Temporally Robust Relay Sets for Mobile Wireless Networks

Justin Dean, David Claypool, and Joseph P. Macker
Information Technology Division
Naval Research Lab, Washington D.C., USA
Email: {justin.dean,david.claypool,joseph.macker}@nrl.navy.mil

Abstract—Existing relay set election algorithms used for self-organizing mobile ad hoc network (MANET) [1] routing control and data forwarding are often designed to continuously minimize the relay set at topological snapshots in time. Due to errors in wireless link sensing and the potential for significant neighbor adjacency fluctuation, present distributed relay set election algorithms can cause significant reelection churn for a unicast or multicast routing protocol since the algorithm is attempting to optimize the relay set for each topological instance. This paper illustrates an investigation of improvements in temporal robustness by minimizing reelection churn caused by these algorithms. In this paper several existing relay set election algorithms are compared. This includes presentation of performance results in time when undergoing increasing congestion and dynamics due to mobility. Simple techniques designed to improve the temporal stability of the relay set population undergoing significant dynamics are presented and tested. Initial results from modeling demonstrating that temporal robustness improvement to these algorithms is achievable and that more work is needed to understand the tradeoffs, such as the additional network overhead required to achieve stability and the effect of different styles of link fluctuation and topological dynamics.

I. INTRODUCTION

The application of distributed cover set algorithms in mobile ad hoc networking systems is a core capability that has been used to realize both improvements to distributed control in unicast protocols [2] [3] [4] [5] and forwarding improvements for multicast traffic Simplified Multicast Forwarding (SMF) [6] in rapidly changing topological environments.

A goal of unicast control plane and multicast forwarding plane use of cover set algorithms is to apply reduced relay sets for more efficient data dissemination within dynamic topologies. Various classes of distributed connected dominating set (CDS) algorithms have been applied in practice. Desired characteristics of algorithms from this past work include the following:

1) Localized election or coordination of any relay sets
2) Heuristic support for preference or election metrics
   (Better enables scenario-specific management of relay set)
3) Reasonable minimization of CDS relay set size given
   above constraints
4) Robustness to topological dynamics and mobility

The minimization and robustness criteria above are often competing design requirements. Mathematically approaching a minimum connecting dominated set for each instance in time often requires frequent reelection of nodes which in turn is typically dependent upon the staleness and correctness of topological detection information collected. Link and neighborhood link status is often in significant temporal flux due to a large number of conditions including: mobility, antenna orientation, environmental conditions (shadowing, fading). In practice it has been observed that the rapid reelection of relay sets can cause decreased effectiveness to any control plane (unicast routing) or forwarding plane (multicast routing) that makes significant use of such information [7]. Non-optimized techniques such as classical flooding can provide improved robustness at light traffic loads but also lead to earlier congestion and failure at higher traffic loads. The goal is to examine tradeoffs and develop approaches to improve the measurement and evaluation of improved algorithms that can achieve increased temporal robustness while maintaining the advantages of distributed reduced relay set election.

A distributed CDS election algorithm under ideal conditions will result in a CDS for the graph upon which it is operating. That means all relays should be connected via a common subgraph and that all other nodes should be at most one hop away from a relay node. If the topology information is stale by the time it is used by the network forwarding or control plane the resultant relay nodes may not form a CDS. Figure 1 illustrates that under ideal conditions the algorithm operates in a distributed manner and connects the network, however, stale neighborhood link information can result in a partitioned network. In scenarios where topological and link fluctuations are common this type of condition is expected to occur more frequently.

Main Hypothesis: Considering the temporal disruption of links and stale election information, a more conservative relay set election strategy (keeping more relays elected, or preferring more stable relay links) will result in a more stable network with improved effectiveness both in time and against congestion.

Tradeoffs: Sensing Periodicity, Reelection Periodicity, Traffic Statistics, Link Dynamics/Error statistics

II. MANET RELAY SET ALGORITHMS

While there a large number of potential distributed optimized relay set algorithms this study is limited to three classes
of CDS algorithms used presently within MANET routing prototypes. These include the following:

- Classical Flooding (CF): A non-optimized relay set in which every node relays once. Duplication detection is provided to minimize transmission and prevent forwarding loops. Included as a comparison baseline.
- Source specific multi-point relay (S-MPR): Defined by the Optimized Link State Routing (OLSR) protocol [2] and the core foundation of other variants such as CDS-MPR. Also specified in the Appendix of the SMF Internet Draft [6]. S-MPR relay nodes are not self elected but are designated by neighboring nodes as multi-point relays (MPR). Due to this, S-MPR forwarding is previous hop dependent so multiple CDSs can exist at the same time in a single network. S-MPR guarantees shortest hop path forwarding from source nodes to all receivers.
- Essential Connected Dominating Set (E-CDS): A core algorithm specified as a building block in MANET-OSPFv3 MDR unicast algorithm [4]. Also specified in the Appendix of the SMF Internet Draft [6]. E-CDS relay nodes are self elected providing a single CDS which is independent of previous hop or multicast source. E-CDS does not guarantee shortest hop path forwarding. These reduced relay set algorithms operate by electing forwarders based on two hop network neighbor information. The validity of this information can play a major role in the performance of these algorithms. While both E-CDS and S-MPR provide some methods for assigning router priority they both currently operate using only binary link information, a link is either up or down, to elect forwarders. This limits the possible accuracy of neighbor link sensing.

III. PREVIOUS WORK

Distributed CDS election development has been largely driven by MANET/Mesh routing protocols need to distribute network topology information throughout the network [8] [9] [10]. As such, many CDS election algorithm studies [11] [12] are done in relation to routing control traffic or supporting other network layer functions. The focus of many of these studies is to discover how well these algorithms scale and often measure the amount of overhead associated with distributing topology information. Henderson in [12] does examine delivery ratios but only with regard to unicast data delivery, not link state update messages delivery rates. This is consistent with evaluating CDS effectiveness as a part of a larger unicast routing protocol and not a user data forwarding method.

Simple unit disk graph (UDG) physical models are often employed in studies examining distributed CDS algorithms [8] [10]. These models assume perfect connectivity exists inside some unit threshold and no connectivity exists outside that threshold. Methods providing redundant CDS election have been developed to help improve robustness of algorithms originally designed with maximal efficiency as the goal [4] [2]. [4] provides for bi-connected forwarding paths through the election of Backup MANET Designates Routers (BMDRs). [2] allows for selection of additional Multi-Point Relays (MPR) through the use of the "MPR_COVERAGE" parameter.

Previous studies which examine robustness of flooded traffic include [13] and [14]. While [14] examined CDS robustness using actual data traffic, one of its limitations was its use of a simpler 802.11 wireless model within NS2 which has known issues [15], [13] investigates the robustness of both self selected and neighbor designated, referred to here as E-CDS and S-MPR respectively, by introducing transmission errors, mobility, and collision effects. The transmission error model, used by [13] to conclude that S-MPR election is more robust than E-CDS, did not take distance into consideration. This model, while an improvement over UDG wireless models, is still insufficient for real world modeling.

IV. EXPERIMENTAL APPROACH

Two related issues present themselves in the current implementation and analysis of link-state dependent CDS algorithms: the algorithms represent links as binary, all or nothing link quality measures, and the analysis environment in which they are tested also represent links as such in many cases. This leads to a false sense of clean graph connectivity without regard to the temporal stability of the links. A mathematical method of tracking link state locally which can indicate to algorithms a relative and configurable measure of link quality has been devised for understanding the link quality with greater temporal relevance. This notion, combined with analysis which models links as varying entities beyond simple unit-disk or noise models, can yield a more accurate representation of the environment and a more representative understanding of network graph structure.

In this initial work studying the temporal nature of link states, the variability of delayed turn off of relay set election is first utilized in a more realistic path loss model environment. CDS algorithms S-MPR, E-CDS, and CLASSICAL as listed in [6] are tested as well as modified E-CDS algorithms, E-CDS2 and E-CDS4, which have respectively 2 and 4 second delays in turning off previously elected relay sets. Algorithms running
this delayed turn off feature continue to forwarding packets for the respective amount of time after the idealized algorithm tells them to stop forwarding. This results in more relay nodes in highly dynamic networks and no additional relay nodes in static networks consisting of stable link topologies than standard algorithm. Delayed turn off for S-MPR was not implemented or tested due to its source based nature, i.e., routers are not self electing.

In addition to delayed turn off metrics, the forwarding structure provided by the various CDS algorithms was tested through the use of a modified SMF implementation which included a per-packet forwarding delay. Upon reception of a packet to be forwarded the SMF router will check its forwarding queue. If the queue is empty a uniform random number between 0 and max jitter (10 microseconds in presented results) is selected as the hold time and the packet is added to the queue. If the queue is non-empty the packet is added to the queue and will be forwarded as soon as possible after the proceeding packet in the queue. This method of implementing forwarding jitter reflects recommendations for MANETs provided in [16].

