

Received April 6, 2020, accepted April 21, 2020, date of publication May 6, 2020, date of current version May 21, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2992599

Self-Forming Multiple Sub-Nets Based Protocol for Tactical Networks Consisting of SDRs

RUKAIYA^{ID} AND SHOAB A. KHAN^{ID}

Department of Computer and Software Engineering, National University of Sciences and Technology, Islamabad 44000, Pakistan

Corresponding author: Rukaiya (rukaiya@ceme.nust.edu.pk)

ABSTRACT The paper presents a novel approach for tactical networks in which radios form self-regulatory virtual sub-nets on the basis of control messages. The design uses hybrid of frequency division multiple access (FDMA) and time division multiple access (TDMA) approaches with less call setup delays and increases in network throughput. This multiple sub-nets based distributed algorithm exploits available spectrum resources, provides collision-free simultaneous transmissions and autonomous selection of time slots over different frequency sub-bands with self-organizing and self-forming network capabilities. We propose two schemes which provide multi-channel medium access control with autonomous scheduling of time slots for software-defined radios (SDRs). The schemes use request and acknowledgment frames as control messages to devise a distributed solution. These control messages alone help to form virtual sub-nets, preserve frequency channels and schedule transmissions over multiple time slot intervals, depend on the type of data messages. In order to demonstrate the behavior of sub-nets for tactical networks, theoretical findings are exploited with experimental analysis to provide practical implementation of schemes using contention-free time slotted common control channel for nodes coordination and time slotted collision-free multi-channel environment for data transmissions. The results show the effective coexistence of multiple transmissions in a network with increase in network throughput and lower the data latency up-to 76.8%, when compare to conventional MAC protocols. The design is workable for time sensitive, mission critical networks and expected to support multi-hop transmissions in similar manner.

INDEX TERMS Tactical networks, time critical applications, software-defined radios, virtual sub-nets.

I. INTRODUCTION

Tactical networks are mission critical, congested and delay sensitive. These networks use mobile ad-hoc networks (MANETs) for instant and better communication in military applications mainly for the provision of voice and data transmission capacity. The nodes in tactical networks require communication support with mostly no centralized supervision over the network operations. In several cases, isolated systems are introduced in response to perceive needs or to take advantage of existing technology [1], [2]. However, all systems are limited to deal with single problem and ignore the design constraints of tactical networks.

For tactical application, incessant communication with precise and accurate information is rapidly increasing the importance of interoperability among radio nodes. Many times in radio networks, real time voice services need more bandwidth or quality of service (QoS) for abrupt and continu-

ous transmissions than any other application. Therefore, it is imperative to have multi-access protocol that is implemented locally without any implicit central coordination and able to handle tactical network constraints include limited bandwidth, low latency, narrow effective communication range, intermittent communication links and other conventional medium access control (MAC) issues.

This paper presents a novel MAC design for self-forming and self-organizing networks in tactical settings. The design organizes the network of software-defined radios (SDRs) into plurality of logical communication channels to perform simultaneous transmission of messages. These channels are configured as multiple access channels, so that they function as sub-networks, also referred to as 'sub-nets' or simply as 'nets'. Typically, the sub-net based approaches provide efficient communications and collaborations among nodes besides dedicate sub-nets to a specific purpose. However, this is foreseeable that few sub-nets have more members than others, thereby leading to inefficient utilization of network bandwidth.

The associate editor coordinating the review of this manuscript and approving it for publication was Tawfik Al-Hadhrami^{ID}.

Our idea of virtual confinement of radios into sub-nets is a novel approach and to best of our knowledge nobody used this concept in tactical networks. This virtual sub-nets formation provides collision-free simultaneous transmissions over different frequency sub-bands. It enables many transmissions to perform within same time slot over different narrow-band channels which reduces delays and increases throughput in tactical communication. Hence, it improves resource distribution and promotes efficient use of resources in tactical networks.

Radio networks for tactical communication require series of standard formatted messages which are used to exchange digital/analog data between radios, associated with the system. The exchange of this information permits continuous coordination and harmonization among radio nodes and sometimes between the tactical control systems involved [3], [4]. It minimizes mutual interference and significantly increases the effectiveness of the systems in a joint operation area. In an attempt to expand the capabilities of network systems and make them as flexible in use as possible, un-necessarily detailed information is frequently provided [5]. Too much information can create indecision, just as can too little information. Therefore, in tactical communication minimum control messages must be exchanged in order to make decisions related to data transmission. It is important to observe that nodes do not perform any explicit optimization and/or computation rather by locally deciding with exchange of few control messages.

Our design proposes two schemes (i) *Request, Acknowledgment, Request (RAR)* and (ii) *Optimized RAR (O_RAR)*. Both schemes use request and acknowledgment frames as control messages to build a transmission table on each node. This enables nodes to assess data slots for sending data and privileges transmitters to use multiple time slots according to the type of data transmitted e.g. text or multi-media. The optimized version of the design scheme reduces control messages overhead by transmitting multiple request acknowledgments in same control frame. This optimization reduces call setup time and access delays which are not possible in other proposed designs where each transmission request needs individual acknowledgment to synchronize transmission information on all nodes.

On radio channels, the exchange of messages creates multiple access interference due to concurrent nodes transmission at the same time. Time division multiple access (TDMA) based approaches result into delays in communication. These communication delays are usually encountered in TDMA based approaches where each node has its own time slot for data transmissions which reduces spectral efficiency. Whereas frequency division multiple access (FDMA) based approaches suffer with the problem of cross-talk or interference of signals. In military applications, these constraints should be handled precisely.

Our proposed design uses hybrid of TDMA and FDMA approaches to combine the strength of both access methods which mutually overcome each others

shortcomings. This distributed intelligent algorithm enables collision-free simultaneous radio transmissions using FDMA for non-intermittent high network throughput in time distributed manner. The adapted time slot allocation for radio transmission performs through TDMA over multiple FDMA carriers for each sub-net as no more than one radio is transmitting over a FDMA carrier at the same time, taking benefit of FDMA to counter the constraint of TDMA. This ensures throughput maximization and QoS in tactical communication.

Generally, to ensure the accuracy of transmissions, close connectivity of radios is necessary. In radio networks, there is very less chance that few radios are not in range of any other radio. Given the impact of network connectivity especially in MANET, it is a difficult and trivial task to manage time sensitive communication of mobile nodes with dynamic behavior of the network.

The proposed schemes address the problems with the objective of maximizing the throughput of co-existing transmissions among multiple peer radios. We describe and evaluate a novel fully decentralized medium access solution. In indulgence of tactical networks rather link bandwidth, the focus is more on simultaneous transmissions over non-overlapping frequency sub-bands. The simulation results show that our proposed schemes improve call setup delays with the use of minimum control messages and accelerates it more with the use of optimal solution. The experimental analysis proves that the design increases network throughput with the use of autonomous virtual sub-nets when compare to conventional MAC designs.

A. RESEARCH CONTRIBUTIONS

Previous researches demonstrate the efficient use of resources among pre-formed static sub-networks of generalized ad-hoc networks [6], [7]. The proposed work is designed to be the first to consider tactical network as the collection of autonomous dynamic sub-networks. The design yields major contributions to the research field. It provides:

- 1) Self-forming and self-organizing virtual sub-networks without having any centralized control.
- 2) Dynamic formation of network groups for efficient utilization of resources.
- 3) Interference free channel access periods for control and data transmissions.
- 4) Distributed frequency and slot selection for simultaneous transmissions.
- 5) Less control signaling to overcome control messages overhead with optimized use of control packets.
- 6) High network throughput with minimum call setup and access delay.

II. LITERATURE REVIEW

Few considerable researches have carried out to support distributed sub-network based communication in tactical networks. An algorithm for software-defined wireless

sensor network (SDWSN) is proposed by [8], which optimizes network structure using sub-nets. The algorithm uses sub-controllers in each sub-net to collect data packets, compress it and sent towards controller for further processing. In order to minimize latency for high priority messages, a sub-net based multiple access method for wireless network is proposed by [7]. In this method, nodes are able to receive messages simultaneously on at least two sub-nets, from which one send low latency (LL) messages and other use for standard messages. An acknowledgment protocol is also used to retransmit failed messages, faced collisions due to contention based medium access approach.

As shown by [9], network lifetime for MANET is maximized through optimal sub-net size estimation and assignment of nodes to sub-net heads. This research focuses on the energy consumption issue of the network. A design for tactical spectrum access mobile ad-hoc network is proposed by [10] in which SDRs communicate on a single frequency. In this design, the radios are organized into clusters and use frequency that may change autonomously by the network to respond jamming or interference, after some delay in frequency switching.

The problem with existing techniques is that these are not fully distributed and use sub-controllers or sub-heads for management within sub-nets. Some use sub-nets based approach for address assignment or subject energy consumption [11]–[13], hence mostly tailor one problem at a time. Furthermore, the techniques require multiple control cycles in sub-net formation and frequency allocation whereas our proposed scheme requires only one request and acknowledgment frames per data message.

