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Research Article

A Cross-Layer Design for a Multihop, Self-Healing, and Self-Forming Tactical Network

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In mission and time critical applications, bandwidth and delay optimizations are the key goals of communication systems. This paper presents a cross-layer framework design that reduces the call setup time, provides collision-free communication, and reuses the empty slots of Time Division Multiple Access (TDMA) protocol which otherwise causes low throughput and large delay. As number of communicating nodes in tactical networks is small as compared to commercial mobile ad hoc networks (MANETs), classical TDMA will yield huge number of empty slots and any Carrier Sense Multiple Access/Collision Detection (CSMA/CD) technique may cause more delay in some critical scenarios. Proposed methodology gives a Cross-Layer Architecture for Network (NET) Layer and Medium Access Control (MAC) Layer. Our design provides bandwidth efficient, collision-free communication to Software-Defined Radios (SDRs) in self-forming and self-healing tactical networks with low call setup time and multihop routing. For this purpose TDMA as MAC layer protocol and Ad Hoc On Demand Distance Vector (AODV) as Network Layer Routing Protocol are used. Our slot allocation (SA) algorithm, Cross-Layer TDMA (CL-TDMA), consists of control phase where AODV control packets are exchanged and data transfer phase where transmission of data and voice occurs. All active radios in vicinity gather information about communicating nodes based on the exchange of control packets by SDRs. Our algorithm then uses this information to help all active SDRs find slot(s) that will be used for collision-free transmission. A number of experiments are performed to establish improved performance of the proposed technique compared to other established techniques and protocols.

1. Introduction

Mission and time critical tactical networks pose a challenging situation for communication in hostile situations. A tactical network with scarce resources must support continuously changing and time varying operational priorities [1].

These networks carry significant role in time and mission critical applications because of their dynamic nature in many aspects such as forming a network on demand and in situations where placement of physical infrastructure-based network is not possible. Such applications demand quick deployment of network in an infrastructure-less approach and handle critical challenges tactfully. Some of the scenarios may be mobile and robust military work stations, SDR mounted devices, and smaller tactical networks in the battle field [2].

Static infrastructure is not appropriate in case of tactical networks because highly mobile networks are required for mobile military devices and vehicles. Moreover mobile military networks need to be operational continuously even in situations where some stations are destroyed and some links are down or congested [3].

In scenarios of military operations and calamities such as hurricanes and tornados, it is essential to provide communication even without any infrastructure-based physical network. Due to these challenges, tactical systems require a reliable, robust, and secure communication system [4].

Applications with large number of mobile consumers need an optimized consumption of bandwidth which is a scarce resource in tactical networking application such as communication in regions affected by natural disasters, integrated battle field management systems, etc. Cognitive radio (CR) technology characterizes innovative solutions to address the issue. Idea of Software-Defined Radio is emerging as a prospective solution: SDR is defined as a group of technologies both hardware and software where operating functions of the SDR are deployed through adaptable firmware or software, functioning on programmable technologies of processing to reproduce several communication standards. This technology enables mobile nodes to adapt dynamically to the communication environment which is time varying, changing locality, accessible bandwidth, and time critical situations [5]. In situations of mission critical applications such as battlefield and catastrophic environments, the intrinsic properties of the underlying applications must be considered. Flexible and programmable characteristics of SDR technology facilitates integration and synchronization in sharing information regarding different types of traffic flows such as distribution of situation awareness, transfer of files, and instant messaging. This increases proficiencies of military forces to enhance the efficiency of mission and time critical applications [6].

Since most of the tactical networks-based missions fall under the same category as far as functional patterns are concerned, basic characteristics of a network such as topology of network topology and data configurations can be predicted accurately. Hence the efficiency of tactical wireless networks can be boosted by identifying essential characteristics of network cognitively and then using appropriate networking strategies adaptively such as cross-layering design techniques. Many cross-layer schemes have been suggested in literature for wireless tactical networks. In cross-layer designs essential information can be shared among the layers of TCP/IP to improve the performance of mobile ad hoc networks. For example, overhead of headers pertaining to each layer can be minimized, mobility, QoS, and security [7].

Efficiency of mobile ad hoc communication networks can be considerably improved by incorporating the idea of cross-layering in communication design system. This paper presents a novel cross-layer design for multihop, self-healing, and self-forming network in tactical settings. Including this section on introduction, this paper is organized in eight sections. The paper is organized as follows. Section 2 lists the published work in relevant areas. Section 3 describes proposed methodology, network model, architecture, and framework of our system. Section 4 explains our methodology with the help of a working example and provides extensive investigation to validate our methodology. Sections 5 to 6 discuss implications of our approach, analytical and simulation results, and qualitative comparison with state of the art MAC protocols for MANETs.

2. Related Work

A considerable work is being carried out by researchers in optimization of network performances using cross-layer and associated technologies for different applications. QoS based enhancement of video transmission is framed by [8] as a problem of cross-layer optimization, whereas [9] proposed a cross-layer architecture of multiple layers that performs coordinated routing, congestion control, and scheduling in multihop relay networks and gives improved QoS evaluation.

Mobility of wireless stations is highly dependent upon energy efficiency. Concept of cross-layering is used in MERLIN (MAC and efficient routing integrated with support for localization) [10] to overcome packet latency which is mostly sacrificed in MAC protocols of sensor network to achieve energy efficiency.

Cross-layer designs are categorized by [7] as manager or nonmanager method based on information sharing mechanism and centralized or distributed architecture based on the network organization. The designs are categorized as layer trigger scheme, joint optimization scheme, and full cross-layering based on number of layers involved in optimization by [11].

Cross-layering also optimizes the performance of parameters belonging to different layers without breaking the abstraction of TCP/IP layering. In optimized version of 802.11 e networks, parameters of MAC layer are adaptively tuned by [21] according to the information extracted from application layer. Similarly MAC layer and network layer parameters are used in coordination to develop criteria of hybrid nature in [22].

Another framework Mobile-Man cross-layer design in [23] presents a methodology where protocols of different layers may share information about network status while keeping the separation of layers intact at the design level.

TDMA protocols are preferred in wireless tactical networks because their capability to support QoS [24], multiple enhancements of TDMA for wireless, and tactical ad hoc networks have been suggested in [25, 26] such as cooperative cognitive TDMA (CC-TDMA) and cooperative relaying TDMA (CR-TDMA).

Another challenge of cross-layering is mechanism of signaling among nonadjacent layers to share vital networking information. One of the solutions to this challenge is proposed in [27] to merge all layers into single layer that is orthogonal to a strict cross-layering architecture solution. Among these two extremes, interlayer signaling is an efficient way of implementing cross-layering for cooperation and coordination of desired information among multiple layers as presented in [28]. Many signaling methods have been proposed in literature, such as using wireless extension header for storing cross-layer information, using Internet Control Message Protocol (ICMP) to exchange cross-layer information, using local profiles for sharing periodically updated information of different layers [29].

Several efforts have been made to achieve MAC access with channel assignment; some methodologies are suggested as part of survey conducted on radios in [30, 31].

3. Proposed Design

Our work presents a novel approach to build tactical network solutions specific to disaster management and military applications where delay and bandwidth are scarce resources. The proposed methodology is unique in terms of network organization and information exchange mechanism. The algorithm is distributed with each SDR executing the same slot allocation (SA) algorithm and creating the same vector. As a result, each SDR is equipped with information about the active communications and refrains from starting its own communication. This protocol ensures collision-free transmission mechanism as opposed to contention based CSMA/CD MAC protocol of 802.11e for MANETs; also it provides bandwidth efficient communication in comparison to channelization access protocol TDMA.

