Performance Evaluation for TCP in Tactical Mobile Ad Hoc Networks

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Abstract: Tactical networks are used in military and rescue operations to provide timely and accurate information to operating teams. Tactical networks have traditionally used long distance narrow band radio links. However, although these links provide robust real-time communication the limited bandwidth makes them less suited for high data-rate applications. To support high-data rate TCP applications such as providing digital images and maps, emerging tactical networks use shorter range but higher data-rate wide band radio links and multi-hop. Due to the requirement of cheap up-front cost, most MANET research has focused on Carrier Sense Multiple Access (CSMA) networks. However, in tactical networks, where bounded delays are important, Time Division Multiple Access (TDMA) can give better possibility to support the Quality of Service needed for real-time communication. The purpose of this paper is to assess and compare the throughput of three state-of-the-art TCP versions and two routing protocols over TDMA based MANETs.

1 INTRODUCTION

During a disaster or a military campaign the regular wired infrastructure is at best semi-functional. Therefore, relying on an infrastructure-based system is in most cases not possible. Prime examples of this are disaster areas, caused by e.g. earthquakes, tsunamis and nuclear disasters, which can render an infrastructure unusable. Tactical networks are also relatively small networks where nodes follow one or several group leaders (Li et al., 2012). A tactical network should also be resilient to node failures and operate with little or no backbone infrastructure.

One network type that promises to do this is Mobile Ad Hoc Networks (MANETs). A tactical network can be seen as a multi-hop MANET where node mobility and traffic follows a special pattern. In a MANET, a node functions both as a host and as a router and nodes can automatically organize themselves and form a network. However, due to limited transmission range, intermediate nodes need to forward packets to form a connected network topology. This creates congestion and multiple points of failure. Node mobility also leads to a highly dynamic network topology, which is prone to frequent changes and errors. This network dynamicity poses several challenges on routing protocols. Two state-of-the art routing protocols for MANETs are AODV and OLSR. AODV is a reactive routing protocol that determines routes only when needed (Perkins et al., 2003). OLSR is a table driven proactive protocol that regularly exchanges topology information with its neighbors (Clausen and Jacquet, 2009).

Although voice, positioning and short messages are the main applications for tactical networks it is also important to support standard applications used on todays Internet, to e.g. provide maps or other content. The obvious solution to support standard applications would be to use standard TCP/IP. However, TCP was designed for data delivery over wired networks. In a MANET, which has a substantially higher packet loss rate and jitter compared to a wired network, the performance of TCP dramatically degrades. Furthermore, due to node mobility, routes break and merge more frequently. This leads to a higher degree of routing induced losses and reordered packets, compared with a wired network.

MANET research has mainly focused on TCP interactions with CSMA MAC based systems due to the availability of cheap IEEE 802.11 radio cards, and the requirement of low up front cost. However, in a tactical network using a TDMA scheme has several ad-

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vantages, e.g. support of bounded delays and a stable network under heavy traffic loads. The novelty of this paper includes a TDMA based MANET evaluation of three well established TCP versions: TCP ELFN (Holland and Vaidya, 2002), TCP New Reno (Floyd et al., 2004) and TCP Westwood+ (Grieco and Mascolo, 2002)(Grieco and Mascolo, 2004), using both reactive and proactive routing protocols and multiple mobility scenarios and node densities.

The rest of the paper is structured as follows. Section 2 describes the background and motivation for this paper. Section 3 describes the implementation and the motivation for the chosen topologies. Finally Sections 4 and 5, respectively describe the experiment results, our conclusions and future work.

2 BACKGROUND

MANETs are wireless networks that do not require any infrastructure for their operation. Intermediate nodes must therefore participate in the route discovery and packet forwarding to other nodes. As nodes are mobile, the network topology and link state is constantly changing (Macker et al., 1999). This makes routing a challenging task and routing protocols need to quickly respond to topology changes.

Routing protocols in MANETs are commonly divided into two categories based on how and when routes are discovered and maintained: reactive and proactive routing protocols. Reactive or on-demand routing protocols establish the route to a destination only when it is needed (Abolhasan et al., 2004). This ensures a low routing overhead when there is a low amount of source-destination pairs. This can lead to an increase of routing overhead in high traffic conditions. A proactive routing protocol on the other hand maintains a consistent and updated view of the network by periodically propagating route updates in the network (Clausen and Jacquet, 2009). This is costly when there is limited amount of traffic (Abolhasan et al., 2004). The routing overhead of a proactive approach should in an ideal case not be influenced by the traffic volume, i.e. the overhead should be low when the traffic volume is large. However, studies in CSMA networks have shown that the neighbor sensing mechanism of proactive routing protocols can be sensitive to both traffic and mobility, due to collisions and radio environment (Voorhaen and Blondia, 2006). Depending on if information is spread regularly or triggered by a link loss, with high mobility, table driven proactive routing protocols can suffer from old route information or high overhead. In this paper we have chosen two state-of-art routing protocols to represent these two categories, reactive AODV and proactive OLSR.