Moreover, an extensive research is done on slot assignment and multi-channel MAC design for tactical environments. A distributed TDMA based slot allocation protocol for narrow-band communication in tactical MANETs is proposed by [14] in which nodes autonomously detect topology changes and use local knowledge to assign slots. The technique improves average channel utilization and reduces control traffic overhead. A paper presents control and data packets optimization to maximize tactical network throughput [15]. It uses data concatenation, optional flags, bit vector representation for control information and fragmentation of packets at IP level. Dynamic TDMA based protocols for tactical data link are studied in [16], in which time slots are allocated by a master node. The reservation is made according to the real-time requirement and time-out degree of messages. The design increases the slot utilization rate and throughput of the network.

The aforementioned techniques state data and control slots information in control frames and exchange it between nodes for slot and channel allocation [17]. The addition of time slots information in control messages increases overhead for which bit vector methods or other optimization techniques were used but still reserve few bits for the information. Whereas in our schemes, there is no information exchange between nodes related to data channels and slot allocation

which reduce control overhead compare to other proposed techniques. Moreover, most of them do not consider the autonomous behavior of tactical radios and thus cannot fairly assign collision-free frequency channels to all nodes in the network.

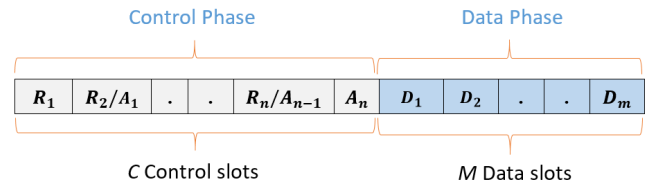


FIGURE 1. TDMA frame format for control and data packets.

III. PROPOSED DESIGN

Our proposed design is a hybrid of TDMA and FDMA based MAC protocol incorporating benefits of both the techniques. The design operates in TDMA frame cycles, comprise of control phase and data phase, as shown in Fig. 1. Each phase operates over time slots from which C control slots are available to transmit control frames on contention free time slotted common control channel. These C control time slots are further divided into request slots (R_i) and acknowledgment slots (A_i). The R_i slots allocation in control channel depends on the number of messages M and corresponds to the node Id. The duration of these control slots are of few milliseconds (ms), determined by the size of control frame. In optimized version of the proposed scheme the number of A_i slots may get reduce keeping more slots for data transmission, is discussed in next section. The design uses common control channel to transmit control frames for node’s coordination that is time slotted and contention-free.

In data phase, M time slots are used to transmit actual voice or data packets over different data channels. The duration of time slot in data phase for a node is variable, that is one or more slots are assigned to a node depending on the type of information, sender wants to transmit. Over these slots, multiple SDRs transmit data at the same time on different frequency channel which are not fixed for data transmission and change every time nodes move up to the next data phase. This not only increases spectral efficiency but also the performance of the system.

The duration of a TDMA frame comprising both control and data slots is fixed. When number of transmitters is large, control messages use data slots leaving less slots for data transmission and nodes buffer data to transmit it in next TDMA frame. The total time for a TDMA cycle is defined in (1).

$$\sum_{r=1}^T \left(\sum_{i=1}^N C_i \times t_r + \sum_{i=1}^M D_i \times t_r \right) \quad (1)$$

where, T is the total number of slots in a TDMA frame, use to send control frame C_i of node i and data messages D_i in time slot t_r of data and control phase respectively. The control

frame C_i can be either request or acknowledgment frame i.e. $C_i = \{c | c \in R_i \vee A_i\}$.

A. FUNDAMENTALS OF PROPOSED DESIGN

Following elements are used to derive a complete design for tactical SDR based communication.

1) CONTROL FRAMES TRANSMISSION

During control phase, all nodes send request (REQ) and acknowledgment (REQ_ACK) frames on time slotted contention-free common channel to share its transmission information. These control frames are overheard by all in range one-hop neighbors of sending nodes due to the broadcasting nature of network. The TX node not only sends transmission request or acknowledgment but also shares its transmission table (T_{table}) with neighbors. Therefore, the frames contain the information of transmitter (TX), its intended receiver(s) (RX), message type specifying control frame and data type (1 bit represents control frame; 0 for REQ and 1 for REQ_ACK , 2 bits for data type; (00 = text, 01 = visuals, 10 = voice, 11 = video) and T_{table} of TX/RX, as shown in Fig. 2.

| Transmitter ID | Receiver ID | Message Type | Transmission table (T_{table}) |
|----------------|-------------|--------------|------------------------------------|
| | | | |

FIGURE 2. Format of request and acknowledgment control frames.

Each node maintains T_{table} by using these control frames and provides visibility of two-hop transmissions to all nodes. Upon receive of REQ frame, nodes match its transmission table with those of its neighbors and update or include the new entry in T_{table} . In return of REQ frame, the RX SDR transmits REQ_ACK frame with its own T_{table} . Thus, control frames inform all two-hop neighbors about the intended transmissions, eliminate hidden/exposed node problem and help to form connected sub-graphs referred as sub-nets.

2) TRANSMISSION TABLE

Each node N_i maintains a transmission table (T_{table}) to store transmissions of its one-hop and two-hop neighbors. This information is typically used by the nodes to divide network into virtual sub-networks called sub-nets, select communication frequency and time slots allocation. The information about TX and RX node of the transmissions is extracted from control frames and stored in two separate columns of T_{table} , as depicted in Table 1. The first column contains the identity of transmitter called $TX_ID(N_i)$. The second column indicates the receiver $RX_ID(N_j)$ of transmission. These values in columns are just the Ids of nodes which are between 1 to N .

Each node updates its own T_{table} , upon receiving new REQ and REQ_ACK frames from its neighbors. After every data cycle, the T_{table} gets refreshed and the entry is removed if does not receive any information regarding it as node may not be its one-hop neighbor anymore.

TABLE 1. Transmission table of a node N_i .

| $T_{table}(N_i)$ | |
|--|-------|
| TX_ID | RX_ID |
| N_i | N_j |
| Transmissions of 1 and 2-hop neighbors | |
| - | - |
| - | - |

3) SUB-NETS FORMATION

The proposed design allows N nodes to exist in the network which are connected with each other via transmission or connectivity links. It divides the actual physical network into distinct virtual sub-networks or sub-nets (S), as shown in Fig. 3. The transmission of subsequent REQ and REQ_ACK frames or transmission of REQ_ACK after all REQ frames leads to the formation of its members (both cases are discussed in next section). Each sub-net S_x contains the node pairs (N_i, N_j), connected with link L and has maximum nodes n i.e. ($1 \leq x \leq n$), defined in (2).

$$S_x = (N_i, N_j) \in L \quad \forall i, j \quad (2)$$

The change in environment and transmission patterns shape the structure of sub-nets. The approach improves resource distribution and promotes efficient use of resources in dynamic network environment. In our design, sub-nets are formed in a way that the transmissions are managed in a contention free manner and all SDRs autonomously organize themselves into disjoint sub-nets.

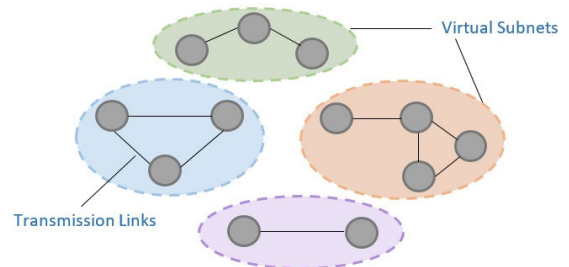


FIGURE 3. Transmission based virtual sub-nets.

The sub-nets formation is all distributed and does not depend on global coordination of network nodes. The formation uses local information, stored in T_{table} of each node and forms on following conditions:

- 1) Id of TX node matches with Id of RX for other entry.
- 2) Id of RX node matches with Id of TX for other entry.

If either of above conditions occurs, the nodes belong to the same sub-net and use selected time slotted data channel accordingly. The number of sub-nets forms depending on the transmission patterns and have maximum diameter equals to total number of nodes in the network.

4) FREQUENCY SELECTION

After sub-nets formation, each sub-net selects its own frequency sub-band f_k autonomously from a frequency band of

range 0 to $f_{(k-1)}$, matches with the lowest member Id of the sub-net. It represents as a function (F) and has its minimum Id over a set of nodes (n_i) in a sub-net S_x , defined in (3).

$$f_{S_x} = F[\min(n_i)] \tag{3}$$

The frequency sub-bands available for data transmissions are actually $f_{(k-1)}$, from which one frequency is being used for control frames transmission. The design uses hybrid of TDMA and FDMA approaches. All the control and data transmissions are performed on time slotted channels. During these transmissions, SDRs use frequency hopping which is the essential part of tactical networks. This frequency hopping is adaptive and saves the attacks as radios incessantly hop over multiple frequencies.

In all tactical radios, the (transmission security) TRANSEC is ensured by frequency hopping. Therefore, there is no one frequency that can be jammed or attacked. The attacker has no easy way of knowing when the network switches to control as the radios are continuously hopping in lock step in different frequencies. The frequency hopping is not only for data transmission but also use during control phase where all radios exchange control frames using adaptive frequency hopping. In military applications, the generation of hop sequence for frequency hopping is under the control of shared secret key or on pseudo random sequence which is out of the scope of this paper [18], [19].

Our proposed design ensures that no sub-net shares its selected frequency with any other sub-net hence, there is no interference expecting during data transmission. The number of frequencies for data transmission varies according to the network condition.

