Comparison of Broadcasting Techniques for Mobile Ad Hoc Networks [*]

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ABSTRACT

Network wide broadcasting in Mobile Ad Hoc Networks provides important control and route establishment functionality for a number of unicast and multicast protocols. Considering its wide use as a building block for other network layer protocols, the MANET community needs to standardize a single methodology that efficiently delivers a packet from one node to all other network nodes. Despite a considerable number of proposed broadcasting schemes, no comprehensive comparative analysis has been previously done. This paper provides such analysis by classifying existing broadcasting schemes into categories and simulating a subset of each category, thus supplying a condensed but comprehensive side by side comparison. The simulations are designed to pinpoint, in each category, specific failures to network conditions that are relevant to MANETs, e.g., bandwidth congestion and dynamic topologies. In addition, protocol extensions using adaptive responses to network conditions are proposed, implemented and analyzed for one broadcasting scheme that performs well in the comparative study.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*network topology, wireless communications*; C.2.2 [**Computer-Communication Networks**]: Network Protocols—*routing protocols*; C.4 [**Performance of Systems**]: Performance Attributes

General Terms

algorithms, design, performance

Keywords

ad hoc networks, broadcast protocols, flooding protocols, mobile networks, IEEE 802.11, MANET

1. INTRODUCTION

Mobile Ad Hoc Networks (MANETs) are created on the fly. No fixed infrastructure is included in the configuration of the network, some nodes in the network are expected to assist in the routing of packets, and all hosts are allowed to move freely through the network. Successful routing protocols provide means to deliver packets to destination nodes given these dynamic topologies.

Network wide broadcasting, simply referred to as "broadcasting" for the remainder of the paper, is the process in which one node sends a packet to all other nodes in the network. Broadcasting is often necessary in MANET routing protocols. For example, many unicast routing protocols such as Dynamic Source Routing (DSR), Ad Hoc On Demand Distance Vector (AODV), Zone Routing Protocol (ZRP), and Location Aided Routing (LAR) use broadcasting or a derivation of it to establish routes. Currently, these protocols all rely on a simplistic form of broadcasting called Flooding, in which each node (or all nodes in a localized area) retransmits each received unique packet exactly one time. The main problems with Flooding are that it typically causes unproductive and often harmful bandwidth congestion, as well as inefficient use of node resources.

Recently, a number of research groups have proposed more efficient broadcasting techniques whose goal is to minimize the number of retransmissions while attempting to ensure that a broadcast packet is delivered to each node in the network. None of these efficient broadcast schemes have been adopted by the unicast protocols mentioned above, perhaps because a unified comparison of these protocols over a wide range of MANET conditions was lacking. Our work addresses this deficiency by categorizing broadcast protocols and comparing sample protocols from each category. Our comparisons are simulation based, designed to test the protocols under specific conditions of increasing neighbor density, traffic rates and node mobility. Each simulation study allows us to pinpoint deficiencies in the protocols and propose solutions to correct for specific problems.

We classify and evaluate all broadcast protocols (which we are aware) that are distributed in nature and designed for asynchronous Medium Access Control schemes. Our simulations utilized the IEEE 802.11 MAC specification [5]. While a significant amount of work in hierarchical broadcasting protocols, cluster-based broadcasting protocols, and broadcast friendly MAC protocols has been done, we do not consider this body of work herein.

In Section 2, we discuss attributes that are common to many, or all, of the protocols described. Section 3 summarizes known broadcasting schemes and the categorization of them. Section 4 provides an outline of the studies we performed, and Section 5 gives the results of these studies. Section 6 presents conclusions and a description of proposed future work.

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2. COMMON ATTRIBUTES

In this section, we describe relevant features of the 802.11 MAC because its operation affects all broadcast protocols evaluated in this paper. We then present two common attributes which exist in many (or all) of the broadcast protocols categorized.

2.1 802.11 MAC Specification

This paper evaluates broadcast protocols on wireless networks that utilize the IEEE 802.11 MAC [5]. This MAC follows a Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA) scheme. Collision avoidance is inherently difficult in MANETs; one often cited difficulty is overcoming the hidden node problem, where a node is not able to ascertain whether its neighbors are busy receiving transmissions from an uncommon neighbor.

The 802.11 MAC utilizes a Request To Send (RTS) / Clear To Send (CTS) / Data / Acknowledgment procedure to account for the hidden node problem when unicasting packets. However, the RTS/CTS/data/ACK procedure is too cumbersome to implement for broadcast packets as it would be difficult to coordinate and bandwidth expensive. Therefore, the only requirement made for broadcasting nodes is that they assess a clear channel before broadcasting. Unfortunately, clear channel assessment does not prevent collisions from hidden nodes. Additionally, no recourse is provided for collision when two neighbors assess a clear channel and transmit simultaneously.

Ramifications of this environment are subtle but significant. Unless specific means are implemented at the network layer, a node has no way of knowing whether a packet was successfully reached by its neighbors. In congested networks, a significant amount of collisions occur leading to many dropped packets. The most effective broadcasting protocols try to limit the probability of collisions by limiting the number of rebroadcasts in the network.

2.2 Jitter and RAD

Suppose a source node originates a broadcast packet. Given that radio waves propagate at the speed of light, all neighbors will receive the transmission almost simultaneously. Assuming similar hardware and system loads, the neighbors will process the packet and rebroadcast at the same time. To overcome this problem, broadcast protocols jitter the scheduling of broadcast packets from the network layer to the MAC layer by some uniform random amount of time. This (small) offset allows one neighbor to obtain the channel first, while other neighbors detect that the channel is busy (clear channel assessment fails).

Many of the broadcasting protocols require a node to keep track of redundant packets received over a short time interval in order to determine whether to rebroadcast. That time interval, which we have arbitrarily termed "Random Assessment Delay" (RAD), is randomly chosen from a uniform distribution between 0 and Tmax seconds, where Tmax is the highest possible delay interval. This delay in transmission accomplishes two things. First it allows nodes sufficient time to receive redundant packets and assess whether to rebroadcast. Second, the randomized scheduling prevents the collisions described in the jitter discussion.

An important design consideration is the implementation of the random assessment delay. One approach is to send broadcast packets to the MAC layer after a short random time similar to the jitter. In this case, packets remain in the interface queue (IFQ) until the channel becomes clear for broadcast. While the packet is in the IFQ, redundant packets may be received, allowing the network layer to determine if rebroadcasting is still required. If the network layer protocol decides the packet should not be rebroadcast, it informs the MAC layer to discard the packet.

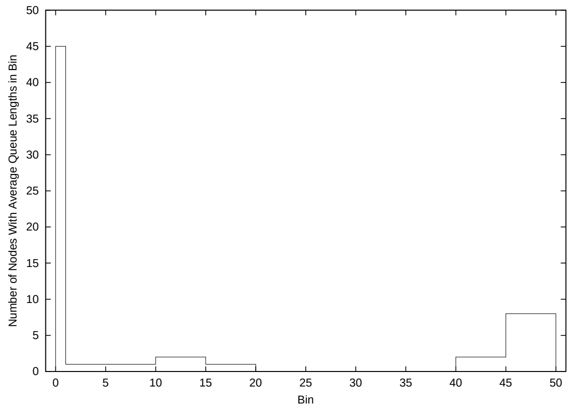

Figure 1: Histogram of Average IFQ Lengths for Nodes Using Simple Flooding

A second approach is to implement the random assessment delay as a longer time period and keep the packet at the network layer until the RAD expires. Retransmission assessment is done considering all redundant packets during the RAD. After RAD expiration, the packet is either sent to the MAC layer or dropped. No attempts are made by the network layer to remove the packet after sending it to the MAC layer.

