Towards Reliable Network Wide Broadcast in Mobile Ad Hoc Networks

Paul Rogers and Nael Abu-Ghazaleh

Abstract—Network-Wide Broadcast (NWB) is a common operation in Mobile Ad hoc Networks (MANETs) used by routing protocols to discover routes and in group communication operations. NWB is commonly performed via flooding, which has been shown to be expensive in dense MANETs because of its high redundancy. Several efforts have targeted reducing the redundancy of floods. In this work, we target another problem that can substantially impact the success of NWBs: since MAC level broadcasts are unreliable, it is possible for critical rebroadcasts to be lost, leading to a significant drop in the node coverage. This is especially true under heavy load and in sparse topologies. We show that the techniques that target reducing the overhead of flooding, reduce its inherent redundancy and harm its reliability. In addition, we show that static approaches are more vulnerable to this problem. We then present a selective rebroadcast approach to improve the robustness of NWBs. The proposed approaches do not require proactive neighbor discovery and are therefore resilient to mobility. Finally, the solution can be added to virtually all NWB approaches to improve their reliability.

I. INTRODUCTION

The network topology in Mobile Ad hoc Networks (MANETs) is defined by the physical location of the nodes, which changes due to mobility. Network-Wide Broadcast (NWB) provides a mechanism to deliver information to nodes in a way that is resilient to topology changes. Therefore, NWB is a heavily used primitive at the core of most MANET routing [1], [2] and group communication protocols [3], [4]. A common approach to performing NWB is flooding: a process where every node that receives a packet for the first time, rebroadcasts it. Flooding has been shown to be wasteful, especially in dense networks, a problem called the broadcast storm [5]. Ni et al, who identified the problem, also proposed several solutions to it based on nodes locally determining whether their rebroadcast is likely to be needed. An alternative, topology-sensitive, approach to the problem attempts to construct a virtual backbone that is tasked with disseminating the broadcast. For example, Connected Dominating Sets (CDS) can be constructed comprising of a connected subset of the nodes that together cover all the nodes in the network; this set can then be tasked with rebroadcasting the NWB packet while all other nodes just receive it.

In this paper, we consider a different problem that adversely affects most NWB protocols: the NWB unreliability problem. This problem affects NWB protocols that rely on MAC level broadcast operations. This includes most existing NWB algorithms including flooding based protocols [5] and virtual backbone approaches (e.g., [1], [6], [7]). More specifically, because MAC broadcasts are unreliable, it is possible for rebroadcasts to be lost due to interference or transmission errors. The loss rate can be considerable if high interference exists or if link quality is bad as has been observed in wireless testbeds [8]. This may lead to the NWB reaching only a subset of the nodes. A particularly bad example of this problem occurs when the initial transmission of the flood packet is lost at all receivers (e.g., due to a collision with another packet). In this case the NWB will not reach any nodes.

NWB algorithms that control redundancy to reduce overhead have increased vulnerability to this problem; redundancy provides some protection against losses. This is especially true for virtual backbone NWB algorithms that statically determine the set of forwarding nodes: if a transmission to one of these nodes is lost, the NWB is lost to the remainder of the backbone and the nodes they cover. Lou and Wei identified the vulnerability of these approaches and proposed a solution for addressing it (Double Covered Broadcast, or DCB) [9]. DCB works by constructing virtual backbone graphs that provide double coverage of all nodes – every node in the graph is in range of two different nodes in the CDS. Therefore, two retransmissions would need to be lost before a node is not covered. They evaluated this approach and found that it improves the reliability of CDS approaches without increasing the overhead substantially. However, we show that static CDS based approaches perform worse than
In this paper, we first classify NWB protocols and outline their properties from a reliability perspective. We show that under high load (or high error rates) coverage for existing NWB algorithms, including flooding and DCB, is poor. We propose a selective additional rebroadcast solution to counter potential broadcast losses. We show that this solution leads to a substantial improvement in NWB reliability (much higher than that obtained by DCB and flooding). This is especially true in sparse networks where regions of the network may not have available redundancy for flooding or DCB to utilize. The broadcast redundancy is introduced dynamically based on the observed behavior of the network. In addition, redundancy through retransmissions can improve coverage in areas where no topological redundancy exists, for example, to bridge a critical hop that connects two partitions of a network. Because the rebroadcast decision is carried out locally, based on the observed behavior of the network, the approach can used with virtually all NWB approaches to increase their robustness. Therefore, a combination of an effective redundancy reduction algorithm, along with selective rebroadcast can yield a low-overhead algorithm without sacrificing robustness against interference and transmission errors.