5) TIME SLOTTING

In control phase, there is only one *REQ* slot per node but may be no, only one or more *REQ_ACK* slot(s) for responses e.g. node N_i can only transmit in the interval time at the i th control slot. If N_i needs to transmit again, it must wait until the i th control slot of next TDMA frame.

For intra-subnet communication, the data transmissions are performed over time slots of multiple intervals using TDMA approach. The algorithm allows a node to grab more than one portion of the channel according to the type of data, node wants to transmit e.g. text, voice, visuals or video. As shown in Fig. 4, at f_2 node 2 has two slot to transmit its data while nodes 3, 5 and 6 have one, one and three slots respectively. Each node of the sub-net knows that the lowest node Id has first time slot for transmission, allocated in ascending order means the lowest Id member has first slot of the slot vector, the second lowest Id node has second slot for data transmission and so on.

After completion of data phase, all reserved frequencies and time slots are released and the process starts again with the next control phase. Depending on the nature of application, multiple data phases can be run for each sub-net. Time slots for control frames are kept small for the whole network operation. There is a possibility to increase the size of slot

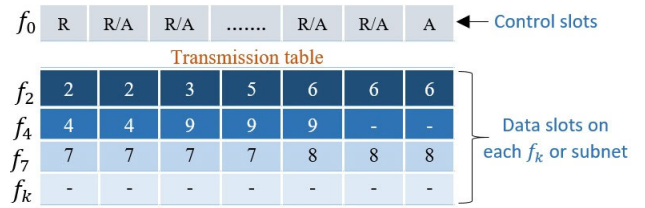


FIGURE 4. Frequency distribution with time slots division.

rather assign multiple slots to a node but it will create time synchronization problem among nodes.

6) DATA TRANSMISSION

The proposed algorithms favor simultaneous data transmissions on separate data channels. It involves transmission of data packet (DATA), contains either text or multi-media information. Acknowledgment (ACK) of DATA can also be transmitted by reserving slots for RX nodes in case of bidirectional data transfer to add reliability and increase in network throughput.

The protocol differs from other designs in many ways where nodes discover the transmission schedule during the control phase autonomously. Unlike other MAC designs, there is no exchange of information on the decision of data channels. It also deals with conventional MAC design constraints.

TDMA based approach and selection of different frequency sub-bands mitigate collisions and interference among nodes transmissions. The scheme is designed in a way that there are no collisions in the transmission. In control phase, each radio can only transmit in its own time slot. Whereas in data phase, radios form sub-nets to avoid any collision. Even within sub-nets the TDMA is used for collision free communication. The retransmissions may occur due to distant radios pair, are dealt with respective (Transmission control protocol) TCP and (Automatic repeat request) ARQ mechanisms by the networking layer protocol.

7) FINITE STATE MACHINE FOR CONTROL AND DATA PHASE

We use a finite state machine (FSM) to implement and precisely analyze the working of proposed method. The MAC design defines the exact set of states, events, conditions and actions required to operate FSM. The state transition diagram for the control and data phase of proposed scheme is shown in Fig.5.

The FSM describes the interaction between all possible states, events and actions for transmit and receive path. The states of FSM have following meaning:

- IDLE: there is no control frame or data to transmit.
- LISTEN: SDR(s) (neither TX nor RX) overhear(s) control frame.
- WAIT ACK: TX_SDR is waiting for acknowledgment of the request.
- WAIT STATE: SDR waits to transmit data upon control phase timeout.

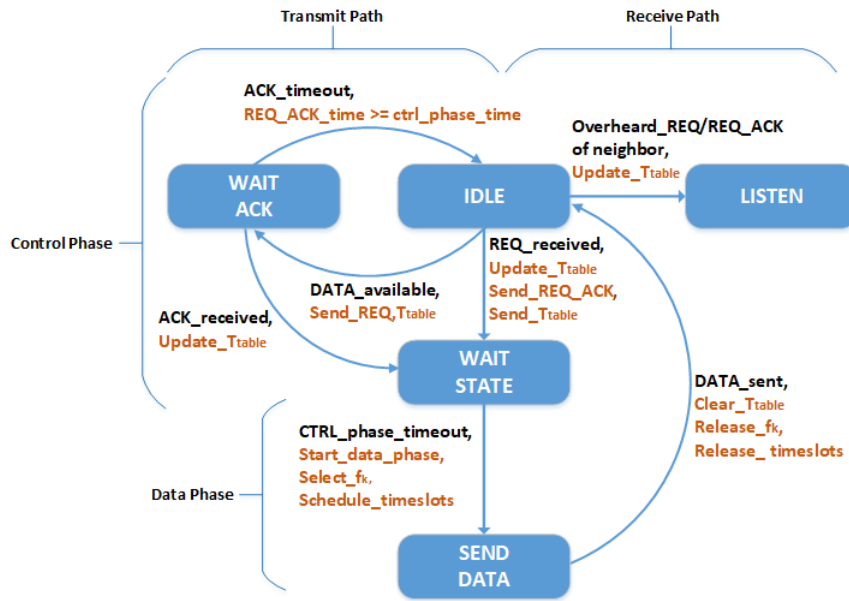


FIGURE 5. Finite state machine for control and data phase.

- SEND DATA: wait time overs and data is sent on selected time slots

The events occur in FSM have following meaning:

- DATA_available: data packet is available at SDR.
- REQ_received: a request message is received at RX_SDR.
- ACK_received: an ACK is received at TX_SDR.
- DATA_sent: data packet is sent towards RX_SDR.
- ACK_timeout: no ACK is received till the timeout.
- CTRL_phase_timeout: time for control frames transmission is completed.
- Overheard_REQ/REQ_ACK from neighbor: SDR(s) overhear REQ/REQ_ACK from another SDR.

The FSM is generally in an idle state until an event is invoked to start the state transition process. Fig. 5 shows that when an event *DATA_available* is set, *Send_REQ* and *Send_T_{table}* actions are taken as the FSM goes from an IDLE state to WAIT ACK state. In next event, FSM looks for either the *ACK_received* or *ACK_timeout* and the transitions depend on which event is observed. After *ACK_received* event, the action *Update_T_{table}* is performed and FSM goes into WAIT STATE. At this state if an event *CTRL_phase_timeout* is taken place, identifies the completion of control phase and probes *Start_data_phase*, *Select_f_k* and *Schedule_timeslots* to enter into SEND DATA state. When FSM performs event *DATA_sent*, it transits to IDLE state with events *Clear_T_{table}*, *Release_f_k* and *Release_timeslots*. The FSM also deals with an event *Overheard_REQ/REQ_ACK* for the SDRs which are neither TX nor RX and transit from IDLE to LISTEN state where SDRs listen the frames and update their *T_{table}* accordingly. The rest of the state transition diagram can be interpreted in similar manner.

Note that the sub-nets formation, frequency allocation and time slot scheduling do not depend on the FSM model. All these are performed using the information stored in *T_{table}*, build during the control phase.

IV. WORKING OF ALGORITHM

The section describes the working of algorithm for a tactical network. The proposed algorithm can function for any number of SDRs which usually ranges from 10 to 80 radios. Among all the SDRs, few are transmitters and others are receivers. Therefore, we specifically consider that half of the SDRs have messages to send. The TX SDR can send a message to any other SDR which can have data for another SDR. The assumptions are made here that each node knows about their all one-hop neighbors and the data packets transmit by any node can be received by its all one-hop neighbors. Now, let us assume a topology of 8 nodes with nodes Id 1, 2, 3, 4, 5, 6, 7 and 8 respectively. Each node has a set of neighbors and can talk to one of its neighbors. Therefore, the contention range is set to one and two-hops to avoid hidden and exposed node problems. The algorithm lets each node to keep record of all data transmissions within its two-hop neighborhood. For algorithm description, we consider 4 messages sent by TX SDRs N_1, N_2, N_3 and N_4 which have data for N_6, N_7, N_8 and N_2 respectively.

Before sending data, SDRs go through a control phase and exchange intended transmissions using control frames in their respective time slots. Whenever a node has data, a REQ frame is sent containing intended transmission along with its complete transmission table to its two-hop vicinity. The assumption is made here that if a node does not have any request message to send, it will broadcast its *T_{table}* in its REQ slot to maintain similar information on every node. The design exchanges REQ and REQ_ACK packets using

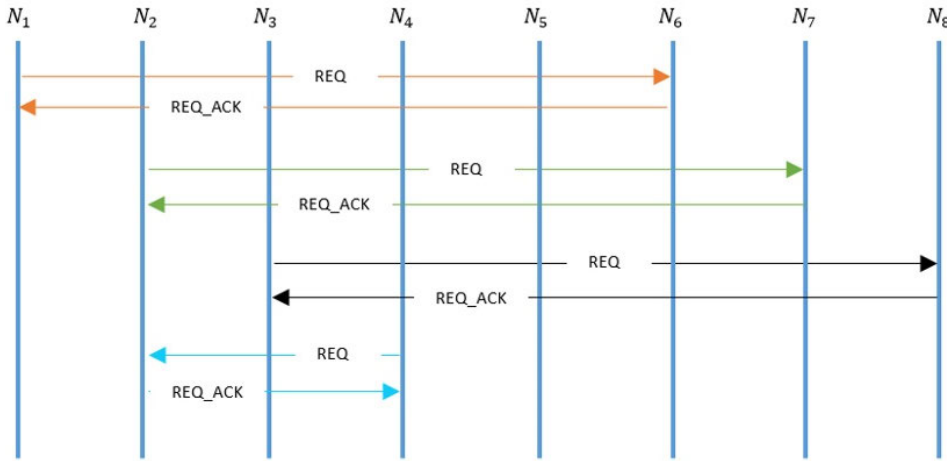


FIGURE 6. Flow graph of control messages for RAR scheme.

