Towards analysis of IP communication in a constrained environment of tactical radio networks*

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ABSTRACT

The trend of unifying communication by deploying TCP/IP also influenced the domain of tactical networks. Commonly used narrowband waveform tactical radios offer only the low bandwidth data transfer. Because of very restricted resources available in these systems running the unmodified TCP/IP protocol stack is problematic if not impossible.

This paper presents a simulation-based approach to a systematic analysis of TCP/IP communication in the narrowband tactical radio networks. The aim is to provide a framework able to analysis the source of problems that avoid deploying TCP/IP in tactical radio communication. The proposed method is demonstrated by providing an analysis of a few Internet protocols and evaluation of the suggested simple improvement to address resolution protocol that reduces the number of the required broadcast messages.

CCS CONCEPTS

• **Networks** → Network performance Evaluation;

KEYWORDS

Ad Hoc Networks; Capacity Analysis and Optimization; Network Protocols; TCP/IP; Goodput; Performance Analysis; Discrete Simulation; Tactical Radios

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1 INTRODUCTION

Battlefield tactical radio networks interconnect combat units by providing voice communication simultaneously with a limited amount of data traffic. Available data rates are enough for services that exchange small or infrequent messages, such as situation awareness or commands of battlefield management system (BMS). New battle management systems are complex network-centric platforms integrating various components and interconnecting different edge networks. Naturally, there is a tendency to employ standard Internet protocols for communication within the BMS network. However, connecting narrowband tactical radio networks [17] is challenging. Even a new generation of tactical radio technology designed according to MANET principles does not meet general requirements concerning TCP/IP protocols. Expensive adoption of new technologies offering wide-bandwidth communication channels is often not among the available options. Therefore, there is the pressure to operate TCP/IP applications over legacy tactical networks. The inherent characteristics of these tactical communication systems, which can be characterized by the low bandwidth and intermittent connectivity represent an obstacle for TCP/IP communication. Moreover, these networks typically operate in a hostile environment [14] which further degrades the attainable data rate. The regular radio network communication is at low speed with changing transmission capacity and affected by substantial error rates. Also, turnaround time is significantly larger than in the typical Internet environment. Studies conducted on the possibility of adoption of IP protocol in narrowband radio networks provided some insight on the class of applications that can be operated in this environment [8].

As the majority of Internet applications rely on the reliable data transfer, they utilize Transmission Control Protocol (TCP) for data delivery. While in principle the TCP guarantees reliable data delivery and efficient utilization of available network capacity the practical experiments showed that it may function poorly under very constrained conditions. TCP uses retransmissions to provide reliable communication. A packet is retransmitted if TCP thinks that it was lost or significantly delayed which cannot be distinguished. This may cause that the network capacity is wasted by frequent unnecessary retransmission. Besides the issue with TCP, the service protocols, in particular, Address Resolution Protocol (ARP) and Dynamic Host Configuration Protocol (DHCP), can suffer in slow networks too. For instance, ARP uses broadcast queries to obtain MAC address of the target node. The number of broadcast messages rises with the number of nodes connected to the network. Although ARP messages are small and infrequent, they can quickly consume available bandwidth. DHCP provides automatic address assignment by exchanging a couple of messages between the client station and the DHCP server. DHCP uses a simple mechanism to deal unreliable data delivery. Most of the implementations use fixed

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timer to wait for the server response. If the response message is lost or delayed too much, DHCP tries to repeat the whole conversation. For congested network, DHCP may be unable to complete address assignment sucessfuly.

The possibility of TCP/IP communication in tactical radio networks was partly addressed by the NATO standard STANAG 5066 [11][9]. Still, there is a debate on whether IP protocol and hence TCP/IP-based applications can efficiently communicate over narrowband radio networks [19].

In this paper, we provide a simulation analysis of the above mentioned problems. Our aim is to design a framework for estimating achievable parameters of TCP/IP communication in narrowband radio networks. We employed existing simulation models of TCP/IP protocols and radio data communication to create a tool that can be used as a cheap but accurate method for evaluating the possibility of running TCP/IP applications in tactical radio networks. The developed framework was used to conduct a preliminary analysis that yields to quantitative results estimating the overhead of ARP and DHCP communication, and to estimate the performance characteristics of TCP.

