Robust Networking for Bandwidth Constrained Mobile Tactical Radios

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***Abstract*—This work investigates an efficient and robust broadcast / multicast scheme for the bandwidth limited tactical environment. A local neighborhood based broadcast / multicast protocol is enhanced through managing dynamic link conditions to achieve required delivery ratio. Employing a realistic tactical radio model and practical tactical deployment scenarios, the proposed mechanism is evaluated using a network simulator. Compared with one of the most efficient standard protocols, the simplified multicast forwarding, the proposed scheme demonstrates improved efficiency and robustness.**

Keywords- routing, multihop tactical networking, broadcast, multicast, protocols, simulation

I. INTRODUCTION

Tactical radios operating in military VHF and UHF bands are one of the most dependable communication devices in battlefields. These tactical radios have long signal range, e.g., VHF radios can reach more than 20 - 30 kilometers in complex terrains. This capability is critical to real-time command-and-control as operations are increasingly deployed in dispersed environments. These radios also exhibit high spectral efficiency by occupying a very small bandwidth, e.g., 25 kHz per VHF channel [1], a critical feature due to spectrum limitations.

Extending multi-hop capabilities to tactical radios is very desirable as it will connect nodes that are temporarily out of range because of terrain impediments or node movement. This is however very challenging due to the very limited link capacity and varying link quality of these radios. VHF and UHF tactical radios typically have link rates, e.g., from 3 to 200 kbps, given the very limited spectrum in the field.

Early studies on tactical radios have identified poor multihop routing performance when network topology changes [2]. These early studies did not include comprehensive mobility models to capture dynamic performance impacts. In the past two decades, many solutions adapted from regular mobile ad hoc networks (MANET) [3-10] have been proposed to provide multihop networking capabilities for tactical radios. Most of the protocol studies assume high bandwidth radios with a link rate of more than 1 Mbps occupying a wide channel of up to 10’s of MHz, an unreasonable assumption in spectrum congested battle fields [11]. Performance studies also often assume on-off disc like radio propagation models and perfect link conditions, which are not valid in the real tactical environment.

In this work, tactical network simulation models are developed employing realistic radio and mobility parameters. A cluster based broadcast / multicast routing scheme, the robust cluster-relay scheme (RCS), is proposed to improve reliability under dynamic link conditions and severe bandwidth constraints. Evaluated in comparison to an enhanced simplified multicast forwarding (SMF) scheme using simulation, RCS achieves better path robustness and a lower protocol overhead.

The rest of the paper is organized as follows: Section 2 describes tactical networking requirements and reviews related work; Section 3 proposes the RCS scheme; Section 4 evaluates the performance and Section 5 concludes the paper.

II. TACTICAL NETWORKS

A. Networking Requirements

Tactical networks consist of a small number of nodes, e.g., 15 – 40, deployed in complex and challenging terrains [12]. The network includes multiple groups of nodes with different roles in a dispersed environment. In tactical communications, reliability, responsiveness and robustness are paramount [12].

Despite its limited bandwidth, the tactical communications traffic is predominantly broadcast and multicast, including all-informed voice, group push-to-talk, situational information sharing, etc. Messages are often concise and realtime. Due to limited link capacity, network paths with a large number of hops are not preferred because they further reduce end-to-end throughput and extend the delivery latency. The maximum number of hops between any two nodes, the network diameter, needs to be small, e.g., at 3 to 4 hops. Tactical radios often reduce transmission speeds to attain a long signal range and a small network diameter. With this small network diameter, networks have been found having high node degrees [13].

Network security and operational situational awareness (SA) are essential. This drives to requirements for network monitoring. For example, a network may be structured into clusters, where cluster heads perform additional control and management functions such as policy coordination, detection, access control (e.g., authentication), data fusion, etc. [9, 10]

B. Overview of Tactical Broadcast/Multicast Protocols

Broadcast/multicast are key communication primitives in the tactical network. Broadcast/multicast has been intensively studied for MANETs, e.g., [3, 5-10]. In a low bandwidth network, applying efficient flooding to implement both broadcast and multicast eliminates the overhead that results from building

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and maintaining a multicast tree/mesh structure [5, 10, 14]. An example of such an approach, namely the SMF protocol, is currently under consideration for standardization in the IETF MANET working group [5-6].