It is important to note that guaranteed reliability requires acknowledgment from all recipients, which in general, cannot be accomplished in approaches that rely on MAC broadcast. For example, fully reliable NWB can be built on top of unicast communication, but at a much higher overhead than broadcast based approaches [10], [11]. We do not pursue guaranteed reliability; rather, we seek to increase the robustness of NWB to MAC broadcast losses. Throughout this paper, we use reliability in this context and not to indicate guaranteed reliability.

The remainder of this paper is organized as follows. Section II overviews MAC level broadcast and the difficulties in making them reliable. Section III presents an overview of NWB approaches and their properties and reviews other related work. Section IV overviews the NWB unreliability problem and shows its effect on node coverage. This section also presents the NWB protocols we use in our studies: we select representatives of the important classes of NWB algorithms. Section V outlines possible solutions to the unreliability problem and discusses solutions to it, including Selective Rebroadcast. In Section VI we evaluate selective rebroadcast of packets using simulation, and show that it considerably improves NWB reliability for all algorithms. Coverage improvement is excellent, but comes at an increase in the NWB overhead. Finally Section VII presents some concluding remarks.

II. BACKGROUND – MAC BROADCAST

Wireless communication properties make wireless transmissions unreliable for two primary reasons: (1) Shadowing and obstacles can cause deep fades in signal power (20dB, or 100x changes in signal power are common). This leads to a large number of transmission errors, especially when the two communicating nodes are far from each other; and (2) Collisions: the wireless channel is non-uniformly shared, giving rise to the well known hidden terminal problems [12]. A hidden terminal is an interfering node out of reception range of the sender, but in interference range with the receiver; such a transmission is not detected by the sender (it is hidden to it), causing a potential collision at the receiver. Furthermore, techniques such as Carrier Sense Multiple Access and Collision Avoidance reduce collisions but do not eliminate them [13].

To improve reliability in the face of losses, MAC protocols like IEEE 802.11 [14] use retransmission of packets that are not acknowledged. Such an approach cannot be used with broadcast packets because there are a number of receivers. Accordingly, if a broadcast packet is lost due to a collision, the loss is not detected by the sender and no retransmission is carried out. This makes MAC level broadcast operations much more susceptible to losses. As a result, NWB operations which rely on MAC level broadcast suffer from loss of coverage: the NWB unreliability problem.

III. RELATED WORK

In this section, we overview NWB approaches. We identify the following three properties: (1) Overhead; (2) resilience to mobility; and (3) robustness to the NWB unreliability problem.

A. Flooding Based Approaches

Flooding is the basic approach to NWB: each node rebroadcasts an NWB packet the first time it receives it. Flooding is a brute force approach that has high overhead, especially in dense networks [5]. Most NWB algorithms target this problem. Flooding does not require topology knowledge; therefore, it is resilient to mobility and does not require an on-going overhead to discover neighbors. Flooding is thought to be resilient to MAC losses due to the high redundancy generally available in MANETs. However, we note that in low density networks, or low density areas of networks, this redundancy is low or even non-existent.
One approach to reducing flooding overhead is to have nodes determine locally whether their rebroadcast is likely to be redundant. Ni et al [5] suggest several such approaches, where a node decides not to rebroadcast a packet: (1) probabilistically; (2) based on the number of rebroadcasts already heard (if several were heard, an additional one is probably not needed); or (3) based on the distance or location of the nearest heard rebroadcast (if it is too close, it is likely that little additional coverage is obtained from another broadcast). These approaches reduce the overhead without appreciably harming coverage. Like flooding, they are resilient to mobility. Because each node locally determines whether its rebroadcast is likely to be needed, the approach dynamically adapts to transmission losses.

B. Topology Sensitive Approaches

An alternative approach is the use of partial network topology information to build a virtual backbone that can cover all the nodes in the network. Only the nodes in the backbone are tasked with forwarding NWB packets. Such approaches have been proposed to replace flooding in routing algorithms [1], [15]. A popular approach to constructing these backbones are Connected Dominating Sets (CDS) algorithms: a CDS is a subset of the nodes that is fully connected and sufficient to cover all the nodes in the network. While finding the optimal CDS is NP-complete, algorithms have been developed to construct them distributedly, and near-optimally in terms of the size of the CDS and the overhead to construct it (e.g., [6], [7]).

In order to build a virtual backbone, nodes exchange information, typically about their immediate or two hop neighbors. Thus, ongoing overhead is required to discover neighbors. As a result, this approach degrades with increasing mobility since the neighborhood information frequently becomes stale. Typically the backbone information is used to statically determine forwarding responsibilities. As a result, this approach becomes especially vulnerable to losses: if a loss of a packet to a node with forwarding responsibilities occurs, the remainder of the backbone reachable through it and the nodes they cover will not receive the NWB.

