Store and Haul with Repeated Controlled Flooding

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***Abstract*—This paper investigates the benefits and drawbacks of repeating controlled flooding at different time intervals in mobile ad hoc networks (MANETs) to overcome episodic connectivity. Specifically, we examine 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 focus on the performance gains in frequently partitioned networks. 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.**

I. 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 network that does not rely on infrastructure. Their design incorporates all network functionalities within the MANET nodes, including routing, forwarding, error control, connectivity, and security [1]. MANETs are often characterized by their pronounced challenges, the most notable of which are dynamic topologies, constrained bandwidth and power, and limited physical security [2]. 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 (Section II). 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.

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]–[6]. 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 research is to explore a new approach that is easy to implement, disseminates data throughout the network, requires minimal memory, and yields notable packet delivery improvements over standard MANETs protocols. The approach uses S&H in conjunction with repeated controlled flooding: S&H+RCF (store-and-haul with repeated controlled flooding).

The rest of the paper is organized as follows: the background of MANETs, S&H, and CF, as well as related work in the subject area are discussed in Section II. Section III explains the S&H+RCF mechanism in detail. Section IV 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 Section V. Finally, conclusions and comments on future work to be done on S&H are discussed in Section VI.

II. Background and Related Work

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 [7]. CF is classified as neither a reactive nor 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 [8]. The most important feature to note about CF is packets are only transmitted to nodes that have not already received the packet [9]; this is the difference between uncontrolled and controlled flooding. It should also be noted that CF is a more difficult in MANETs due to dynamic paths and wireless connections; 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.

MANETs are the progeny of research programs such as Survivable, Adaptive Networks (SURAN) [2] and Survivable Communication Networks (SCN) [2]. 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.

High expectations placed on MANETs are often overshadowed by 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 [10]. This results in the dynamic topologies in which nodes move in and out of communication range. 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. Other challenges include bandwidth limitations, security, and energy constraints.

These challenges are met 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. 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.

Delay-tolerant networks (DTNs) attempt to facilitate communications when connectivity is sporadic or discrete. This means that DTNs take a store-and-forward approach [11], [12] based on the interplanetary Internet (IPN) framework [13]. 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 [14].

Disruption-tolerant networks (DTNs[1]), are a generalization of delay-tolerant networking, encompassing network interruptions other than just delays. MANETs share the property of episodic connectivity with DTNs. Furthermore, MANETs are often sparsely connected or highly dynamic and can benefit from S&H.

III. 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 algorithm is described first with a basic overview and impetus, then provides a detailed description of the algorithm.

A. Overview of S&H+RCF

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 this 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. Performance can be enhanced simply by increasing or decreasing the number of repeats. It can also be enhanced by modifying the interval between repeats, depending upon the characteristics of the MANETs in question. These modifications can even be made in real time depending on the requirements of a particular scenario.

B. Algorithm Description

S&H+RCF communication operates in the following simple 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 1.

There is significant potential in the S&H methodology when combined with RCF. The improvements determine 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 VI.

IV. Simulations and Results

The simulations are run on the network simulator ns-2, a discrete event network simulator. 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. It was customized so the simulated nodes would carry data and transmit that data at the appropriate time. The customizations were done by modifying the C++ source code in ns-2. They started with modifying the native ns-2 *flooding protocol* and made it *controlled* flooding, meaning packets already received by the node should be dropped as

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

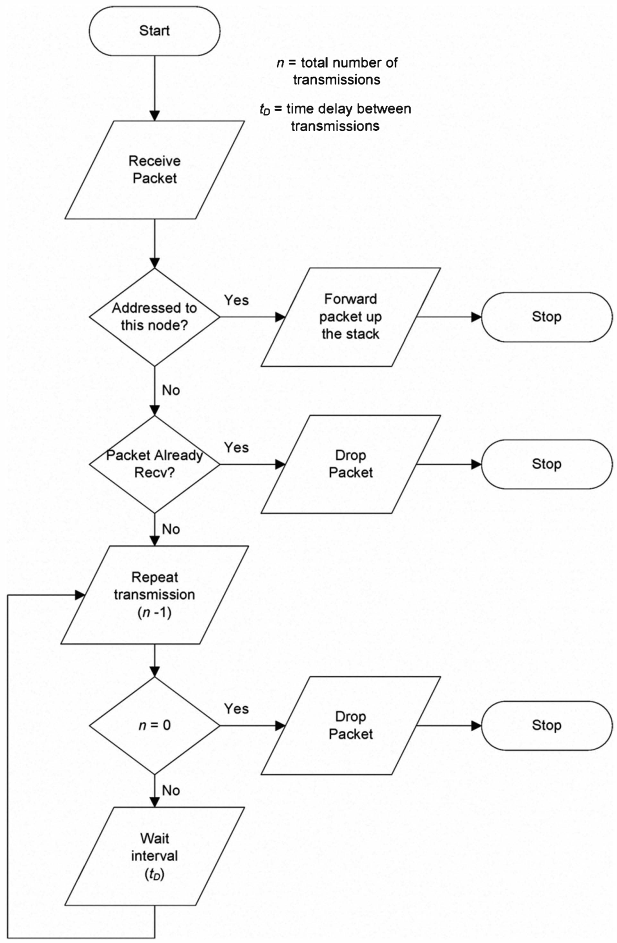

Fig. 1. Flowchart of S&H+RCF

soon as possible. 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 first checks 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.