Most efficient flooding schemes require 2-hop neighborhood information in selecting forwarding nodes [5-7], to effectively reduce forwarding redundancy. A HELLO message is sent periodically to gather the 2-hop neighborhood information [5-7]. HELLO message overhead grows with the neighborhood density. As reported in [13], tactical networks often endure a large node degree to maintain small hop counts between dispersed nodes. This leads to an excessive HELLO message overhead. The latest standardization effort has greatly improved the message format efficiency [16] by applying address compression. The resulted performance improvement in the tactical network needs to be evaluated.

To achieve low protocol overhead and leverage the potential of a cluster head for other network functions such as monitoring, access control, etc., some cluster based protocols have been proposed that employ only 1-hop neighborhood information [8-10]. The passive clustering scheme [10] for example forms clusters on the fly when broadcast/multicast packets are being sent. It thus generates almost no network routing overhead, though it may encounter a long initial delay on each data stream while waiting for the clusters to be formed.

The performance comparison between 1-hop and 2-hop based broadcast/multicast protocols was reported in [17] for a typical tactical network scenario. However, it only focused on the protocol overhead, ignoring other path QoS issues.

This work further compares 1-hop and 2-hop based schemes to investigate the path QoS issues. The improved SMF scheme that adopts the new compressed message format and an improved cluster-based solution are applied in the simulation studies to evaluate various performance metrics.

III. Robust Network Forwarding

A. Tactical Network Model

To evaluate the performance of broadcast/multicast routing schemes in tactical networks, a simulation model was developed in Qualnet. The tactical radio signal propagation model for the VHF band is constructed in Qualnet, based on radio measurement data taken in different deployment terrains [18, 19]. From the measurement data, the signal propagation is decomposed into a path-loss component, a slow varying local component of shadowing that has a log-normal distribution [18] and a fast varying component with a Rician distribution [19]. The Rician distribution results from the characteristics of the VHF signal in a combat radio channel which has a rather narrow channel bandwidth.

As an example, the set of path propagation parameters obtained for a typical semi-rural deployment terrain is listed in Table I, with a central frequency of 57 MHz and a channel bandwidth of 25kHz. In Table I, $\alpha(d_0)$ with $d_0 = 100$ is the mean path loss at a reference distance d_0 in the far-field of the transmitting antenna, η is the path loss exponent. Using the measurements from [18], the random shadowing component was derived to have a zero mean and a standard deviation σ. The Rician K factor was also obtained from the measurement data. The semi-rural environment measured has a significant amount of rural and forested areas, some overgrown farm fields and a few two or three story brick buildings [18]. If using measurement data from the UHF band, the simulation model directly supports scenarios of UHF radios.

TABLE I. Path Loss Parameters (Central Frequency 57.0MHz, d_0 =100 m)

Terrain	Semi-rural
Exponent η	3.18
Intercept $\alpha(100)$ [dB]	68.8
Std. dev. σ [dB]	4.11
Rician K factor	4.7

Given the parameters in Table I, in the semi-rural terrain, nodes less than 7 km apart may hear each other with a probability very close to 1. A detailed link characterization for different terrains and distances can be found in [13, 17-19]. As the nodes are moving further apart, the data reception ratio will decline. The behavior is far from a simple on-off disc model with a fixed radius. This realistic tactical radio layer was built into the simulation model, which was then applied to study the performance of broadcast/ multicast routing protocols.

B. Performance Issues in Multihop Relay

The lightweight cluster-based scheme proposed in [17] and the SMF protocol were selected as typical solutions that are based on 1-hop and 2-hop neighborhood information, respectively. In the cluster-based scheme, each cluster has a Cluster Head (CH) whose one hop neighbor nodes are cluster members. A CH node belongs to only one cluster. Thus when two CH nodes hear each other, one of them will cease to be the CH. A cluster member that hears more than one CH may be selected as a gateway (GW) node. For each packet sent by a source node, its CH will forward it to reach every node in the cluster. A gateway node also forwards the packet to reach one or more new clusters. In the new cluster(s), the packet is further forwarded by the CH [10, 17]. The process continues to cover the entire network.

A node declares itself as a CH based on two factors [17]. The number of its one hop neighbors and the value of its CH priority parameter should both be preferably high. The process starts with a CH node claiming its Cluster ID (C-ID) and the role “CH” in a “Cluster Maintenance (CM)” message. Then all its one hop neighbor nodes automatically join the cluster by sending the C-ID and the role “member” in their own CM messages. A node further out only hears CM messages of some member nodes but not of a CH, it may decide to become a CH based on the criteria described above. The clusters thus are formed propagating from the first CH to the rest of the network. The CM message is one hop only, very small in size, and embedded in the periodic MAC beacon message. A gateway candidate node that hears more than one CH specifies all the C-IDs it has. The CH selects the GW nodes from gateway candidates to reach all the neighboring clusters. More details of this simple clustering scheme can be found in [17], which is a typical low-overhead 1-hop based clustering mechanism [9, 10].