Another class of topology-sensitive approaches tracks neighbor information but dynamically determines membership in the forwarding group. For example, in Flooding with pruning [16], a node tracks its one hop neighbors and includes them in its broadcast retransmission. Other nodes rebroadcast only if their one hop neighbors have not been covered by previous rebroadcasts; this is a local decision. If a particular broadcast is lost, other nodes will rebroadcast to compensate since their neighbors are not covered – (suboptimal) CDS’ are constructed dynamically, making this approach more resistant to MAC losses. However, the overhead is higher, and the size of the backbone is likely to be worse, than the static CDS approaches because decisions are based on incomplete one-hop information that are exchanged with every rebroadcast. The Scalable Broadcast Algorithm [17] is slightly different: instead of including the neighbor-list in the rebroadcast packet, each node tracks all its two hop neighbors. This enables a node A to determine which of its neighbors a node B covered by checking the two hop neighbor information without requiring B to transmit its neighbor list.

In summary, NWB approaches assess forwarding responsibilities either in a topology sensitive way or based on local estimates of the rebroadcast importance. Topology sensitive protocols can provide more optimal NWBs from an overhead perspective, but require ongoing overhead to exchange neighborhood information and are more susceptible to mobility. Within the topology sensitive model, another important classification is whether the forwarding responsibilities are assigned statically or dynamically at each forwarding node. Static responsibilities allow more optimized forwarding, but are more susceptible to loss of coverage due to transmission losses.

C. Addressing NWB Unreliability

All of the approaches above focus primarily on reducing the overhead of NWB relative to flooding and therefore, to varying degrees, result in reducing reliability. Reliability may be helped due to the reduction of the contention among the rebroadcast packets, especially if multiple NWBs are in progress in the network. For example, Ghandi et al. attempt to schedule rebroadcasts within a CDS approach to eliminate self-contention [7]. Pagani et al [10] and Lipman et al [11] propose a fully reliable unicast-based NWB algorithm. Unicast based approaches have a much higher overhead than broadcast-based approaches.

Tang and Gerla proposed modifications to MAC level broadcast to increase its reliability [18]. More specifically, they introduce acknowledgments to broadcasts: if one or more acknowledgments (detected as noise on the channel due to collision of the acknowledgments generated from multiple nodes) are received, it is assumed that the broadcast is successful; otherwise it is rebroadcast. Thus, this approach guarantees that at least one node receives a rebroadcast. This increases the overhead of broadcast operations significantly (each receiver
must now generate an acknowledgment for every MAC broadcast). In addition, because it requires MAC level modifications, it has a high deployment barrier.

Most similar to our work, Lou and Wei recently identified the effect of transmission losses on CDS based approaches [9]. To counter that effect, they proposed a modified CDS algorithm, called Double Coverage Broadcast (DCB), that ensures that every node is covered twice (not just once as per the CDS requirement). While DCB is more resilient to the NWB unreliability problem than basic CDS algorithms, the set of forwarding nodes is statically determined, and therefore, the approach remains vulnerable to losses.

IV. CHARACTERIZING NWB UNRELIABILITY

In this section, we characterize the effect of the NWB unreliability problem, and show that existing NWB algorithms are vulnerable to it. NWB coverage is affected primarily by two factors: the density of the network and the probability of MAC transmission loss. A dense network has multiple redundant paths that the NWB can follow allowing it to tolerate some losses without losing too much coverage. This available redundancy goes down in sparse networks, or for algorithms that aggressively control redundancy making these protocols more unreliable. Both interference and transmission losses do not apply uniformly across the network. More specifically, interference results in losses in areas closest to the interfering traffic, while transmission errors are affected by the surroundings and increase with the distance between the sender and the receiver.

The primary performance metrics we are interested in are: (1) Node coverage: number of nodes that receive the flood; (2) Overhead: number of retransmissions. However, since the number of retransmissions is a function of the number of covered nodes, raw overhead is not meaningful. Therefore, we use normalized overhead, defined as the number of retransmissions per receiving node, as a measure of overhead. For flooding, normalized overhead is always one: every covered node retransmits the packet once. Optimized NWB have targeted lowering overhead to explicitly select a set of 1-hop neighbors to rebroadcast the packet such that all the 2-hop neighbors are covered. AHBP is a CDS based approach that does not make a local decision on rebroadcasting; instead this decision is carried out by the upstream node from whom it received the packet.

Scalable Broadcast Algorithm (SBA) [17]: Each node maintains a list of two hop neighbors using periodic hello messages. When a node A receives a broadcast from node B, it knows the set of B’s neighbors (from its collected 2-hop neighborhood information). If it has additional neighbors that are not covered by B, the node schedules a rebroadcast. This is a dynamic topology sensitive algorithm (nodes decide locally whether their rebroadcast is necessary given the topology information and previous rebroadcasts).