1.1 Related Work

Traditionally, researchers studied the performance of narrowband communication networks for different coding, access methods, usage patterns or environments, e.g., [16], [18], [4].

Some research also targets the particular environment of battlefield tactical radio networks. In the following, we provide a short overview of activities in this field.

Kelsh, Roberts, and Harris [10] discussed issues related to the development of an accurate model for tactical communication networks. They identified some shortcomings if classical network simulators are employed to abstract physical layer properties. They described simulation support requirements for RF network technology developments. Haidong et al. [5] presented notes on the implementation of MANET over legacy tactical radios. They analyzed the requirements of MANETs and compared these demands with properties of legacy tactical radio waveforms. Based on the simulation model, they determined basic radio link characteristics and MAC layer performance, e.g., throughput, Rx/Tx turnaround time, packet transmission overhead. They also proposed possible improvements of their experimental implementation. Demers and Kant [2] presented and analyzed a model of Optimized Link State Routing (OLSR) protocol for MANETs. They aimed at providing efficient routing for reducing overhead and time needed for network convergence, the aspects crucial to support mission critical services. Nakamura [13] examined the environment of low-bandwidth legacy radio concerning overall throughput, aggregation of data, and message latency in a typical battle management application. Quispe and Galan [15] developed a general simulation model of MANET to analyze the throughput of the network under different parameters. Their goal was to determine the limit on the number of active users to overall network performance. Henz at al. [6] presented an emulation platform for MANET application to provide the performance analysis. They included real-time path loss calculations for irregular terrain model to obtain high accuracy of the results. Such computation is very expensive, and their platform was implemented in a high-performance computing cluster. Fossa and Macdonald [3] studied the issue of interconnecting MANETs by employing currently available Internet routing protocols. Using simulation, they demonstrated that the Internet routing protocols, such as BGP, does not meet the requirements of a MANET network routing. Recently, Haavik et al. presented a scheme for narrowband radio networks that automates IP connectivity in the tactical edge, and between the edge and the backbone [12]. They applied a cross-layer address management scheme that enables to provide IP connectivity to end users interconnected by the radios forming a combat radio network.

1.2 Contribution

Narrowband tactical radio networks still represent the key technology for the field communication. The desire to run TCP/IP application also over this networking technology represents a challenge. Not only the overhead needed for establishing end-to-end TCP connection can be a single problem. RFC1122 and RFC1123 define requirements on Internet devices regarding communication services and applications. They should 1) implement fundamental protocols from TCP/IP suite, 2) provide a suitable IP configuration method, 3) work with underlying link layer technology. Except IP protocol at network layer, at least TCP and UDP protocols are required at the transport layer. TCP protocol is used by the most of the Internet applications as it provides reliable data delivery. The price for this service is the overhead, which is acceptable in the Internet, but may represent an obstacle for constrained networks. The easiest way to provide IP configuration in local area networks is to use Dynamic Host Configuration Protocol (DHCP). This protocol automatically configures a set of IP parameters including unique IP address, default-gateway and DNS server. Address Resolution Protocol (ARP) was designed to support the multi-access link layer technologies. The ARP uses Ethernet broadcast messages to reach the destination, which then informs the source of the query about its MAC address. We will show how this broadcast communication impacts the overall radio network throughput. Narrowband tactical radio is modelled as a multi-hop network employing TDMA scheme, because this model covers a wide range of different tactical radio networks. It may be possible to consider also different access schemes, some of which may give slightly better results. The domain and parameters of considered class of radio networks are similar to [12].

A simulation model proposed in this paper can be used to analyze parameters of TCP/IP communication in narrowband tactical radio networks. The developed model enables to measure various network parameters for different network settings and different characteristics of TCP/IP traffic. Contrary to experiments with a real network environment the presented approach is cheap, but it can provide accurate results. The main contribution can be expressed as follows:

- Design of simulation model that can be parametrized to represent different network configuration and characteristic of the environment.

- Evaluation of the reliability and performance characteristics of the core TCP/IP protocols, namely Address Resolution Protocol (ARP), Dynamic Host Configuration Protocol (DHCP) and Transmission Control Protocol (TCP).
- Proposals of a simple improvement for ARP that significantly reduces the amount of ARP broadcast messages.