TABLE 2. Transmission table of all nodes after completion of control phase in RAR scheme.

| $T_{table}(N_1)$ | | $T_{table}(N_2)$ | | $T_{table}(N_3)$ | | $T_{table}(N_4)$ | |
|------------------|---------|------------------|---------|------------------|---------|------------------|---------|
| TX_Node | RX_Node | TX_Node | RX_Node | TX_Node | RX_Node | TX_Node | RX_Node |
| 1 | 6 | 1 | 6 | 1 | 6 | 1 | 6 |
| 2 | 7 | 2 | 7 | 2 | 7 | 2 | 7 |
| 3 | 8 | 3 | 8 | 3 | 8 | 3 | 8 |
| 4 | 2 | 4 | 2 | 4 | 2 | 4 | 2 |

| $T_{table}(N_5)$ | | $T_{table}(N_6)$ | | $T_{table}(N_7)$ | | $T_{table}(N_8)$ | |
|------------------|---------|------------------|---------|------------------|---------|------------------|---------|
| TX_Node | RX_Node | TX_Node | RX_Node | TX_Node | RX_Node | TX_Node | RX_Node |
| 1 | 6 | 1 | 6 | 1 | 6 | 1 | 6 |
| 2 | 7 | 2 | 7 | 2 | 7 | 2 | 7 |
| 3 | 8 | 3 | 8 | 3 | 8 | 3 | 8 |
| 4 | 2 | 4 | 2 | 4 | 2 | 4 | 2 |

two schemes (i) RAR (Request, Acknowledgment, Request) and (ii) O_RAR (Optimized-RAR). Both schemes are used to maintain T_{table} which supports transmission scheduling on multi-channel network for at-least two-hops.

A. RAR SCHEME

In RAR scheme, the time for control phase is divided into consecutive REQ and REQ_ACK time slots. In REQ slots, all nodes send REQ frames containing their intended transmission along with their updated T_{table} . On receive of request message, all neighbors of the node learn about two-hop neighbors’ transmissions information. In this scheme, every REQ frame gets its immediate response in next time slot from the receiver to which it sent the request. The response is the REQ_ACK frame which also contains the updated T_{table} of RX SDR. Since, request is made to RX SDR, only RX can use the succeeding REQ_ACK slot (if no request was made during the preceding REQ slot, one of TX’s neighbors can use the REQ_ACK slot time).

In consideration of above mentioned topology of 8 nodes, there are 4 nodes which have transmission need as depicted in Fig. 6. The nodes send REQ messages in their respective slot and get immediate response of that message i.e. N_1 has

| TX_ID | RX_ID | Msg_type | T_{table} |
|-------|-------|----------|-------------|
| 1 | 6 | 000 | 1 → 6 |

FIGURE 7. Request frame of Node 1.

| TX_ID | RX_ID | Msg_type | T_{table} |
|-------|-------|----------|-------------|
| 6 | 1 | 100 | 1 → 6 |

FIGURE 8. Acknowledgment frame from Node 6.

transmission need for N_6 , sends REQ to N_6 , and overhears by all of its neighbors. The N_1 request frame includes message type is shown in Fig. 7. The nodes including RX node update their table with the addition of N_1 transmission request. It is shown in Table 2 (the colors of each message show entries, added due to matching colored arrows in Fig. 6) that N_3, N_4, N_5 and N_6 are neighbors of N_1 and update their transmission table. All other nodes follow the same process and transmit their REQ and REQ_ACK frames. The nodes which cannot get the REQ message of N_1 , can learn about the transmissions through REQ_ACK frames sent form N_6 as they are two-hop away from TX but are at one-hop of RX node and so on. The REQ_ACK frame of node N_6 for N_1 REQ frame is shown in Fig. 8.

TABLE 3. Transmission table of all nodes after completion of control phase with incomplete transmission information.

| $T_{table}(N_1)$ | | $T_{table}(N_2)$ | | $T_{table}(N_3)$ | | $T_{table}(N_4)$ | |
|------------------|---------|------------------|---------|------------------|---------|------------------|---------|
| TX_Node | RX_Node | TX_Node | RX_Node | TX_Node | RX_Node | TX_Node | RX_Node |
| 1 | 6 | 1 | 6 | 1 | 6 | 1 | 6 |
| 2 | 7 | 2 | 7 | 2 | 7 | 2 | 7 |
| 3 | 8 | 3 | 8 | 3 | 8 | 3 | 8 |
| 4 | 2 | 4 | 2 | 4 | 2 | 4 | 2 |
| 5 | 6 | 5 | 6 | 5 | 6 | 5 | 6 |

| $T_{table}(N_5)$ | | $T_{table}(N_6)$ | | $T_{table}(N_7)$ | | $T_{table}(N_8)$ | |
|------------------|---------|------------------|---------|------------------|---------|------------------|---------|
| TX_Node | RX_Node | TX_Node | RX_Node | TX_Node | RX_Node | TX_Node | RX_Node |
| 1 | 6 | 1 | 6 | 1 | 6 | 1 | 6 |
| 2 | 7 | 2 | 7 | 2 | 7 | 2 | 7 |
| 3 | 8 | 3 | 8 | 3 | 8 | 3 | 8 |
| 4 | 2 | 4 | 2 | 4 | 2 | 4 | 2 |
| 5 | 6 | 5 | 6 | 5 | 6 | - | - |

On completion of control phase, all nodes build same T_{table} and form virtual sub-nets on the basis of transmission information in that table. With above topology, three sub-nets are formed where $S_1 = \{(N_4, N_2), (N_2, N_7)\}$, $S_2 = \{(N_3, N_8)\}$ and $S_3 = \{(N_1, N_6)\}$, shown in Fig. 9. Frequency channel is selected for each sub-net and is divided into time slots equal to the number of TX SDRs and message type. The minimum node Id decides the frequency channel for the sub-net and gets the first time slot as shown in Fig. 10. After sub-nets formation and time division on the frequency spectrum, common slot allocation vectors are created by each node of sub-nets. Within respective time slots of a slot vector, nodes perform simultaneous data transmissions without disrupting each others transmissions.

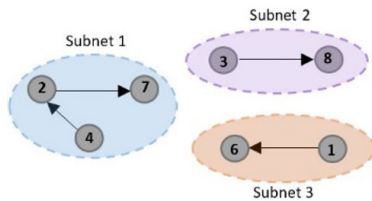


FIGURE 9. Virtual sub-nets formation.



FIGURE 10. Time and frequency distribution vector.

The scheme allows nodes to perform simultaneous data transmission in multi-channel environment. In many cases, it performs efficient information exchange but we counter cases where after the completion of control phase, few nodes lack in having all transmissions entered in their T_{table} . This happens when a node is neither a TX nor RX as well as the neighbor of one of them hence, cannot listen both REQ and REQ_ACK messages. It happens because of sending request messages for same receiver which in response uses individual

allocation packet to confirm the transmissions. It is shown in Table 3, when N_5 sends REQ message for N_6 which listens by all neighbors of N_5 . The REQ_ACK message listens by all neighbors of N_6 which update their T_{table} . The nodes which are neither the neighbor of TX nor RX suffer. In this case, N_8 will not update its T_{table} for the entry because it is neither the neighbor of N_5 nor N_6 .

The problem is encountered by using an additional round in which all nodes share their T_{table} with their neighbors just to converge the network at common information. This additional round helps in convergence but effects network throughput and call setup delay which eventually increase the time duration for the control phase.

B. O_RAR SCHEME

In this scheme, we optimize RAR approach in which the control phase is divided into two rounds. All nodes send REQ messages in request round follows with the acknowledgment round. If a node receives multiple REQ messages as an intended receiver, then it sends acknowledgment of all the REQ frames within same REQ_ACK frame in acknowledgment round. It eliminates the issue of indifference among T_{table} of all nodes and also reduces the number of REQ_ACK messages, send against each REQ message for same receiver. It is shown in Fig. 11 that N_1 and N_5 have data for N_6 and send REQ frames, in return N_6 uses same REQ_ACK frame to respond both requests. It is observed that before sending last two REQ_ACK messages, the T_{table} on all nodes has been converged with all the transmission needs mentioned in REQ messages, is depicted in Table 4.

The optimized version of the scheme reduces control messages overhead, call setup time and converges the network efficiently. It takes less time to propagate the information to all neighbors using minimum number of control frames.