Figure 1 is a histogram for average node IFQ lengths given 60 nodes Flooding 80 new packets per second, which is the highest congestion level studied in this paper (see Section 4 for other simulation parameters). From the histogram we see that 45 of 60 nodes (75%) have average queue lengths of less than 1 packet. An informal analysis of the network showed a strong direct correlation between number of neighbors and queue length, the nodes with the most neighbors had the longest queues. We surmise that perimeter nodes fail clear channel assessment less often than internal nodes, allowing the perimeter nodes more frequent access to the channel and barraging the interior nodes with traffic. For those perimeter nodes, if the network layer informs the MAC layer to remove a particular packet from its IFQ, it is unlikely the packet will still be pending in the queue. Thus, we chose to implement the RAD via the second approach discussed. We do however note that given the RTS/CTS/ACK procedure required by 802.11 for unicast packets, it is likely that a mixture of unicast and broadcast traffic would produce a more even distribution of queue lengths as unicast packets would have more tendency to block at the head of the queue.

2.3 Prevention of Infinite Loops

None of the protocols categorized in this paper require that a node rebroadcast a given packet more than one time. Thus, each broadcast protocol requires that nodes cache the original source node ID of the packet and the packet ID. This allows the protocol to uniquely identify each broadcast packet and assign appropriate behavior upon reception of a packet.

3. CATEGORIZATION OF PROTOCOLS

Twelve broadcast protocols are described in this section. A comprehensive comparison of these protocols would include simulating all twelve under a wide range of parameters. This exercise requires significant work that we did not believe necessary in order to glean an overall understanding of strengths and weaknesses of the protocols. Instead, our approach was to categorize the protocols into four families: Simple Flooding, Probability Based Methods, Area Based Methods and Neighbor Knowledge Methods. Evaluating one or two representative protocols from each category allows us to make conclusions regarding applicability of all protocols within each family. We give a brief overview of each category in the following paragraph. We then provide details in Sections 3.1-3.4. Section 3.5 discusses the five protocols we chose to evaluate via simulation.

Simple Flooding requires each node to rebroadcast all packets. Probability Based Methods use some basic understanding of the network topology to assign a probability to a node to rebroadcast. Area Based Methods assume nodes have common transmission distances; a node will rebroadcast only if the rebroadcast will reach sufficient additional coverage area. Neighbor Knowledge Methods maintain state on their neighborhood, via "Hello" packets, which is used in the decision to rebroadcast. Note that our four categories are presented in order of increasing algorithm complexity and per node state requirement. The goal of the added cost is to reduce the number of redundant transmissions.

3.1 Simple Flooding

The algorithm for Simple Flooding [7, 8] starts with a source node broadcasting a packet to all neighbors. Each of those neighbors in turn rebroadcast the packet exactly one time and this continues until all reachable network nodes have received the packet. In [7], Ho et al. propose Flooding as a scheme to achieve reliable broadcast and multicast in highly dynamic networks. [8] is an IETF Internet Draft proposing the use of Flooding as a "Simple Protocol" for broadcasting and multicasting in ad hoc networks which are characterized by low node densities and/or high mobility.

3.2 Probability Based Methods

Probabilistic Scheme: The Probabilistic scheme from [11] is similar to Flooding, except that nodes only rebroadcast with a predetermined probability. In dense networks multiple nodes share similar transmission coverages. Thus, randomly having some nodes not rebroadcast saves node and network resources without harming delivery effectiveness. In sparse networks, there is much less shared coverage; thus, nodes won't receive all the broadcast packets with the Probabilistic scheme unless the probability parameter is high. When the probability is 100%, this scheme is identical to Flooding.

Counter-Based Scheme: Ni et al [11] show an inverse relationship between the number of times a packet is received at a node and the probability of that node being able to reach additional area on a rebroadcast. This result is the basis of their Counter-Based scheme. Upon reception of a previously unseen packet, the node initiates a counter with a value of one and sets a RAD (which is randomly chosen between 0 and Tmax seconds). During the RAD, the counter is incremented by one for each redundant packet received. If the counter is less than a threshold value when the RAD expires, the packet is rebroadcast. Otherwise, it is simply dropped. From [11], threshold values above six relate to little additional coverage area being reached.

The overriding compelling features of the Counter-Based scheme are its simplicity and its inherent adaptability to local topologies. That is, in a dense area of the network, some nodes won't rebroadcast; in sparse areas of the network, all nodes rebroadcast.

3.3 Area Based Methods

Suppose a node receives a packet from a sender that is located only one meter away. If the receiving node rebroadcasts, the additional area covered by the retransmission is quite low. On the other extreme, if a node is located at the boundary of the sender node's transmission distance, then a rebroadcast would reach significant additional area, 61% to be precise [11]. A node using an Area Based Method can evaluate additional coverage area based on all received redundant transmissions. We note that area based methods only consider the coverage area of a transmission; they don't consider whether nodes exist within that area.

Distance-Based Scheme: A node using the Distance-Based Scheme compares the distance between itself and each neighbor node that has previously rebroadcast a given packet[1]. Upon reception of a previously unseen packet, a RAD is initiated and redundant packets are cached. When the RAD expires, all source node locations are examined to see if any node is closer than a threshold distance value. If true, the node doesn't rebroadcast.

Location-Based Scheme: The Location-Based scheme [11] uses a more precise estimation of expected additional coverage area in the decision to rebroadcast. In this method, each node must have the means to determine its own location, e.g., a Global Positioning System (GPS).

Whenever a node originates or rebroadcasts a packet it adds its own location to the header of the packet. When a node initially receives a packet, it notes the location of the sender and calculates the additional coverage area obtainable were it to rebroadcast. If the additional area is less than a threshold value, the node will not rebroadcast, and all future receptions of the same packet will be ignored. Otherwise, the node assigns a RAD before delivery. If the node receives a redundant packet during the RAD, it recalculates the additional coverage area and compares that value to the threshold. The area calculation and threshold comparison occur with all redundant broadcasts received until the packet reaches either its scheduled send time or is dropped.

3.4 Neighbor Knowledge Methods

Flooding with Self Pruning: The simplest of the Neighbor Knowledge Methods is what Lim and Kim refer to as Flooding with Self Pruning [9]. This protocol requires that each node have knowledge of its 1-hop neighbors, which is obtained via periodic "Hello" packets.

A node includes its list of known neighbors in the header of each broadcast packet. A node receiving a broadcast packet compares its neighbor list to the sender's neighbor list. If the receiving node would not reach any additional nodes, it refrains from rebroadcasting; otherwise the node rebroadcasts the packet.

Scalable Broadcast Algorithm (SBA): The Scalable Broadcast Algorithm (SBA) [13] requires that all nodes have knowledge of their neighbors within a two hop radius. This neighbor knowledge coupled with the identity of the node from which a packet is received allows a receiving node to determine if it would reach additional nodes by rebroadcasting. 2-hop neighbor knowledge is achievable via periodic "Hello" packets; each "Hello" packet contains the node's identifier (IP address) and the list of known neighbors. After a node receives a "Hello" packet from all its neighbors, it has two hop topology information centered at itself.

Suppose Node B receives a broadcast data packet from Node A. Since Node A is a neighbor, Node B knows all of its neighbors, common to Node A, that have also received Node A's transmission of the broadcast packet. If Node B has additional neighbors not reached by Node A's broadcast, Node B schedules the packet for delivery with a RAD. If Node B receives a redundant broadcast packet from another neighbor, Node B again determines if it can reach any new nodes by rebroadcasting. This process continues

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[1] The authors of [11] note that signal strength can be used to calculate the distance from a source node; in other words, this protocol is implementable without a Global Positioning System (GPS).

until either the RAD expires and the packet is sent, or the packet is dropped.

The authors of [13] propose a method to dynamically adjust the RAD to network conditions; they weight the time delay based on a node's relative neighbor degree. Specifically, each node searches its neighbor tables for the maximum neighbor degree of any neighbor node, d_{Nmax}. It then calculates a RAD based on the ratio of:

$$\left(\frac{d_{Nmax}}{d_{me}}\right),$$

where d_{me} is the node's current number of neighbors. This weighting scheme is greedy; nodes with the most neighbors usually broadcast before the others.