Moreover, in novel design presented in this paper, CL-TDMA (cross-layer TDMA) control messages of AODV are used for exchanging cross-layer information rather than designing a separate signaling methodology.

The idea of cross-layer design is to preserve the core functionalities related to the layers of TCP/IP suit while allowing collaboration, cooperation, and joint optimization of protocols by sharing information between multiple layers [32].

Due to time sensitive nature of communication, CSMA/CD based MAC algorithms are not appropriate for tactical networks-based applications. The traditional TDMA suffers from bandwidth wastage, delay, and low throughput when used in a tactical combat networks where number of communicating nodes is less than the available time slots. In case of tactical networks, the probability that all the nodes are communicating simultaneously is very small and causes inefficient utilization of a large number of available slots. Therefore, a cross-layer-based slot allocation algorithm is proposed for optimized utilization of bandwidth and time. Our proposed technique relates to wireless communication, specifically for time and mission critical infrastructure-less tactical networks.

To develop CL-TDMA for a multihop self-healing and self-forming tactical network of SDRs, a cross-layer protocols is proposed which works with coordination and cooperation of parameters of NET layer and MAC layer. All of the important parameters of proposed protocol are enlisted in Table 1.

Table 1: Important parameters of proposed protocol.

Symbol	Parameters
R_n	Network Data Rate
S_s	Size of time slot
S_c	Control slot
S_d	Data Slot
n	No. of nodes
f_c	Control frames
f_d	Data frames
h	No. of hops
N	No. of Slots in a frame
L	No. of Control frames
M	No. of frames in one super frame
P_s	No. of packets in one slot
P_f	No. of packets in one frame
$data_T$	No. of bits to be transmitted
O_{head}	Call setup overhead
HELLO	AODV control message
RREQ	AODV route request message
RREP	AODV route reply message

3.1. Network Model. Consider a self-healing and self-forming tactical MANET [33] of SDRs in a time and mission critical environment where mobility of SDRs is slow as compared to commercial MANETs. There is no central controller in the network, and SDRs coordinate their transmissions in a distributed way. The source SDR for each communication starts the process of network formation, route calculation, and formation of slot allocation vector by sending a HELLO message. Each mobile SDR generates best-effort data traffic. Communication is collision-free because of TDMA MAC protocol. The total number of nodes in the network is denoted by symbol n, which changes slowly with time due to user mobility. Some important variables and parameters are enlisted in Table 1.

3.2. Cross-Layer Architecture. Based on the challenges posed by mission and time critical applications of tactical networks, a cross-layer design is proposed to provide routing and collision-free channel access. Control messages of AODV are used for providing necessary signaling between NET layer and MAC layer. The novel approach of cross-layer design proposed in this paper works in nonmanager and decentralized fashion where data is exchanged directly between any two layers and there is no centralized node or tier.

3.3. Stringent Constraints of Tactical Network. The proposed slot allocation algorithm is specially designed for tactical networks; tactical networks are of different types depending upon the application's requirements, for example, Air Defense Network, Integrated Battlefield Management System, and Artillery Fire Control System. Every network has its own stringent requirements and characteristics [34]. Some of the important characteristics can be defined as follows:

(i) Number of radios in tactical network
(ii) Number of hops
(iii) Radio range
(iv) Data requirement of each node/data range
(v) Extent of change in topology
(vi) Permissible delay
(vii) Frequency of communication
(viii) Error correction coding schemes
(ix) Modulation schemes

3.4. Slot Allocation Algorithm. In slot allocation (SA) algorithm, TDMA frames of MAC are divided into two classes. The first class of frames consists of control frames. These control frames are used to exchange control messages of AODV in the first phase of call setup process. Second class of TDMA frames comprises data frames for communication of data such as text and voice in the first phase of call setup SDRs transmits control packets. The information collected during this exchange helps all active SDRs to get awareness

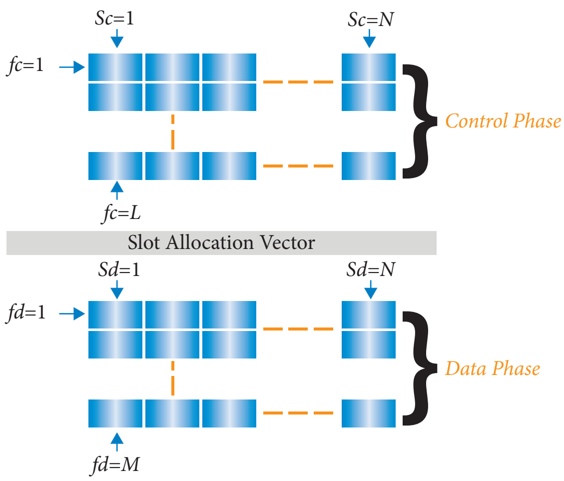

Figure 1: Architecture of CL-TDMA slot allocation algorithm.

about the communicating SDRs in the vicinity. The SA algorithm assigns slot(s) to all active SDRs by using the information collected during exchange of control messages, hence ensuring the collision-free exchange of data packets. As all SDRs in the vicinity are aware of active radios and active communications, collision-free transmission is guaranteed for communicating SDRs. SA algorithm allows communicating radios to use empty slots of other inactive SDRs, thus adding the advantage of reusability which ensures optimized utilization of bandwidth.

3.5. Architecture of CL-TDMA. Architecture diagram of CL-TDMA is given in Figure 1 depicting control phase and data phase. In control phase each slot is represented as s_c called control slot and each frame is labeled as f_c known as control frame. Length of control frame is variable ranging from 1 to N. Control phase will have L number of control frame. Value of L varies according to the number of SDRs involved in communication and the complexity of communication scenario. At the end of the control phase each SDR will have an SA (slot allocation) vector.

In the next phase of the algorithm, SDRs transfer data. In Figure 1, s_d represents data slot and f_d represents data frame.

Length of each data frame ranges from 1 to N data slots. M represents total number of data frames involved in any communication. Value of M varies according to the size of communication. Number of data frames in any communication forms one super frame. After the completion of data transfer, control phase will run again for other active communications.

3.5.1. Setup/Control Phase. Dividing the task into two phases makes it easier to utilize the slots which are being wasted in classical TDMA techniques. During the control phase, only control messages of AODV such as HELLO, RREQ, and RREP are exchanged and when this exchange is over, all the active SDRs are equipped with vital information such as the following:

(a) Active communications: identification of SDRs that want to send (source) data, receive (destination) data and relay data

(b) Dynamic slot allocation: this will be achieved by running SA algorithm which utilizes the information that each node gathers during the exchange of control messages.

(c) Collision-free communication in phase II

(d) Reusability of empty slots

(e) Optimized use of already scarce bandwidth in tactical networks

Figures 2 and 3 give detailed flow of control messages of AODV along with corresponding frame and slot. Frame numbers and slot numbers are also labeled to give visual representation of call setup procedure. This flow graph is designed for the best case scenario where only six control frames complete the process of call setup. Once all the SDRs have SA vector, they can start exchanging data frames. Figure 2 represents the scenario where SDR_2 wants to start communication, so it will send HELLO message in slot 2 of control frame 1. Slot 1 of control frame 1 will be empty as SDR_1 is not the source SDR. Now SDR_1 can broadcast its HELLO message in slot 1 of control frame 2. When SDR_3 receives HELLO message from SDR_2, it will broadcast its HELLO message in slot 3 of control frame 1. This process will continue till the end of control frame 1; by then all the SDRs in vicinity will broadcast their HELLO message in their respective slots of control frame 1.

