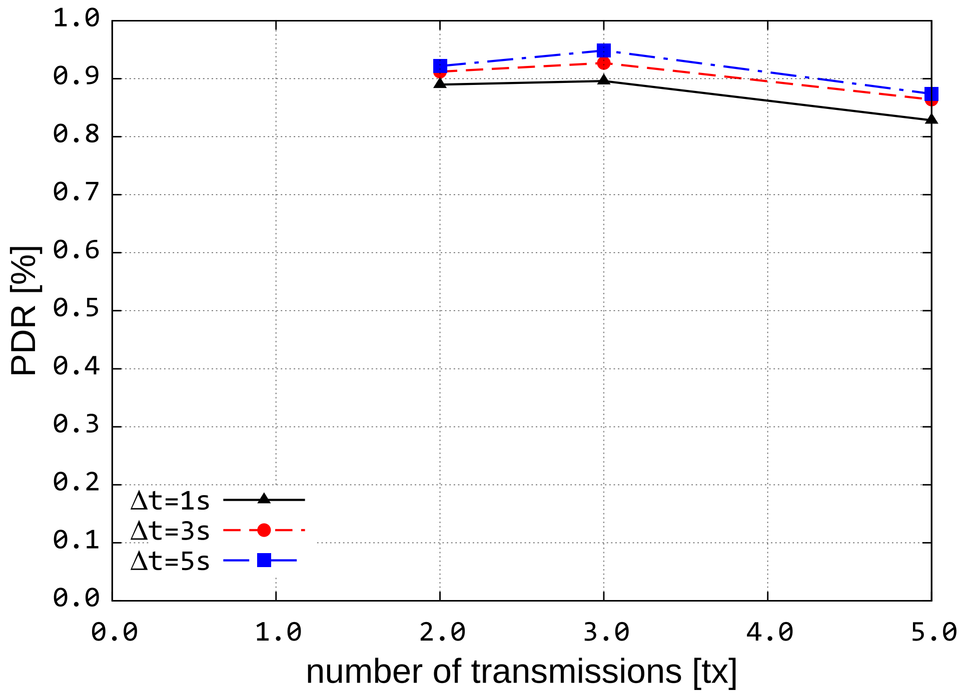

Figure A.21. PDR; P=2

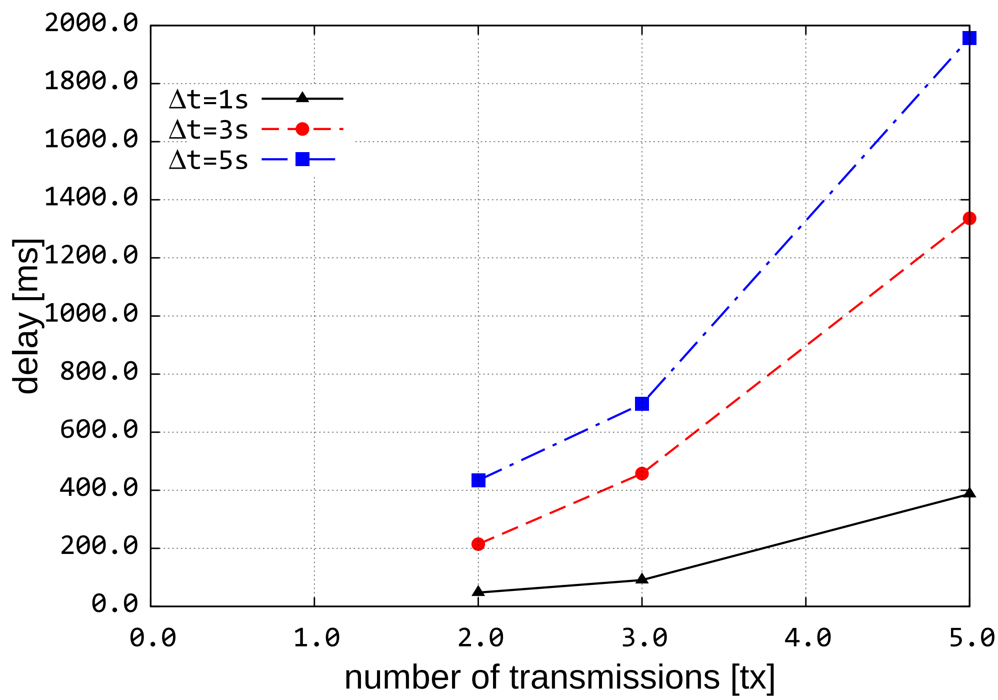

Figure A.22. Delay; P=2

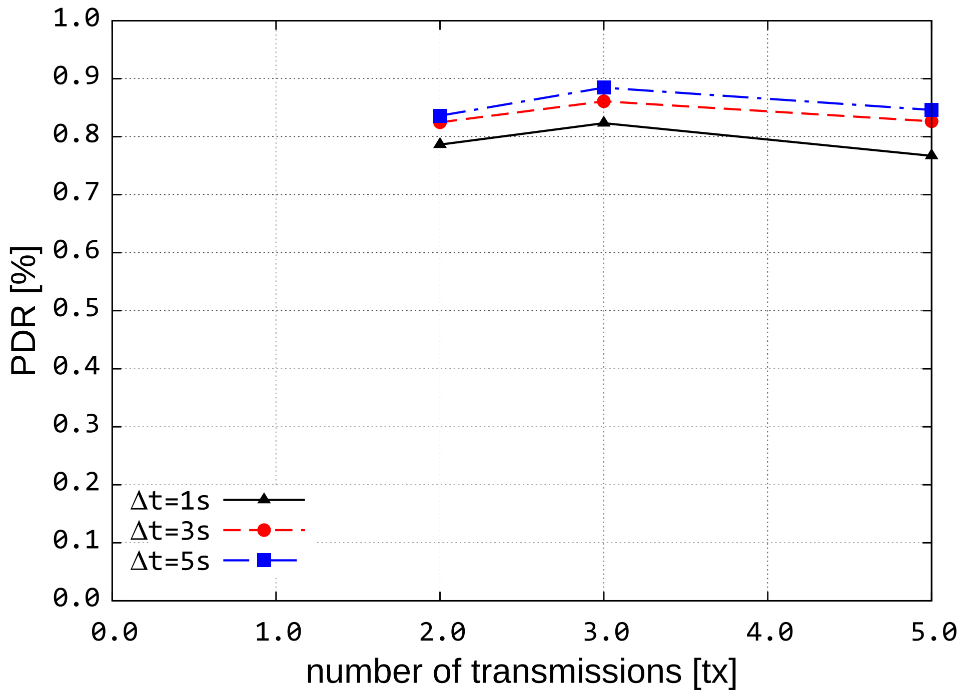

Figure A.23. PDR; P=3

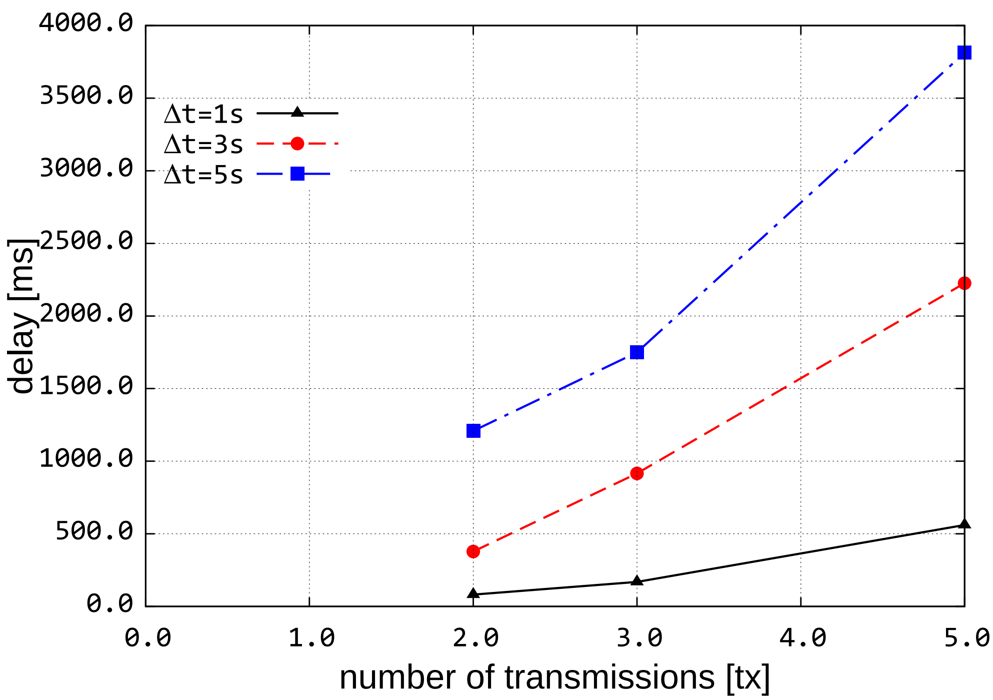

Figure A.24. Delay; P=3