Dominant Pruning: Dominant Pruning also uses 2-hop neighbor knowledge, obtained via "Hello" packets, for routing decisions [9]. Unlike SBA, however, Dominant Pruning requires rebroadcasting nodes to proactively choose some or all of its 1-hop neighbors as rebroadcasting nodes. Only those chosen nodes are allowed to rebroadcast. Nodes inform neighbors to rebroadcast by including their address as part of a list in each broadcast packet header.

When a node receives a broadcast packet it checks the header to see if its address is part of the list. If so, it uses a Greedy Set Cover algorithm to determine which subset of neighbors should rebroadcast the packet, given knowledge of which neighbors have already been covered by the sender's broadcast. The Greedy Set Cover algorithm, as adapted in [9] from [10], recursively chooses 1-hop neighbors which cover the most 2-hop neighbors and recalculates the cover set until all 2-hop neighbors are covered.

Multipoint Relaying: Multipoint Relaying [15] is similar to Dominant Pruning in that rebroadcasting nodes are explicitly chosen by upstream senders. For example, say Node A is originating a broadcast packet. It has previously selected some, or in certain cases all, of it one hop neighbors to rebroadcast all packets they receive from Node A. The chosen nodes are called Multipoint Relays (MPRs) and they are the only nodes allowed to rebroadcast a packet received from Node A. Each MPR is required to choose a subset of its one hop neighbors to act as MPRs as well.

Since a node knows the network topology within a 2-hop radius, it can select 1-hop neighbors as MPRs that most efficiently reach all nodes within the two hop neighborhood. The authors of [15] propose the following algorithm for a node to choose its MPRs:

1. Find all 2-hop neighbors that can only be reached by one 1-hop neighbor. Assign those 1-hop neighbors as MPRs.
2. Determine the resultant cover set (i.e., the set of 2-hop neighbors that will receive the packet from the current MPR set).
3. From the remaining 1-hop neighbors not yet in the MPR set, find the one that would cover the most 2-hop neighbors not in the cover set.
4. Repeat from step 2 until all 2-hop neighbors are covered.

Multipoint Relaying is described in detail as part of the Optimized Link State Routing (OLSR) protocol defined by an Internet draft [4]. In this implementation, "Hello" Packets include fields for a node to list the MPRs it has chosen. Anytime a node receives a "Hello" packet, it checks if it is a MPR for the source of the packet. If so, it must rebroadcast all data packets received from that source. Clearly, the update interval for "Hello" packets must be carefully chosen and, if possible, optimized for network conditions.

Ad Hoc Broadcast Protocol: The Ad Hoc Broadcast Protocol (AHBP) [14] utilizes an approach similar to Multipoint Relaying. In AHBP, only nodes who are designated as a Broadcast Relay Gateway (BRG) within a broadcast packet header are allowed to rebroadcast the packet. BRGs are proactively chosen from each upstream sender which is a BRG itself. The algorithm for a BRG to choose its BRG set is identical to that used in Multipoint Relaying (see steps 1-4 for choosing MPRs).

AHBP differs from Multipoint Relaying in three ways:

1. A node using AHBP informs 1-hop neighbors of the BRG designation within the header of each broadcast packet. This allows a node to calculate the most effective BRG set at the time a broadcast packet is transmitted. In contrast, Multipoint Relaying informs 1-hop neighbors of the MPR designation via "Hello" packets.
2. In AHBP, when a node receives a broadcast packet and is listed as a BRG, the node uses 2-hop neighbor knowledge to determine which neighbors also received the broadcast packet in the same transmission. These neighbors are considered already "covered" and are removed from the neighbor graph used to choose next hop BRGs. In contrast, MPRs are not chosen considering the source route of the broadcast packet.
3. AHBP is extended to account for high mobility networks. Suppose Node A receives a broadcast packet from Node B, and Node A does not list Node B as a neighbor (i.e., Node A and Node B have not yet exchanged "Hello" packets). In AHBP-EX (extended AHBP), Node A will assume BRG status and rebroadcast the node. Multipoint relaying could be similarly extended.

CDS-Based Broadcast Algorithm: Peng and Lu describe the Connected Dominating Set (CDS)-Based Broadcast Algorithm, a more calculation intensive algorithm for selecting BRGs, in [12]. Where AHBP only considers the source of the broadcast packet to determine a receiving node's initial cover set, CDS-Based Broadcast Algorithm *also* considers the set of higher priority BRGs selected by the previous sender [12]. For example, suppose Node A has selected Nodes B, C and D (in this order) to be BRGs. When Node C receives a broadcast packet from Node A, AHBP requires Node C to add neighbors common to Node A to the initial cover set. CDS-Based Broadcast Algorithm *also* requires that Node C adds neighbors common to Node B, because Node B is a higher priority BRG. Likewise, Node D is required to consider common neighbors with nodes A, B and C.

Once the initial cover set is determined, a node then chooses which neighbors should function as BRGs. The algorithm for determining this is the same as that for AHBP and Multipoint Relaying (see steps 1-4 for choosing Multipoint Relays).

LENWB: The Lightweight and Efficient Network-Wide Broadcast (LENWB) protocol [17] also relies on 2-hop neighbor knowledge obtained from "Hello" packets. However, instead of a node explicitly choosing nodes to rebroadcast, the decision is implicit. In LENWB, each node decides to rebroadcast based on knowledge of which of its other one and two hop neighbors are expected to rebroadcast. The information required for that decision is knowledge of which neighbors have received a packet from the common source node and which neighbors have a higher priority for rebroadcasting. The priority is proportional to a node's number of neighbors; the higher the node's degree the higher the priority. Since a node relies on its higher priority neighbors to rebroadcast, it can proactively compute if all of its lower priority neighbors will receive those rebroadcasts; if not, the node rebroadcasts.

3.5 Chosen Protocols

We chose to implement the Simple Flooding, the Counter-Based scheme, the Location-Based scheme, SBA and AHBP. This section explains our choices. Since only one protocol exists in the Simple Flooding category, this protocol is evaluated.

For the Probability Based methods, the choice was clear. Both the Probabilistic scheme and Counter-Based scheme were proposed in the same paper. Comparisons in [11] indicated that the Counter-Based scheme out performed the Probabilistic scheme in most of the simulated conditions.

For a similar reason, the Location-Based scheme was chosen to represent the Area Based methods. In general, the Location-Based scheme was shown to be more robust than the Distance-Based scheme [11]. Our implementation mimics the original proposal of using a convex polygon approximation to determine the expected additional transmission coverage when the number of redundant receptions is greater than three. The authors of [11] were vague in their description of how the protocol reacts when the number of redundant receptions is less than three. Our version verifies that the source of each redundant transmission is farther than a threshold distance from the receiving node; otherwise the node does not rebroadcast. In other words, our simulated protocol combines the Distance-Based and Location-Based schemes.

Neighbor Knowledge is the largest category; it contains seven protocols from six different articles. We chose to implement two protocols to represent this category: SBA and AHBP. The following discussion justifies this choice.

The seven neighbor knowledge protocols can be classified by whether a node makes a local decision to retransmit a broadcast packet. A node that uses Flooding with Self Pruning, SBA, or LENWB makes this local decision. A node that uses Dominant Pruning, Multipoint Relaying, AHBP, or CDS-Based Broadcasting is told (either via the packet or via a previously sent control packet) whether it needs to retransmit a broadcast packet.

We chose SBA to represent the protocols that make local decisions on whether to rebroadcast. Although Flooding with Self Pruning was applicable in some network conditions, it was shown to be inefficient in others [9]. Similarly, the authors of LENWB [17] show that the base protocol performs poorly over a range of network conditions common to MANETs. SBA, on the other hand, uses neighbor knowledge efficiently and was shown to obtain good simulation results in [13].

We chose AHBP to represent neighbor knowledge protocols that do *not* make a local decision on whether to rebroadcast. AHBP uses a more efficient algorithm for selecting next hop rebroadcasting nodes than Dominant Pruning. In addition, AHBP appears to benefit from the three ways in which it differs from Multipoint Relaying. Other work on connected dominating set based routing in ad hoc networks include [16] and [18], both of which propose distributed algorithms to efficiently approximate a minimum CDS in a network. However, since AHBP and its mobility extension (AHBP-EX) are well defined in [14] we chose it over the CDS-Based Broadcast Algorithm.