After *controlled* flooding was implemented the next step was to create *repeated controlled* flooding. C++ data 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. 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.

TABLE I
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

A. 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. These settings remained consistent throughout all simulations. The static parameters used in the simulations are shown in Table I.

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.

B. 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).

TABLE II
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

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

V. ANALYSIS

Each scenario is run three times using ns-2 and all the trace files are collected for parsing and data extraction. 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 II along with their possible values. Some runs used a scaled time to produce simulation runs in reasonable time; these are indicated by a * in the plots, with scaled and unscaled runs at 10s and 10s* for purposes of comparison.

A. Analysis of Network Density

Network density is simply the concentration of nodes in a given area, while the number or partitions is the number of segregated groups such that the nodes in a group are out range and unable to communicate with other groups. This analysis is an examination of network density in relation to the other two dynamic variables. Network density values are along the x-axis, PDR or delay values are along the y-axis, and the other network variables are placed into separate plots. PDR decreases as the network becomes increasingly partitioned and would eventually go to zero as P approaches n. CF (n=1) is used as a baseline case to the S&H+RCF test case. In most

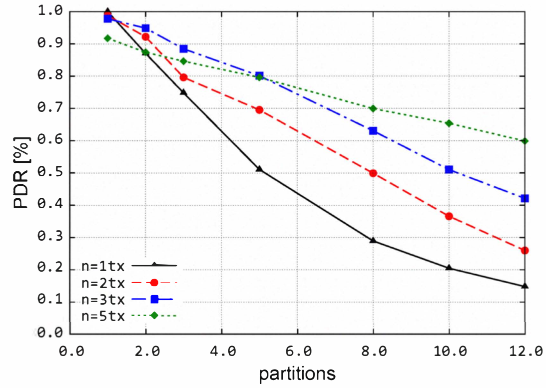

Fig. 2. Avg PDR; Δt=5 s

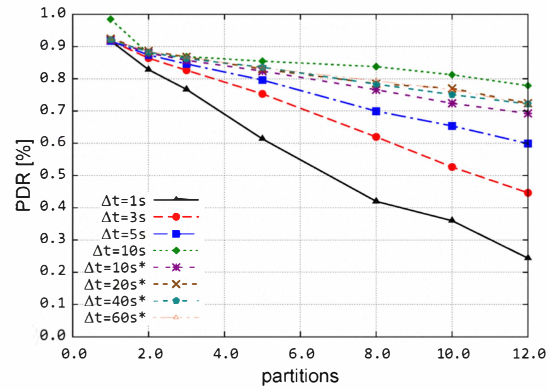

Fig. 3. Avg PDR; n=5 tx

cases S&H+RCF outperforms CF in PDR, except when the network is connected (only one or two average partitions). This is due to the additional collisions and interference created by RCF and can be seen in Figures 2 and 3. However, as the network becomes more partitioned, S&H+RCF begins and continues to outperform CF – shown in the figures where the n=1 plot intersects with the other plots.

The extremes for PDR increase can be seen in Figures 2 and 3. The more attempts made to retransmit a packet, the higher the likelihood it reaches it destination (when $P \geq 3$). Likewise, the longer the interval between transmissions the higher the likelihood the packet reaches its destination. Additionally, diminishing returns are seen in S&H+RCF, as PDR will eventually plateau in the face of increased transmission or elongated intervals between transmissions. Although those plateaus were not fully explored in this paper (Future Work).

Average E2E delay is significantly increased with S&H+RCF, but that additional delay is created by those packets that would have never been delivered by CF. In other words, the packets that would have been received using CF are received in the same amount of time when S&H+RCF is used.

Delay extremes are seen in Figures 4 and 5. This side effect to S&H+RCF should be accounted for when relying