C. ALGORITHM

The algorithm 1 defines the working of proposed design for which we consider network topology as a graph $G = (V, E)$ where in each case the set of vertices (V) is a finite set of nodes with finite number of edges, say $|V| = N$ and E is a

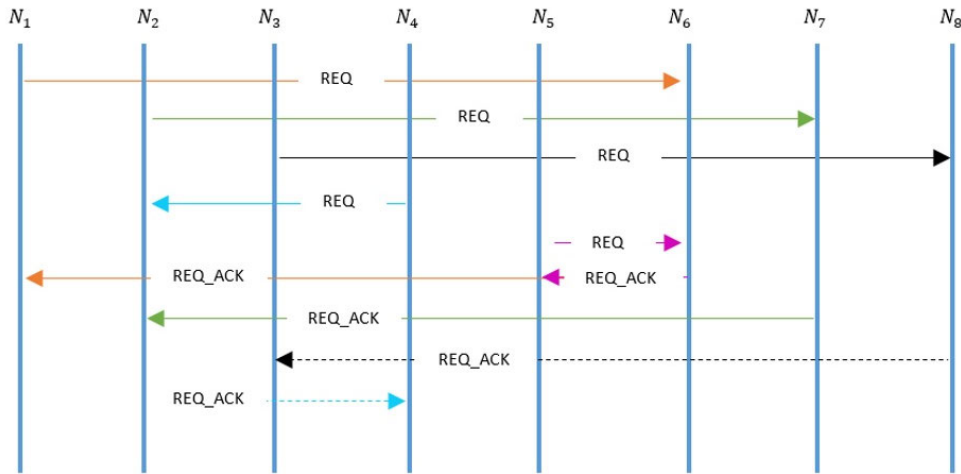


FIGURE 11. Flow graph of control messages for O_RAR scheme.

TABLE 4. Transmission table of all nodes after completion of control phase with complete transmission information for O_RAR scheme.

| $T_{table}(N_1)$ | | $T_{table}(N_2)$ | | $T_{table}(N_3)$ | | $T_{table}(N_4)$ | |
|------------------|---------|------------------|---------|------------------|---------|------------------|---------|
| TX_Node | RX_Node | TX_Node | RX_Node | TX_Node | RX_Node | TX_Node | RX_Node |
| 3 | 8 | 2 | 7 | 2 | 7 | 2 | 7 |
| 4 | 2 | 3 | 8 | 3 | 8 | 3 | 8 |
| 5 | 6 | 4 | 2 | 4 | 2 | 4 | 2 |
| 1 | 6 | 1 | 6 | 1 | 6 | 1 | 6 |
| 2 | 7 | 5 | 6 | 5 | 6 | 5 | 6 |

| $T_{table}(N_5)$ | | $T_{table}(N_6)$ | | $T_{table}(N_7)$ | | $T_{table}(N_8)$ | |
|------------------|---------|------------------|---------|------------------|---------|------------------|---------|
| TX_Node | RX_Node | TX_Node | RX_Node | TX_Node | RX_Node | TX_Node | RX_Node |
| 1 | 6 | 1 | 6 | 1 | 6 | 1 | 6 |
| 3 | 8 | 2 | 7 | 2 | 7 | 2 | 7 |
| 4 | 2 | 3 | 8 | 3 | 8 | 3 | 8 |
| 5 | 6 | 4 | 2 | 4 | 2 | 4 | 2 |
| 2 | 7 | 5 | 6 | 5 | 6 | 5 | 6 |

link on V satisfies the symmetric property $rEw \rightarrow wEr$ for all r and w in V .

Each vertex V has edges connected to a set of vertex or has at-least one vertex connected to it such that $\delta(v) = 1$, called neighbor(s) of the node. The objective of the algorithm is to partition the network graph G into different sub-graphs $S = (V_1, E_1)$ if $V_1 \subseteq V$ and $E_1 \subseteq E$. These directed sub-graphs are shaped into disjoint sub-nets, form on the basis of transmission patterns which direct the transmissions flow over a frequency band f_k .

Following assumptions are made which are common to most radio data link protocols

- 1) All nodes in the network are homogeneous in terms of physical characteristics.
- 2) Nodes are half-duplex that is, at any given instant nodes can either transmit or receive but not both.
- 3) Each node has unique identifier denoted as Id, moves with constant speed and there is no mobility during protocol operation.
- 4) We assume ideal MAC layer conditions e.g. perfect data transmission, no physical interference.
- 5) Transmission power of each node is fixed and uniform across the network.

V. EXPERIMENTS, RESULTS AND ANALYSIS

The proposed schemes are evaluated via extensive simulations, using MATLAB and OMNET++5.4.1 with INET framework 4.6.0. The convergence of T_{table} , sub-nets formation, frequency and time slot allocations are performed in MATLAB whereas, time slot vectors calculation and network performance are evaluated in OMNET++. We performed experimental analysis of design schemes to prove design feasibility for which a network scenario is considered. The network consists of twelve nodes, out of which six nodes have data to transmit (i.e. half are TX and other half are RX). For instance, in Fig. 12, node1 and node5 want to communicate with each other, node2 also has data for node5, node3 to node10, node4 to node12 and node6 to node2. The number of frequencies (f_k) are assumed to be more than the number of nodes, or say almost twice the number of nodes. A random mobility pattern is considered for nodes and the speed of nodes is slow. We also assumed that each node can reserve multiple slots to transmit data which varies depending on the type of service it requires (discuss later in this section).

For above scenario, total three sub-nets are formed where nodes 1, 2 and 5 become the members of sub-net1, node3 and

Algorithm 1 Subnet Based MAC Schemes**Notation:**

1. The finite set of symbols δ_i denoted by $\sum^* = \{N, \Gamma(N), S, C_{slots}, D_{slots}\}$, where N = number of nodes, $\Gamma(N)$ = set of one-hop neighbors
2. v_i : elements of V with $1 < i \leq N$
3. S_x : elements of sub-graph or Subnet S , where x is a finite non-negative integer
4. $|S|$: size of sub-graphs or subnet
5. f_k : elements of frequency-band, where k is a finite non-negative integer
6. C_{slots} = Control slots and D_{slots} = Data slots

Initialization: $T_{table} \leftarrow \phi$ (empty); $k \leftarrow 0$

```

1 while ( $C_{slots} == True$ ) do
2    $V_i$  sends  $REQ$  frame
3   insert  $TX$  and  $RX$  in  $T_{table}(V_i)$ 
4   if ( $control\_frame == REQ \ \&\& \ RX == V_j$ ) then
5     search  $TX$  and  $RX$  in  $T_{table}(V_j)$ 
6     if found then
7        $V_j$  sends  $REQ\_ACK$  frame
8     else
9       insert  $TX$  and  $RX$  in  $T_{table}(V_j)$ 
10       $V_j$  sends  $REQ\_ACK$  frame
11    end
12  end
13  // for O_RAR scheme  $REQ\_ACK$  frames are
14  // sent after  $REQ$  round
15  if ( $control\_frame == REQ\_ACK \ \&\& \ RX == V_i$ )
16  then
17    search  $TX$  and  $RX$  in  $T_{table}(V_i)$ 
18    if found then
19      exit
20    else
21      insert  $TX$  and  $RX$  in  $T_{table}(V_i)$ 
22      All neighbors perform steps 4 to 19 for
23      every  $REQ$  and  $REQ\_ACK$  frames
24    end
25  end
26  // for all entries in  $T_{table}(V_i)$ 
27  if ( $V_i == TX \ \&\& \ V_j == RX$ ) || ( $V_i ==$ 
28   $RX \ \&\& \ V_j == TX$ ) then
29    add  $V_i$  and  $V_j$  in  $S$ 
30     $k \leftarrow S \{min(V_{\{1,2,3,\dots,x\}})\}$ 
31     $S_x = (V_i, E_i)$  and  $S_x \leftarrow f_k$ 
32    Assign  $D_{slots}$  to  $V_i$  according to  $MSG\_TYPE$ 
33     $V_i$  transmits data to  $V_j$ 
34  end
35 end

```

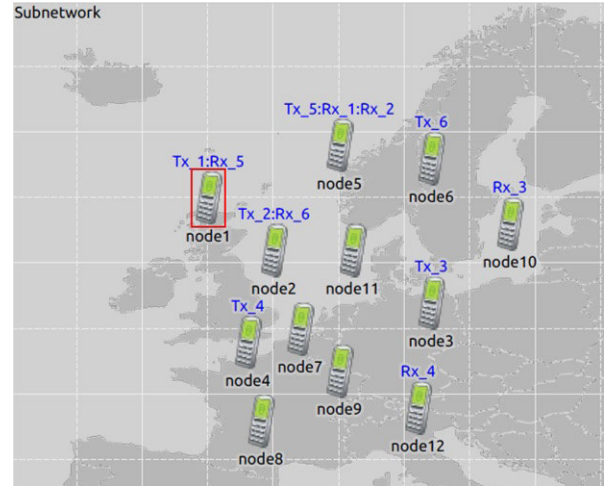


FIGURE 12. Network topology of twelve nodes.

node10 are part of sub-net2 and node4 and node12 are in sub-net3, depicted in Fig. 13.

In design of RAR scheme, the frequency distribution and time slot vectors along with the sub-net information are computed and summarized in Table 5. It can be seen, that node6 has data for node2 but not becomes the member of any sub-net due to the issue in control signaling pattern of RAR scheme.