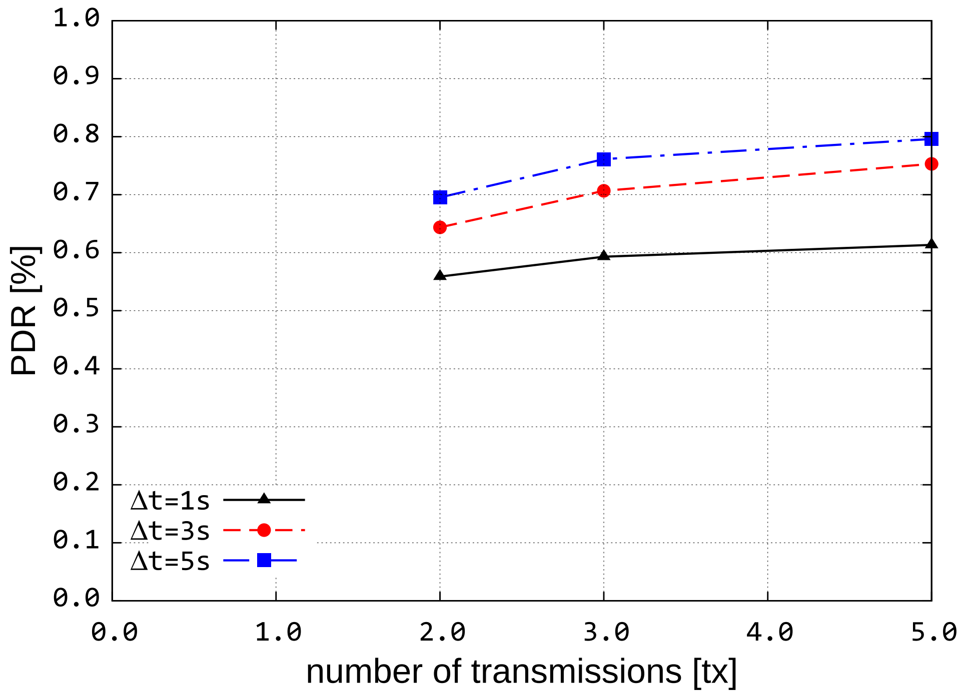

Figure A.25. PDR; P=5

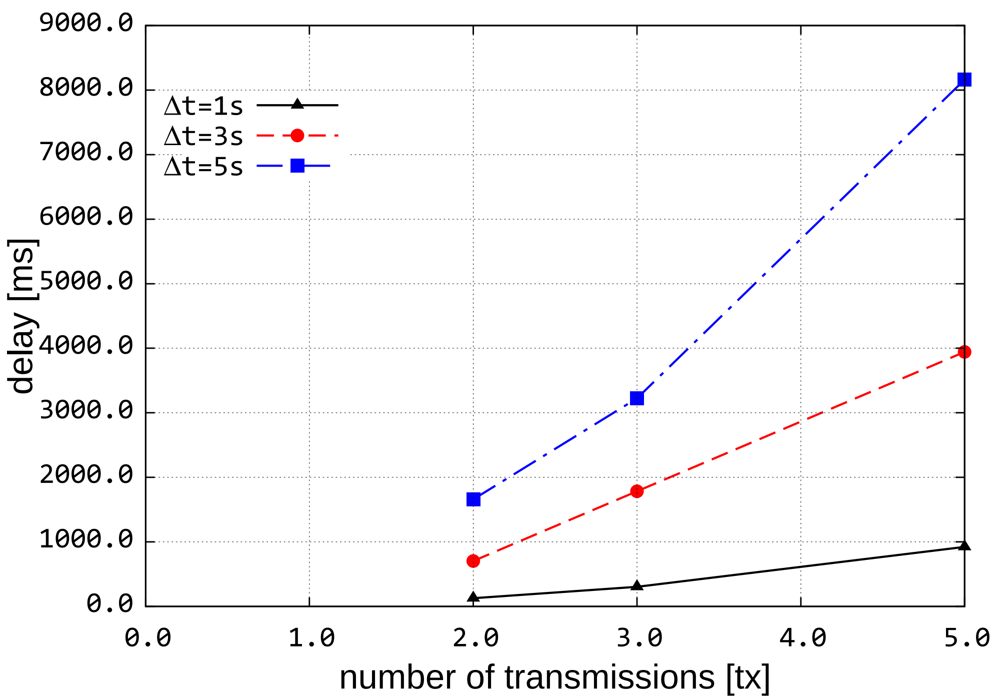

Figure A.26. Delay; P=5

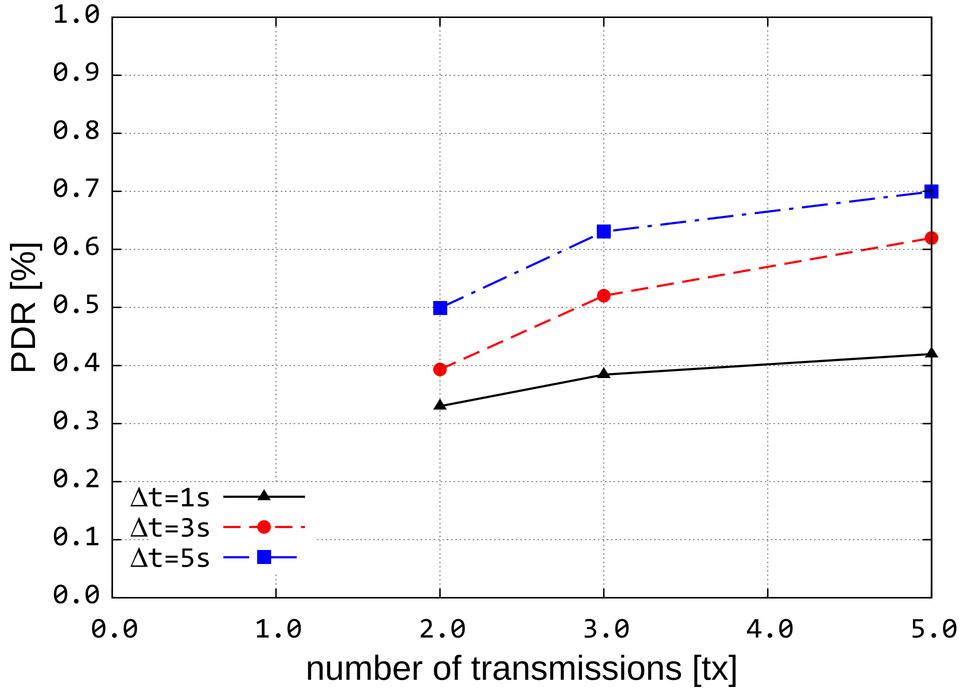

Figure A.27. PDR; P=8

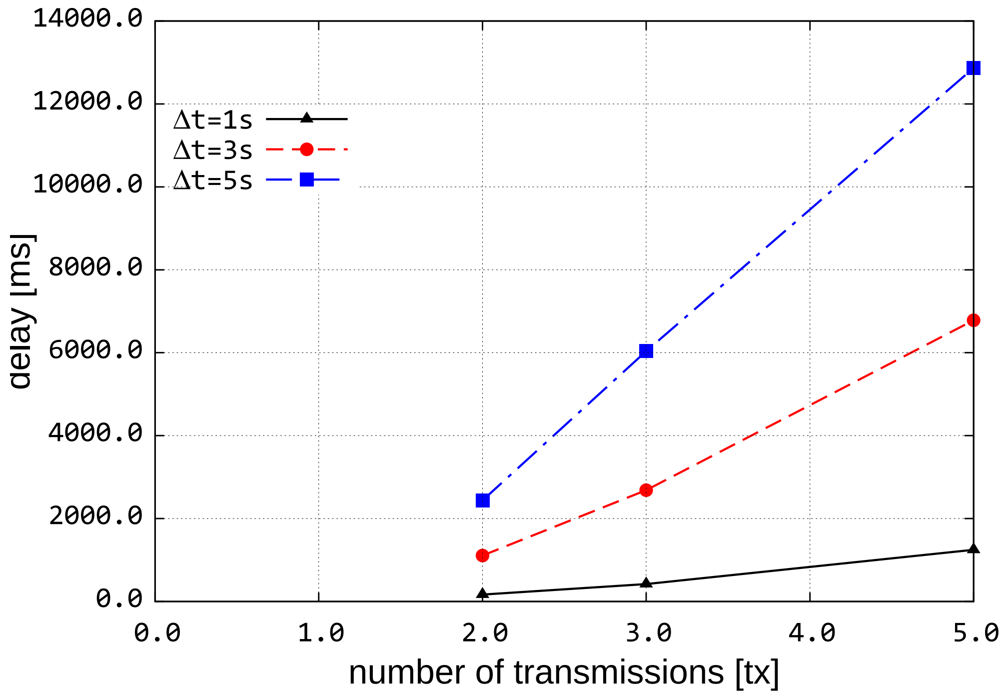

Figure A.28. Delay; P=8