Experimental results presented in this paper were obtained using the NS2 simulator in conjunction with the dei802.11mr wireless model [17]. Table I lists the NS2 parameters used. Figure 2 shows the link delivery ratio characteristics of the two different wireless models, UDG and Lossy, which were used for evaluation of CDS performance. Goodput, the ratio of non-duplicate data delivered vs maximal possible non-duplicate delivery across all routers, is presented as the primary metric. For all test presented, 50 mobile routers in a 1500x300 grid with a maximal radio range of 250 meters was used. This rectangular layout was selected to increase stress, higher hop count and fewer redundant network paths, compared to a square layout given the same mobility parameters. Figure 1 represents a typical network layout. All random walk mobility patterns used were fully connected throughout each 10 minute test run. In all tests, one mobile router was designated as a multicast source with all other mobile routers assigned as multicast receivers. To minimize topological effects due to random selection of a single sending router, each data point represents the average across 10 different simulation runs. The SMF protocol was used to perform duplicate packet detection and forwarding (implementation Protolib’s protomanet kernel for NS2 [19]). To drive the CDS algorithms within SMF the OLSR protocol (implementation NRLOLSR [18]) was used for its neighbor sensing mechanism, using half second hello update intervals and link timeouts of 1.5 seconds. NRLOLSR’s unicast routing functionality was turned off, including both sourcing of topology control messages and performing routing table calculations.

V. RESULTS

In the first set of experiments, Figure 3, uses the dei802.11mr UDG model and mobility patterns with maximum speeds of 12 m/s. Average goodput is measured with regard to increasing offered multicast load. The resulting "flat" curves have very poor performance for all algorithms, even at very low data rates, contradicting previous work [14]; the major difference between simulation approaches is the use of the dei802.11mr radio model, which includes

| Parameter          | Value         |
|--------------------|---------------|
| PHYDataRate        | Mode6Mb       |
| Phy/WirelessPhy PT_ | 2.2818        |
| Phy/WirelessPhy freq | 2437/6       |
| Phy/WirelessPhy L_  | 1             |
| Phy/WirelessPhy CSThresh | 4.27e-10   |
| 80211gTrivellato noise UDG | 1.35e-10 |
| 80211gTrivellato noise Lossy | 4.05e-10 |
| Mac/802_11 bSyncInterval | 20e-6      |
| Mac/802_11 gSyncInterval | 10e-6      |
| Mac/802_11 ShortRetryLimit | 3          |
| Mac/802_11 LongRetryLimit  | 5           |
| Mac/802_11/Multirate RTSThreshold | 10e-5       |
| Mac/802_11/Multirate dump_inert  | 0           |

TABLE I
PHY AND MAC LAYER PARAMETERS USED IN SIMULATION.
an updated interference and capture model. With increasing traffic loads an increase in goodput was observed as congestion was approached. Congestion occurs at different injected traffic loads for the different algorithms due to differences in algorithm efficiency. S-MPR and E-CDS curves do not exhibit this increase in goodput as congestion was not reached. This is due to queuing delay mitigating packet collisions upon forwarding. Also note that algorithms which are typically more robust, e.g. select more forwarders, are performing worse than algorithms which are more efficient. Figure 4 uses the same settings as Figure 3 but uses the newly introduced per-packet forwarding jitter. Introducing forwarding jitter removes the pathological contention which was resulting in a very large number of packet collisions and dropped packets. The results of Figure 4 match expectations and clearly illustrate the tradeoff of CDS efficiency and robustness with E-CDS2 and E-CDS4 filling the gap between standard E-CDS operation and CLASSICAL flooding. The differences in experimental results of Figure 3 and Figure 4 clearly illustrates the importance that forwarding jitter can have in certain systems. Figure 6 uses the same settings as Figure 4 but operates with the Lossy link model illustrated in Figure 2. Goodput is reduced across the board; loss rates are effectively doubled compared to results obtained using the UDG link model (i.e., poor performing algorithms did even worse under low load conditions). To examine the effect of motion on SMF performance characteristics in an environment using the Lossy link model, tests were conducted with a non-congested traffic load in increasingly mobile network scenarios; the results are presented in Figure 7. The use of the Lossy link model in semi-stable topologies results in the election of efficient CDS election in terms of number of forwarders but leads to poor performance due to forwarding paths using low quality links.

VI. FUTURE WORK

Future work in investigating performance of delayed turn off CDS algorithms involves striving to study the algorithms in context with more advanced link loss models. As a result, the next stages have begun and the authors have created a modular, more realistic approach to modeling the links between the nodes. Network link behavior in mobile environments has shown the link to be rather sporadic much more complex than a simple all-or-nothing packet success rate. Even with simple
interference models and basic probabilistic models, links often experience even terrain-independent longer-period fluctuations in performance. Links may completely die off for several seconds, only to reappear as a solid no-loss link for several seconds later. The newer link state modeling approach takes into account node mobility, relative position, terrain information, and waveform characteristics to generate a combination and time-varying link state that can more accurately represent real-world performance to replicate some of the more difficult to study aspects of the links.