SDR_1 will broadcast its HELLO message in slot 1 of control frame 2. Source SDR_2 will broadcast its RREQ message in slot 2 of control frame 2. SDR_3 will relay this RREQ. This process will continue until SDR_4 broadcasts RREP message.

Proposed SA algorithm provides dynamic allocation of time slots to the active SDRs only in contrast to the classical slot allocation scheme TDMA where slots are fixed. After running this algorithm each SDR in the vicinity has its own SA vector, updated routing tables, and paths to the destinations of active communication.

3.5.2. Data Transfer Phase. During this phase source SDRs, relay SDRs and destination SDRs perform communication in slots allocated to them in call setup phase. Communication is collision-free and bandwidth efficient.

3.6. Slot Allocation Algorithm. Slot allocation algorithm for MAC CL-TDMA is shown in Algorithm 1.

4. Working of Algorithm

In this section we describe working of SA algorithm for a specific communication scenario in a tactical network setting, where mobility of nodes is limited. Though the algorithm works for any number of nodes that are typical in a tactical network ranging from 10 to 80, for this particular case the number of nodes/SDRs is 30, number of hops is 2, and topology is changing very slowly. All important parameters for this scenario are given in Table 2.

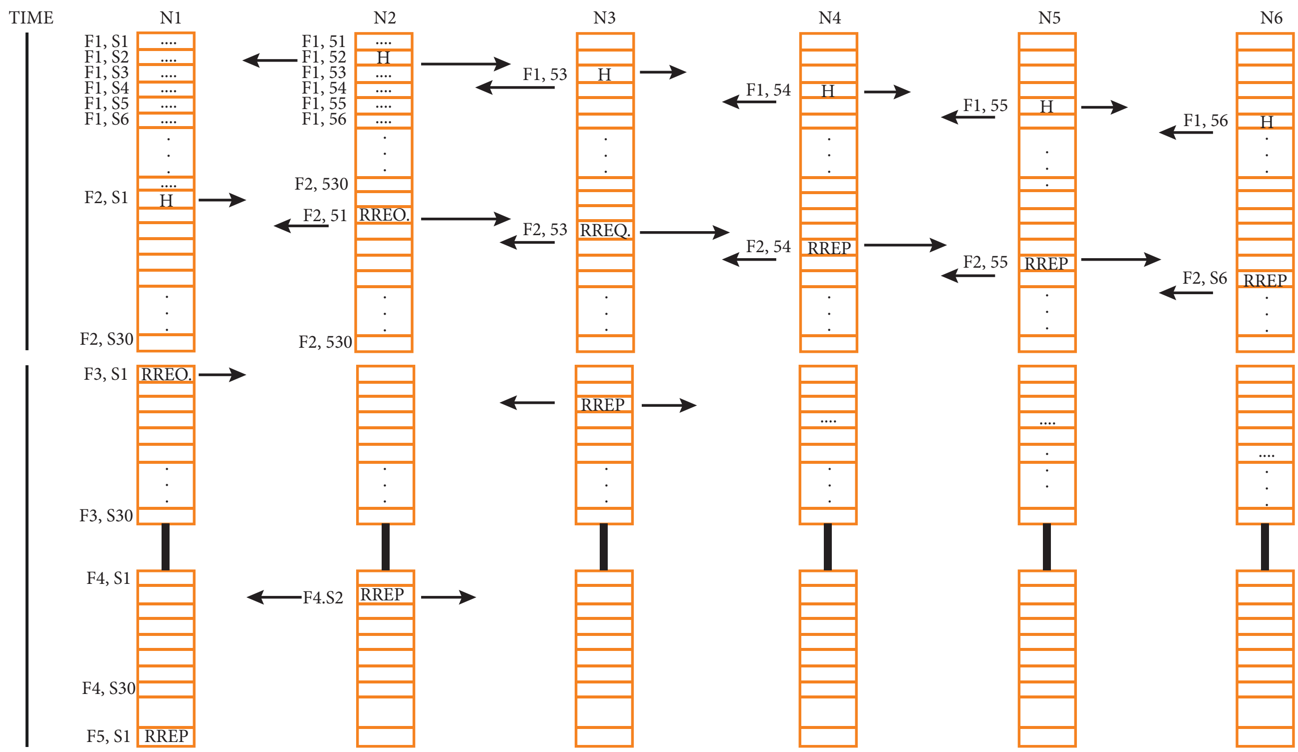

Figure 2: Flow graph of AODV control messages for call setup.

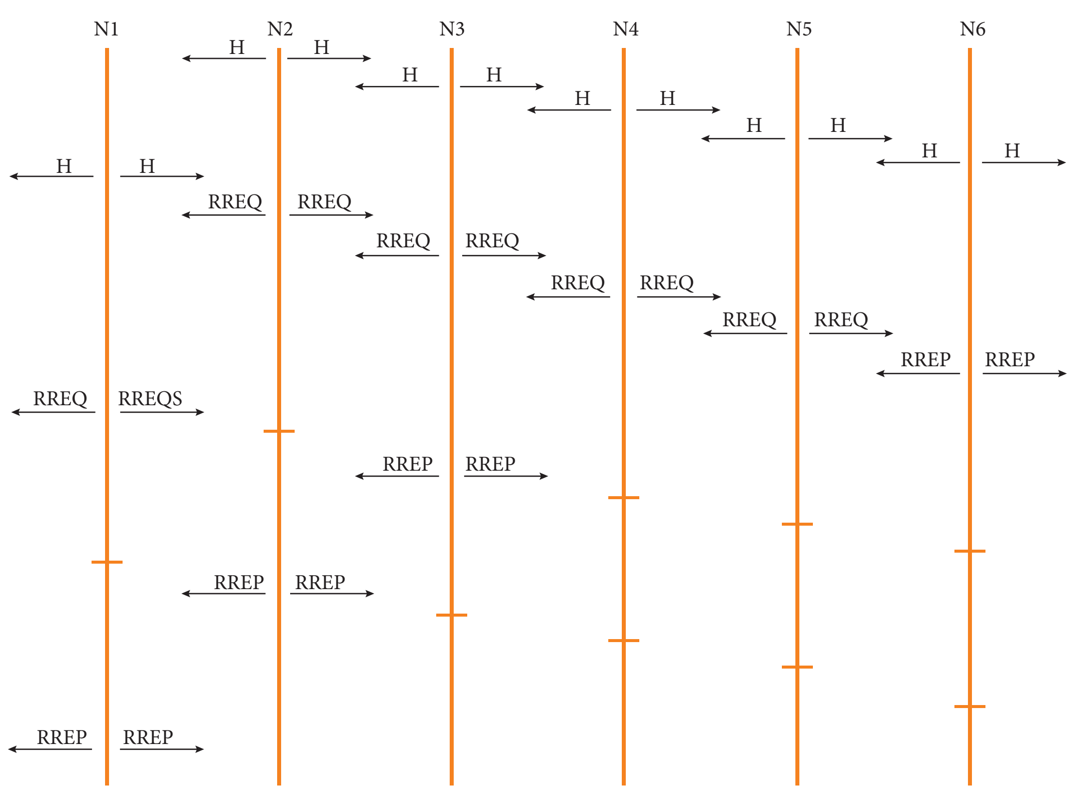

Figure 3: Flow graph of AODV control messages with respect to time.