Double-Covered Broadcast (DCB) [9]: This is a static topology-sensitive CDS-based algorithm with built in redundancy (double-coverage for every node).

For CBR interference, the sources and destinations of the interfering connections were picked randomly. In each experiment, one NWB is generated per node. We time the NWBs to ensure that successive operations do not interfere. Each data point represents an average of 20 scenarios with different random seeds. To mitigate unintended routing artifacts from interfering connections (flood overheads and silent times due to artificial disconnections that may arise under high load [20]) we use static routes in the interfering connections.

In addition to flooding, we also study the following NWB algorithms:

- Location Based Algorithm (LBA) [5]: In this algorithm, a node includes its location in the rebroadcast packet. Receiving nodes keep track of the rebroadcasts that they overhear. Based on this information a node decides whether its rebroadcast provides sufficient coverage to be worth sending. This is a dynamic localized approach that is not topology sensitive.
- Ad Hoc Broadcast Protocol (AHBP) [21]: Nodes collect two hop neighbor information and use this information to explicitly select a set of 1-hop neighbors to rebroadcast the packet such that all the 2-hop neighbors are covered. AHBP is a CDS based approach that does not make a local decision on rebroadcasting; instead this decision is carried out by the upstream node from whom it received the packet.

Figure 1 and Figure 2 show the node coverage obtained with flooding for scenarios with randomly deployed nodes. In Figure 1 interference is created using competing CBR flows whose characteristics are shown

---

1We are thankful for Tracy Camp’s group at Colorado Mines for providing us with the base code for LBA, SBA and AHBP protocols. We also thank W. Lou for the DCB code.
on the x-axis. In this case, the level of interference created by the interfering connections is not controllable; we do not control the location or the number of hops of the interfering connection(s). In contrast, Figure 2 simulates interference by dropping broadcast packets at the receiver with a fixed probability. In this case, it is clear that a large drop in the node coverage is seen due to interference. The primary observation is that the severity of the problem is more pronounced in sparse networks because of the limited redundancy available in them. As the density increases, flooding becomes more resilient to losses.

Figure 3 and Figure 4 show the coverage obtained by the different NWB alternatives with CBR interference and probabilistic dropping respectively for scenarios with 30 nodes. Several observations can be made on this figure: (1) coverage degrades for all 5 approaches as the interference increases. This fact that this occurs is not surprising, since all these protocols rely on the unreliable MAC level broadcast. However, the severity of the problem is surprising; (2) flooding remains the most reliable approach because the other approaches reduce the redundancy available in flooding; (3) the static algorithms (AHBP and DCB) perform worse than the dynamic approaches because the forwarding responsibilities are determined statically making it difficult to recover from losses. Contrast this with the location based approach where other nodes may rebroadcast the packet if a broadcast is lost since their local coverage threshold will not be exceeded. The poor performance is somewhat surprising in the case of DCB because of its double-coverage feature.

Figure 5 shows the normalized overhead of the different NWB approaches. As expected, AHBP, DCB, and SBA have a much lower overhead than flooding, due to their neighborhood knowledge algorithms. However, note that for topology sensitive algorithms (AHBP, DCB and SBA), this graph does not factor in the cost of the 'HELLO' messages that are periodically sent to accomplish neighborhood discovery. Neighbor discovery cost is more expensive than the cost of flooding since every node sends an update and receives several updates; it is even more expensive if two hop neighbors are tracked as is the case in SBA. However, this cost may
be amortized over several NWBs if multiple NWBs take advantage of a single round of discoveries. Thus, the overhead shown in Figure 5 is a lower bound for the topology-sensitive protocols, that can be quite optimistic if neighborhood discovery frequency is not much lower than NWB frequency.

The overhead of AHBP and SBA increases with the loss probability. We conjecture that this occurs because in these low redundancy algorithms, many nodes are covered by exactly one CDS member. As the probability of the loss of such broadcasts increases, the effective coverage drops per transmission, leading to higher normalized overhead. The higher redundancy in the other algorithms mutes this effect – the loss of a transmission does not necessarily lead to coverage loss if other redundant transmissions cover the same area.

The normalized overhead works well for comparing the relative overhead of the different NWB algorithms. However, it does not provide a measure for the absolute overhead in terms of the stress it places on the network, consuming power and bandwidth. This absolute overhead is application sensitive. For example, if NWBs are used for discovering paths in routing protocols, a single NWB may uncover multiple paths which can be used to transport thousands of packets before another NWB is needed. In such an application, the overhead of the NWB is marginal compared to the total number of packets sent; increasing the overhead to improve the reliability of the flood does not detract from the performance of the network appreciably. Alternatively, in an application where NWBs are dominant, the efficiency of the NWB is more important.