Problems associated with the deployment of TCP/IP stack in narrowband networks are known, and ad-hoc solutions were proposed in various areas to overcome it. However, we believe that providing a simulation platform for quantitative analysis of TCP/IP traffic in tactical radio networks will establish an environment for the systematic analysis and design of new solutions to these issues.

1.3 Paper Organization

The paper is organized as follows: Next section introduces a simulation model built for the class of tactical radio networks under analysis. The model is build in OMNeT++ simulator that offers a rich collection of protocol, traffic, and network component models. Section III provides the simulation results. In this section, we analyze the traffic of the three Internet protocols, namely, ARP, DHCP, and TCP. Section 4 concludes the paper by discussing the results and suggesting some possible outcomes.

2 SIMULATION MODEL

The developed simulation model enables to analyze TCP/IP communication in different radio network configurations. The simulation model is designed to provide results on the quality of TCP/IP communication. Because of this, the characteristics of radio links are abstracted. The model is built in OMNeT++ simulator. OMNeT++ offers a rich collection of predefined simulation models. We design the model of the radio network (RN) by adjusting the available wireless communication model from the OMNeT++ library. The purpose of the radio network model is to simulate communication among different radio stations. Each radio station is modelled as a networking node that contains a single wireless interface for communicating in the radio network and the Ethernet interface for connecting to other devices.

2.1 Network Model

The modeled radio network consists of stations denoted as Radio-Frequency nodes (RF–nodes). Each RF–node has two interfaces, wireless radio interface, and Ethernet wired interface. The wireless interface uses lightweight medium access (LMAC) protocol for controlling the access to the shared radio data link [7]. This protocol is configured to work in the time-division multiple access (TDMA) mode. Each station has assigned a time slot for sending the data to the shared wireless medium. Slot duration and the scheme of time slot assignment can be specified as simulation parameters. The RF–node is also capable of forwarding communication from neighboring nodes thus supporting the multi-hop data delivery. RF–node simulation model is depicted in Figure 1(a) along with the description of its subcomponents. The RF network for which the TCP/IP communication analysis is demonstrated is shown in Figure 1(b). The network consists of four edge radio networks:

- Backbone network which interconnects edge networks. This network contains nodes denoted as `RDST_C`, `RDST_F`, `RDST_I` and `RDST_J`. Also `host_D` is connected to this network via Ethernet interface of RF–node `RDST_J`.
- Edge network A which contains RF–nodes `RDST_A` and `RDST_B`, and station `hostA`.
- Edge network B which contains RF–nodes `RDST_D` and `RDST_E`, and station `hostB`.
- Edge network C which contains RF–nodes `RDST_G` and `RDST_H`, and station `hostC`.

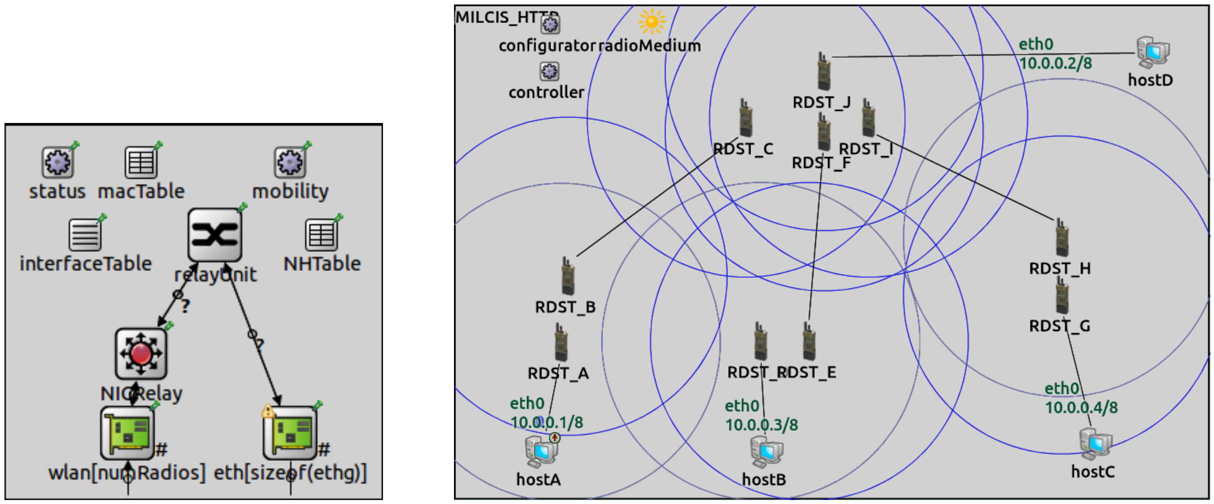
An IP network can be mapped to this physical topology in different ways. In this paper, we assume that all radio systems comprise a single local area network1. For the RF–node configuration, this means that all interfaces are bridged, and thus, they belong to the same IP network. Underlying radio layer implements (multi-hop) connectivity of all RF–nodes in the same radio network.