Terrain, relative distance, and Doppler effects are all used to form a deterministic representation of the link loss between two nodes. This is then combined with a Markov chain to replicate the time-variant loss models. This loss rate, which in boundary regions can range greatly from high to low, is traversed over time, and is fully parameterized for a given waveform. A link at the verge of connectivity may be seemingly fully connected for some time, then wander into high loss, and come back into connection again independent of motion and instead modeled as part of the waveform real-world characteristics.

Using this approach, the CDS algorithms will need to be adapted to better sense and use the overall link state over a give usable time-frame: A link that is fully connected for several seconds at a time only to return to a lossy state needs to be treated as such. Current wireless modeling efforts do not exercise CDS algorithms in this way. Additionally, current CDS algorithms are not designed to take advantage of or maintain an awareness of these more dynamic link types. Experiments beginning with changing the history length of the graph determination and progressing to more in-depth link state tracking will be used to understand more about what values work in real-world scenarios. The hypothesis becomes that using this wandering loss model will result in a better understanding of the behaviors seen in real-world loss scenarios and can help understand how the algorithm can be improved.

The mathematics of detecting and maintaining an understanding of a lossy but usable link is being devised. Suppose we take a unit disk approach: The graph edges are unlabeled they are either present between a pair of nodes at a given point in time, or they are not. Represented as a time stamped binary matrix, the ability for an algorithm to understand the trend of links going away or forming, is unavailable in such a representation, but this is exactly the type of graph used so often in network modeling. While the logical incremental step from this is a labeled graph indicating a continuous value representing a normalized fractional link quantity or a known unit (db loss, or percent packets perceived lost), such a method is not temporally aware and is at its best simply a moving window of a region of time in understanding the link state. Instead, each connection (edge) of the graph receives a label composed of a matrix of its own.

\[
E = \begin{bmatrix}
  p_{11} & \cdots & p_{1t} \\
  \vdots & \ddots & \vdots \\
  p_{qt} & \cdots & p_{qt}
\end{bmatrix}
\]

Each edge detected (E) contains a matrix comprised of (q) rows: each row represents a given metric averaged to within a given window of time. For example, a two row matrix could be used, where the first row represents detected packet success rate, ranging from 0 to 1, and the second row represents perceived path loss rate (from, for example, a PHY layer interface which can yield such statistics, if available), normalized to 0 to 1, where 1 is a perfect signal and 0 is a completely unusable signal. The mathematical relationship between rows is unimportant, as each can later be used independently. The columns are time intervals ranging from most recent to furthest back and do not need to be of equal length. In our initial analysis, it is assigned that the time intervals double in each column, and is controlled by a separate, pre-shared interval configuration column matrix which indicated the proportion of time each column of historical values holds. By manipulating and scaling this configuration matrix and multiplying with the edge matrix data for a given link, a temporally relevant understanding of link quality can be quickly calculated for use in CDS algorithms. Figure 8 represents the data collection interval for each individual link detected by a node to a neighbor, and the variability of the historical values. From this data, differential and time-period relevant measurements can be extracted on demand. Implementing this mathematical approach is the logical next step to this work.

**VII. Conclusion**

It has been shown that delaying turn off of self elected CDS routers provides increased redundancy and improves goodput in non-congested scenarios. The cost of this improvement, a less efficient forwarding set, is only paid when operating in dynamic networks minimizing overhead. Delayed CDS turn off shows promise as a short term method for increasing goodput performance; effectively halving loss rates of E-CDS in lossy mobile environments while operating outside of the congestion zone. Unlike other CDS redundancy algorithms, such as biconnected CDS in [4] and multi-point relay redundancy coverage in [2], the delayed turn-off method differs in two distinct ways: it may be applied to various CDS election algorithms as it is
orthogonal to any particular selection algorithm; the overhead cost incurred is non-constant and depends on the dynamics of the network topology. The introduction of forwarding jitter for SMF can be critical, especially in simulation, but it is dependent on MAC layer modeling and overall system jitter. The introduction of jitter in the forwarding plan raises issues regarding queue sizes and acceptable network wide latency which should be considered when being deployed. Not all network systems will require extra forwarding jitter when rebroadcasting multicast packets but it can be essential in reducing dropped packets due to packet collisions. Lossy link modeling illustrates some limitations with current CDS algorithms. S-MPR algorithm in particular selects shortest hop forwarding paths, often electing the most unstable links for critical path forwarding. However all election algorithms tested exhibited limitations due to the use of a "link up" vs "link down" neighborhood model. This can and should be mitigated with better neighbor sensing and modified algorithms which take these link metrics into consideration.

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