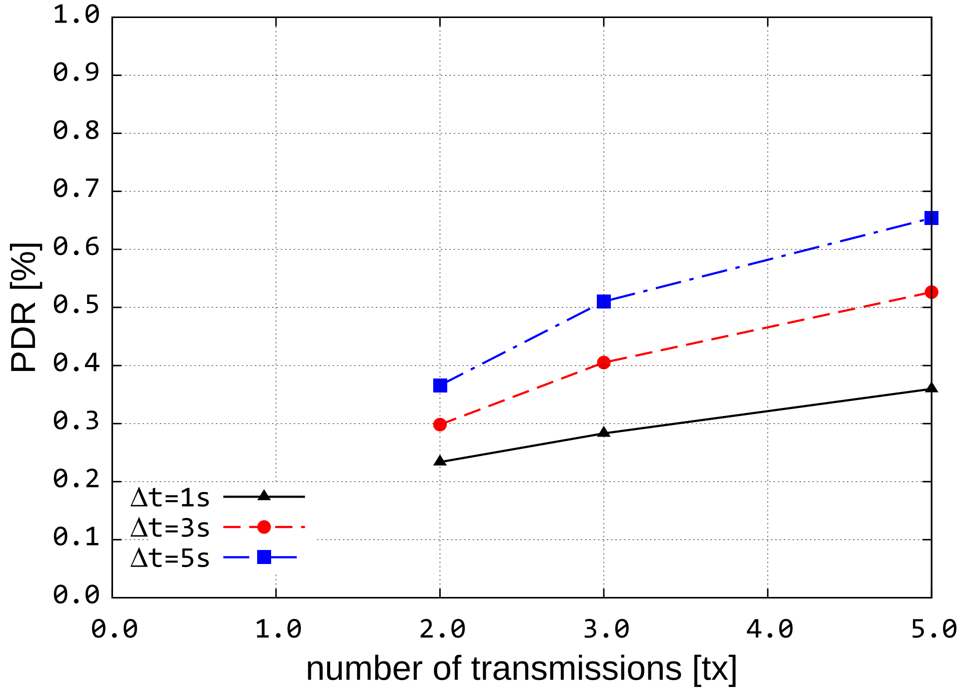

Figure A.29. PDR; P=10

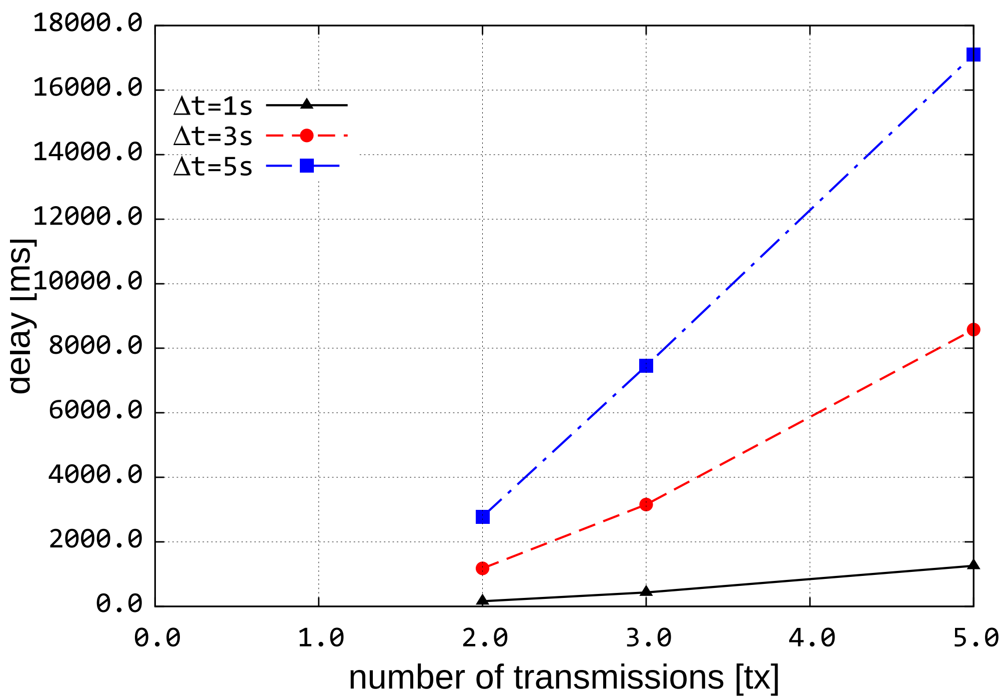

Figure A.30. Delay; P=10

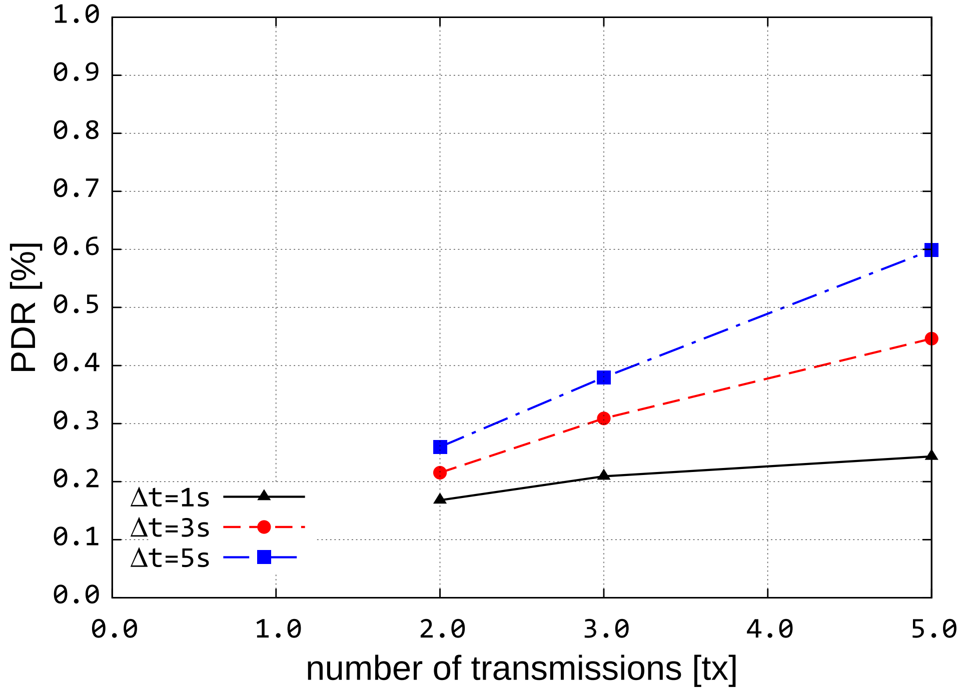

Figure A.31. PDR; P=12

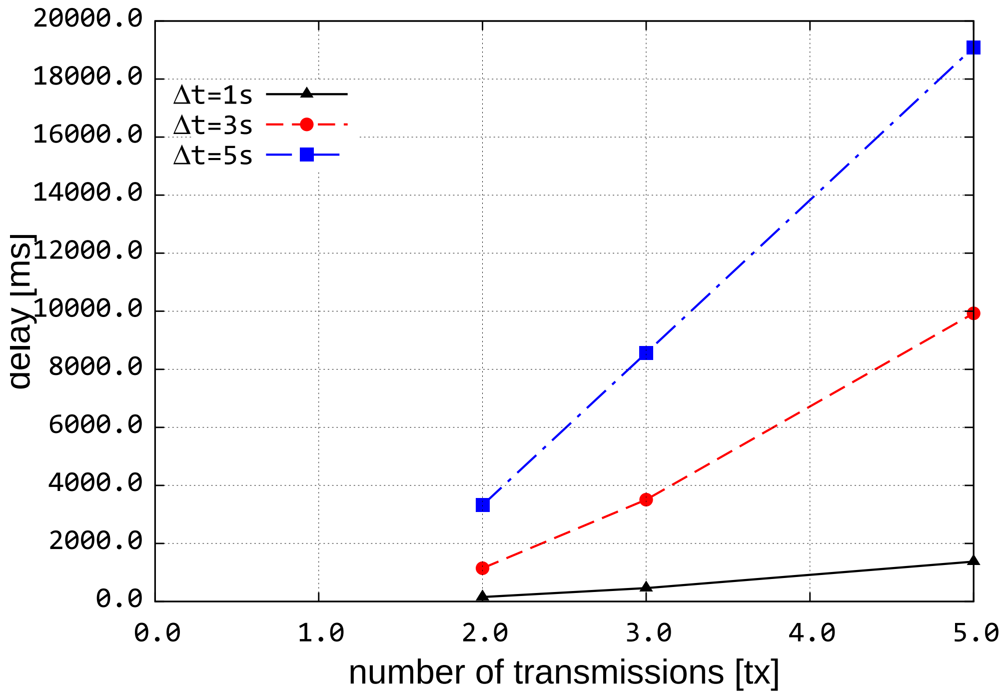

Figure A.32. Delay; P=12

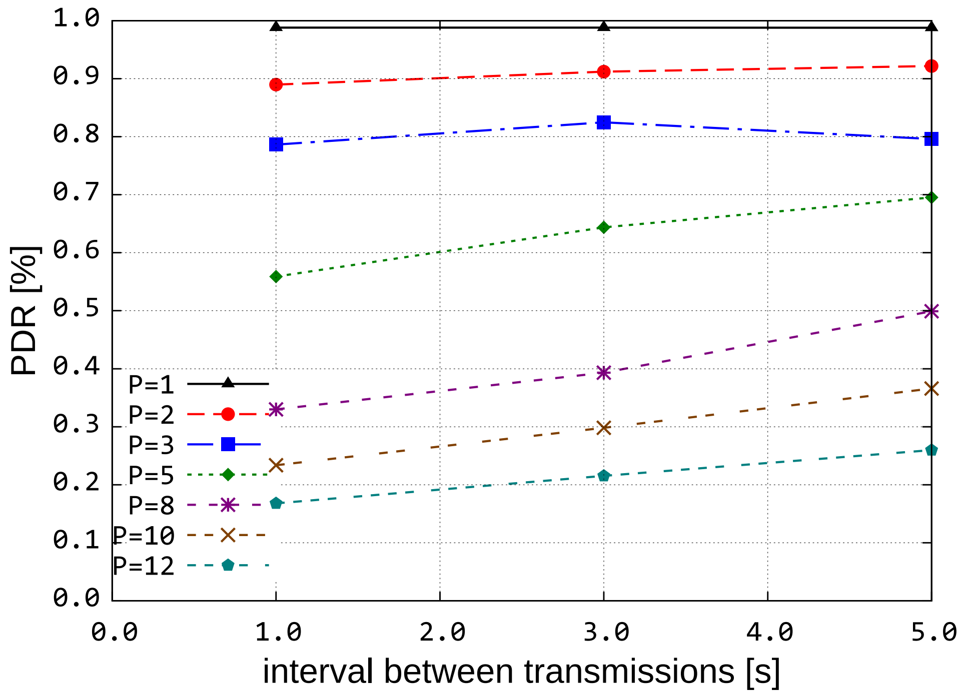