This cluster-based scheme and the SMF protocol were then simulated using the tactical network simulator. The average broadcast data delivery ratios of both the cluster scheme and SMF were often below 90%. The data loss is caused by link errors, especially with increased distance between the nodes. The selected relay nodes in both schemes experienced dynamic link degradations, caused by node mobility and radio path random fading. Then, certain nodes in the network fail to receive the packets from the relay nodes that are supposed to forward them the packets.

C. Robust Cluster-relay Scheme (RCS)

To improve path robustness of the cluster based solution, a new robust cluster-relay scheme (RCS) extends the previous simple cluster-based approach by employing two techniques. First, a link metric is established so that path formation seeks to select high quality links. Second, local redundancy is employed to form a strong neighborhood of each cluster.

To monitor link status, two parameters are gathered based on the reception history reported from the MAC layer. The first is the recent link average status α which depends on the number of beacons received in the past X consecutive beacon intervals. The second parameter is the link trend status β based on the number of beacons consecutively received in the Y most recent intervals. In the simulation, $X = 2Y$ with $X = 8$ is selected. The link metric δ is then computed using the average status and the trend status, e.g., as $\delta = \lfloor(\alpha + \beta)/2 + 0.5\rfloor$. In the implementation, links under about 50% in the counts in *X(Y)* intervals are marked with level "0", links with full count during the intervals marked with level "3", and links with counts in the middle marked with "1" and "2", for both α and β. The generated metric δ ranges from "0" to "3" indicating low to high quality respectively of the link, capturing both the average link status and also the trend of the link quality.

Each node establishes the link metric δ monitoring links connecting all its neighbors. To reduce message overhead, δ is not advertised for every link. Instead, each node reports only the metric δ of the link connecting its CH(s), which takes 2 bits for each cluster that the node belongs to, embedded in the CM. It is found in the experiment that the 4 levels of δ with the given X and Y settings are sufficient for distinguishing the link qualities while maintaining a very small overhead.

The received δ is employed to improve path reliability both within a cluster and across clusters. Within a cluster, a report of missing beacon messages from the MAC layer at any member node x will trigger the selection of a "local-repair" (LR) node. Node x chooses its LR as a node that has the highest available link metric connecting to itself and also the highest link metric available connecting to the CH. Node x sends this LR node a message to activate it. Then, when the CH forwards a message, the LR node will forward it again to improve the reception ratio at node x. An LR node indicates its role of "LR" in its CM message, using the existing "role" bits [17], seen by all its neighbors. Therefore, a node z in need of an LR will reuse an existing one if there is no better alternative, to maintain a low packet forwarding redundancy.

The CH selects GW nodes to relay across clusters also based on the link quality. A CH node selects the GW nodes that have the highest possible link quality connecting to itself and also to external clusters, based on the reported link metrics δ from all GW candidate nodes. The link quality takes precedence over the minimum number of gateways as a tactical network often has a small number of clusters due to the long range radio links and small network diameters [13]. Thus, the number of GW nodes tends to be small.

IV. Performance Evaluation

A. Simulation Parameters

In the evaluation, a typical VHF combat channel bandwidth of 25 kHz is selected with a link rate of 64 kbps, which is fairly high for the band. The path loss margin is estimated to be around 140 dBm, with an achievable SNR (Signal to Noise Ratio) from 6 to 15 dB. The radio transmission power is less than 46 dBm, representative of vehicle-mounted radio units.

Most MAC layers for tactical radios have some time division multiple access (TDMA) components, i.e., either a TDMA or a TDMA hybrid scheme to meet the real-time requirements for voice traffic. In the simulation, a simple static round robin TDMA MAC layer supplied by the Qualnet package is used. The MAC layer sends its beacon at every 2s.

The SMF simulation uses the latest compressed message format, reducing HELLO message size by up to 75% [15]. The addresses configured in the simulated network follow a common prefix structure to maximize the compression ratio. The default HELLO interval of 2s [5] was found to generate too much overhead to support any stable broadcast data throughput. The HELLO interval is thus set at 10s to allow the broadcast data traffic. In SMF cases, MAC beacon message has to be turned off to prevent more overhead. This does not affect the scheduling function of the static round robin MAC layer.