4. DESCRIPTION OF STUDIES

We provide a side by side comparison of the broadcast protocol categories in this paper. Specifically our goals are to:

1. Compare the protocols over a range of network conditions including node densities, node mobility and traffic rates.
2. Pinpoint areas where each protocol performs well and areas where they could be improved.
3. Propose protocol enhancements to improve performance.
4. Discover if any one protocol stands out in its current form as being appropriate for diverse network conditions. That protocol may serve as an appropriate model for standardization or as a benchmark for further work.

To attain these goals we focus on a four part study. Each study is outlined in a subsection below. While our four studies vary some network parameters, the ones outlined in Table 1 remain constant for all simulations. Our network area and node transmission distances were chosen to allow reasonably timed simulation of networks characterized by high node density, congestion level and node mobility.

Simulation Parameter	Value
Simulator	NS-2 (1b7a)
Network Area	350 x 350 meter
Node Tx Distance	100 meter
Data Packet Size	64 bytes payload
Node Max. IFQ Length	50
Simulation Time	100 seconds
# of Trials	10
Confidence Interval	95%

Table 1: Simulation Parameters Common to All Studies

4.1 Study 1 - Algorithm Efficiency

The purpose of this study was to evaluate the core algorithms of the different protocols by comparing their performance in a static network using a Null MAC. Each algorithm has a different level of complexity and one would hope that the more complex protocols have the best performance. The algorithms are highly dependent on the density of the network. In sparse networks, the protocols are expected to perform similar to Flooding, as each node may have to rebroadcast to reach isolated neighbors. As density increases, proportionally fewer nodes should rebroadcast.

In addition to the “worst-case” bound provided by Simple Flooding, we also include a theoretical “best-case” bound provided by the Minimum Connected Dominating Set (MCDS). An MCDS is the smallest set of rebroadcasting nodes such that the set of nodes are connected and all non-set nodes are within one-hop of at least one member of the MCDS. It is impossible for any algorithm to perform better than the MCDS and unlikely to perform worse than Simple Flooding. Thus, these two bounds provide a useful spectrum to gauge the relative performance of the protocols. Most previous broadcast papers compare specific protocols to Flooding; to our knowledge, this “best-case” bound comparison has not been done in any previous work.

We note that the determination of an MCDS is an NP Hard problem. A number of papers have proposed *approximation* algorithms to determine MCDS, e.g., [6]. However, since we want the exact MCDS, we implemented a Brute Force and Ignorance (BFI) method that, given a static topology, iterates through every possible node combination for a proposed MCDS size to determine if indeed there is an MCDS of that size.

For this study, we varied the number of nodes randomly placed in the network area from 20 to 110. Table 2 shows the average number of neighbors (i.e., the actual neighbor count for each node averaged over 10 runs). Our average number of neighbors covers the gamut of sparse to dense networks.

By using a static network and Null MAC, we avoid any effects that mobility and congestion may have on the protocols. In other

# Network Nodes	Avg # of Neighbors
20	3.8
30	6.0
40	7.6
50	9.1
60	11.2
70	13.9
90	18.1
110	21.2

Table 2: Average Number of Neighbors for Different Numbers of Network Nodes

words these conditions give a good quasi-theoretical view of the core algorithms of the protocols. In addition these conditions also approximate networks which may be characterized by high stability and very low traffic rates. A broadcast packet origination rate of 10 packets per second was used, although the use of a Null MAC renders the origination rate irrelevant.

4.2 Study 2 - Congested Networks

The purpose of this second study is to quantify the effect of congestion on each of the protocols. Obviously the delivery ratio of Simple Flooding will suffer in this study, as a congested network causes numerous collisions and/or queue overflows. The other protocols, as more efficient schemes, should be less sensitive to congestion. This study was performed using the contention based 802.11 MAC scheme.

Congestion can be obtained by increasing packet size, increasing frequency of packet origination or both. We chose to fix the packet size and vary the packet origination rate (source rate) because we anticipate broadcast packets, as control type packets, to generally be small in size. In this study, the payload portion of each packet was set at 64 bytes and the rate was varied from 1 packet per second to 80 packets per second. To create a random traffic pattern, each new packet was assigned a source node randomly chosen from the entire pool of network nodes.

The number of network nodes was set at 60, which roughly represents the median value from Study 1. One might expect significantly different results using different numbers of network nodes. However, the goal of this study is to obtain a general trend for the effect of a congested network.

A static network was used for this study to ensure that the effects of mobility would not interfere with the effects of congestion. To avoid any anomalies in one static network topology, we average the results over 10 unique topologies for each packet source rate.

4.3 Study 3 - Mobile Networks

Study 3 focuses on the ability of each protocol to react effectively to node mobility in the network. Previous work has demonstrated that Simple Flooding is relatively insensitive to mobility [7]; the optimized schemes should mimic that behavior.

A Null MAC is used in this study to ensure no effect from congestion. The packet source rate was set at 10 packets per second; Since all results are provided on a per packet originated basis, and since a Null MAC is evaluated, the packet source rate is fairly inconsequential. Similar to Study 2, the number of network nodes was set at 60.

We use the random waypoint mobility model [2] with zero pause time. The range of mean speeds is varied from 1 to 20 meters per second in our simulations. In our simulations, nodes chose a random location in the simulation area and moved to that location at a given mean speed plus or minus 10%. When a node reached the location, it immediately chose a new random location and speed and moved to that new location at the newly chosen speed.

The choice to use zero pause time and this range of speeds is somewhat arbitrary. Previous work shows that pause times over 20 seconds adds significant stability to dynamic networks [1, 3]. Since we preferred to test the protocols without this added stability, we chose to use zero pause time.

One could argue that our simulations are unrealistic, especially at the 20 meter per second scenario. We agree that it is unlikely to have nodes moving at close to 50 miles per hour in this pattern in a 350x350 meter space. However, we view mobility as a proxy for link change rates in general. For example, links may break from nodes moving behind obstructions (or vice versa), from interference from other utilizations of the public bandwidth, or even from node devices being turned off. Although we have no supportive data to conclude that these mobile scenarios match real world networks in terms of link change rates, the range of node speeds does provide a diverse range of network conditions.

4.4 Study 4 - Combined Networks

In the previous three studies we focus on particular network conditions by varying node density, congestion and network mobility. In order to isolate the effects of those changes, we only varied one parameter. The downside is the behavior at one set of constant parameters may be different than the behavior at another set of constant parameters. Also, we risk missing the combined effects of mobility, congestion and node density.

This study attempts to address those concerns. To perform a complete study, one should simulate all combinations of node density, node speed and packet source rates. Since that breadth of coverage isn't appropriate for the scope of this paper, we chose to aggregate parameters into five trials to give an overview of performance at combined conditions.

In the previous studies we increase node density, traffic source rates and average node speed. In other words, we evaluate the protocols as the severity of the network environment increases. We maintain this trend of increasing severity along the x-axis. The five trials are designed so that Trial 1 takes a combination of the least severe conditions and Trial 5 takes a combination of the most severe conditions. The specific parameters are shown in Table 3.

This particular aggregation of the three previous studies provides several bits of important information. Among others things, it demonstrates how the protocols react in real networks. It allows us to gauge relative importance of node density, mobility, and congestion to the overall performance of each protocol. It illustrates the general limits of each protocol for a given network environment. Lastly, it provides a cursory indication of which protocol reacts best over a range of network severities.