With increasing density, the performance of the NWB protocols improve, but the problem remains. This is demonstrated in Figure 6 and Figure 7 which show the coverage and overhead for the case of 50 nodes. Again, the static approaches (AHBP and DCB) perform badly in terms of coverage, but have the lowest overhead. The dynamic approaches perform much better than they do in the 30 node case as they benefit from the increased available redundancy. We focus on the 30 node scenario in our experiments because sparse areas of a network are the most vulnerable/challenging to the flood unreliability problem. In addition, we present sample results with denser scenarios.

V. PROPOSED SOLUTIONS

Increasing the flood reliability requires increasing the probability of the reception of flood rebroadcast operations. This is especially true in situations where their loss is likely or the redundancy in the network is low (e.g., under high interference or low connectivity). We seek to improve the reliability of the flood, rather than insure complete reliability; guaranteeing reliability requires too much overhead (for example, neighbor discovery and the use of unicast packets). Two classes of solutions can be identified: (1) MAC level; and (2) Network level.
This class of solutions modifies the operation of the MAC protocol to increase reliability. Tang and Gerla [18] proposed a scheme for increasing the reliability of MAC broadcast that works as follows. They require that broadcasts be acknowledged. If the broadcast is not acknowledged by at least one receiver, they retransmit the packet. Requiring that receiver acknowledgment may result in a number of receiving nodes concurrently sending an acknowledgment, leading to a collision at the receiver. They address this possibility by assuming that any noise heard on the channel when the acknowledgment is expected is due to a collision on the acknowledgment (no retransmission is needed). It is not clear how accurate this assumption is in the presence of other traffic in the network. Moreover, while this approach may guarantee that at least one node has received the broadcast, it does so at the cost of generating an acknowledgment from all receiving neighbors (an overhead that can exacerbate unreliability if the network is already under high load).

We identify an alternative MAC layer solution which we call directed broadcast. In this approach, one of the neighbors is tasked with responsibility for handshaking on the broadcast. The broadcast packet specifies the identity of the responsible neighbor. All nodes that receive the packet treat it as a broadcast packet; only the identified neighbor acknowledges the packet. It is also possible to carry out full RTS/CTS/Broadcast/ACK dialog with this neighbor but this is unlikely to be useful since broadcast packets tend to be short. The choice of the neighbor can be simple (any neighbor known from a currently active connection, a recent flood, or through listening promiscuously on nearby transmissions), or sophisticated (e.g., proactively discovering neighbors and choosing the one most likely to benefit the flood). Directed broadcast would be ideal for protocols that require neighborhood knowledge such as SBA [17] and AHBP [21]. While it guarantees delivery of the broadcast only to one of the neighbors, this increases the overall success of the MAC broadcast [18].

Changes to the MAC protocol require redesign of the wireless cards and the MAC standard and therefore face a high deployment barrier. Moreover, they cannot easily adapt to the surrounding conditions, which may lead to unnecessary overhead if the network is sparse or lightly loaded. For this reason we do not pursue these solutions further in this paper, and instead focus on network layer solutions.

A. MAC Level Solutions

B. Network Layer Solutions

Lou and Wei discussed a network layer solution to increasing CDS-based NWB algorithms [9]; this approach was discussed in detail in Section III. The approach we pursue in this paper is Selective Rebroadcast (SR): NWB packets are selectively rebroadcast if they are suspected to have been lost. We trade-off an increase in overhead for an increase in reliability/node coverage. This solution is dual to the solutions that attempt to reduce the broadcast storm problem [5] by cutting down on the redundancy. Those solutions selectively eliminate rebroadcasts of the flood packet if it is suspected to be redundant to cut down on the flood overhead. In contrast, we propose rebroadcasting important packets an additional time if it is suspected to be lost in order to increase reliability.

It is important to note that SR should be applied judiciously. In dense regions of the network topology, the available redundancy is high and the broadcast algorithm should cut down on the number of rebroadcasts, especially if interference is low. However, in sparse regions of the network topology, and in the presence of interference, SR can significantly improve the reliability of the NWB.

We explore the following criteria to decide when to rebroadcast a packet an additional time. This criteria mirrors ones proposed as solutions for the broadcast storm problem [5]. However, while they determine an upper threshold beyond which a rebroadcast is canceled, we use a lower threshold beyond which a rebroadcast is repeated.

1) Probabilistic Solution: a packet is rebroadcast with a fixed probability. In general, this solution is problematic because it does not adapt to the density or loss rates in the network. Therefore, it may result in large increases in the overhead when it is not needed (e.g., in dense areas and/or when interference is low).