During the simulation, all nodes are broadcast sources. The broadcast data traffic is generated at each source at a speed of 1 short packet every 4s, representing the concise style of tactical communications. The network is simulated for 3000s. The delivery ratio is averaged across all senders to all receivers.

B. The Field Deployment Scenario

In the scenario, 38 radio nodes were deployed in a semi-rural 20 km by 20 km field. The field was divided into four 10 km by 10 km non-overlapping quarters. Among all the nodes, 3 of them form a commander group positioned in an area of 5 km by 5 km at the centre of the field. A group of 8 nodes is deployed in each of the four quarters. The mobility of commanders and the 4 groups are based on the reference point group mobility (RPGM) model [20]. The remaining three nodes are individual nodes with assigned tasks for special operations. These three nodes move in the entire 20 km by 20 km field following a random waypoint model. All the nodes travel in the speed range of 30 – 80 km/h with an average pause time of zero to 10 minutes, except for the commander group. The commander group has an average pause time of 30 minutes and moves at speeds ranging from 0 to 30 km/h. Within each group, the maximum distance from any node to the group center varies between 2 km and 4 km. Given the radio propagation parameters shown in Table I, in a single group, the nodes may be within one hop to each other for most of the time, because they are often less than 8 km apart. Across groups, multi-hop relays may be needed.

The delivery ratio and the average end-to-end latency normalized on the former are depicted in Fig. 1, plotted for different network diameters. As discussed in the previous section, the tactical network has a small diameter. The maximum number of hops was found to vary under dynamic link conditions. Adjusting the transmission power levels, network configurations are generated having diameters ranging from 3 to 7.

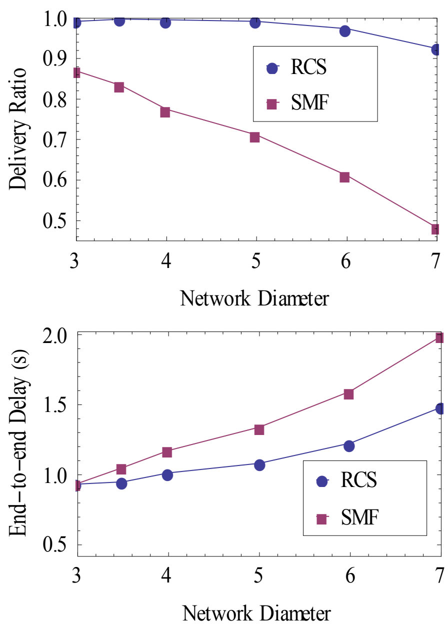

Figure 1 Performance for 20 km by 20 km Network with 38 Nodes

By considering link conditions, RCS achieves a delivery ratio close to 100% and sustains relatively well as the network diameter increases. SMF on the other hand suffers increased delivery losses. SMF could also apply link metrics, however, this increases the HELLO message load dramatically as it can no longer be compressed. In a neighborhood that shares a 64 kbps bandwidth capacity, this may amount to a total HELLO load of 20kbps.

The normalized average end-to-end delays in the RCS case are slightly better than SMF for networks with small diameters. Increasing network diameters, the normalized average delay of SMF starts rising faster due to its poor packet delivery ratio. SMF loses packets when traversing multiple hops. The long end-to-end latency incurred in both schemes is caused by the simple TDMA MAC in Qualnet that is used in the simulation. First, because of the static round robin scheduler, the sending node has to wait even though the slots for other nodes are not used. Secondly, the MAC does not allow multiple packets to be aggregated for sending in a single time slot.

C. *The Wing Deployment Scenario*

In a second scenario, a 20 km by 5 km area is divided into 4 non-overlapping quarters of 5 km by 5 km along its length. Four groups of equal size are deployed, each occupying one of the quarters. A commander group is deployed additionally in the middle, moving within the central area of 2.5 km by 2.5 km. The mobility model for each type of nodes is the same as in the previous scenario. This topology may be encountered in road side operations or convoy movements. The scenario is more challenging than that of a general convoy example, as nodes in the latter move more uniformly than the RPGM model used here. When representing convoy deployment, the moving speeds in the model represent relative velocities in addition to a common speed towards a common direction. The common speed is not modeled as it produces no topology updates. The number of nodes and their types are shown in Table II.