2.2 Radio Layer Visibility

The RF–node visibility is specified by giving connectivity table as one of the inputs the simulation. Based on this, the internal routing algorithm computes paths between nodes within the same radio network. In this way, we provide a simple but sufficient abstraction of routing and forwarding at the radio network layer. If necessary, this representation can be refined by specifying, for instance, a distance between nodes to compute more accurate reachability model. RF–nodes are not visible at network layer because they provide only link layer connectivity. In other words, RF–node behaves as a network bridge forwarding frames from the Ethernet interface to wireless interface and vice versa. Also, the RF–node itself does not perform fragmentation, so to seamlessly support typical TCP/IP hosts, the RF–node has to support Ethernet MTU. To implement the intended bridging behavior of an RF–node , the model contains two relay components. The first one, relayUnit, is used to transmit Ethernet frames between Ethernet interface and wireless part. The second one, NICRelay, together with the next-hop table (NHTable) implements loop-free multi-hop forwarding. NICRelay also encapsulates the Ethernet frame into RF-Frame. RF-Frame contains UID of the RF–node sender, destination, and retrans- lating node. UID of retranslating node provides information for multi-hop broadcast/multicast frame delivery. The RF–node does not remove Ethernet header from packets received on eth interface. When the frame is relayed to the wireless section, it is encapsulated into RF-Frame. Therefore, the RF–node model can be used in conjunction with any existing protocol from INET Library.

2.3 Intra-LAN communication

Host stations connected to RF–nodes are all on the same Ethernet LAN. RF–nodes are bridges in this LAN network, and radio network provides connectivity among the bridges. Backbone radio network interconnects bridges of edge radio networks thus providing full connectivity for all host stations. For LAN communication, a host station needs to know Ethernet MAC address of a target node. RF–nodes acting as bridges have to maintain MAC tables to translate an MAC address to a path ending at the RF–node connecting the target host. MAC table is populated by the same algorithm as implemented in Ethernet switches. The developed simulation model contains the implementation of this algorithm to maintain MAC tables at RF–nodes . On the network layer, an IP node employs Address



(a) RF-node model (b) RF-network model

Module name	Description
wlan	This module represents wireless NIC participating in a RF network. It uses a LMAC to synchronize access to the medium.
eth	This module represents generic Ethernet capable interface.
NICRelay	This module provides RF–node with multi-hop capabilities. It retranslates messages to the correct RF–node .
relayUnit	This module provides RF–node with relays PDUs between wlan and eth interfaces. It also performs the ARP Cache algorithm and serves as transparent ARP Proxy. It does not alter the Ethernet header of PDUs.
NHTable	This module provides routing table like information for NICRelay module to support multicast and broadcast over wlan interface.
macTable	This module is extended standard MAC Table with the property of address of RF–node and IPv4 Address.

Figure 1: Simulation Model

Resolution Protocol (ARP)[1] to translate the IP address of a target node to the corresponding MAC address. ARP request packets are broadcasted to all nodes in the local network. A node with the same IP address as specified in the ARP request then sends ARP reply packet directly to the requester. To reduce the number of broadcast messages, ARP proxy is implemented as an optional feature at RF–nodes . The ARP proxy caches IP to MAC mappings. When the host station sends ARP request, then the ARP proxy of the closest RF–node is searched for the required record. The impact of ARP broadcast on the radio network is analyzed in the next section.