Figure A.33. PDR; n=2 tx

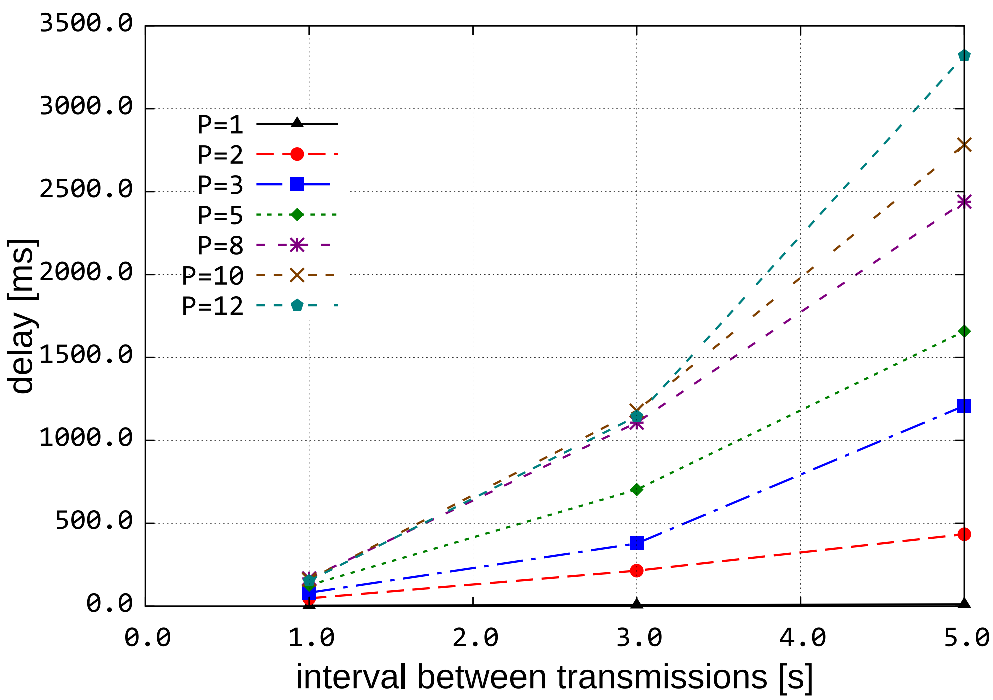

Figure A.34. Delay; n=2 tx

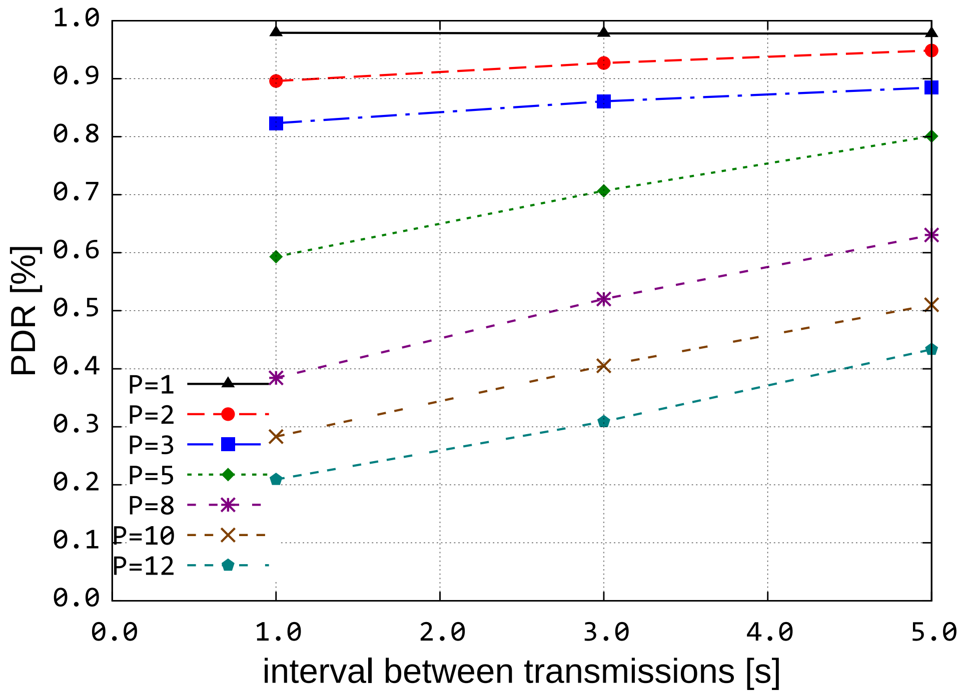

Figure A.35. PDR; n=3 tx

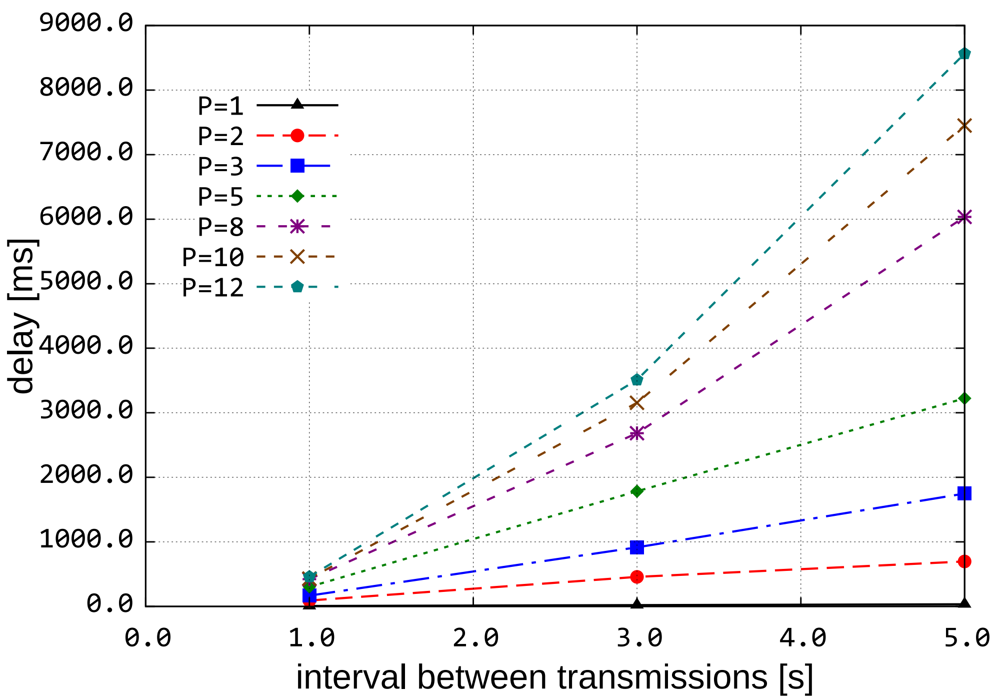

Figure A.36. Delay; n=3 tx

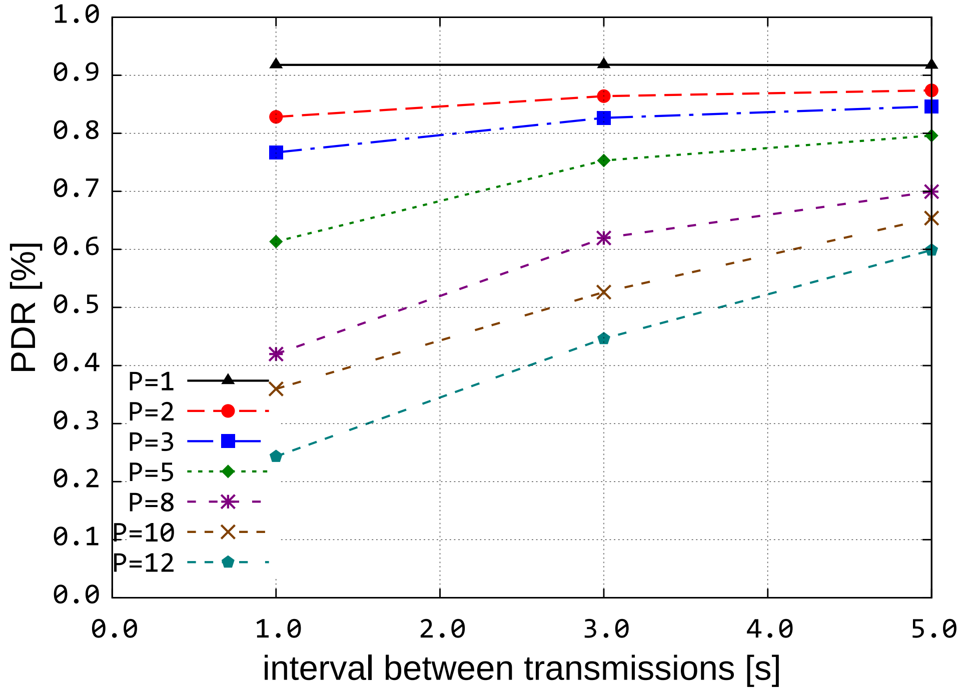