Another important consideration in MANETs is the Media Access Control (MAC) layer. A TDMA channel access method allows several stations to share the same medium by dividing the time into small time slots. While mobility and radio environment are the same for TDMA as for CSMA based networks, there are significant differences where packets are dropped in the two channel access methods. In static TDMA based networks there should be no collisions; neighbor sensing for proactive protocols should therefore be more stable than in CSMA networks. Therefore in a static network, no packets are dropped due to collisions. However with node mobility, the TDMA slot assignment could temporally be incorrect creating collisions and packet loss.

By design TDMA have a number of other advantages over contention-based approaches, such as: fairness, bounded delays and asymptotic behavior under heavy traffic loads. The main drawback of TDMA scheduling is that it requires clock synchronization between the nodes which increases the overhead and makes nodes more complex and expensive to build. In addition in multi-hop environments, an interference free slot assignment becomes computational expensive.

The critical component of a TDMA protocol in MANETs is how to assign different time slots to any two conflicting nodes in a distributed way. One solution that we evaluate in this paper is DRAND (Rhee et al., 2006). DRAND was introduced to minimize collisions and promote bounded delay for the purpose of real-time communication (e.g. voice communication). One of the benefits of DRAND is that it can re-compute the TDMA schedule without involving global changes, i.e. DRAND performance is scalable to partial topology changes.

Because of its inheritably probability based nature, DRAND requires time to adapt with topology changes and is expected to perform worse when the number of topology changes increases. The implementation of DRAND that we used is the implementation done by the Computer Science department of the North Carolina State University, USA (Networking Research Lab, 2012). The choice of using DRAND is not for optimality to the evaluated scenarios. The choice should rather be seen as one viable way of implementing a TDMA scheme that works both for stationary and mobile networks.

In the scenarios targeted in this paper, communications are often among groups which tend to coordinate their movements, i.e. a rescue team. We have therefore focused on using Reference Point Group

Mobility Model (RPGM) that try to capture the movements when nodes are influenced by a group leader (Camp et al., 2002)(Aschenbruck et al., 2008).

In a MANET there will due to the node mobility always be a certain amount of route breaks. This leads to packet loss or jitter, as re-routing and link layer retransmission causes delay variations. The main problem for TCP in MANETs is its inability to distinguish congestion loss from other losses and that the proper response can be orthogonal. A congestion loss requires the sender to reduce the sending rate to not overwhelm the network. However, a loss due to a lossy wireless channel, on the other hand, requires the sender to quickly retransmit without necessarily reducing the congestion window.

A great amount of research has been invested in dealing with TCP performance issues in MANETs, e.g. (Wang and Zhang, 2002) (Chen et al., 2003). Most proposals are based on the idea of changing the functionality and/or the behavior of TCP to adapt it to the network environment. In this paper we instead focus on three TCP variants that represent three different design choices: TCP New Reno, TCP Westwood+ and TCP ELFN. While TCP New Reno (Floyd et al., 2004) is one of the most common and well established TCP variants, TCP Westwood+ and TCP ELFN have been designed for specific environments.

TCP Westwood+ (Grieco and Mascolo, 2002) is a sender-side-only modification of TCP New Reno that is intended to better handle large bandwidth delay product paths with potential packet loss due to transmission or other errors. This property makes TCP Westwood+ very attractive to use in wireless systems. TCP Westwood+ relies on monitoring the ACK stream for information to help set the congestion control parameters, i.e. slow start threshold (ssthresh) and congestion window (cwnd), better. Due to mobility, the ACK stream will have larger fluctuations in a MANET than in a static network. These none congestion related fluctuations can reduce TCP Westwood+'s ability to correctly determine the available throughput.

TCP ELFN (Explicit Link Failure Notification) (Holland and Vaidya, 2002) is a cross layer approach to inform the TCP layer about route failures. The proposal uses an ELFN message, which is transported by or piggy backed on routing messages to the sender upon a route break. The ELFN message contains the sender, receiver addresses and ports, as well as the TCP packet sequence number. On receiving the ELFN message, the source responds by disabling its retransmission timers and enters a ”frozen” state. During the ”frozen” period, the TCP sender probes the network to check if the route is restored. When the route is restored, i.e. the sender starts to see acknowledgments of the probe packets; the TCP sender leaves the ”frozen” state and resumes its state as before the freeze event. The probe interval is a crucial parameter as it determines how quickly TCP ELFN will detect that a new route is established. However, a too small probing interval will introduce unnecessary overhead. In (Holland and Vaidya, 2002) the authors propose to use a probe interval of 2 sec. Upon route restoration, the proposals use the values of RTO and cwnd from prior to the route failure. In the original paper the authors used DSR (Johnson et al., 2007), which is a reactive source routing protocol. In this paper we are evaluating TCP ELFN with both proactive and reactive routing protocols.