Trial	1	2	3	4	5
# of Nodes	40	50	60	70	90
Avg. Speed (m/sec)	1	5	10	15	20
Pkt. Src. Rate (pkts/sec)	10	20	40	60	80

Table 3: Study 4 Trial Simulation Parameters

5. RESULTS

In addition to the simulation parameters provided in Section 4, protocol parameters must be specified. Protocol parameters for all simulations, unless otherwise noted, are shown in Table 4. The Counter-Based and Location-Based threshold values were chosen

Parameter	Value
CB Threshold	3
LB Threshold	45 meters
RAD Tmax	0.01 seconds
“Hello” Beacon Interval	1/second

Table 4: Protocol Parameters

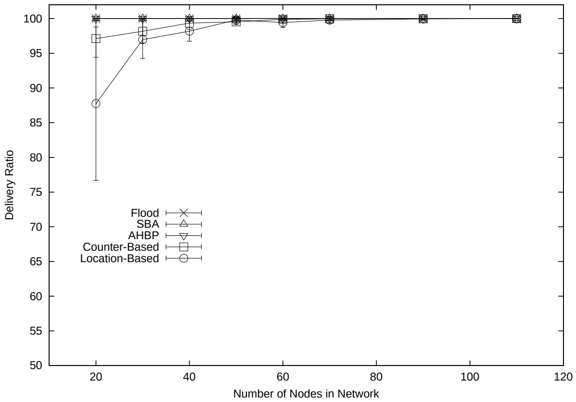

Figure 2: Delivery Ratio versus Number of Network Nodes

to minimize the number of retransmitting nodes with the constraint of maintaining at least 95% delivery ratio in a 30 node network (the effects of threshold values are illustrated in Study 1). RAD Tmax times, which affect all protocols except Flooding and AHBP, are important for studies that do not use a Null MAC (Study 2 and Study 4). Finally, a beaconing period, for SBA and AHBP, is needed for studies where the nodes move (Study 3 and Study 4); for studies with a static network, “Hello” packet costs are not considered.

As mentioned in Section 4, each point on each graph presented in this section is the average of 10 simulation runs. We include error bars which indicate 95% confidence that the actual mean is within the range of said interval. In certain cases, the confidence intervals are small enough that they are obscured by the symbol itself.

5.1 Study 1 - Algorithm Efficiency

Figure 2 shows the delivery ratio (the percent of network nodes who receive any given broadcast packet) for each protocol as the number of nodes is increased in a static network with a Null MAC. As shown, all protocols are highly reliable in dense networks; in sparse networks, Simple Flooding and protocols that utilize neighbor knowledge are the most reliable.

Figure 3 shows the number of retransmitting nodes required by each protocol as the node density increases. The figure illustrates that each broadcasting scheme except Flooding is scalable in terms of higher node density in a fixed network area. As expected, the protocols utilizing more complex algorithms require the least number of rebroadcasts. In general, the neighbor knowledge schemes require fewer rebroadcasts than the area based schemes, which require fewer broadcasts than the probability based schemes. In other words, neighbor knowledge schemes benefit from the “Hello” packet and high algorithmic costs by having fewer nodes retransmit each broadcast packet. In sparse networks all schemes converge to Flooding, as each node must retransmit each packet. In dense networks (e.g., in the simulations with 110 nodes), the theoretical best case MCDS requires 8% of the nodes to rebroadcast versus AHBP which requires 18% of the network nodes to rebroadcast. While there is room for improvement, AHBP approximates the minimum fairly well. Note that actual MCDS values were only calculated for networks up to 70 nodes; the BFI calculations were too computationally intensive for networks with more than 70 nodes. We project MCDS for more than 70 nodes in the network with a dotted line. We note that the MCDS size is relatively constant over the range of node densities in Figure 3, which intuitively makes sense. Given a fixed node transmission distance, MCDS size should only increase with network area. Simulation results not shown in this paper verify this expectation.

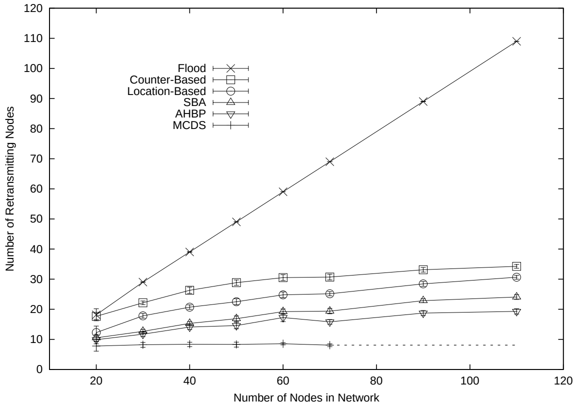

Figure 3: Number of Retransmitting Nodes versus Number of Network Nodes

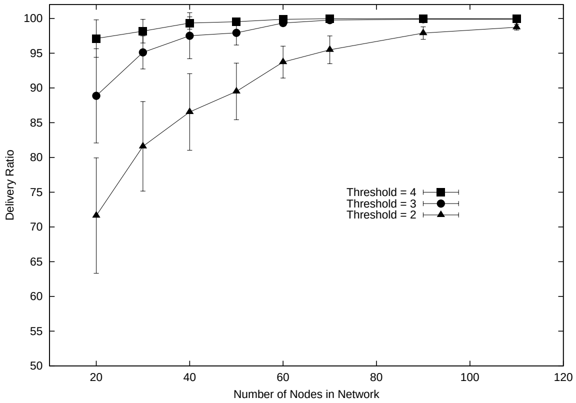

Figure 4: Counter Based Scheme - Sensitivity of Delivery Ratio to Threshold Value

In the previous two graphs, the threshold values for the Counter Based and Location Based Schemes were held constant. Those values, however, are not optimal over the range of node densities simulated. Figure 4 shows the delivery ratios for the Counter Based scheme given various threshold values. To maintain a high delivery ratio in sparse networks, a higher threshold is needed; to maintain a high delivery ratio in dense networks, a lower threshold can be used. Figure 5 illustrates that a lower threshold value means fewer nodes retransmit. Thus, extending the Counter-Based scheme to adapt its threshold value based on neighbor density would improve the overall performance of the protocol. This extension would likely require the use of “Hello” packets. One could argue, however, that if “Hello” packets are used, a protocol should use the available neighbor information more intelligently.

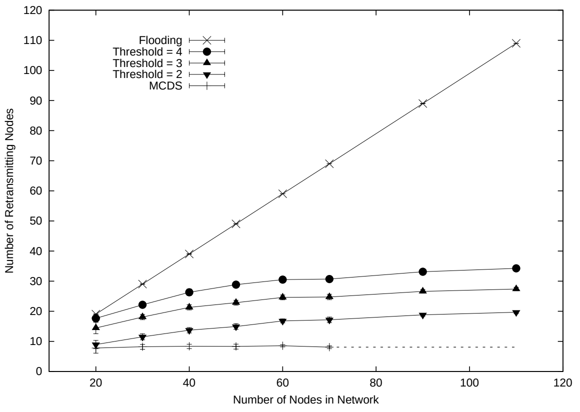

Figure 5: Counter Based Scheme - Sensitivity of Number of Retransmitting Nodes to Threshold Value