Figure A.37. PDR; n=5 tx

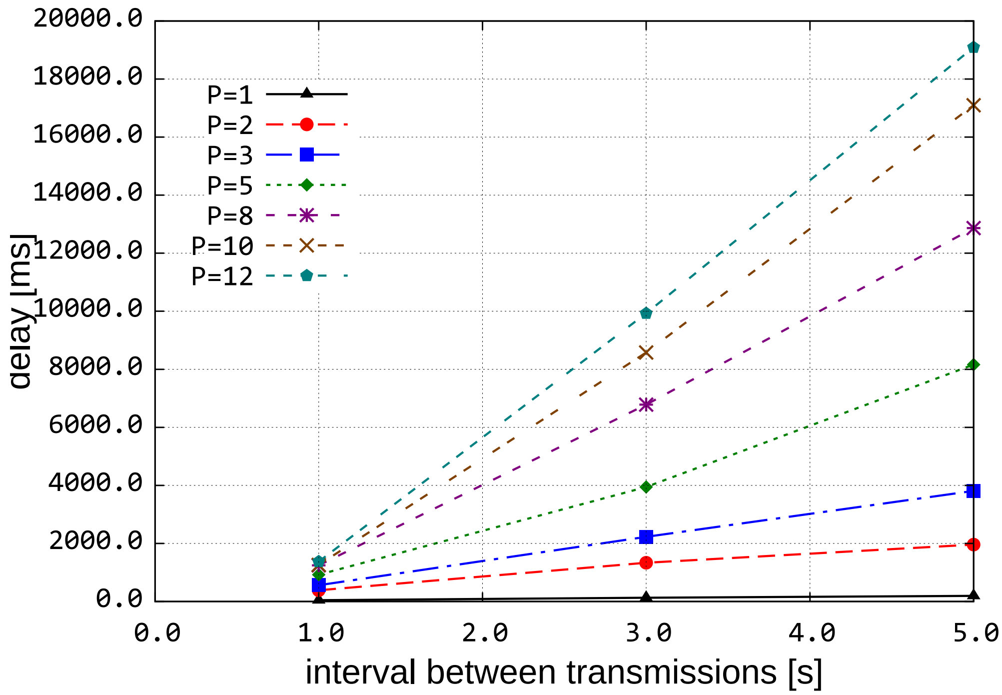

Figure A.38. Delay; n=5 tx

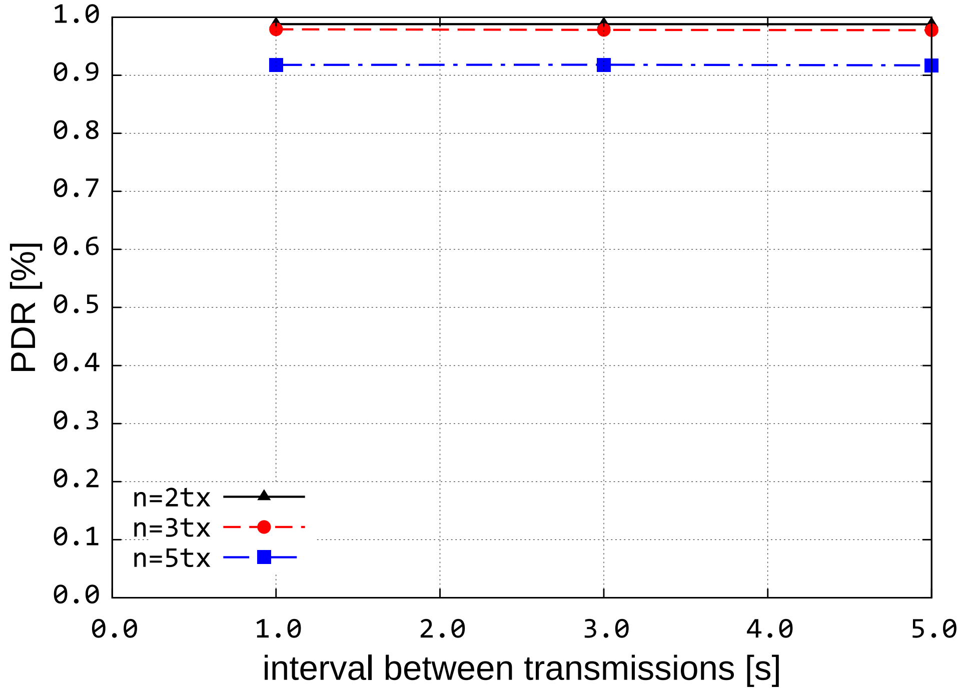

Figure A.39. PDR; P=1

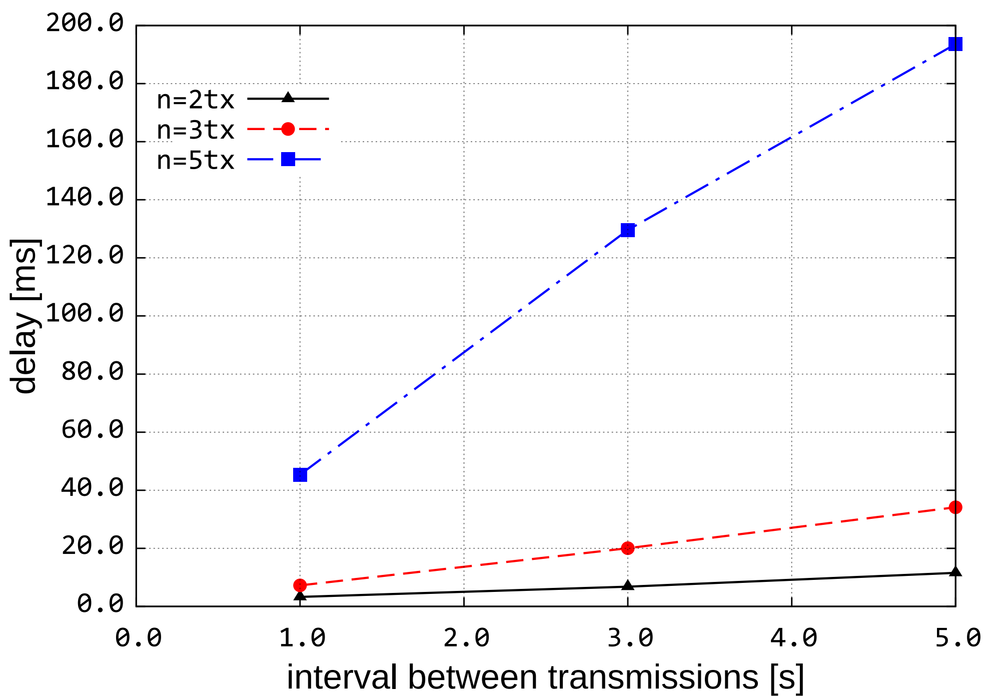

Figure A.40. Delay; P=1

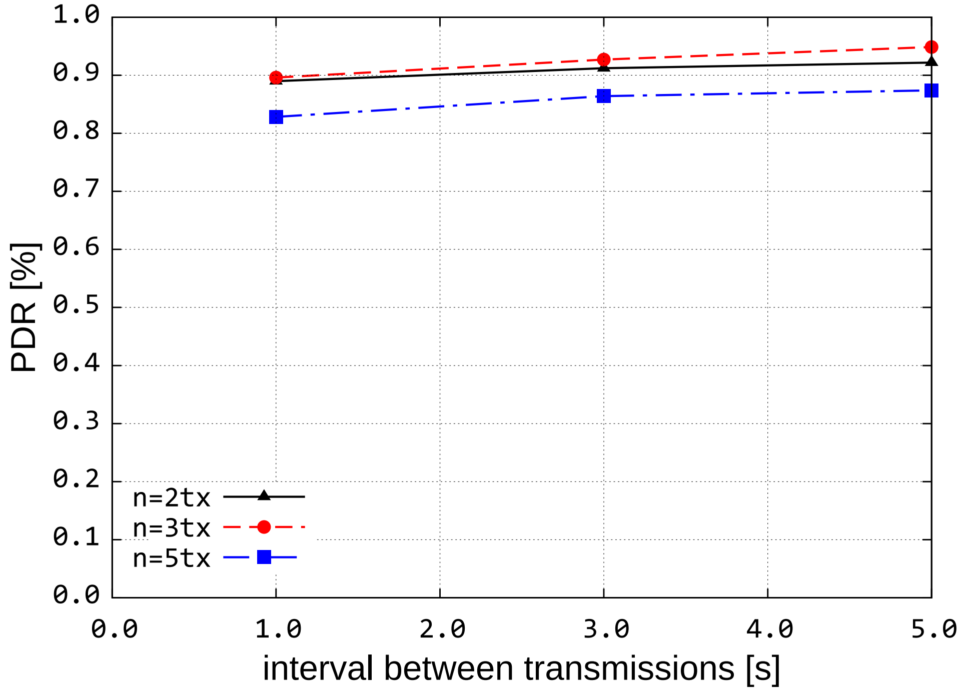