Input: Topology, Node that breaks silence, No of slots in a frame
Output: Slot allocation vector.
(1) Declare an array 'B'.
(2) x={[∑for all RREPs(HopCount+1)] ∗ 2}%30
(3) sort RREPs in each node with respect to RREP IDs
(4) **For** each RREP perform the following steps to find the slot numbers to occupy
(a) Declare an array 'A' of size [hopCount+1]∗2
Note: (hopCount from RREP)
(b) **If** this node is originator **then**
(i) Allocate the first slot in 'A'
(c) **Else If** this node is receiver **then**
(i) Allocate this slot in 'A' to the node
(ii) Update hopCount as [hopCount(∗)+1]+1
Note: (∗) represents hopCount from RREP received from destination)
(d) **Else If** this node is relaying, two slots will be allocated, one for forward communication and one for backward communication)
(i) Allocate forward slot in 'A' by [hopCount(∗∗)+1]+1
Note: (∗∗) represents hopCount from originator/source)
(ii) Allocate backward slot in 'A' by
[hopCount(∗ ∗ ∗)+1]+[hopCount(∗)+1]+1
Note: (∗ ∗ ∗) hopCount to destination from routing table and (∗) represents hopCount from RREP)
(iii) Allocate backward slot in 'A' by
[hopCount(∗ ∗ ∗)+1]+[hopCount(∗)+1]+1
Note: (∗ ∗ ∗) hopCount to destination from routing table and (∗) represents hopCount from RREP)
(e) Append array 'A' to array 'B' and clear A.

Algorithm 1: CL-TDMA slot allocation algorithm.

Table 2: Scenario No.1.

Serial No.	Parameter	Values
01	No of Nodes	30
02	No of Hops	2
03	Data Rate	High
04	Frequency of Communications	Medium
05	Permissible Delay	Low
06	Extent of Change in Topology	Limited mobility
07	Radio Range	Small

Architecture of 30 slots is used to test the proposed design. Here basic assumption is that the SDRs which are communicating are at a distance of 2 hops at maximum and topology is slowly changing. Now let us assume a topology with 6 nodes with node id 1, 2, 3, 4, 5, and 6, respectively, and arranged as in Figure 4; SDR_2 wants to talk to SDR_5 and the rest of the SDRs are silent. SDR_3 and SDR_4 will work as relaying SDRs to generate SA vector for communication of SDR_2 and SDR_5. This example scenario will demonstrate following:

(i) Informing all SDRs about the communication of SDR_2 and SDR_5

(ii) Allocation of slots of inactive SDRs to those which are now communicating

Step 1 (initialization). Let us assume all the SDRs are silent, the proposed protocol ensures that the SDR that is interested in starting communication will break the silence by sending an AODV HELLO packet. In above the example SDR_2 will broadcast a HELLO control message; all the neighboring SDRs will receive this control message and will update their routing tables.

Step 2 (updating routing tables). Now the silence period is over and all the active SDRs will start exchanging the control messages in first control frame given in Table 3. So when SDR_3 and SDR_1 receive HELLO packet of the SDR_2 both will update their routing tables, given in Tables 4 and 5 and add an entry for a route to SDR_2 with a hop distance of zero which indicates that SDRs with hop distance zero are direct neighbors. Then SDR_3 will broadcast its HELLO packet and so on and at the end of the first frame SDR_2 through SDR_6 have broadcasted their HELLO packets and at the end of this frame the routing tables will be like SDR_2 having an entry of SDR_3 with hop distance of zero. SDR_2 has not received any HELLO message from SDR_1 so its routing table will not contain entry to SDR_1; SDR_3 will have two entries, one for

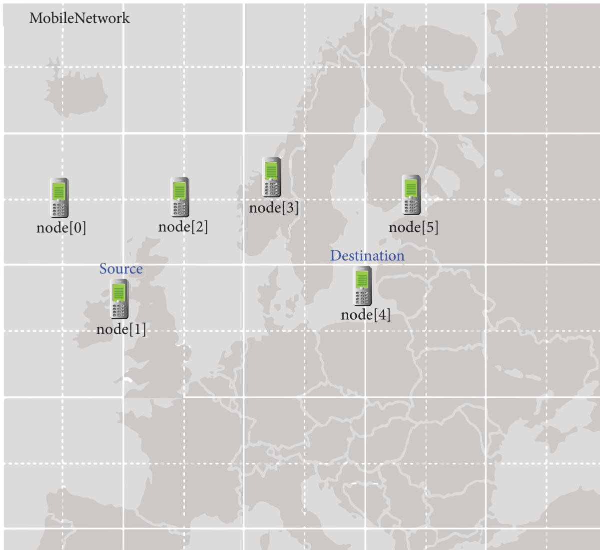

FIGURE 4: Topology No.1.

TABLE 3: Control frame 1.

Slot No.	1	2	3	4
Frame 1	Silent	SDR_2 will Broadcast HELLO	SDR_3 will broadcast HELLO	SDR_4 will broadcast HELLO
Slot No	5	6	.....	30
Frame 1	SDR_5 will broadcast HELLO	SDR_6 will broadcast HELLO		

TABLE 4: Routing table for SDR_2.

To	From	Next Hop	Hop Distance
1	2	-	-
2	2	-	0
3	2	Direct Neighbor	0
4	2	-	-
5	2	-	-
6	2	-	-

SDR_2 and the other for SDR_4, both at a hop distance of zero; SDR_4 will have entry of SDR_3 and SDR_5, both at zero hop distance, given in Table 6; SDR_5 will have entry of SDR_4 and SDR_6 both at a hop distance of zero, depicted in Table 7; SDR_6 will have entry of SDR_5 at zero hop, shown in Table 8. SDR_1 has to wait for the second control frame to send its HELLO message as the silence was broken by SDR_2 and SDR_1 was unable to broadcast its HELLO before the second control frame. Table 3 represents the first control frame. Routing table of SDR_1 is not created yet, as it has not sent its HELLO message in frame 1.

Now in the second control frame given in Table 9, SDR_1 will broadcast its HELLO packet. After receiving this HELLO packet SDR_2 will add a second entry to its routing table with a route to SDR_1 with a hop distance of zero. The updated information is shown in Table 10.

TABLE 5: Routing table for SDR_3.

To	From	Next Hop	Hop Distance
1	3	-	-
2	3	Direct Neighbor	0
3	3	-	0
4	3	Direct Neighbor	0
5	3	-	-
6	3	-	-

TABLE 6: Routing table for SDR_4.

To	From	Next Hop	Hop Distance
1	4	-	-
2	4	-	-
3	4	Direct Neighbor	0
4	4	-	0
5	4	Direct Neighbor	0
6	4	-	-

TABLE 7: Routing table for SDR_5.

To	From	Next Hop	Hop Distance
1	5	-	-
2	5	-	-
3	5	-	-
4	5	Direct Neighbor	0
5	5	-	0
6	5	Direct Neighbor	0

TABLE 8: Routing table for SDR_6.

To	From	Next Hop	Hop Distance
1	6	-	-
2	6	-	-
3	6	-	-
4	6	-	
5	6	Direct Neighbor	0
6	6	-	0

TABLE 9: Frame 2.

Slot No.	1	2	3	4
Frame 2	SDR_1 will broadcast HELLO	SDR_2 will broadcast RREQ	SDR_3 will re-broadcast RREQ	SDR_4 will broadcast RREP
Slot No	5	6	.....	30
Frame 2	SDR_5 will re-broadcast RREP	SDR_6 will re-broadcast RREP		

Table 10: Routing table of SDR_2 in frame 2.

To	From	Next Hop	Hop Distance
1	2	Direct Neighbor	0
2	2	-	0
3	2	Direct Neighbor	0
4	2	-	-
5	2	-	-
6	2	-	-

Table 11: Routing table of SDR_4 in frame 2.