3 ANALYSIS AND RESULTS

In this section, we provide analysis of interconnected radio networks for TCP/IP communication. Typical narrowband tactical radio network offers link rates from 20 to 96 kbps [1]. Based on [13, Table 2] throughput may degrade to 45–85% of the theoretical data rate. We reflect this in our model by considering different slot times rather than by complicating the model with varying data rate parameter. It means, that for fixed data rate of 40 kbps, the simulation uses 300 ms slot time to accommodate 1500 B MTU in radio packet. In a degraded state, the slot time can be, for instance, only 75ms, which corresponds to MTU of size 375 B. The base setup consists of 4 hosts and 10 RF nodes as depicted in Figure 1(b). RF nodes are associated with backbone and edge radio networks. Each radio network uses its frequency band. TDMA is used to media access control in the radio network. The other nodes are simulated by adding empty slots to TDMA round. Blue circles around each RF–node depicts its communication range.

Three variables are used as parameters of the simulation model:

- `numSlots` - specifies a number of time slots in a round, which also expresses the maximal number of nodes able to communicate on one shared segment (5, 10, 15, 20).
- `slotDuration` - is the duration of a single time slot (80, 150, 300, 500, and 750ms).
- `queueLength` - is the maximal length of a queue holding PDUs waiting for a time slot to be transmitted (1 - 10). If this queue is full then new frames are discarded. We analyzed

[1]https://rfc-editor.org/rfc/rfc826.txt

the network model with applied different combinations of parameters for DHCP and ARP communication. Also, we identified the effect of various parameters to host- to-host TCP conversation. The results are presented in the remained of this section.

3.1 ARP

First analyzed scenario deals with the issue of ARP broadcasts. We measure the number of ARP broadcasts in the radio network in the course of running a simple request-response UDP communication. We also introduce the simple improvement for ARP processing at RF–nodes . The PDU is dropped in the LMAC module during processing, if ARP Request or ARP Reply is already present in the queue. It limits the number of outstanding PDUs in a queue when the combination of (numSlots, slotDuration) is bigger than the frequency in which the requests are produced. Additional improvement can be made by implementing the ARP Cache mechanisms. Each RF–node maintains (IP address, MAC Address, RF–node ID) mapping in its ARP Cache. For each frame incoming from wireless interface carrying IPv4 datagram, the mechanism learns source IP address, source MAC address, and source RF–node ID and insert this information into the ARP Cache together with current timestamps. If such entry is already present, it updates its timestamp only. When an RF–node receives a frame on the wired interface, it goes through the following decision process:

(1) If the destination MAC address is unicast and present in the ARP Cache, set appropriate RF–node id as the destination node.
(2) If the destination MAC address is multicast, send it to all RF–nodes as broadcast.
(3) If the destination MAC address is broadcast and frame type is ARP Request, check if the destination MAC address is in ARP-Cache. If so, generate ARP Response and send it onto the wired interface. Otherwise send the ARP Request to the wireless interface as broadcast.
(4) If it is DHCP PDU with broadcast MAC address, send it as broadcast to the wireless interface.
(5) Drop all packets that do not match any of the preceding conditions.