Figure A.41. PDR; P=2

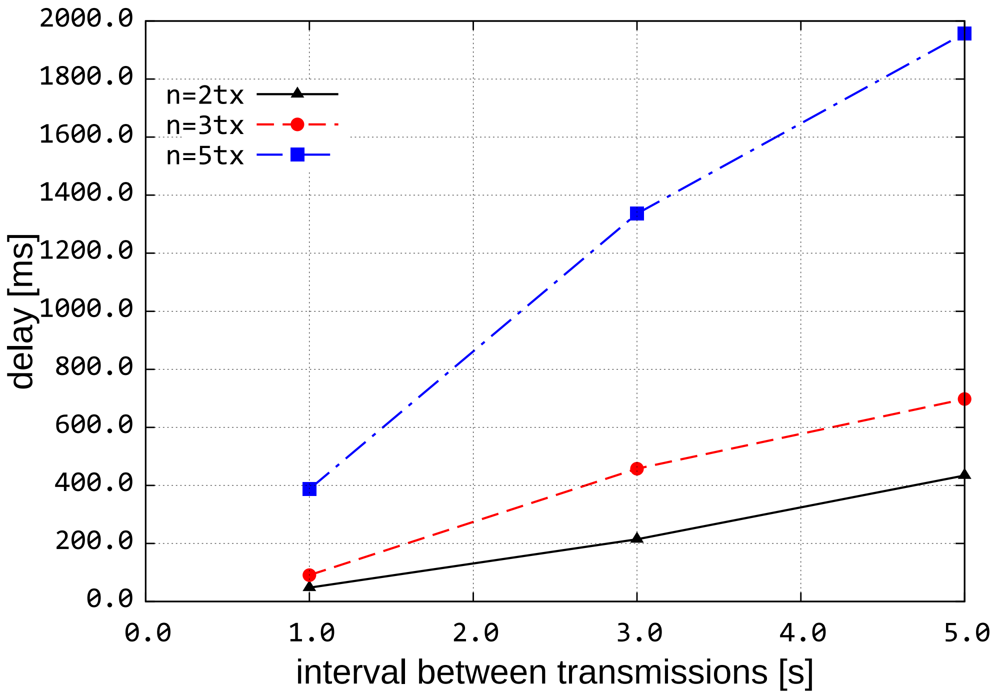

Figure A.42. Delay; P=2

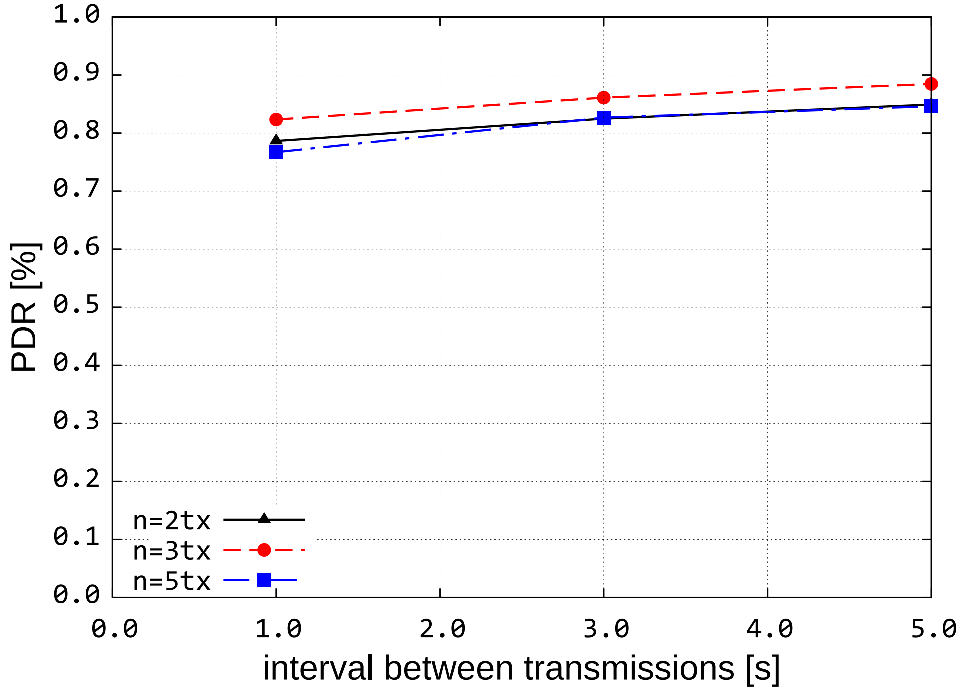

Figure A.43. PDR; P=3

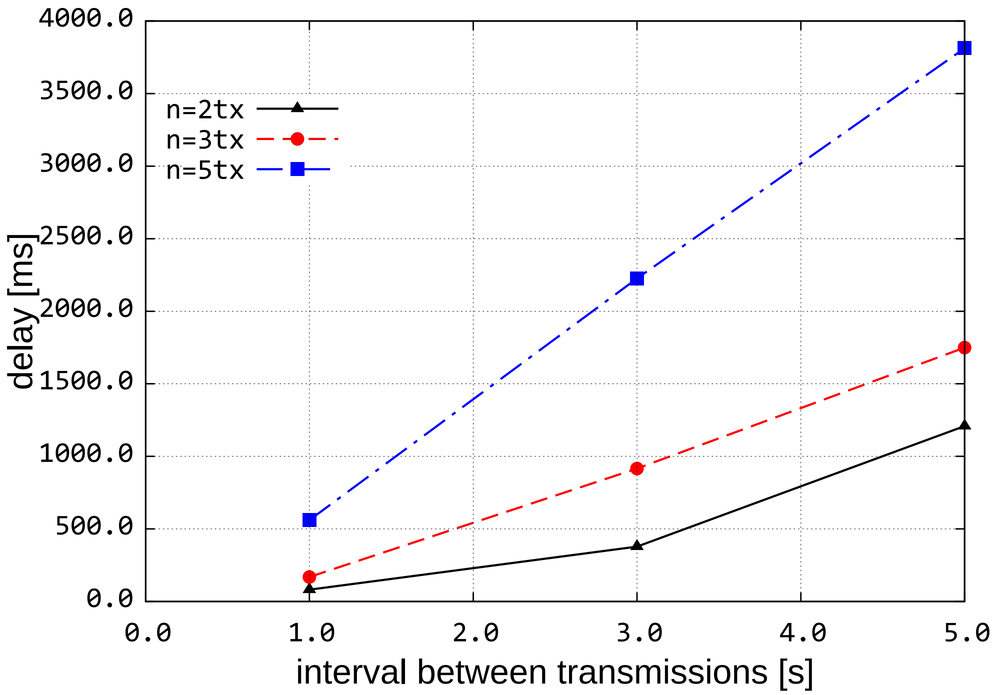

Figure A.44. Delay; P=3

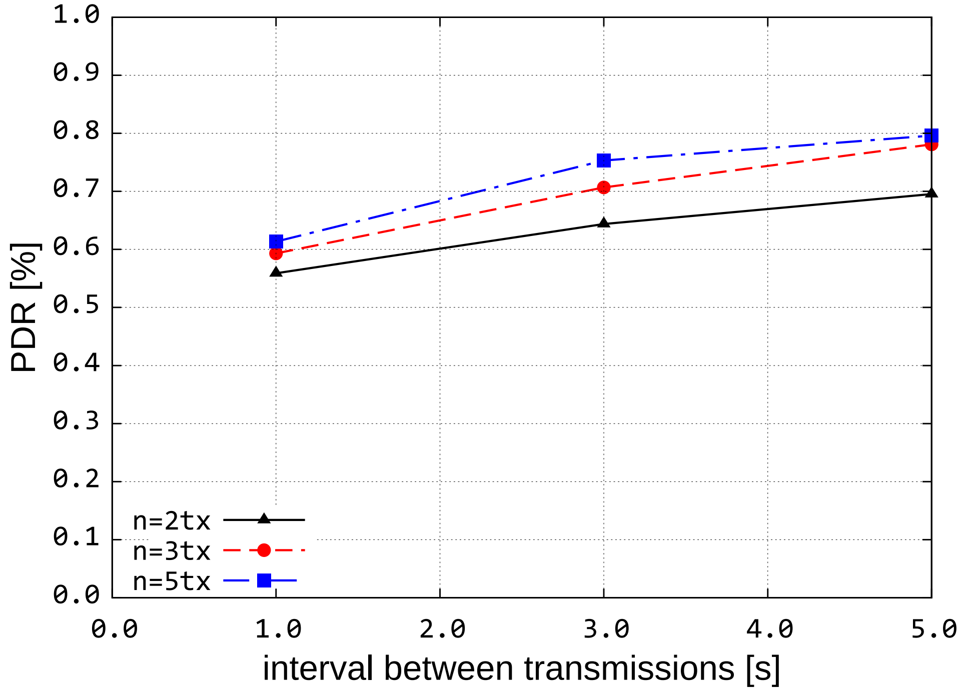