2) Counter-Based Solution: if the node does not hear \( n \) other nodes rebroadcast the packet within a certain amount of time, it will rebroadcast it again. This solution is attractive because it naturally adapts to the interference level and density of the network. In a dense/low interference area, a number of rebroadcasts is likely to be received after a node rebroadcasts a packet. But in sparse/high interference areas, this is not the case, and the algorithm rebroadcasts a packet to enhance reliability.

In this work, we do not explore other criteria such as measuring the interference level or the density of the network (e.g., using hello messages) to determine when to rebroadcast the packet even though density information
is available in some of the NWB algorithms we explore (e.g., SBA and AHBP). For example, the probabilistic approach can be biased with the current interference level (e.g., measured as the observed utilization of the channel at the MAC level [22]) such that the probability of rebroadcast is increased if interference is high. Both such schemes and MAC level approaches are in our future work plans.

VI. EXPERIMENTAL EVALUATION

We implemented Selective Rebroadcast (SR) according to the criteria presented in the previous section (probabilistic and counter based). Since this criteria is computed based on locally available information, SR can be added to all of the NWB algorithms we are considering as follows. For the probabilistic approach, a rebroadcast timer is set probabilistically after the initial rebroadcast. In the counter based approach, the rebroadcast is initially set with a timeout value, and then canceled if \( n \) other rebroadcasts are overhead. For the NWB algorithms other than flooding, the additional rebroadcast is only scheduled if an initial rebroadcast is decided upon by the algorithm. For example, in AHBP where a subset of the nodes is selected to relay the packet further, only those nodes that have an original forwarding responsibility are tasked with an additional rebroadcast according to the probabilistic or counter-based criteria. Unless otherwise stated, we use scenarios with 30 nodes in a 1000 by 1000 meter area.

A. Analysis of Flooding

Figure 8 shows the effect of counter based SR on the coverage of flooding under CBR interference. Each graph shows the coverage with standard flooding, and the improved flooding for two density levels. Figure 9 shows the coverage for the same scenarios with probabilistic rebroadcast. While probabilistic rebroadcast shows improvement in coverage, the counter-based approach performs better because it is sensitive to the density and interference levels.

The level of interference generated by the CBR connections is unpredictable and non-uniform (interference will be generated around the hops that make up the interfering connections). Therefore, we repeated the experiment with the controlled drop scenario, where packets are dropped with a predetermined probability to simulate interference (Figure 10 and 11). The trend holds more clearly here with the improved solutions resulting in a large improvement of coverage. Again, counter-based solutions outperform probabilistic rebroadcasts; for the remainder, we present results only with Counter SR.

Figure 12 and 13 show the normalized overhead of the flood augmented with SR for a controlled drop scenario of 30 nodes. The probabilistic approach results in an increase in normalized overhead proportional to the rebroadcast probability. The counter based approach also results in an increase in the flood overhead. It is interesting to note how the overhead increases with the drop probability indicating a key property of this approach: as the loss rate increases, additional nodes compensate dynamically and generate a rebroadcast. Thus, the SR algorithm automatically increases its coverage redundancy as the loss rate increases. The overhead of DCB does not follow the same pattern because the degree of redundancy is statically fixed (at 2) regardless of the loss rate experienced in the network.

B. Other NWB Algorithms

Figure 14 shows the effect of the counter-based SR on the coverage of the other NWB algorithms with CBR interference. In all cases, Similarly, Figure 15 shows the normalized overhead with the counter based rebroadcast. Recall that the performance of the standard version of
these algorithms performed worse than flooding in terms of coverage (Figure 3). In all cases, the coverage is improved well beyond flooding. This additional coverage comes at an increase in the overhead due to the additional rebroadcasts as can be seen in Figure 15. We believe that the rather high overhead for the counter based approach is skewed due to the nodes at the edge of the network. Such nodes do not have many neighbors and end up not receiving enough rebroadcasts to satisfy the counter threshold, leading to unnecessary rebroadcasts. Utilizing neighborhood knowledge would result in appreciable improvement of this problem by adapting the threshold to the number of neighbors. This is a topic of our future research.

LBA shows a modest increase in overhead over standard flooding, but a large increase in reliability. This is due to the fact that it adapts its retransmission to the density and level of interference in the network. This is also true for SBA (and partly true for AHBP). The overhead for these protocols is lower than flooding; however, for SBA and AHBP, the overhead figure does not include the ongoing overhead of maintaining neighborhood knowledge. Finally, we believe that the overhead results are somewhat inflated due to boundary nodes where additional rebroadcasts would be unnecessarily generated. This effect can be reduced or eliminated with neighborhood knowledge.