The authors of (Liao et al., 2002) propose a novel reactive QoS routing protocol for TDMA based MANETs. With the proposed protocol, the authors show that it is possible to search for and establish routes in a MANET supporting a given bandwidth constraint. The bandwidth requirement is realized by letting the route reply reserve time slots as it traverses links on the reverse path. Our work differs in that we evaluate TCP and different routing protocols over a TDMA based MANET.

3 IMPLEMENTATION

The original ELFN was designed and tested with DSR (Holland and Vaidya, 2002). In short, whenever DSR detects a route break, it generates a route error message which traverses back to the traffic source. With the ELFN modification, these messages are intercepted and processed at the TCP layer. For the purpose of the current study and to be independent of the underlying routing protocol we have implemented the routing error message by using an additional ICMP message. The main advantage of using an ICMP message as opposed to piggy backing the information on a routing message is that the routing protocol is decoupled from the TCP layer. This makes it possible to implement a TCP layer that can operate with different routing protocols in the same framework, e.g. IEEE 802.11s (Hiertz et al., 2010). The main drawback of our proposal is the extra overhead of the ICMP messages (in the case of AODV). As with all approaches that do an indirect coupling between protocol layers there is a possibility for race conditions. In our case this race condition is between the routing layer detecting a path loss and a TCP timeout. That is, if TCP times out due to a path loss before the routing layer have detected and transmitted the ICMP message to the sender, TCP ELFN might freeze in an undesirable state.

AODV was modified in a similar way as in (Romanowicz, 2008) to work together with TCP ELFN. When a link loss (route break) is detected AODV generates a route error message. In our modification, the route error message is preceded by an ICMP message which is sent back to the traffic source. Once the TCP sender recives the ICMP message it will freeze its timers and start the probing phase as described in (Holland and Vaidya, 2002). When AODV has established a new route and the TCP source have received an acknowledgement from one of the probing packets, it restores the timers. A link break is detected when three or more HELLO messages are lost.

When using the pro-active OLSR, the ELFN operation becomes much more peculiar. With OLSR, a node is notified about any topology change (route break) regardless of whether it is participating in a data forwarding process or not. The implementation has been changed to reflect this by removing the explicit ICMP message from the node that detects the route break. Instead, whenever the OLSR agent at the traffic source tries to forward packets to a destination that it does not have a route for, it sends an ELFN message to itself. In the simulations we set the OLSR neighbor link discovery (HELLO) interval to 1 second and the topology control (TC) message interval to 5 seconds.

The ELFN probe packet interval was set to two seconds for both routing protocols. We further disabled link layer feedback for both ADOV and OLSR as initial experiments showed that link layer feedback caused performance degradation. Preliminary analysis shows that in certain situations the links became unstable, triggering unnecessary route error messages and route flapping. This is, however, outside of the scope of the current paper and has been left for future work.

The topology we used was a square of 1000 meters by 1000 meters without any obstacles or heterogeneity. Radio communication distance was 150 meters and carrier sensing distance was 300 meters. The physical layer speed was set to 1 Mbps. The reason for selecting 1 Mbps is that it can be considered as a challenging data rate when mobile tactical networks need to support TCP services. Moreover, today most mobile tactical radios rarely support more than a few Mbps. For the mobility model we used the RPGM mobility model with two node densities, consisting of 3 and 16 groups of 6 nodes thus forming scenarios with 18 and 96 nodes. Group radius was set to 250 meters to ensure that internal group communication was forwarded by at least one intermediate node. The node speed was random in the range of 1,5 - 5,0 m/s. The simulation time was 360 seconds and traffic flows started at 60 sec, giving time for the routing protocols to converge. There where two independent TCP flows simulating large file transfers, between two different node pairs in all scenarios. Each experiment was performed both with and without background traffic. When using background traffic, 10% of the nodes in a scenario where each generating a 20 Kbit/s UDP flow. The total background traffic volume varied between 20 Kbit/sec (18 nodes scenario) and 180 Kbit/s (96 nodes scenario). This setup will produce a low amount of background traffic when the node density is low and a high amount of background traffic when the node density is high. However, when the node density is high there is more possibility for concurrent non competing traffic.

4 RESULTS AND ANALYSIS

In this section we will describe the results from our experiments. The results show the aggregate average TCP throughput measured in kilobits per seconds (Kbit/s). To compare TCP performance, we used the ns 2.26 simulator (McCanne et al., 2012) with TCP-New Reno, -ELFN and -Westwood+. The routing protocols are slightly modified versions of OLSR and AODV as described in the previous section.