To	From	Next Hop	Hop Distance
1	4	-	-
2	4	SDR_3	1
3	4	Direct Neighbor	0
4	4	-	0
5	4	Direct Neighbor	0
6	4	-	-

Now SDR_2 will broadcast its RREQ packet to search for the route to SDR_5 from the neighbors, SDR_1 and SDR_3. As we know that when a RREQ is received an SDR will setup a backward path also by adding an entry to its routing table with the SDR id of the originator of RREQ and hop count.

Now SDR_3 will rebroadcast RREQ message as it does not have route to SDR_5 in its routing table. SDR_4 will process this RREQ and first update its table with the entry of the originator and its hop count. It will add an entry of SDR_2 with a hop count of 1. Updated routing table entries for SDR_4 are shown in Table 11.

SDR_4 has route to SDR_5 in its routing table so it will prepare RREP message. In CL-TDMA slot allocation this RREP message will be broadcasted instead of unicasting to source SDR as in traditional AODV. Proposed scheme adds this modification in traditional AODV because RREP contains the information of the communicating SDRs and we want this RREP to reach all the active SDRs. With the help of this RREP, they can update themselves with the information such as, which SDRs are communicating and which ones are inactive. This information will help in slot allocation and reusability of empty slots. In proposed scheme a node will broadcast RREP in two cases:

(i) In reply to a RREQ

(ii) A node having received RREP from its neighbors; it may or may not be an intermediate node in a communication.

After receiving RREP, SDR_5 will rebroadcast this message and will also add an entry to the routing table as path to SDR_2 with a hop count of 2. Updated routing information of SDR_5 is shown in Table 12. Finally SDR_6 will just rebroadcast the RREP.

Table 13 depicts the structure of control frame 3. In control frame 3, SDR_1 has a RREQ received from SDR_2 and it does not have a path to SDR_5. It will rebroadcast this RREQ.

Table 12: Routing table of SDR_5 in frame 2.

To	From	Next Hop	Hop Distance
1	5	-	-
2	5	SDR_3	2
3	5	-	-
4	5	Direct Neighbor	0
5	5	-	0
6	5	Direct Neighbor	0

Table 13: Control frame 3.

Slot No.	1	2	3	4
Frame 3	SDR_1 will re-broadcast RREQ		SDR_3 will re-broadcast RREP	Silent
Slot No	5	6	.....	30
Frame 3	Silent	Silent		

Table 14: Routing table of SDR_3 in frame 3.

To	From	Next Hop	Hop Distance
1	3	-	-
2	3	Direct Neighbor	0
3	3	-	0
4	3	Direct Neighbor	0
5	3	SDR_4	1
6	3	-	-

Table 15: Control frame 4.

Slot No.	1	2	3	4
Frame 4		SDR_2 will re-broadcast RREP	Silent	Silent
Slot No	5	6	.....	30
Frame 4	Silent	Silent		

SDR_2 has nothing to do so it will wait for the response to its RREQ sent in control frame 2. SDR_3 will rebroadcast the RREP and update its routing table with the entry of the destination in the RREP and its hop count. It will add a route to SDR_5 with hop count of 1. Updated routing table entries for SDR_3 are shown in Table 14. SDR_4, SDR_5, and SDR_6 are silent in this frame.

In control frame 4 represented in Table 15, SDR_2 will rebroadcast RREP received from SDR_3 and update its routing table with an entry to SDR_5 with hop count 2. SDR_3, SDR_4, SDR_5, SDR_6 will remain silent in this frame. Updated routing table entries for SDR_2 are shown in Table 16.

In control frame 5 which is represented in Table 17, SDR_1 will rebroadcast RREP received from SDR_2. Control frame 6 shown in Table 18 will be empty as there are no more control messages to be exchanged.

2	3	4	5	4	3	2	3	4	5	4	3	2	3	4	5	4	3	2	3	4	5	4	3	2	3	4	5	4	3

Figure 5: Slot allocation vector for best case topology.

Table 16: Routing table of SDR_2.

To	From	Next Hop	Hop Distance
1	2	Direct Neighbor	0
2	2	-	0
3	2	Direct Neighbor	0
4	2	-	-
5	2	SDR_3	2
6	2	-	-

Table 17: Control frame 5.

Slot No.	1	2	3	4
Frame 5	SDR_1 will re-broadcast RREP	Silent	Silent	Silent
Slot No	5	6	.....	30
Frame 5	Silent	Silent		

Table 18: Control frame 6.

Slot No.	1	2	3	4
Frame 5	Silent	Silent	Silent	Silent
Slot No	5	6	.....	30
Frame 5	Silent	Silent		

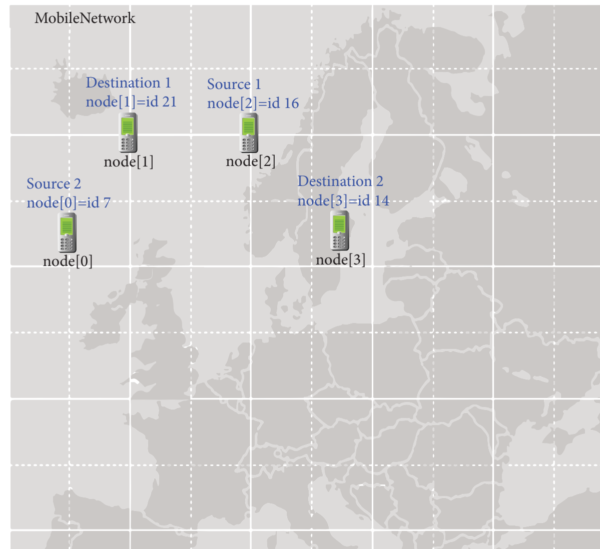

Figure 6: Worst case topology.

In our design, even the worst case scenario for current set of parameters, consumes only six control frames to exchange all the control messages necessary for the call setup procedure. This may vary for different set of parameters and complex scenarios.

After the exchange of control packets every active SDR will have the RREP packet in their memory. Each SDR will run Algorithm 1: MAC CL-TDMA SA algorithm and finds an allocation vector that assigns multiple slots to active SDRs. Allocation vector generated as a result of running SA algorithm is shown in Figure 5.

Slot reusability and bandwidth optimization is obvious from this vector. This vector is distributed among all SDRs participating in active communication. SDRs will transmit data in data transfer phase according to this vector. In current case SDR_2 will start transmission in slot 1 of data frame 1, SDR_3 and SDR_4 will relay in slot 2 and slot 3, respectively, and SDR_5 will transmit data (reply) in slot 4, which will be relayed by SDR_4 and SDR_3 in slot 5 and slot 6, respectively.

SDR_1 will also have slot allocation vector even it is not part of the communication. Algorithm suggests that all the nodes in network should have this vector to gain awareness about active communications to refrain from starting their own communication during active transfer, hence ensuring collision-free transmission.

Next we discuss the proposed algorithm for worst case scenario and an average case scenario. In worst case scenario two simultaneous communications are represented. One communication is active between source SDR_{16} and destination SDR_{21}. Second communication is active between source SDR_7 and destination SDR_{14} where SDR_{21} and SDR_{16} are relay radios. Topology is given in Figure 6.

Slot allocation vector for this communication is shown in Figure 7. This vector shows that 24 slots in each frame are occupied, while 6 slots in each frame are wasted.

Next we run our algorithm for an average case scenario. Slot allocation vector for this communication is given in Figure 8.