Figure 16 presents the coverage achieved by SR in the more dense 50 node scenario. These results are shown to demonstrate that solution applies at higher density. Again, coverage is considerably improved with SR at a modest cost in terms of overhead. We believe that for many applications, such as route discovery, the increased reliability is worth a small increase in overhead.

C. Effect of Mobility

Figure 18 and Figure 19 show the effect of random waypoint mobility with 5 m/s and 15 m/s average speed respectively on node coverage achieved by the NWB algorithms. Neighborhood discovery was carried out every 1 second. Even at such an aggressive neighbor discovery frequency, it is clear that the performance of AHBP and DCB degrades with mobility. The dynamic approaches appear more resilient to mobility. Overhead
did not appreciably change with mobility, as can be seen in figure 20 (again, this overhead does not include the neighborhood discovery component).

Figure 21 shows the performance of the NWB algorithms with SR (counter-based with 2 rebroadcast threshold). Again, SR improved the coverage of all protocols. Overhead (Figure 22) did not change perceptibly with mobility.

VII. CONCLUSIONS

Network-Wide Broadcasts (NWBs) are important operations in Ad hoc networks that are used in several routing and group communication algorithms. Existing research has targeted efficient NWB to reduce the amount of redundancy inherent in flooding (the simplest NWB approach). As a result, the NWB becomes more susceptible to loss of coverage due to transmission losses that result from heavy interference or transmission errors. This problem arises because NWBs rely on an unreliable MAC level broadcast operation to reach multiple nodes with one transmission for a more efficient coverage of the nodes. In the presence of interference or transmission errors, this results nodes not receiving the NWB.

We outline the NWB solution space and explain the properties of the different solutions in terms of overhead, resilience to mobility as well as reliability. We demonstrate the problem using interference from CBR connections as well as using probabilistic dropping of packets (which allows us to control loss rate systematically). As the loss rate rises, and as the density of the network goes down, the coverage achieved by an NWB operation drops. We showed that this is especially true for other NWB algorithms that also rely on MAC level broadcasts because they target reducing the redundancy present in floods, making them more susceptible to losses. Furthermore, we showed that approaches that statically determine the set of forwarding nodes perform much worse than ones that dynamically evaluate whether their rebroadcast is likely to be redundant. As a result, the recent DCB algorithm, while it improves coverage relative to other static approaches, remains substantially more vulnerable to losses than dynamic approaches.

Several approaches to address this problem were discussed. Improving reliability at the MAC level requires a mechanism to allow acknowledgments (or partial ac-
knowledge of packet reception. Tang and Gerla had proposed such an approach where receiving nodes acknowledge a packet and acknowledgment collisions (detected as noise) are interpreted as a successful broadcast. We proposed another approach (directed broadcast) with a much lower overhead and more control on the receiving node.

We did not evaluate MAC level approaches because of the deployment barrier facing MAC level changes. Instead, we focused on network level solutions which can be directly implemented in the routing algorithm. The intuition behind our selective rebroadcast approach is to selectively rebroadcast a packet if it is suspected that it has been lost, especially if the network density is locally low. We explored two simple approaches: (1) probabilistic rebroadcast: a packet is resent after the initial forwarding with a fixed probability; and (2) counter-based rebroadcast: a packet is resent if we do not hear $n$ subsequent retransmissions of the same packet (indicating that other nearby nodes have received it).

The two criteria were added to the four NWB algorithms (LBA, SBA, AHBP and flooding). The results show that a large improvement in coverage results in all cases, with coverage higher than that of flooding, and significantly higher than that of DCB. However, this comes at an increase in overhead that rises with the loss rate (to retain coverage level in the face of losses). LBA with selective rebroadcast had lower overhead than flooding except at very high loss rates, with a large improvement in coverage. While the topology sensitive algorithms (LBA, SBA, AHBP and DCB) have lower overhead, this does not take into account the potentially high cost of neighborhood discovery.

We believe that overhead can be reduced substantially with more sophisticated policies for selective rebroadcast. For example, the nodes near the boundary of the simulated area for the counter-based approach will always rebroadcast the packet unnecessarily because they are likely to be leaf nodes for the broadcast and no subsequent rebroadcasts will result; since the counter threshold is not reached, this triggers unnecessary selective rebroadcasts. We are working on more effective policies that infer the local interference and density and use this information to more intelligently assess when selective rebroadcasts are useful. We envision an NWB algorithm that adaptively controls rebroadcasts to reduce redundancy while maintaining reliability in the presence of interference. This is one of the areas we are exploring in our future research.

REFERENCES

[1] T. Clausen and P. Jacquet, “Optimized link state routing protocol,” Internet Draft, Internet Engineering Task Force, Oct. 2003. http://www.ietf.org/internet-drafts/draft-ietf-manet-olsr-11.txt.