Figure A.45. PDR; P=5

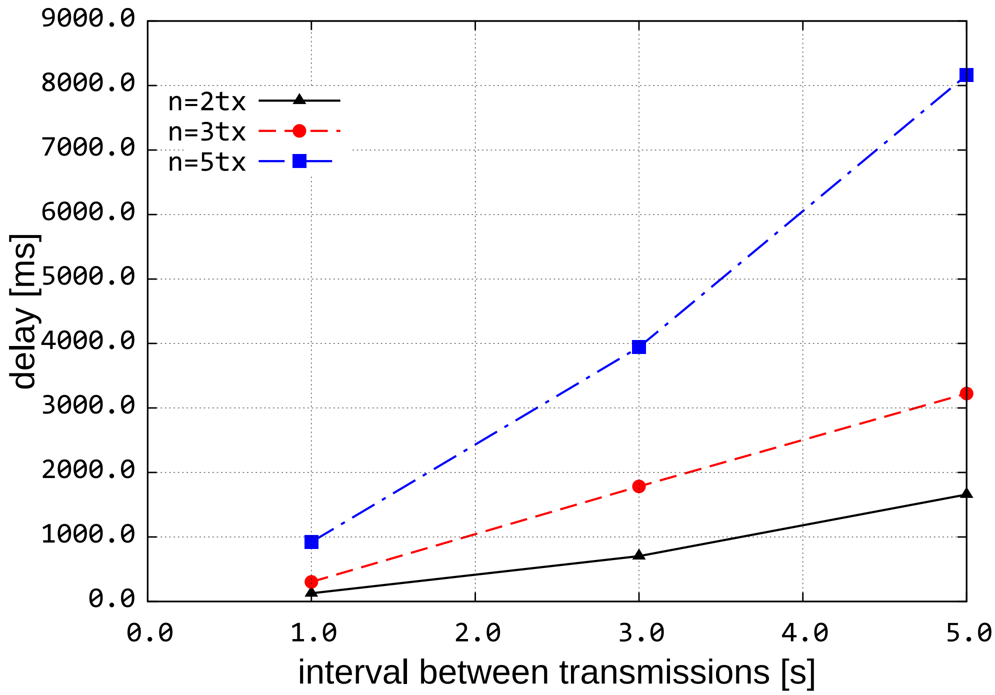

Figure A.46. Delay; P=5

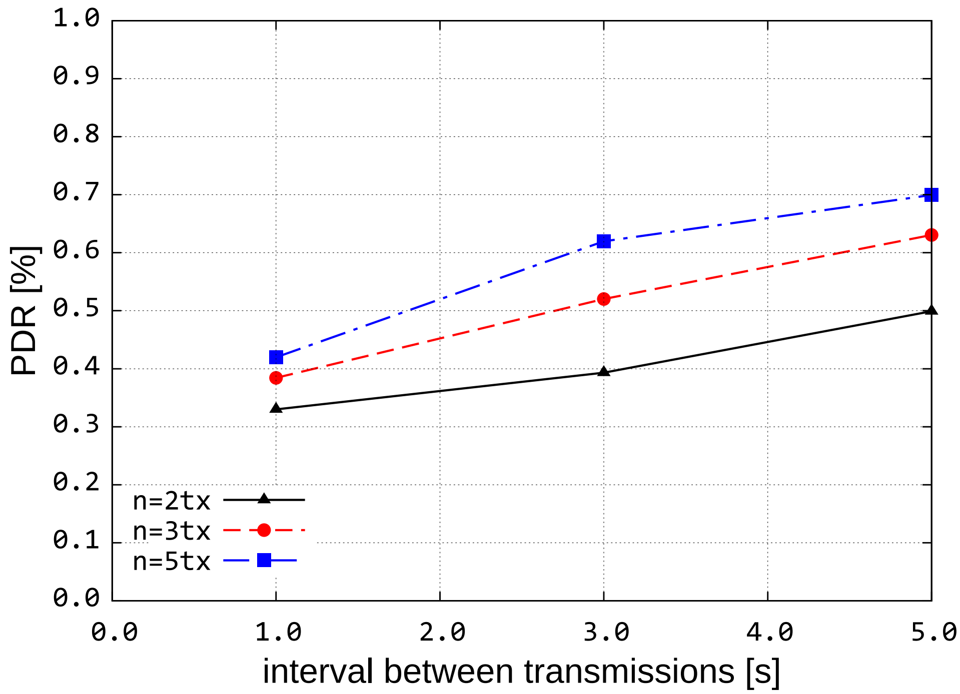

Figure A.47. PDR; P=8

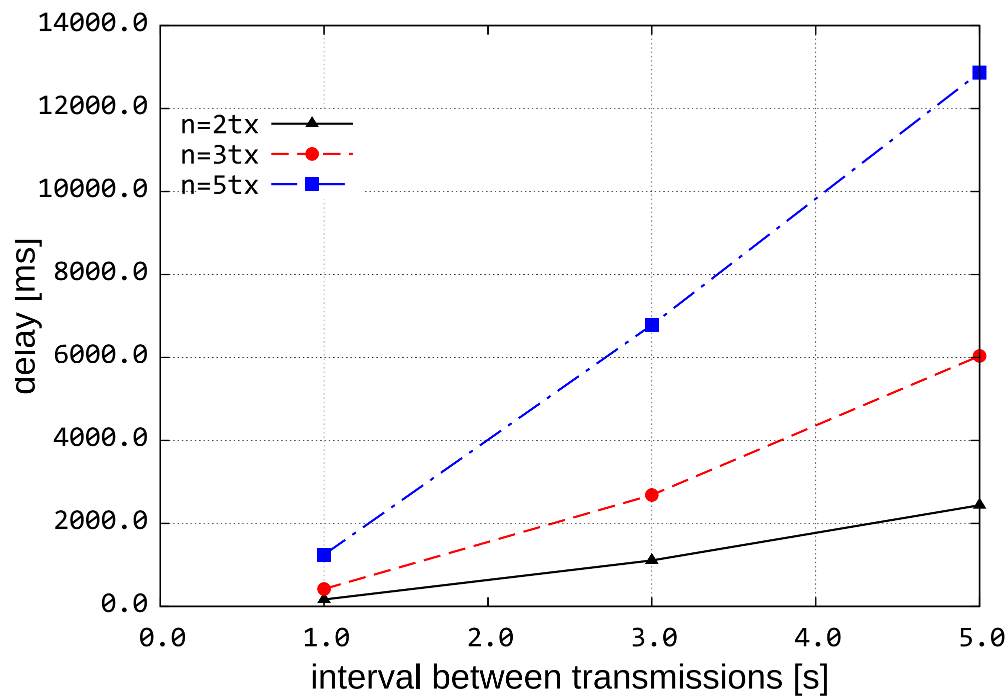

Figure A.48. Delay; P=8

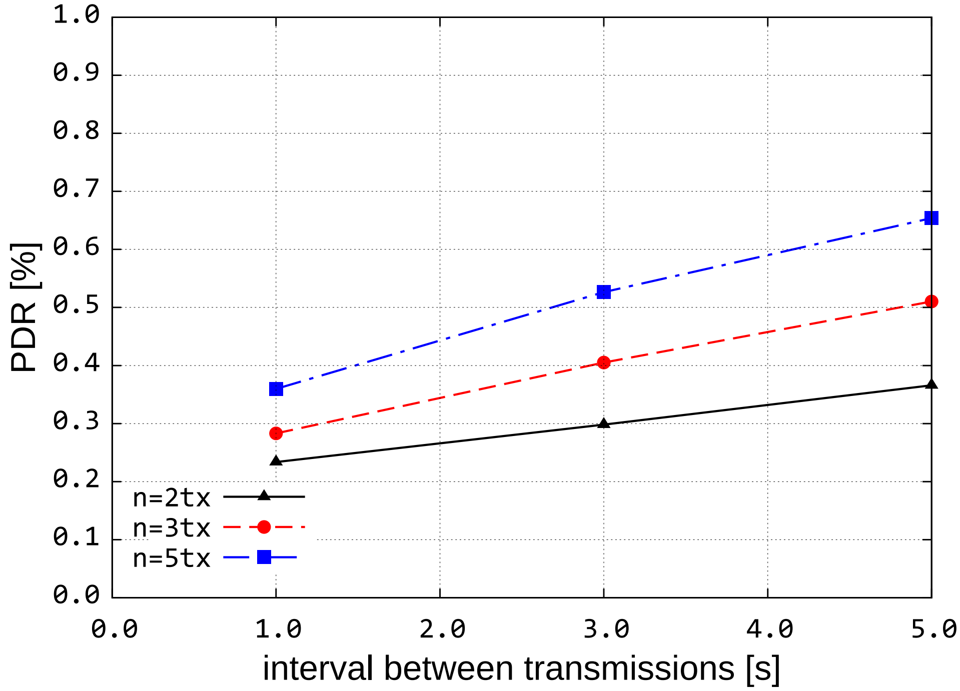