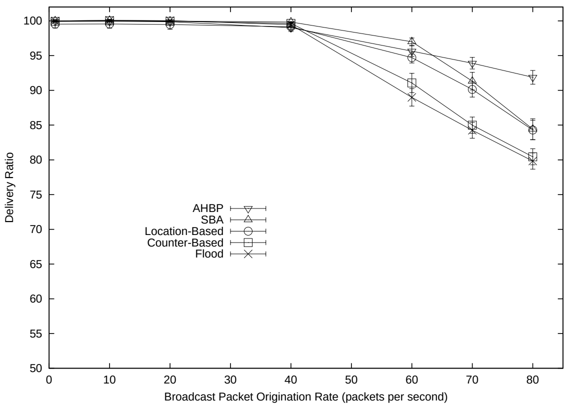

Figure 6: Delivery Ratio versus Packet Origination Rate

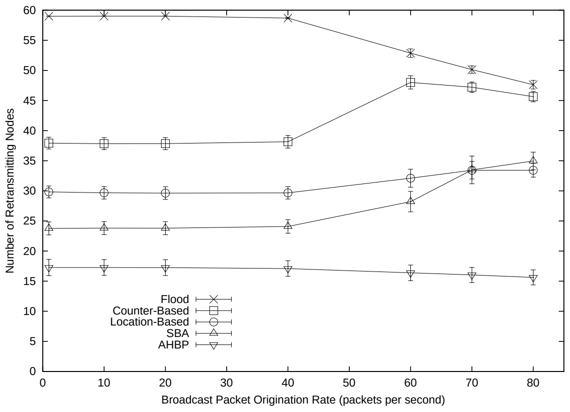

Figure 7: Number of Retransmitting Nodes versus Packet Origination Rate

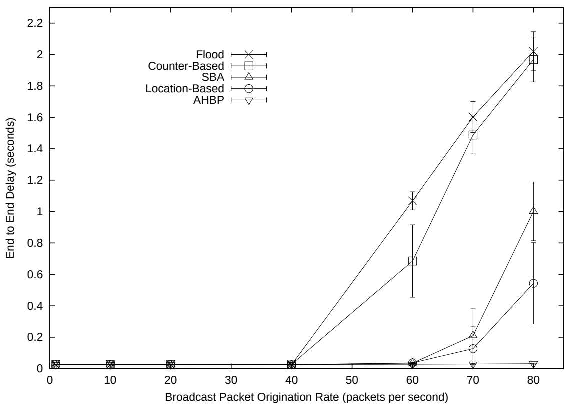

Figure 8: End to End Delay versus Packet Origination Rate

A similar study was performed for the Location-Based scheme in which threshold values were evaluated at 35, 45, 65 and 85 meters. Results show that a threshold value of 35 meters is preferred for sparse networks and 85 meters is preferred for dense networks. Thus, the Location-Based scheme would also benefit from adaptation based on neighbor density.

5.2 Study 2 - Congested Network

Recall that the goal of Study 2 is to test the protocols under the constraint of limited bandwidth using the IEEE 802.11 MAC. Thus, all figures presented in this section increase the number of broadcast packets originated per second along the x-axis.

Figure 6 illustrates that each protocol suffers as the network becomes more congested. Comparing this figure to Figure 3 shows the relationship between performance in congested networks and the number of redundant retransmissions: protocols that minimize the number of redundant retransmissions deliver the most packets in congested networks.

Figure 7 shows the number of retransmitting nodes as the network becomes more congested. Since the number of network nodes and the simulation area remain constant, one might expect the number of retransmitting nodes to remain constant in Figure 7 as well. Indeed, AHBP seems to basically follow this trend. The Counter Based, Location Based and SBA protocols, on the other hand, incur increased number of retransmissions per broadcast packet as the number of broadcast packets originated increase. This increase in retransmissions is due to the RAD utilized by each of these three protocols. In the Null MAC case of Study 1, the RAD had little consequence because delivery of packets was instantaneous. In this study, the delivery of packets is subject to delay due to the transmission times, back-offs from failed clear channel assessments, and blocked IFQs. Essentially, higher congestion prohibits redundant packets to be delivered during the RAD; therefore, more nodes rebroadcast. More rebroadcasts further congest the network resulting in a snowball effect. For Flooding, the number of retransmitting nodes drops as the network becomes congested, which directly illustrates the effect of collisions and queue overflows in congested networks.

Figure 8 verifies that there is a strong correlation between end to end delay (the time it takes for the last node to receive a given packet) and the origination rate of packets in the network. To maintain high delivery rates and low end to end delay, we propose that RAD be adapted to the state of network congestion. We evaluate this proposal in the following discussion.

Figure 9 shows the delivery ratio and Figure 10 shows the end to end delay of SBA for different Tmax values used in RAD determination. Recall that the RAD time is randomly chosen between 0 and Tmax seconds. Note that the higher assessment delay is effective in increasing the delivery ratio of SBA in congested networks. Combining the results in Figures 9 and 10 provides the following two conclusions. First, when a network is not congested, low RAD values are desired. Second, when a network is congested, high RAD

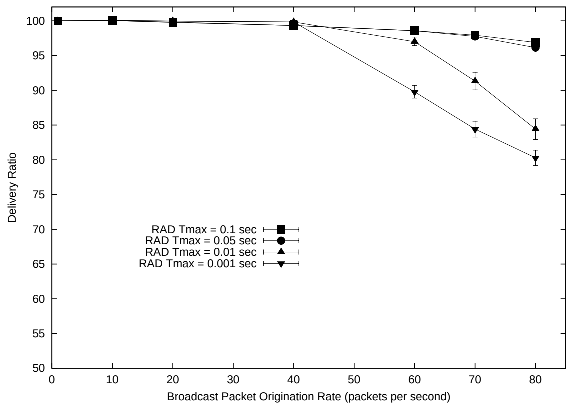

Figure 9: SBA - Sensitivity of Delivery Ratio to RAD Tmax

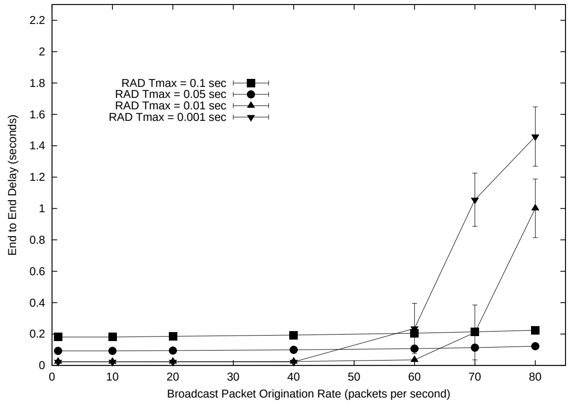

Figure 10: SBA - Sensitivity of End to End Delay to RAD Tmax

values are desired. Adapting RAD in this manner maximizes delivery ratio and minimizes end to end delay. The rest of this section describes results for our adaption of SBA to congestion. A similar adaptation is possible for any protocol that uses a RAD (e.g., the Counter-Based and Location-Based schemes).

In Section 2, we show that queue lengths are not a good indication of congestion in the network in our simulations. Therefore, to adapt SBA's RAD Tmax to congestion levels, each node keeps track of the number of packets received per second. Table 5 provides average packet reception rates for SBA given various broadcast packet origination rates. A clear relationship exists between congestion and number of packets received[2]. Our SBA adaptive scheme is a simple one: if the node is receiving more than 260 packets per second on average (which correlates roughly to a broadcast packet origination rate of 50 packets per second), the node uses a RAD Tmax time of 0.05 seconds. Otherwise, the node uses a RAD Tmax time of 0.01 seconds.

Figure 11 shows the performance of our adaptive SBA scheme against the original SBA scheme and AHBP. The adaptive SBA is the best performer with respect to delivery ratio; in fact, it is the only protocol with 95% delivery ratio for all congestion levels. While not shown, the adaptive SBA does require more retransmitting nodes per sourced packet than AHBP (e.g., 38% of network nodes versus 28% for all congestion levels); the improved delivery ratio comes at a cost of individual node resources.

Pkt Orig. Rate	Avg. Rcvd. Pkts / Second
10	49
40	192
60	324
80	407

Table 5: Average Packet Reception Rate for a Given Packet Origination Rate

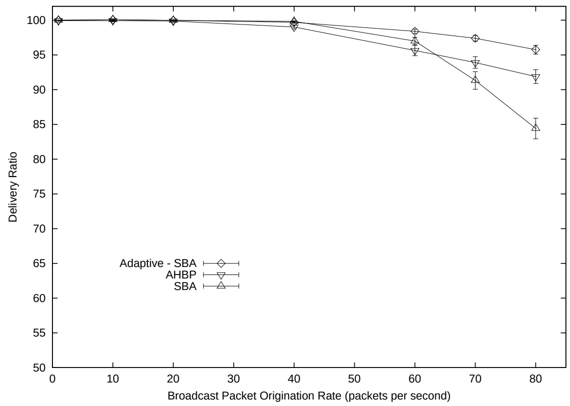

Figure 11: Delivery Ratio for Adaptive SBA

This study shows that methods which minimize the number of rebroadcasting nodes deliver the highest number of packets in congested networks. From this we conclude that (in general) neighbor knowledge methods out perform area based methods which out perform probability based methods in congestive situations. The improved performance corresponds to higher algorithmic cost and, for neighbor knowledge methods, processing cost of “Hello” packets.