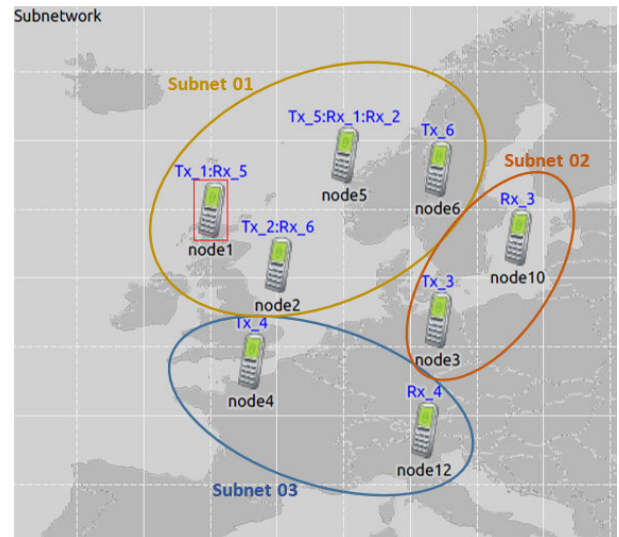


FIGURE 13. Sub-nets formation after control phase for $N = 12$.

To deal with this convergence issue, after control phase an additional *synchronization phase (SYNC)* is added in RAR scheme. This SYNC phase resolves the issue and probes all nodes to broadcast their T_{table} in their respective time slot. It makes node6 a member of sub-net1 as all nodes now acquired information about all the transmissions, shown in Table 6.

By keeping the same data messages, we use *O_RAR* scheme over the scenario and achieve similar results without

TABLE 5. Frequency and time distribution of radio network for RAR scheme with N = 12, m = 6.

| Node | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Sub-net | 1 | 1 | 2 | 3 | 1 | - | - | - | - | 2 | - | 3 |
| Control channel | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 |
| Data channel | f_1 | f_1 | f_2 | f_3 | f_1 | - | - | - | - | f_2 | - | f_3 |
| Time Slot | t_1 | t_1 | t_1 | t_1 | t_3 | - | - | - | - | t_2 | - | t_2 |

TABLE 6. Frequency and time distribution of radio network for RAR (with sync phase) and O_RAR schemes with N = 12, m = 6.

| Node | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|-----------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Sub-net | 1 | 1 | 2 | 3 | 1 | 1 | - | - | - | 2 | - | 3 |
| Control Channel | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 | f_0 |
| Data Channel | f_1 | f_1 | f_2 | f_3 | f_1 | f_1 | - | - | - | f_2 | - | f_3 |
| Time Slot | t_1 | t_1 | t_1 | t_1 | t_3 | t_4 | - | - | - | t_2 | - | t_2 |

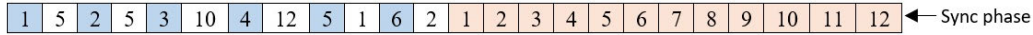


FIGURE 14. Control time slots for control frames of RAR scheme with SYNC phase (slots = number of nodes).

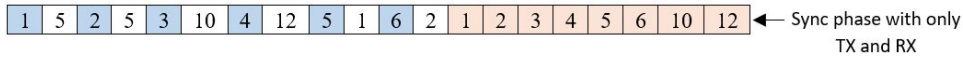


FIGURE 15. Control time slots for control frames of RAR scheme with SYNC phase (slots = number of control frames).

having any additional sync phase, as shown in Table 6. During the request phase, all nodes transmit their communication needs (along with its own and 1 or 2-hop transmissions, if have received previously) in their respective time slots. On completion of request phase, every node has learn about all of its neighbor’s transmissions and if any of its neighbors wants to transmit data to it. The scheme outperforms due to acknowledgment phase with cumulative replies for same receivers and there is no need of any other control frames to transmit T_{table} other than the control phase.

In above scenario, nodes N_7, N_8, N_9 and N_{11} are not involved in transmissions hence not become part of any sub-net but being neighbors of TX or RX are known to every transmission of the network and hold same T_{table} as TX/RX nodes. These nodes can run a separate control phase at frequency f_0 parallel to the preceding data phase if have data for each other. This strategy can lead towards the interleaving of control and data phases using the same designed scheme.

A. PERFORMANCE ANALYSIS OF PROPOSED SCHEMES

We derived the performance of schemes in terms of call setup delay, control overhead, network throughput and latency.

1) CALL SETUP DELAY

The proposed algorithm is designed using hybrid of TDM and FDM with multi-channel configurations on physical layer. The request time which is the call setup time is calculated and for that we consider the size of control slot is equal to the size of control frame. In case of 12 nodes, the control frame is of 59 bits (TX ID + RX ID + Message Type + (T_{table} (bits for node ID (TX + RX) × number of messages)) = (4bits + 4bits



FIGURE 16. Control time slots for control frames of RAR scheme.



FIGURE 17. Control time slots for control frames of O_RAR scheme.

+ 3bits + (8 × 6) = 59bits). The transmission rate for control channel is considered to be 16 Kb/s and the size of control slot is 3.7 ms. Each transmission request uses 2 control slots, one for REQ frame and one slot to send REQ_ACK in reply of the request message.

In RAR scheme, the call setup time for each transmission request remains constant as each node gets immediate reply of the REQ frame in its subsequent slot, as shown in Fig. 16. Whereas, in O_RAR scheme the delay is more than RAR scheme and varies. However, this delay puts less impact on network performance as compared to RAR scheme when one or more RX send(s) cumulative ACK for REQ frames, as shown in Fig. 17. There is an assumption that if no REQ is made in preceding slot, then the neighbor of the current REQ node can use it to send REQ_ACK frame which tells other nodes that the ACK phase has started and merge the request time slot with allocation slots.

Moreover, O_RAR scheme consumes less control phase time as compared to RAR scheme where, after transmission of all control frames there is an additional synchronization phase in which each node just share its T_{table} with its one-hop neighbors. There can be a possibility whether all nodes broadcast their T_{table} or only TX and RX of REQ frames will use the slots in SYNC phase, as shown in Fig. 14 and Fig. 15.

Both approaches have significant impact on the network performance which not only increases control overhead, also the total control phase time.

The call setup delay of proposed schemes for above scenario is compared in Table 7 with conventional TDMA MAC design. In case of conventional TDMA the call setup time is large as each node has to wait for N number of time slots to get the turn and transmits *ACK* of the *REQ* frame(s).

TABLE 7. Call Setup Delay (in ms) for data transfer with $N = 12$.

| TX | RX | Slot size (ms) | <i>RAR</i> | <i>O_RAR</i> | TDMA |
|-------|----------|----------------|------------|--------------|------|
| N_1 | N_5 | 3.7 | 7.4 | 25.9 | 62.9 |
| N_2 | N_5 | 3.7 | 7.4 | 22.2 | 59.2 |
| N_3 | N_{10} | 3.7 | 7.4 | 22.2 | 74 |
| N_4 | N_{12} | 3.7 | 7.4 | 22.2 | 77.7 |
| N_5 | N_1 | 3.7 | 7.4 | 22.2 | 33.3 |
| N_6 | N_2 | 3.7 | 7.4 | 22.2 | 33.3 |

In *O_RAR* scheme, we observe that for cumulative *ACK*s, there is a need of few more bits to identify multiple RX nodes Id in *REQ_ACK* frame which increases *ACK* frame size. As discussed in previous section, every time each node matches its T_{table} with the table of requesting or replying node, it updates its own T_{table} if any change is found. So, we suppose that by just using one RX node Id in *REQ_ACK* frame other entries can get directly from T_{table} rather mentioning all receivers in *ACK* frame, explicitly.

The *O_RAR* scheme can further be optimized by combining both *REQ* and *REQ_ACK* frames in one single frame. It can use piggybacking for the entry where node5 is sending its own *REQ*, can also acknowledge nodes 1 and 2 within same frame. This definitely reduces the call setup delay but may end up on the same issue we encountered in *RAR* scheme.

Accordingly, the average call setup delay for 5 to 50 nodes is evaluated from which almost half of the nodes are transmitters. With reference to both *REQ* and *REQ_ACK* frames for one-hop transmissions, the call setup time includes the last bit sent from TX until the RX receives *REQ* frame and sends *REQ_ACK* frame. In *RAR* scheme, each node gets immediate response of its *REQ* message that is why the average call setup time remains too low for every number of nodes, as shown in Fig. 18. Whereas, in *O_RAR* scheme the call setup time for *REQ* cycle depends on the number of messages whereas for *REQ_ACK* cycle it varies because receiver sends aggregate reply towards senders in same *REQ_ACK* frame. The schemes reduce call setup delay when compares to other SDR based protocols but it is trivial as a node can communicate to only one node at a time.

In some cases, the call setup time in *O_RAR* scheme reduces more when the receiver is same for most of the transmissions. This call setup time has significant impact on total time taken in a control phase. The *O_RAR* scheme takes less time to complete a control phase than *RAR* scheme, as shown in Fig. 19. In *RAR* scheme, the time grows exponentially with the number of messages which require individual acknowledgment for each *REQ* frame.

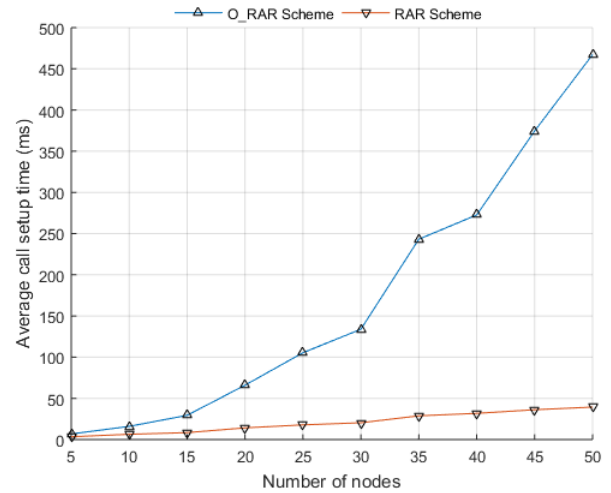


FIGURE 18. Average call setup time for *RAR* and *O_RAR* schemes.