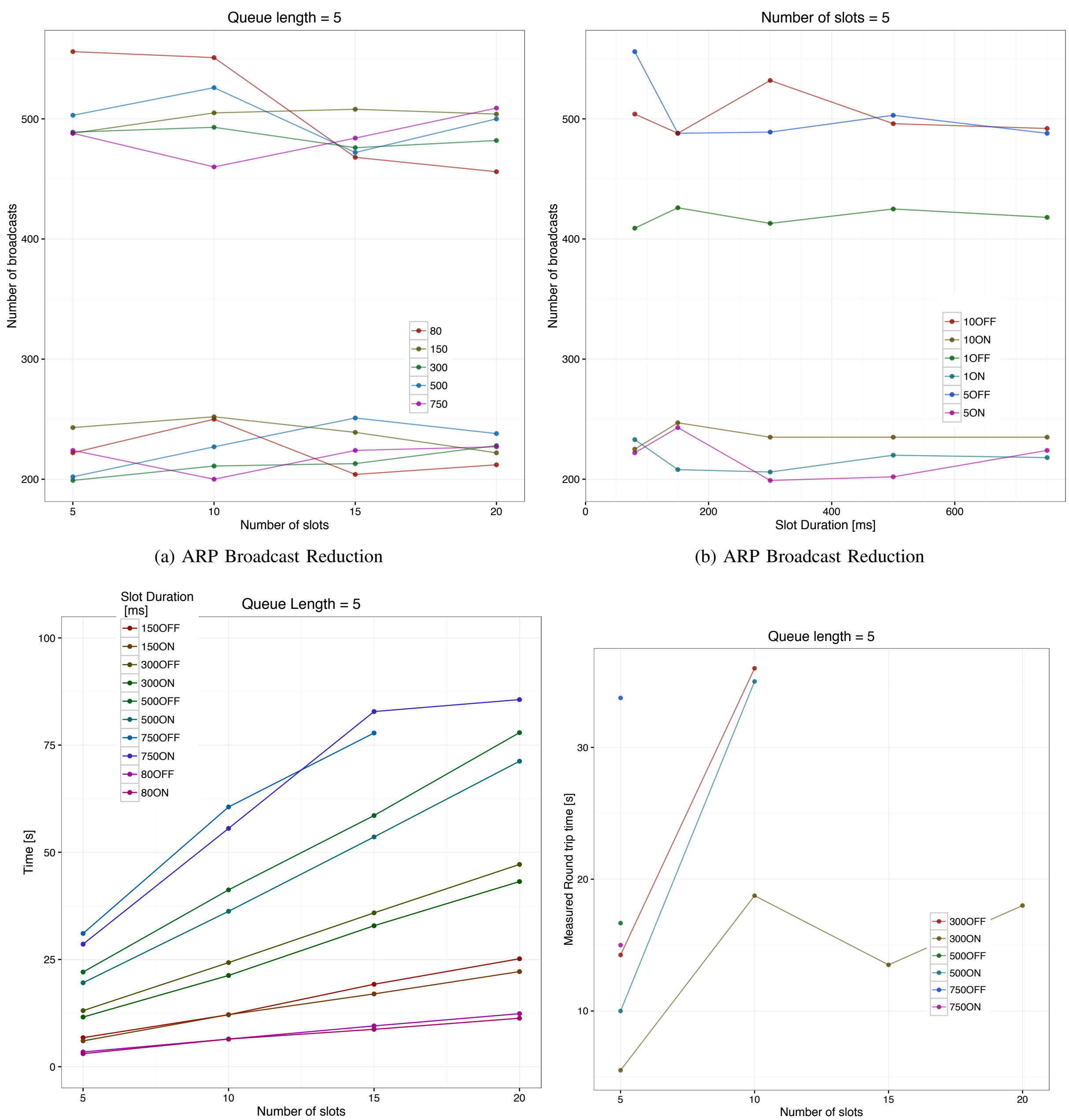
This simple idea can help to reduce the number of ARP broadcast in the radio network. While the ARP packet is only 28 bytes, it may occupy the single time slot, and thus, it has the significant impact on the goodput of a radio network. Figure 2(a) shows that an amount of broadcast can be reduced to about half by applying the described mechanism. Results for the queue of length five are only presented, but similar reduction ratio was also obtained for other queue lengths. Figure 2(b) shows a comparison between different queue lengths. Again the optimized version reduces the number of broadcasts. ARP analysis reveals that the standard ARP implementation produces a lot of broadcast messages. It is because the ARP cache at each host uses a timer to remove expired records. By extending RF–nodes with ARP cache mechanism, it is possible to reduce the number of ARP broadcasts.