Algorithm has been tested over a set of topologies in all three categories of best case, worst case, and average case scenarios of different communication conditions enlisted in Table 19. Even in the worst case scenario, control phase does not exceed six frames and bandwidth utilization for data transfer phase ranges within 80%~100%. Flow graph of slot allocation algorithm is given in Figure 9.

This work is extended further; a mathematical model is developed for a cross-layer design for application layer and physical layer. This work focuses on the optimized trade-offs between various configurations settings of the SDRs to accomplish optimization such as efficient utilization of energy and delivery of data packet reliably at suitable data rate and within tolerable latency constraints. The proposed work enhances the performance and enables SDRs to efficiently adjust to the dynamically changing environment [35].

Figure 7: Slot allocation vector for worst case.

Figure 8: Slot allocation vector for an average case topology.

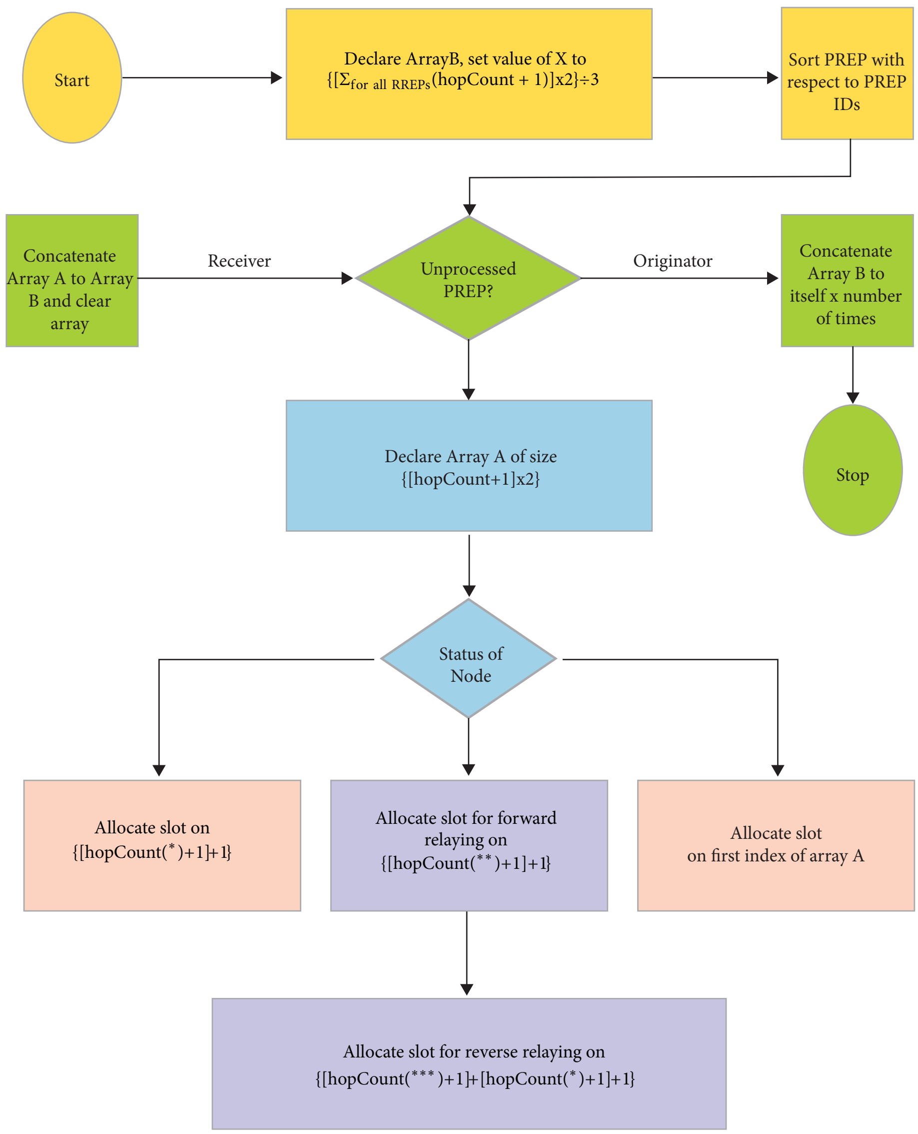

Figure 9: Flow graph.

5. Analytical and Simulation Results

The proposed cross-layer design of CL-TDMA has been simulated and tested in OMNET++ and MATLAB for multiple topologies such as peer-to-peer topology, multihop topologies for single and simultaneous communications for best case, average case, worst case, and many other random scenarios. The protocol is then ported in an SDR being used for many tactical applications. This research is supported by Center for Advanced Research in Engineering of Software-Defined Radio group [36].

It is not simple task to establish a fair comparison between TDMA-based MAC protocols as each of them has been developed with a different architecture and for a specific class of applications [37]. We compared the throughput, call setup overhead, and latency of CL-TDMA against those of conventional TDMA for multiple scenarios listed in Table 19 in Section 5.1, while in Section 5.2 a qualitative comparison is

Table 19: Communication scenarios.

Sr.	Communication Scenarios
1	Unidirectional single communication of SDRs.
2	Bidirectional single communication of SDRs.
3	Unidirectional simultaneous communication of SDRs
4	Bidirectional simultaneous communication of SDRs
5	Unidirectional Single communications of zero and multiple hops.
6	Bidirectional Single communications of zero and multiple hops.
7	Unidirectional simultaneous communications of zero and multiple hops.
8	Bidirectional simultaneous communications of zero and multiple hops

conducted among CL-TDMA and other state of the art MAC protocols for mobile ad hoc networks.

We derived the performance of CL-TDMA system in terms of throughput, call setup overhead, and latency. First we define the throughput for source SDRs and relay SDRs in CL-TDMA system as an average of number of packets transmitted in each f_d (data frame) with respect to R_n (network data rate/network throughput).

5.1. Comparison of CL-TDMA with Classical TDMA Protocol

(i) Throughput of CL-TDMA

$$T_{put} = \frac{\left(S_s \times \sum_{m=0}^{W} P_{sm}\right) \times \left(\sum_{t=1}^{T} f_{dt}\right)}{R_n} \quad (1)$$

In (1) S_s represents slot size and P_s represents number of packets transmitted per slot. In second term summation of f_d represents number of data frames transmitted in one minute. The product calculates data transmitted in one time slot, and second term represents the total number of data frames in one second. When we divide the product of both by channel capacity R_n we obtain throughput of CL-TDMA.

(ii) Call Setup Overhead

$$O_{head} = \frac{\sum_{i=1}^{L} \sum_{j=1}^{N} f_{cij}}{\left(\sum_{i=1}^{M} \sum_{j=1}^{N} f_{dij} + \sum_{i=1}^{L} \sum_{j=1}^{N} f_{cij}\right)} \quad (2)$$

Call setup overhead is calculated by dividing the number of control frame by total number of control and data frames involved in any communication. Formula is given in (2). It is obvious that if there is a small number of control frames, call setup overhead will be low.

(iii) Latency: latency for CL-TDMA is defined as the time lapse between data transmission turns of a node. For example, if there are two SDRs in communication, and data frame f_d has N data slots s_d, then the latency of communicating nodes will be equal to the size of one data slot for CL-TDMA, as out of N slots SDR_1 and SDR_2 will be allocated N/2 slots for their communication. In case of conventional TDMA, for this scenario each SDR will have to wait for N number of data slots to get the next turn to transmit data.