5.3 Study 3 - Mobile Network

This study focuses on the response of the protocols to mobile environments; we track performance as mean node speed increases along the x-axis. To remove any congestion effects, a Null MAC was used[3]. We chose 60 nodes (i.e., the median value from Study 1) and a 10 packet per second source rate.

Figure 12 shows that AHBP suffers from a changing topology. The mobility extension for AHBP (AHBP-EX) marks an improvement over AHBP; however, it still under performs the other protocols. As discussed in Section 3, AHBP-EX requires a node which receives a packet from an un-recorded neighbor (i.e., a neighbor not currently listed as a 1-hop neighbor) to act as a Broadcast Relay Gateway (BRG). In other words, AHBP-EX handles the case when a neighbor moves inside a node's transmission range between “Hello” intervals. The extension does not handle the case when a chosen BRG is no longer within the choosing node's transmission range. No recourse is provided in AHBP-EX to cover the 2-hop neighbors that this chosen BRG would have covered.

SBA, another neighbor knowledge method, is less sensitive to changing topologies than AHBP because SBA requires each node to assess its own topology. Recall that if a SBA node receives a

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[2] We only measure packets received because our simulations only include SBA broadcast packets of the same size. Tracking bytes received per second would be a better metric for congestion in networks utilizing a number of different packet types and sizes.

[3] The use of a Null MAC precluded the need to simulate the Adaptive SBA defined in Study 3.

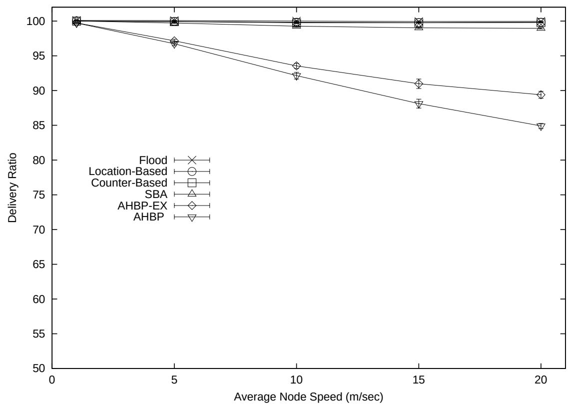

Figure 12: Delivery Ratio versus Average Node Speed

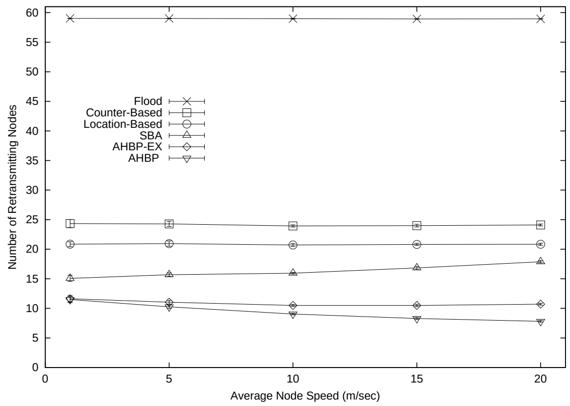

Figure 13: Number of Retransmitting Nodes versus Average Node Speed

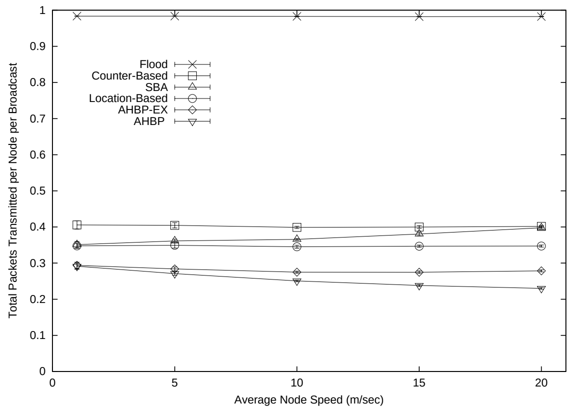

Figure 14: Total Packets Transmitted per Node per Broadcast Originated versus Average Node Speed

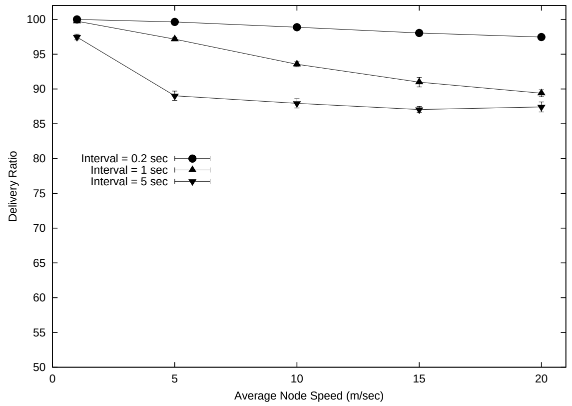

Figure 15: AHBP-EX - Sensitivity of Delivery Ratio to "Hello" Packet Interval

packet from a new neighbor, it is unlikely to know of any common 1 or 2-hop neighbors previously reached; thus the node is more likely to rebroadcast. As shown in Figure 13, SBA naturally adapts to mobility by requiring more nodes to rebroadcast. AHBP and AHBP-EX, on the other hand, have fewer nodes rebroadcast as speed increases.

We evaluate the total transmission overhead (broadcast packets plus "Hello" packets) of AHBP and SBA and compare them to the protocols that do not require periodic beaconing in Figure 14. Figure 14 illustrates that at the one second beaconing period AHBP-EX remains the least transmission expensive while SBA becomes more expensive than the Location-Based Scheme and as expensive as the Counter-Based scheme at high mobility. The result indicates that neighbor knowledge methods must use "Hello" packets judiciously; otherwise the cost of beaconing outweighs the benefits of having fewer rebroadcasting nodes. As an example, one viable adaptation technique to correct for high mobility in AHBP-EX is to use shorter intervals between "Hello" packets. Figure 15 demonstrates that shortening the "Hello" interval from 1 second to 0.2 seconds allows AHBP-EX to maintain a high delivery ratio with a changing topology. Figure 16 shows the cost of the shorter interval in terms of total packets transmitted per node per broadcast and compares the costs to that incurred by the Counter-Based scheme. The shortest interval (0.2 seconds) is required for AHBP-EX to have a delivery ratio above 95%, but the total transmissions needed are nearly twice that required by the Counter-Based scheme. Furthermore, while a node only transmits one "Hello" packet per update interval, it will receive a "Hello" packet from each of its neighbors. The reception overhead is high, especially in dense networks.

We note that the broadcast traffic packet origination rate of 10 packets per second means the cost of the "Hello" packets was amortized over a moderately low number of broadcast packets. A higher traffic rate, while hiding the "Hello" packet cost in a larger number of total transmissions, still produces the same general trend: decreasing the "Hello" packet interval incurs node resource costs that outweigh the performance gains.

5.4 Study 4 - Combined Network

In the previous three studies, we evaluated increasing the number of nodes, the amount of congestion and the degree of a changing topology independent of each other. In this study we evaluate the effect of all three parameters changing simultaneously by aggregating parameters into trials. Table 3 lists specific parameters; to summarize, as the trial number increases, the severity of the network environment also increases. Combining the conditions allows us to make observations regarding the relative effects the conditions have on each other.