3.2 DHCP

The second scenario focuses on Dynamic Host Configuration Protocol. While this protocol is not necessary for assigning IP configuration to a host machine, it is often utilized to automate IP address assignment. We measure the time needed for a station to complete the DHCP procedure. In our model, a host depicted as hostD runs the DHCP server and hosts hostA, hostB, and hostC initiates DHCP client procedure to obtain IP configuration. DHCP uses transaction IDs to distinguish between different active sessions on the LAN. Because DHCP communication is unreliable, it uses a timer to resend requests, when the response does not arrive in the defined interval. To improve the performance, we implemented a simple mechanism applied to a message queue in LMAC module. Before a `DHCP_DISCOVERY` packet is inserted into the queue in the LMAC module we check whether the previous DHCP packet from the same node is already in the queue. If so, we update the transaction ID of the DHCP message in the queue and drop the incoming message. Minimum MTU is 300 B to support DHCP, which equals to theoretical 60 ms slot duration. In practice, at least 80 ms is necessary for slot length. The results are presented in Figure 2(c). The better results are for shorter time slots that contribute smaller communication latency. With an increasing number of slots, the DHCP time grows linearly. However, for longer time slots, the communication latency has a significant impact on the DHCP performance. For instance, for 300ms time slot, the DHCP configuration takes about a minute for 15 nodes per a radio network. The graph also exposes the effect of the proposed improvement. For most of the cases, this effect can be neglected. However, for slotDuration = 750ms, numSlots = 20 some hosts were unable to acquire an IP configuration. When the improvement was in use, the same hosts could complete DHCP configuration. The analysis of DHCP traffic reveals that large round trip time represents the most significant problem for this kind of communication. The DHCP relies on the exchange of only a few messages. However, if the response to the request takes too long, the timer expires prematurely and resets the DHCP algorithm. Using the minimal slot duration enables to complete DHCP configuration within several seconds that is comparable to a typical LAN environment.

3.3 TCP

In the third scenario, we observed the behavior of TCP. In this scenario, we simulate a web server running on hostA and web browsers running on hostB and hostC. The TCP can adjust occupied bandwidth to the network condition. Thus, by this analysis, we test how TCP algorithm can cope with the very constrained environment of radio networks. For TCP scenario, we omitted slot size of 80ms and 150ms, because these slots do not provide enough space to transmit full 1500 B frame. Figure 2(d) depicts average round-trip time. The results also show that long latency causes that ARP records can expire and thus ARP requests are broadcasted during TCP communication occupying network bandwidth and having an adverse impact on TCP communication. With the help of proposed ARP cache mechanism, it was possible to keep TCP session for more than ten hosts (slots) per radio network (line denoted as 300ON). It means that standard RF–nodes were able to



(a) ARP Broadcast Reduction

(b) ARP Broadcast Reduction

(c) DHCP completion time

(d) Average RTT of segments for TCP data transfer

Figure 2: Simulation Results

communicate only if the radio group is not larger than 5 RF–nodes . And even in those cases, the average RTT is more than 15 s.

4 DISCUSSION

The presented simulation analysis has aimed at demonstrating the issues of TCP/IP communication in low-bandwidth networks. We provide a simplified model of a battlefield tactical network comprising of interconnection of low bandwidth radio networks. This network organization corresponds to the typical tactical network deployment. The simulation model reveals the following problems:

- A combination of low bandwidth and high latency is a major problem even for simple Internet protocols. Local area protocols such as DHCP and ARP expects that network meets some minimal quality concerning latency, bandwidth and error rate. However, the legacy military radio systems do not fulfill them.

- The TCP was designed to work on WANs, and thus, it can cope with high latency and low throughput quite well. Although the network capacity is the limitation, the TCP can keep its session even under severe conditions. Once a TCP session is created, the session may survive for a long time. It is implementation dependent when the endpoint closes the session if it does not receive any segment from another side.

Also, Internet protocols may be seen as having unnecessary overhead in terms of header size and a number of messages exchanged to achieve a goal. For instance, instead of using DHCP, some lightweight option can be adopted. The RF-node can implement a lightweight DHCP server. The pool of addresses can be assigned before RF-node is deployed or during its registration to the radio network. Based on the presented results, we may conclude that direct adoption of TCP/IP protocol suite into constrained tactical networks can work only for a very limited number of hosts. The possible workaround for the presented problems is in the implementation of supporting mechanism in underlying radio layer or using application gateways to translate the communication to protocols better suited for radio networks. The future work is focused on performing real world experiments in order to prove these simulation results and on research mechanism to support TCP/IP implementation for low bandwidth networks.

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