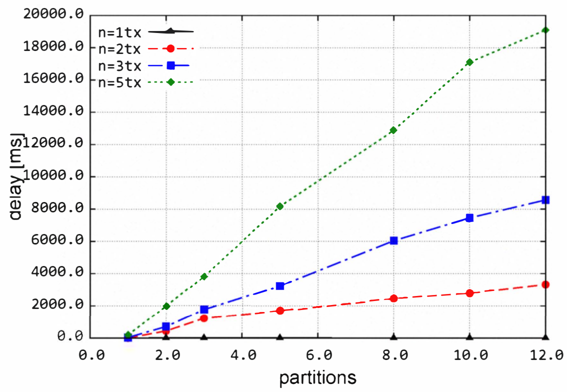

Fig. 4. Avg E2E Delay; Δt=5 s

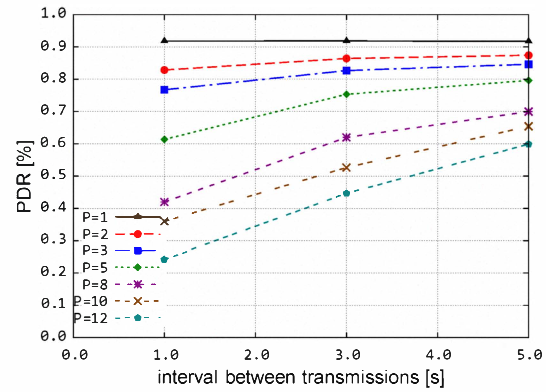

Fig. 6. Avg PDR; n=5 tx

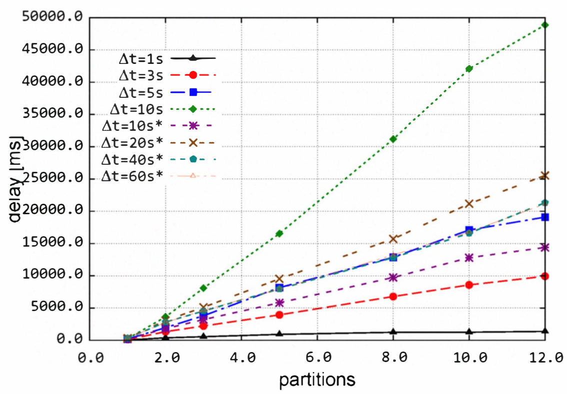

Fig. 5. Avg E2E Delay; n=5 tx

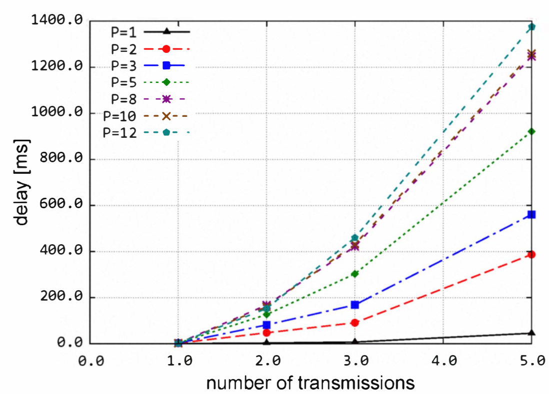

Fig. 7. Avg E2E Delay; Δt=1 s

on expected PDR values. While in some scenarios S&H+RCF produces three to four times the amount of PDR over CF, it can also mean packets may have an average E2E delay of forty or fifty seconds.

B. Analysis of Transmission Interval

Analysis with respect to the interval between transmissions, or Δt, shows the same trends seen in the previous analysis. The tradeoff between PDR and delay, the plateaus, extremes, and intersections delimiting where S&H+RCF begins to outperform CF. It also shows that the biggest gains in PDR are when the networks is most segregated (Figure 6 – showing higher aggregated slopes for higher values of P).

C. Analysis of Transmission Quantity

Analysis of transmission quantity (the number of transmissions n) shows many of the aforementioned characteristics of S&H+RCF, but also shows the exponential increase in average E2E delay with repeated transmissions. This can be seen in the curves created when plotting against the number of transmissions (Figure 7). These delays render some network applications incompatible and classify S&H+RCF a true DTN.

D. Quick Comparisons

In order to provide a better understanding and a framework for making decisions, results were put into matrices for quick comparisons. Table III shows the expected PDR when S&H+RCF variables are set according to the values on the matrix. While Table IV shows the corresponding and resulting average E2E delays. For example, when P= 12, n= 5 tx, and Δt= 3 s generates 45% PDR and 9,928 ms of delay. The values for CF (the baseline control case) only generated 12% PDR and had 840 ms of delay. This is because when S&H+RCF repeats five times at three second intervals there is a 32% increase in PDR. The additional delay incurred is only from those packets that would have never been delivered using CF.

TABLE III
PDR INCREASE FOR P = 12

	1 s	3 s	5 s
2 tx	17%	22%	26%
3 tx	21%	31%	42%
5 tx	25%	45%	60%

TABLE IV
AVERAGE E2E DELAY FOR P = 12

	1 s	3 s	5 s
2 tx	153 ms	1146 ms	3321 ms
3 tx	460 ms	3510 ms	8564 ms
5 tx	1375 ms	9928 ms	19,094 ms

VI. Conclusions and Future Work

This paper presented a new S&H+RCF (store-and-haul with repeated controlled flooding), algorithm for routing in for sparsely-connected mobile wireless networks. 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 tradeoffs. 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 to a more detailed and varied level. 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.

The S&H+RCF protocol should be directly compared to Epidemic routing. 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. 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.

Acknowledgments

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