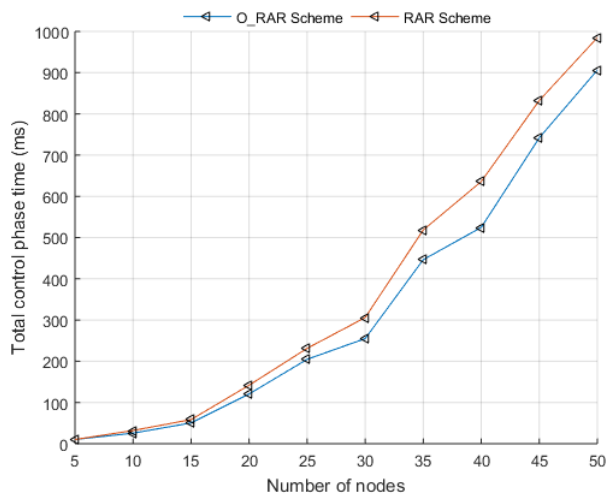


FIGURE 19. Total control phase time for *RAR* and *O_RAR* schemes.

The total control phase time for *RAR* scheme grows considerably high when additional sync phase is added to the control phase. In comparison with original control phase time, the difference with additional phase is almost double the time of *REQ* and *REQ_ACK* frames. The comparison is shown in Fig. 20, where the slots in sync phase are equal to the number of nodes in network. Whereas, if we assume to have only the repetition of the preceding frames with same TX and RX in sync phase then it takes little less time which is still much higher than *O_RAR* scheme as shown in Fig. 21.

Corollary: The optimization on *REQ_ACK* frames puts impact on number of data slots which can be used for data transmission. Also, the optimization on packet size (using packet header and data compression) can be embedded. Suppose, if a node i is having multiple communication sessions with node j , multiple data packets can be embedded in a single DATA slot (if packet sizes permit). Hence, the optimization can be done for both control and data packets depend on the application requirement.

TABLE 8. Specifications of data messages with respect to slot and data size for N = 30.

| Message Type | Bit Identification | Slots Allocated | Slot Time (ms) | Data Size |
|--------------|--------------------|-----------------|----------------|-----------|
| Text | 00 | 1 | 10.2 | 3.68kbps |
| Visuals | 01 | 2 | 20.4 | 64kbps |
| Voice | 10 | 3 | 30.6 | 160kbps |
| Video | 11 | 4 | 40.8 | 8Mbps |

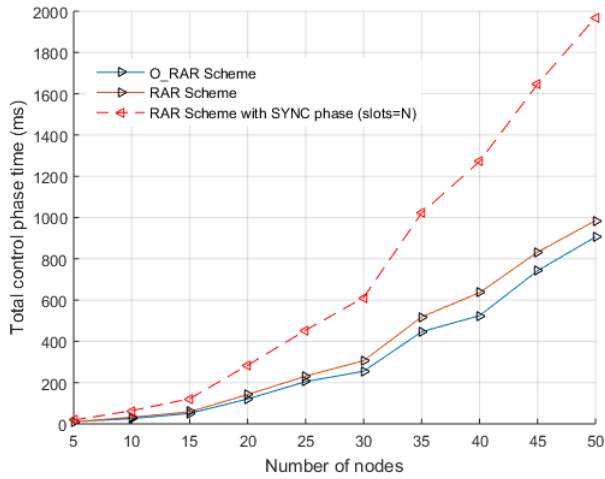


FIGURE 20. Total control phase time of RAR Scheme with SYNC phase in comparison with O_RAR scheme.

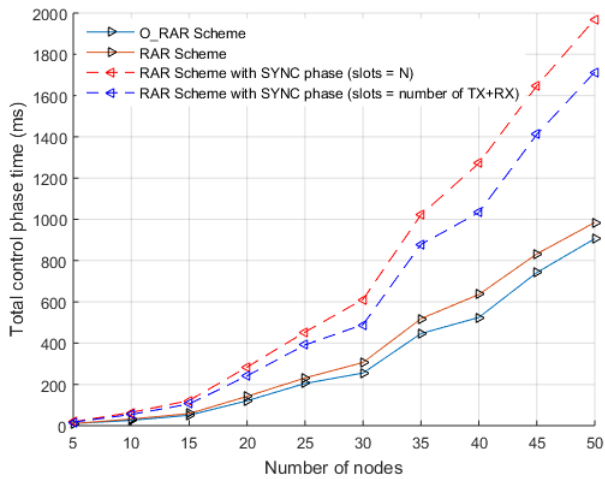


FIGURE 21. Total control phase time of RAR Scheme with SYNC phase in comparison with O_RAR scheme.

In our case, we just consider the control packet optimization which makes the scheme substantial for larger number of nodes. More number of radios can be incorporated by using more number of control slots which may cause longer call setup delay.

2) CONTROL OVERHEAD

For O_RAR scheme, the control overhead is much lesser than other protocols as each node takes autonomous decisions over sub-net formation, frequency and time slot allocation by just using a transmission table and two control frames.

In comparison of RAR and O_RAR scheme, the control overhead in prior scheme is 14% more than the optimized version of the scheme. However, the overhead increases to 56.8% for RAR scheme when additional sync phase is added to the control phase time, where additional slots are equal to the number of nodes in network.

For instance, in a tactical network of 30 nodes the control overhead amounts to 58.4% in RAR scheme (with additional SYNC phase) and 16.7% in O_RAR scheme which further mitigates due to multiple data channels as the approach helps in optimizing throughput of the channel.

3) NETWORK THROUGHPUT

Throughput of the network is calculated using (4), defines the transmission of bits b_m per message (m) by node n_i allocated a channel k of data rate R_k kbps divided by time duration of a TDMA frame T_f .

$$Network\ Throughput = \sum_{k=1}^F \left(\frac{\sum_{i=1}^N (n_{ik} \times b_m / R_k)}{T_f} \right) \quad (4)$$

In proposed design each sub-net uses different frequency channels divided into time slots of equal sizes therefore, we add the throughput of each channel to calculate the network throughput. In network throughput calculation, we do not include control messages overhead and only the data of message.

For analysis of network throughput, we consider the channels of capacity 200kbps to 1000 kbps based on the M-ary modulation selected by [20]. Assuming the data slot size is doubled the control slot size such as for 30 nodes, data slot size is 20.4 ms. With this statistics seven sub-nets are formed and assigned seven different frequency channels. Further, we assume data sizes for each message type which are specified in Table 8. The number of slots are allocated based on the size of the data in multiples of slot size 10.4 ms. When data size increases, more time is required to transmit the bits.

4) NETWORK THROUGHPUT WITH RESPECT TO CHANNEL CAPACITY

The graph in Fig. 22 shows four different curves of network throughput (in kbps) for the proposed scheme. Each curve is stating different message type for 30 nodes in network, out of which 15 are TX nodes. The network throughput is calculated on wide-range capacity of channels starts with 200kbps to 1000kbps with difference of 100kbps. For analysis, we assume the data slot size is doubled the size of control slot and total number of slots is equal to the number of messages i.e. $t_d = 10.4ms$ and $M = 15$.

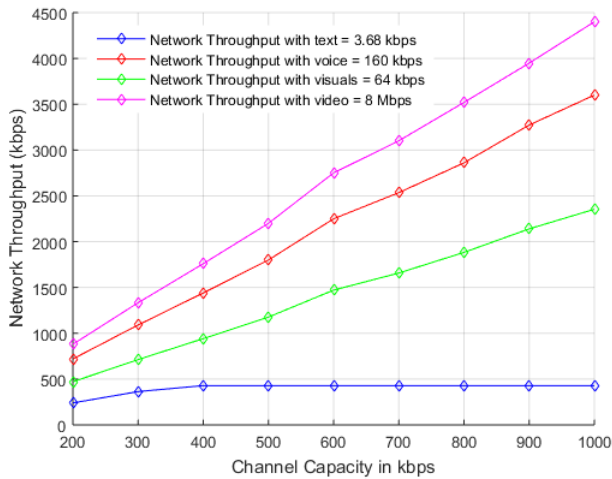


FIGURE 22. Network Throughput of proposed scheme with different message types for N = 30.

To transfer text of 460 bytes over data rates of 200kbps and 300kbps, the slot size of 10.4ms is not enough. Under these channel capacities nodes will be able to transmit 56.5% and 85.6% bits of 3680 bits, respectively. And in this case, TX nodes buffer the remaining bits, which will be transmitted in next TDMA cycle.

However, with data rate of 400 kbps, all nodes are able to transmit 460 bytes of text keeping the slot size unchanged. But the increase in data rate only favors the successful transmission of all the bits under a slot. This increase in data rates does not force nodes to use all 15 slots hence, the capacity of channel goes undermining. For example, on frequency f_1 , five nodes reserve five starting time slots to transmit the data, parting remaining slots unused. In this case, the channel utilization decreases and critically effects network throughput.