TABLE II. NETWORK CONFIGURATIONS

Total number of Nodes	Commanders	Group nodes	Special Ops
15	2	3 (per group) x 4	1
20	2	4 x 4	2
25	3	5 x 4	2
30	3	6 x 4	3

For this scenario, the transmission power is adjusted so that nodes within 3 km achieve above 99.99% packet reception. The traffic model is the same as for the previous scenario. The delivery ratios are illustrated in Fig. 2 for four different network sizes. The delivery ratios are lower for both RCS and SMF, compared with the previous scenario.

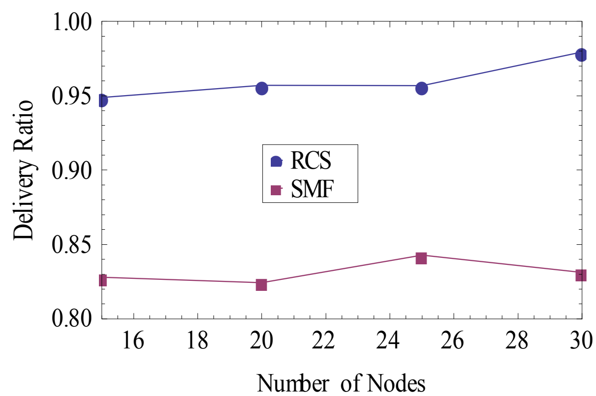

Figure 2 Delivery ratio for 20km by 5km Network

The lower delivery ratio is caused by the shorter signal range compared with the long stretch of the deployment area of 20km, giving rise to some weak links. Packets that traverse more hops start to fail along the path due to loss on one of the weak links. RCS, by adapting to link conditions, achieves comparatively higher delivery ratios.

The end-to-end delays for the SMF and the RCS cases are comparable. Due to space limitations, they are not plotted here.

D. *Protocol Overhead*

Fig. 3 illustrates the control message overhead for both scenarios. The results for the field scenario are depicted in Fig. 3 (a) and for the wing scenario in Fig. 3 (b). The overhead is measured in each neighborhood which has a shared 64 kbps capacity, without counting the packet headers. The real volume of HELLO message is thus higher, including the IP headers. The RCS overhead includes that of all the MAC beacon messages.

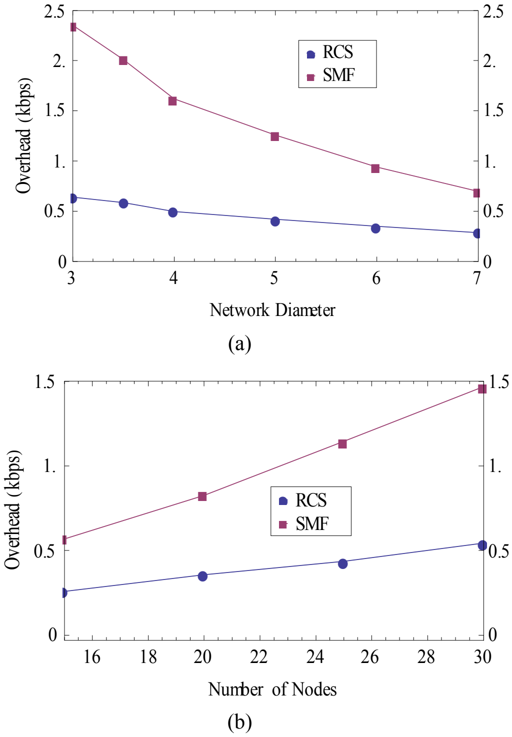

Figure 3. Protocol Overhead

HELLO messages are sent every 10s. If instead we send them at the default 2s interval [5], the HELLO message volume is about 5 times more than shown. In Fig. 3 (a) when the network diameter decreases from 7 to 3, the average node degree grows from 13.7 to 32, increasing HELLO message volume in each local neighbourhood. The overhead of RCS is relatively stable against the rise of the node degree. It should be noted that tactical radios often reduce transmission rates to enhance link quality as well as to maintain a small network diameter. The resulting high node degree, if leading to increased control message overhead, can be detrimental to the system performance. Thus, it is critical to maintain a very small control message overhead.

V. Conclusions

This work investigates broadcast/multicast schemes for the bandwidth constrained tactical environment to achieve protocol efficiency and path performance robustness. It has been found that improved relay performance is needed to reach a good multi-hop delivery ratio. The improved SMF scheme with compressed message format has significantly reduced HELLO message overhead. However, its overhead may still be problematic if the link bandwidth capacity is below several hundred kbps. The improved clustering scheme RCS considerably increases the data delivery ratio by considering link quality when selecting relay nodes.

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