Figure A.49. PDR; P=10

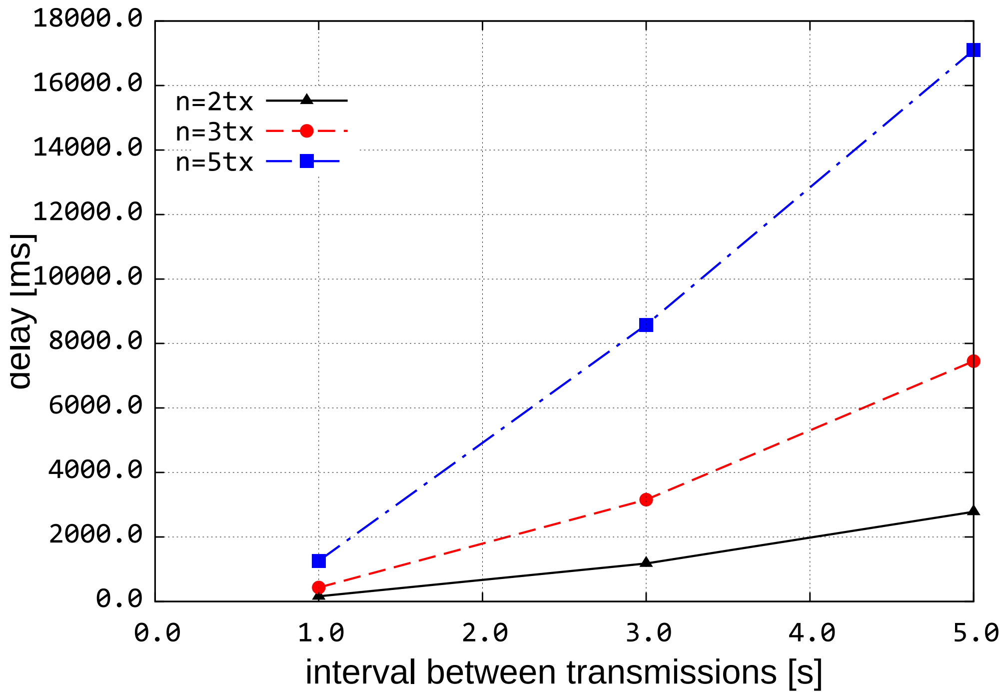

Figure A.50. Delay; P=10

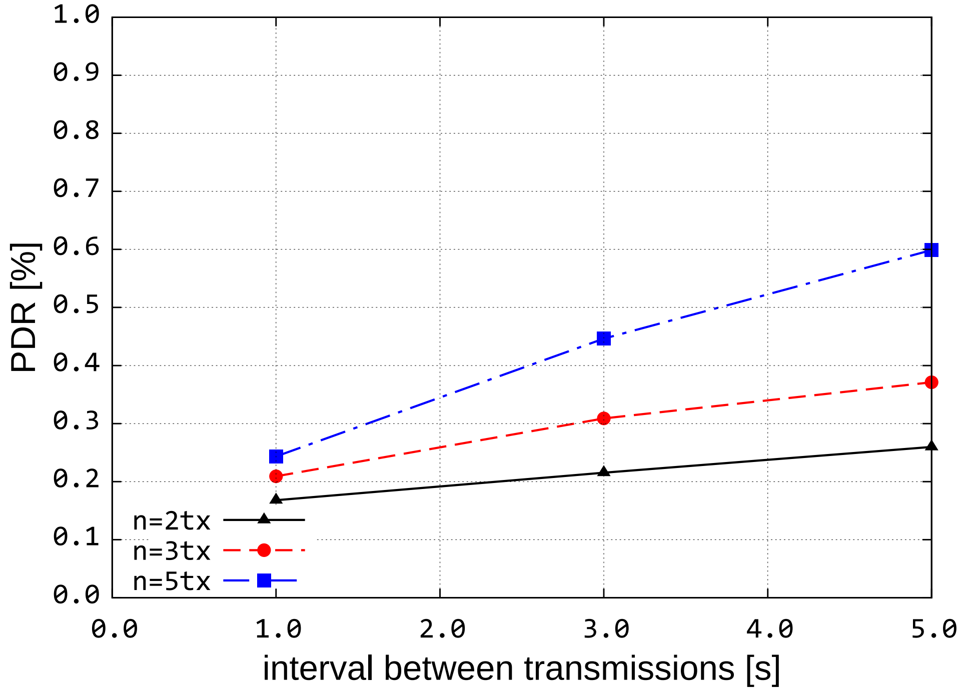

Figure A.51. PDR; P=12

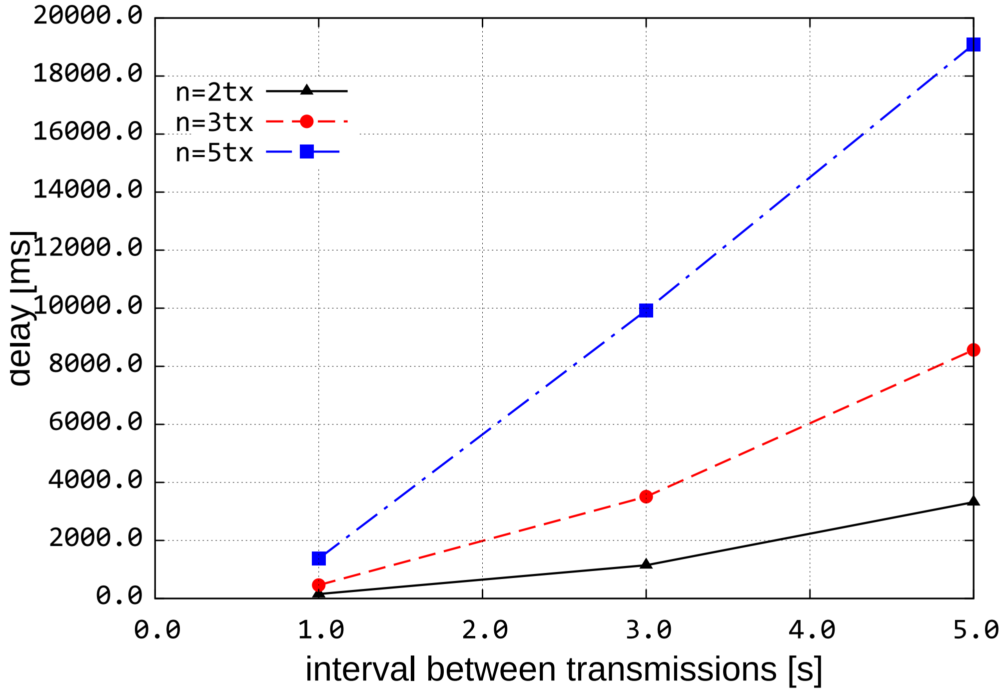

Figure A.52. Delay; P=12

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