(iv) Observations: while testing CL-TDMA for multiple scenarios enlisted in Table 19, we have the following important observations:

(i) Throughput of CL-TDMA can be increased:

  (a) By enhancing channel data rate R_n
  (b) By increasing the slot size S_s
  (c) For large communication size $\boldsymbol{data_T}$

(ii) Throughput of CL-TDMA will be optimal for small number of L: for small the number of control frames, throughput will be higher and call setup delay will be low.

(iii) Throughput of CL-TDMA system starts converging towards conventional TDMA if large number of SDRs is communicating simultaneously.

(v) Throughput evaluation and analysis with various R_n: if we increase the size of communication for a tactical network, throughput of CL-TDMA will be improved. In this section we calculate throughput of CL-TDMA for different values of R_n and communication size $data_T$ as follows. The graph in Figure 10 represents performance of CL-TDMA with different values of channel capacity R_n, for three different communications of varying sizes.

CL-TDMA performs optimally for larger communications with small number of SDRs, where no. of $f_d \gg$ no. of f_c .Such communications yield minimal call setup overhead. The first curve with communication size $data_T = 1 \times 10^4$ is plotted for different values of R_n ranging from 200kbps to 1Mbps. For this communication size, throughput of CL-TDMA is optimized for channel capacity of 200kbps. This is because, for 200kbs channel capacity, data frames required to complete communication will be larger than the control frames involved in call setup. But as the channel capacity increases, throughput suffers because communication of 1×10^4 will be completed in small number of data frames and call setup overhead will affect the throughput.

Now if communication size is increased to $data_T = 1 \times 10^6$, throughput of CL-TDMA will increase. As can be seen from the graph, throughput of CL-TDMA is approximately 100% for 200kbps data rate.

(vi) Throughput evaluation and analysis with different S_s: next performance of CL-TDMA is evaluated for different slot sizes

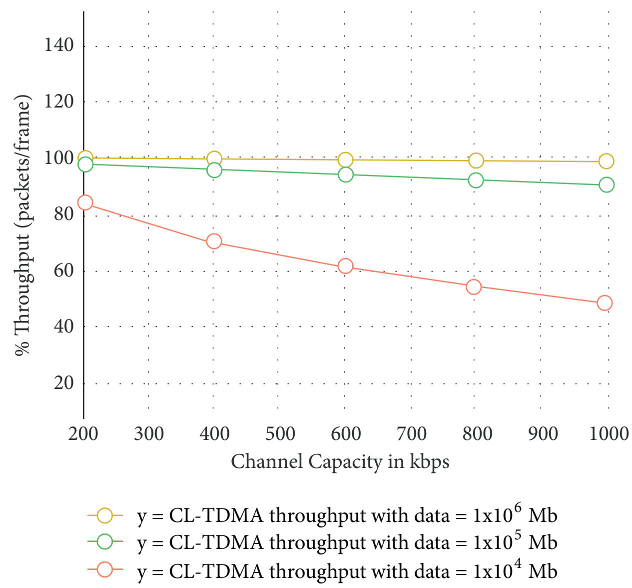

FIGURE 10: Performance analysis of CL-TDMA with different R_n.

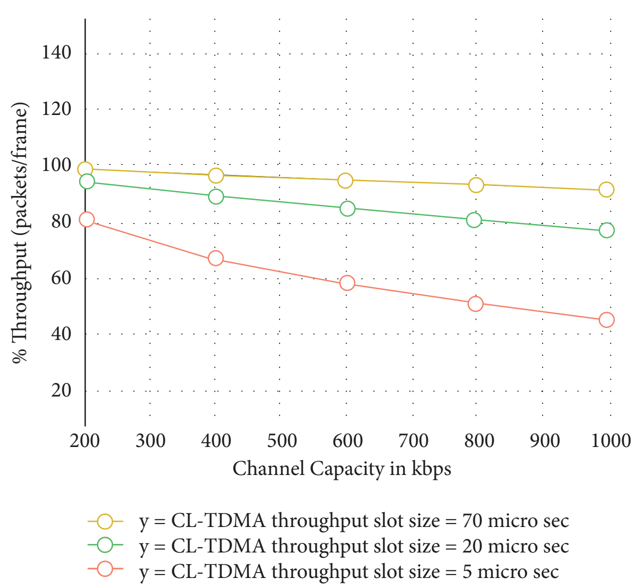

FIGURE 11: Performance evaluation of CL-TDMA for different S_s.

S_s. The larger the size of slot, the more the number of bits that can be transmitted in one unit of time.

Graph in Figure 11 presents three different curves of CL-TDMA throughput for three different s_s such as 5μs, 20μs, and 70μs.

Graph shows that when slot size is 70μs, throughput will be approximately 100% even for 200kbps. But as the channel capacity increases, the same slot size of 70μs throughput suffers, because the higher the channel capacity, the less the number of data frames will be consumed to complete the communication. This will increase the call setup overhead given in (2).

Here we conclude that CL-TDMA performs optimally when *no. of* $f_d \gg$ *no of* f_c. This brings us to an important conclusion that CL-TDMA may perform optimally even for lower channel bandwidth if the constraint *no. of* $f_d \gg$ *no. of* f_c is fulfilled. This is the first and foremost requirement of time and mission critical networks

However, it may be adapted for higher channel bandwidths if available, for longer communications with an appropriate trade-off between control frames and data frames.

(vii) Comparative analysis of CL-TDMA and conventional TDMA: this has been achieved for two important networking performance parameters, bandwidth and latency.

(a) Bandwidth: in our evaluation, network data rate R_n is 1Mbps and slot size s_s is 576.9μs. In addition, each data frame f_d is 30 slots long (N=10) and each super frame comprised 30 (*M=30*).

Figure 12 shows the performance of CL-TDMA and conventional TDMA for single communications in tactical networks. X-axis represents the hops between source and destination SDR, while Y-axis represents the percentage throughput as number of packets transmitted per frame.

The first curve of the graph has been plotted for CL-TDMA without call setup overhead. Throughput of communication for 0, 1, 2, 3, 4, and 5 hops between source and destination SDRs ranges between 95% and 100%.

Second curve represents the throughput for best case scenarios of communication, where call setup overhead is minimized, and throughput drops to the range of 78% to 84%. The drop in throughput of CL-TDMA is because of the overhead incurred by the call setup delay.

Third curve in graph has been plotted for worst case scenarios of communication where throughput of CL-TDMA drops down to 40%. This drop is because of the complex communication scenarios and increased call setup overhead delays.

Lastly, TDMA performance curve shows that the throughput increases linearly as the number of communicating SDRs increase. It shows that if more number of SDRs is actively participating in active communication, at one point performance of CL-TDMA converges to conventional TDMA. This is very unlikely for tactical combat network where number of communicating SDRs is very small as compared to commercial MANETs.

In both best case and worst case scenarios performance of CL-TDMA is much better than conventional TDMA.

Graph in Figure 13 compares the performance of CL-TDMA and conventional TDMA for multiple simultaneous communications.

For best case scenario, throughput of CL-TDMA drops down to approximately 80%. This is because data slots have been divided among multiple communications. But still performance of CL-TDMA is far better than conventional TDMA.

(b) Latency: graph in Figure 14 represents the comparison of latency between CL-TDMA and conventional TDMA. The curve for single communication scenario for CL-TDMA shows smaller values of latency for fewer number of hops.