Figure 17 shows delivery ratios for each protocol in each trial. As the severity of the network environment increases, each protocol has a "breaking point" in terms of its ability to deliver packets. Flooding breaks first, after Trial 2. The Counter-Based and

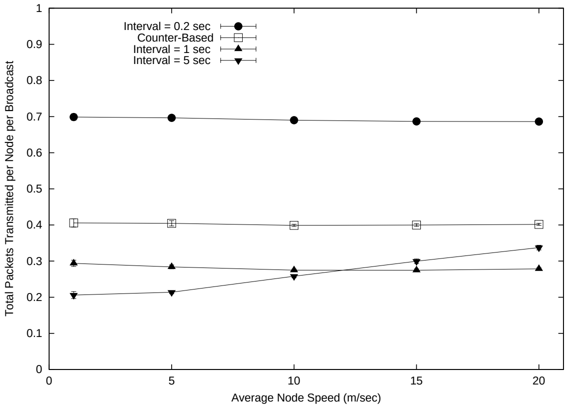

Figure 16: AHBP-EX - Sensitivity of Total Packet Transmitted to "Hello" Packet Interval - Compared to the Counter-Based Scheme

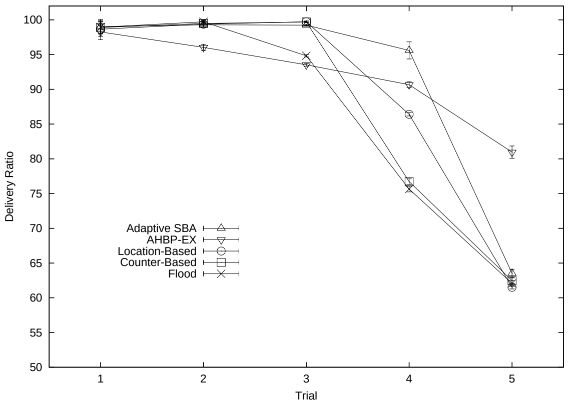

Figure 17: Delivery Ratio as Severity of Network Environment Increases

Location-Based protocols break second, after Trial 3, and the Neighbor Knowledge protocols break last, after Trial 4. The Adaptive SBA scheme is the highest performer through Trial 4, after which congestion appears to catastrophically interfere with its ability to deliver packets. Our simple adaptation described in Study 2 was not sufficient to handle the congestion caused by high packet origination rate coupled with high node count. A more robust adaptation, which uses longer RADs, is possible and is an appropriate topic for future research.

The changing topology causes AHBP-EX to be the worst performer through the first three trials. However, AHBP-EX degrades the most gracefully, and in Trial 5 it outperforms all other protocols by roughly 20%.

Figure 18 shows the number of retransmitting nodes for each trial. All protocols experience an increase in the number of rebroadcasting nodes as the severity of the network environment increases. In fact, the Counter-Based scheme appears to mimic the behavior of Flooding after Trial 3 in terms of both the number of retransmitting nodes and the delivery ratio provided. As expected, the neighbor knowledge methods have the fewest number of retransmitting nodes.

Figure 19 shows end to end delay as network severity increases. The end to end delay results follow the trends shown in Figure 17.

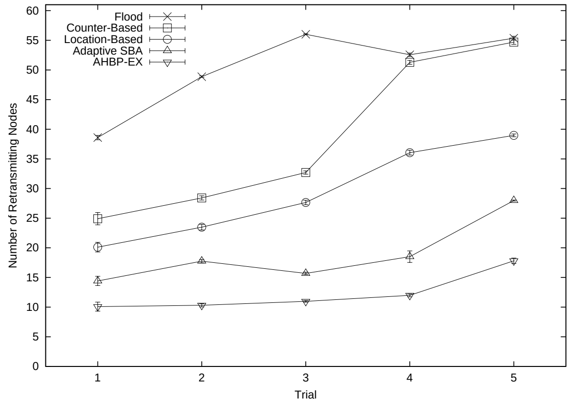

Figure 18: Number of Rebroadcasting Nodes as Severity of Network Environment Increases

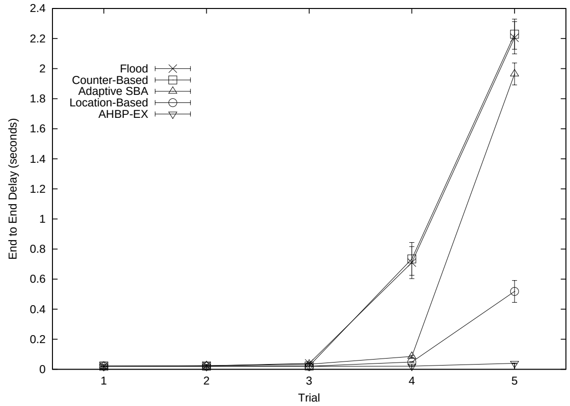

Figure 19: End-End Delay as Severity of Network Environment Increases

6. CONCLUSIONS

Our performance evaluation of broadcast protocols shows the following:

1. Increasing node count in a static network disproportionately hurts the Probability Based and Area Based schemes in terms of number of rebroadcasting nodes. SBA and AHBP, two Neighbor Knowledge methods, approximate the MCDS fairly closely as the number of nodes in the network is increased.

2. The schemes that utilize a RAD suffer in congestive networks unless a mechanism to adapt a node's RAD to its local congestion level is implemented.

3. The Neighbor Knowledge methods that do not use local information to determine whether to rebroadcast have difficulty in mobile environments; outdated 2-hop neighbor knowledge corrupts the determination of next-hop rebroadcasting nodes.

Given the inability of the Probability Based and Area Based methods to minimize the number of rebroadcasting nodes, protocols in these two categories fail to operate efficiently in congested networks. We could improve the protocols in these two categories by adapting the protocol to a node's neighbor count and local congestion level. The implementation of this improvement, however, would require the addition of both "Hello" packets and an adaptive RAD. Unfortunately, these extensions negate the inherent simplicity of the protocols, which is their most attractive feature. Furthermore, if "Hello" packets are used, a protocol which makes more intelligent use of the obtained neighbor knowledge is preferred.

We show that adapting RAD to the current congestion level improves SBA's performance in congested networks; at the highest congestion levels, the delivery ratios of Adaptive SBA were higher than AHBP. However, the gain in performance of our Adaptive SBA protocol requires a higher number of rebroadcasting nodes than AHBP. In addition, because SBA naturally adapts to dynamic topologies by increasing the number of rebroadcasting nodes, the RAD adaptive version of the protocol is unable to cope with a severe network environment (i.e., high node mobility, high node count and high bandwidth congestion).

AHBP-EX provides the best performance in the most severe network environment studied. Unfortunately, its sensitivity to node mobility produces the lowest delivery ratio in networks where the environment is dominated by topological changes (see Section 5.3).

Generally, one would expect the trade off between algorithm complexity and redundant retransmissions to be a net gain; that is, power requirements for more complex calculations is likely to be less than that required to transmit redundant packets. Combining the power ramifications with our performance results leads us to conclude that Neighbor Knowledge methods are preferred over other types of broadcast protocols. Unfortunately, there is no clear choice between the two Neighbor Knowledge methods we have evaluated. That is, based on our performance evaluation, we conclude that Adaptive SBA and AHBP-EX each fit a niche area. AHBP-EX is recommended for semi-static topologies or extremely congested networks. Adaptive SBA is recommended for all other expected scenarios. Based on the conclusions from our study, we recommend further performance evaluations and improvements of Neighbor Knowledge methods.

Our performance evaluation of broadcast protocols provides other directions for valuable future research as well. In Section 5.1 we demonstrate that AHBP approximates MCDS within 10% in dense networks. While the CDS-Based Broadcast Algorithm and other algorithmic optimizations provided in [16] and [18] may improve the approximation of MCDS, the fact that these protocols all rely on extremely accurate neighbor knowledge information makes them unattractive in dynamic networks; in other words, they share AHBP's deficiency in non-static networks. Therefore, further research in algorithmic optimizations should take a back seat to research in making these protocols effective in mobile networks.

Another important area for future research relates to SBA's RAD. Recall that SBA weights the RAD to a node's relative neighbor degree. We recommend that SBA's RAD determination be modified such that nodes with isolated neighbors rebroadcast first, similar to both AHBP and Multipoint Relaying. The goal of this proposed SBA modification is to minimize the number of rebroadcasting nodes and make it more effective in networks characterized by high congestion. Similarly, more research into adapting RAD to congestion might provide a more robust solution than the simple scheme we propose in Section 5.2.

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