[2] S. Das, C. Perkins, and E. Royer, “Performance comparison of two on-demand routing protocols for ad hoc networks,” in Proc. of INFOCOM 2000, Mar. 2000.
Fig. 21. Coverage with Counter SR and Mobility (15 m/s)

Fig. 22. Overhead with Counter SR and Mobility (15 m/s)

[3] M. Lewis, F. Templin, B. Bellur, and R. Ogier, “Topology broadcast based on reverse-path forwarding (tbrpf),” Internet Draft, Internet Engineering Task Force, June 2002, http://www.ietf.org/internet-drafts/draft-ietf-manet-tbrpf-06.txt.

[4] E. Royer and C. Perkins, “Multicast operation of the ad hoc on-demand distance vector routing protocol,” in Proc. of the ACM International Conference on Mobile Computing and Networking (MobiCom’99), 1999, pp. 207–218.

[5] S. Ni, Y. Tseng, Y. Chen, and J. Sheu, “The broadcast storm problem in a mobile ad hoc network,” in Proceedings of ACM/IEEE International Conference of Mobile Computing and Networking (MOBICOM’99), Sept. 1999.

[6] K. Alzoubi, P.-J. Wan, and O. Frieder, “Message-optimal connected dominating sets in mobile ad hoc networks,” in Proceedings of the 3rd ACM international symposium on Mobile ad hoc networking and computing (MobiHoc 2002), 2002, pp. 157–164.

[7] R. Gandhi, S. Parthasarathy, and A. Mishra, “Minimizing broadcast latency and redundancy in ad hoc networks,” in Proceedings of the 4th ACM international symposium on Mobile ad hoc networking and computing (MobiHoc 2003), 2003, pp. 222–232.

[8] D. De Couto, D. Aguayo, B. Chambers, and R. Morris, “Performance of multihop wireless networks: Shortest path is not enough,” in Proceedings of the First Workshop on Hot Topics in Networks (HotNets-I), Oct. 2002.

[9] W. Lou and J. Wu, “Double-covered broadcast (dcb): A simple reliable broadcast algorithm in manets,” in Proc. of INFOCOM 2004, 2004.

[10] E. Pagani and G. Rossi, “Reliable broadcast in mobile multihop packet networks,” in Proceedings of ACM MOBICOM’97, Sept. 1997, pp. 34–42.

[11] J. Lipman, P. Bousted, and J. Chichar, “Reliable optimised flooding in ad hoc networks,” in Proceedings of the IEEE 6th CAS Symposium on Emerging Technologies: Frontiers of Mobile and Wireless Communication, May 2004.

[12] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, “MACAW: A media access protocol for wireless lan’s,” in Proc. SIGCOMM ’94, 1994, pp. 212–225.

[13] C. L. Fullmer and J. J. Garcia-Luna-Aceves, “Solutions to hidden terminal problems in wireless networks,” in Proceedings of SIGCOMM 1997, 1997, pp. 39–49.

[14] B. Crow, I. Widjaja, J. Kim, and P. Sakai, “IEEE 802.11 wireless local area networks,” IEEE Communications Magazine, pp. 116–126, Sept. 1997.

[15] R. Sivakumar, P. Sinha, and V. Bharghavan, “Braving the broadcast storm: Infrastructure support for ad hoc routing,” Computer Networks: The International Journal of Computer and Telecommunication Networking, vol. 41, no. 6, pp. 687–706, Apr. 2003.

[16] H. Lim and C. Kim, “Multicast tree construction and flooding in wireless adhoc networks,” in Proceedings of the ACM International Workshop on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM), 2000.

[17] W. Peng and X. Lu, “On the reduction of broadcast redundancy in mobile ad hoc networks,” in Proc. of MobiHoc 2000, 2000.

[18] K. Tang and M. Gerla, “MAC layer broadcast support in 802.11 networks,” in Proc. of IEEE MILCOM 2001, Oct. 2001, pp. 544–548.

[19] UC Berkeley/LNBL/ISI, “The ns-2 network simulator with the cmu mobility extensions,” 2002, http://www.isi.edu/nsnam/ns/.

[20] S. Xu and T. Saadawi, “Revealing the problems with 802.11 medium access control protocol in multi-hop wireless ad hoc networks,” Computer Networks, vol. 38, no. 4, pp. 531–548, Mar. 2002.

[21] W. Peng and X. Lu, “AHBP: An efficient broadcast protocol for mobile ad hoc networks,” Journal of Science and Technology (Beijing, China), 2002.

[22] G.-S. Ahn, L.-H. Sun, A. Veres, and A. Campbell, “SWAN: Service differentiation in stateless wireless ad hoc networks,” in Proc. of INFOCOM 2002, 2002.