The results shown in Figure 1 are from a scenario with 18 nodes in 3 groups and with no background traffic. The network density is low which causes temporal route breaks and network divisions between nodes and groups. However, due to the low node density, the impact of the choice of routing layer is limited. The low congestion in this scenario also gives the possibility to achieve a high TCP throughput. However, both TCP New Reno and TCP Westwood+ cannot utilize this possibility as the route breaks limit the congestion window. Therefore both of the approaches have similar performance. TCP ELFN on the other hand freezes its congestion window during the route breaks and can therefore maintain a high congestion window.

Figure 2 refers to a high node density scenario with 96 nodes divided in 16 groups. In this scenario the connectivity is high, but the mobility combined with the amount of nodes increases the stress on both routing layer and TDMA scheduling. Due to this the overall throughput is less. This leads to a smaller average congestion window for all TCP versions and consequently TCP ELFN has less benefits of freezing the congestion window. What also can be seen is that in this scenario the routing layer starts to impact the results. Due to the increased amount

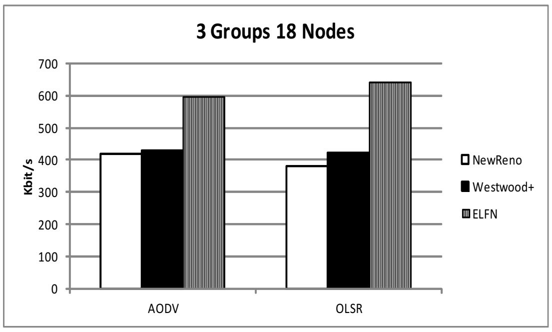

Figure 1: Low node density with no background traffic.

of topology changes, a proactive protocol as OLSR experiences a higher amount of stale routes and the possible formation of routing loops. In this scenario the amount of TC messages for OLSR was, as expected with a higher node density, ten fold higher then when using 18 nodes. TCP New Reno also performs better with AODV compared to using OLSR. On the other hand as the route lookup is more variable with AODV (OLSR have a route or not), TCP Westwood+ have more difficulties to determine the available bandwidth.

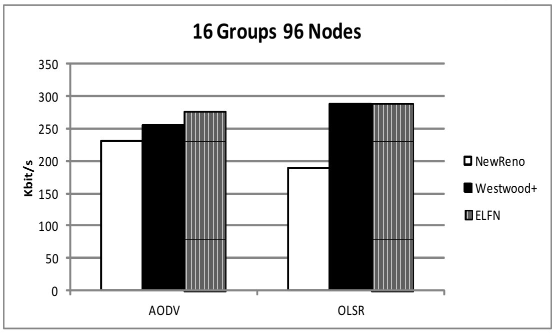

Figure 2: High node density with no background traffic.

Figure 3 shows results for an 18 node density scenario with 20 Kbit/s of background traffic. With low congestion, TCP ELFN outperforms both TCP Westwood+ and TCP New Reno. In this scenario the TCP throughput for all TCP versions is reduced as compared to Figure 1, reflecting the lower available bandwidth due to the background traffic. Since we are now sending traffic between more node pairs and as AODV only detects route errors on actively used routes there is also a higher possibility for route errors. This is different from when using OLSR where all route errors are detected, whether it is on an active route or not.

The amount of route error messages when using AODV also increased, with all TCP variants, by around 50% compared to when we had no background traffic.

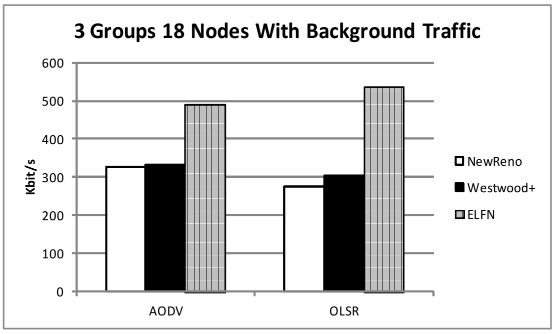

Figure 3: Low node density with low amount of background traffic.

The amount of congestion in the scenario with 180 Kbit/s of background traffic and 96 nodes reduced the performance of all TCP proposals. In this scenario the network is overloaded with traffic and therefore none of the TCP proposals has a throughput higher than 50 Kbit/s, due to space constraints we have omitted the figure.

5 CONCLUSIONS

In this paper we have investigated the TCP performance of three TCP versions in a TDMA based MANET using both OLSR and AODV as routing protocols. We used reference point group mobility model to simulate a typical tactical network scenario. The results show that TCP ELFN achieves the overall highest throughput. The gains are, however, reduced in low throughput scenarios as the benefit of freezing the congestion window is less. The performance of TCP ELFN was similar regardless of which routing protocol was used.

Future work will further investigate the performance of TCP ELFN in high density networks and the possibility to enhance the performance when using OLSR.

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