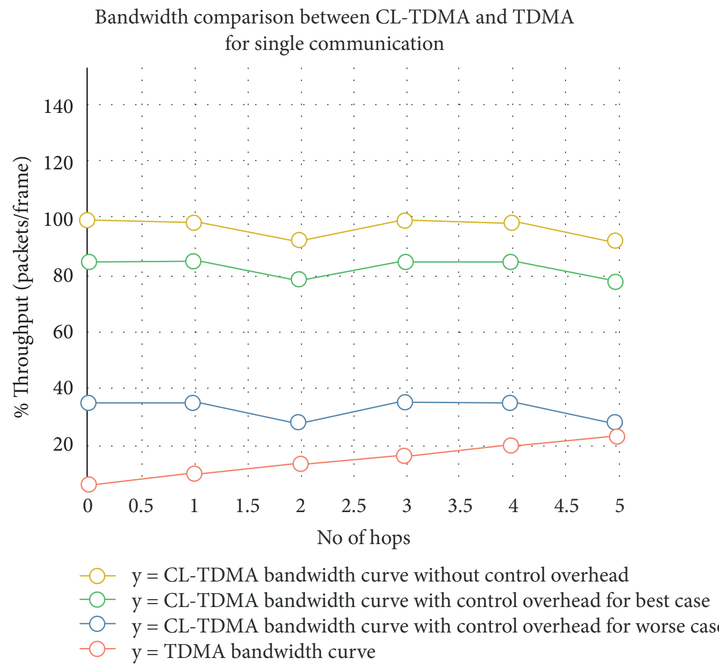

Figure 12: Bandwidth comparison of CL-TDMA and conventional TDMA for single communications.

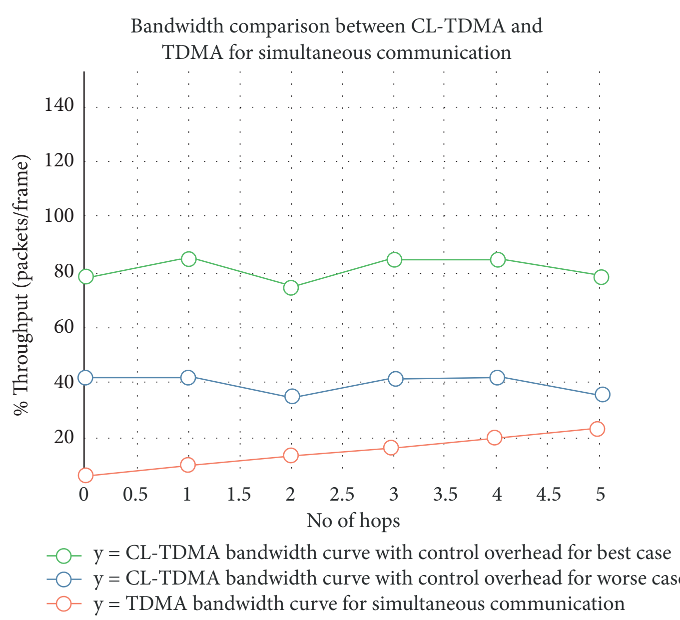

Figure 13: Bandwidth comparison of CL-TDMA and conventional TDMA for simultaneous communications.

As the number of hops increases, the value of latency also increases.

In case of simultaneous communication scenarios, latency increases because of more number of active communications and also because of number of relaying hops.

On the other hand, in case of TDMA, latency is quiet high. This is because, for both single and simultaneous communicating scenarios, each SDR will have to wait for N number of data slots for its next turn to transmit data.

5.2. Comparison of CL-TDMA with Other MAC Protocols for Multihop Ad Hoc Networks. Cross-layer MAC protocols for multihop ad hoc networks, presented in literature are strictly application specific. For example a cross-layer design developed for applications which are in dire need of throughput optimization may not be able to handle delay sensitive applications. Therefore a fair comparison of different application specific cross-layer designs is not possible. Table 20 provides qualitative comparison of CL-TDMA with other state of the art MAC protocols for mobile ad hoc networks over a set

Table 20: Qualitative comparison of CL-TDMA with other MAC protocols for multihop ad hoc networks.

Category	Protocol & Reference	Comments
Cross Layer based MAC protocols for Multi-hop Ad-hoc Networks	[12, 13]	These cross layer design based protocols use channel sensing and contention methods such as p-persistent CSMA scheme. This is not feasible for mission critical tactical networks where time for decision and response is a key constraint. Secondly in mission critical network collision is intolerable. CL-TDMA reduces call setup time by providing dynamic scheduling and collision free transmission.
TDMA-Based MAC Protocols for Vehicular Ad Hoc Networks	CS-TDMA [14], STDMA [15], ATSA [16]	Protocols in this category are specifically designed for congested vehicular networks and are not feasible for using in mission critical tactical networks. These designs do not use the concept of cross-layering causing huge overhead, which is intolerable in tactical networks such as artillery fire control systems. Moreover many protocols in this category use combination of contention based schemes and TDMA, which impacts response time adversely.
Cross Layer based TDMA protocols for Multi-hop Ad-hoc Networks	DD-TDMA [17], DTSS [18]	The protocols in this category are strictly application specific. DD-TDMA specifically targets real-time multiplayer game support [19] and DTSS is developed specifically to support slot scheduling for BeMAP [20], while CL-TDMA can be applied to any TDMA for self-forming and self-healing tactical networks. Moreover in CL-TDMA dynamic slot scheduling is achieved using AODV control messages. This feature provides efficient routing and no separate signaling protocol is required. However DTSS provides low access delay for less denser tactical networks, which is similar to the performance of CL-TDMA but this protocol does not help in routing in the signaling phase.

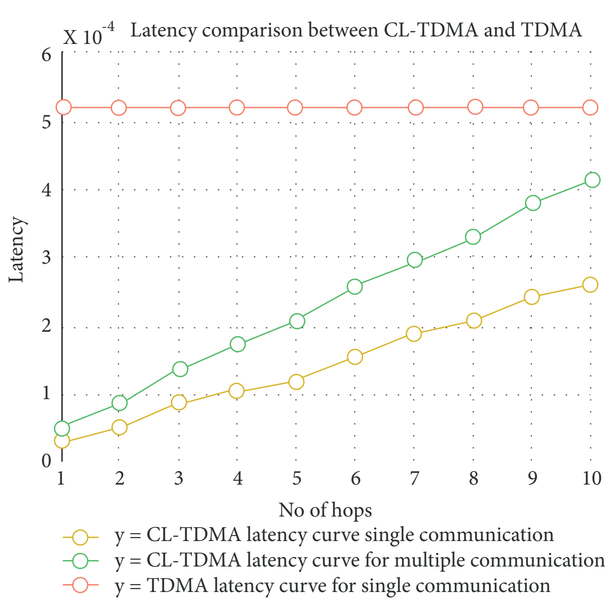

Figure 14: Latency comparison between CL-TDMA and conventional TDMA.

of parameters such as channel sensing, contention overhead, response time, and routing overhead.

6. Conclusion

In this paper we proposed a TDMA-based cross-layer MAC protocol (CL-TDMA) for multihop, self-healing, and self-forming tactical networks. CL-TDMA exploits empty slots, which are inherent in reservation-based MAC protocols. The cross-layer architecture provides efficient route calculation in parallel to call setup phase of SDRs, that reduces the route calculation overhead of network layer. We presented a novel design of slot allocation model for the proposed CL-TDMA with cross-layer support for route calculation by using AODV control messages and validated it through simulations. The results show that CL-TDMA effectively improves the tactical network performance in terms of throughput, call setup delay and latency. A qualitative comparison of the proposed approach is made with state of the art in cross-layer designs to show its validity for tactical applications. The protocol is ported in an SDR and is tested in the field in many tactical networks settings for the satisfaction of the users.

Data Availability

All the data supporting the results is provided in the article. The data scenarios not mentioned in article can be provided whenever needed.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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