For visuals, voice and video messages, the network throughput increases as we allocate two, three and four slots to each node for respective message types.

The allocation of multiple slots with $M = 15$ has diverse impact on channel utilization. In case of voice and video transmissions, few nodes may not get all or even no slot to transmit the data. This forces nodes to transmit their data in next cycle which is not in favor of tactical networks.

Fig. 23, shows the percentage of transmitted bits with respect to totals bits need to be transmitted for each channel capacity. The analysis shows that with slot sizes of 20.4ms, 31.2ms and 41.6ms, nodes are not able to transmit all bits of large data sizes such as visuals, voice and video.

5) IMPACT ON NETWORK THROUGHPUT WITH INCREASE IN SLOT SIZE

The scheme can produce effective results for large data sizes if we increase the size of time slot (slot size = 20.4ms for text and other types accordingly), the nodes will be able to send

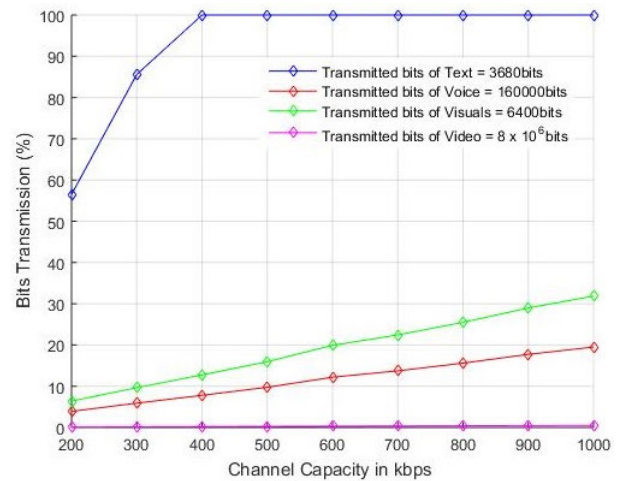


FIGURE 23. Successful bits' transmissions of proposed scheme with different message types for N = 30.

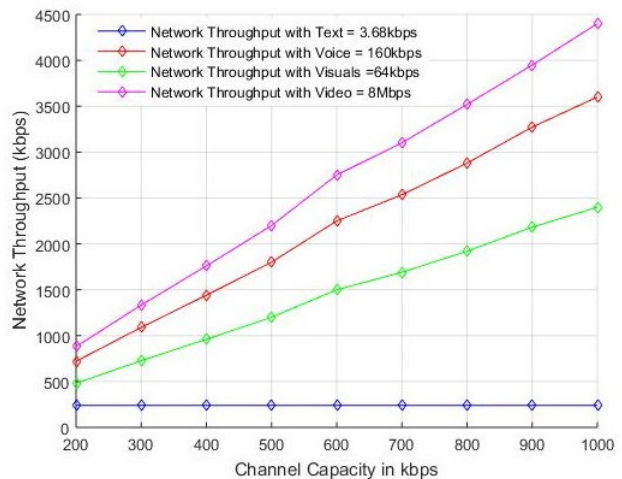


FIGURE 24. Network Throughput of proposed scheme with different message types with different slot size.

more bits in one-time slot, as shown in Fig. 24 and Fig. 25. The throughput with increased slot size is almost same for every channel capacity as shown earlier in Fig. 22. However, this will not increase channel utilization if the number of nodes is less than the number of slots in a TDMA frame. Because as we increase number of slots, the overall size of TDMA frame also increases. Therefore, we fixed the duration of one transmission cycle including control and data phase. As number of TX nodes increases, the more control slots will get utilized leaving few slots for data phase.

Two possibilities which are being observed and put major impact on network throughput

- 1) After completion of data transmission for a TDMA frame, the unused slots of the frame can be repeated by following same time and frequency allocation patterns. This not only increases network throughput but also saves nodes to undergo into next control cycle.

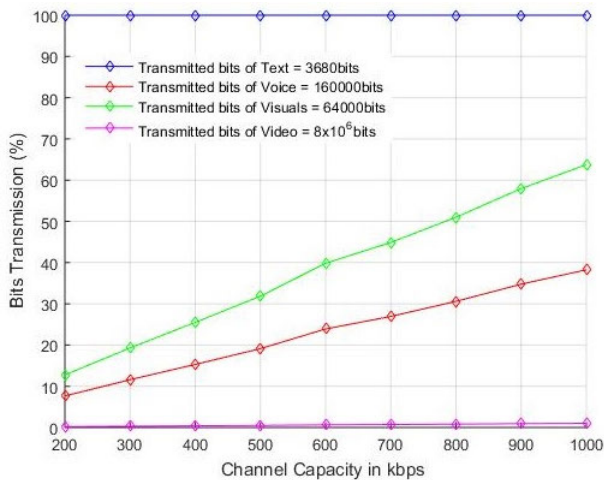


FIGURE 25. Successful bits' transmissions of proposed scheme with different message types with increased slot size.

- 2) If there is bi-directional communication in sub-nets where each member of a sub-net can transmit data, will increase good-put of the network.

6) ANALYSIS OF NETWORK THROUGHPUT ENVISIONING SUB-NETS

The idea to divide network into different sub-networks is to perform simultaneous transmissions over multiple channels. These transmissions increase network throughput and reduce call setup time that is difficult to achieve in single channel networks. For analysis we consider that nodes can transmit data of any type specified in above section with data rate of 500kbps and $t_d = 10.4ms$. The throughput is computed over different sub-nets ranged from 1 to 11 sub-networks formed by each network of 5 to 50 nodes, considering only TX nodes have data to transmit. With these considerations the network throughput increases with number of sub-nets, as shown in Fig. 26. With only eleven sub-nets the network throughput increases from 500kbps to 2900kbps which can further be increased if bi-directional communication is performed or the TX nodes send continuous data by reserving whole channel capacity of the frequency band.

There can be a possibility that few nodes become member of each sub-net and result in low throughput of the network. However, it depends on the number of communicating nodes and the type of message nodes want to transmit.

In order to extend a tactical network to have more radios and to enable their simultaneous communication, high network throughput is a critical requirement. As most of the networks operate in narrow-band mode. Our proposed methodology results in an increase in network throughput with increase in number of sub-nets.

7) LATENCY

Latency for proposed design is defined as the time taken between data transmission of nodes. For example, if there are

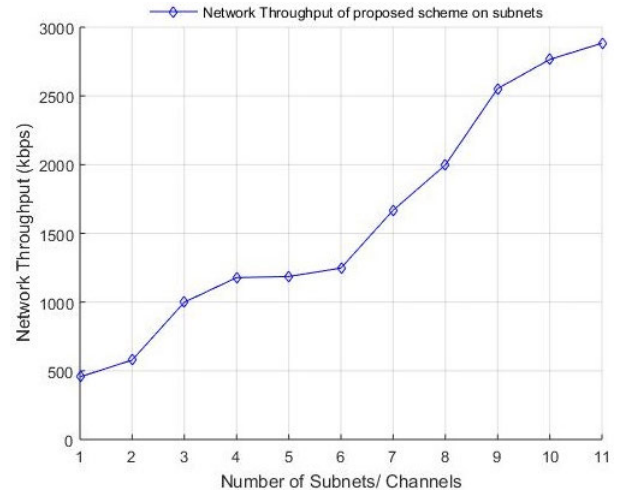


FIGURE 26. Network throughput of O_RAR scheme with respect to sub-nets.

multiple SDRs in communication then each gets slots according to the type of service. We restrict the number of slots (M) for each service and allocate (M/V) slots for transmission of nodes (V) in a sub-net (S_x) i.e. $S_x(V)$. Whereas in case of conventional TDMA, each SDR will have to wait for its turn which comes after m_t data slots, where m_t is time slots to transmit messages of a particular service.

The autonomous decision on time slot makes the system collision free and improves fairness in slots usage as each node has common network view. The algorithm improves channel utilization because it supports transmission of different message types such as text, visuals, voice and video. The protocol efficiency increases if number of nodes in each sub-net is more than 2 or 3.

B. COMPARISON OF PROPOSED DESIGN WITH OTHER MAC PROTOCOLS

1) QUANTITATIVE COMPARISON

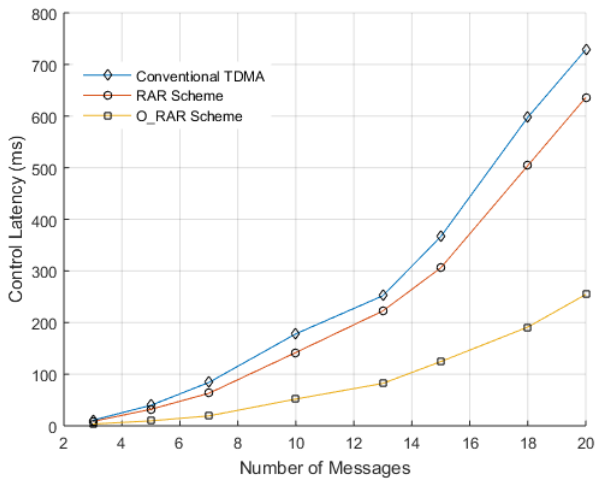
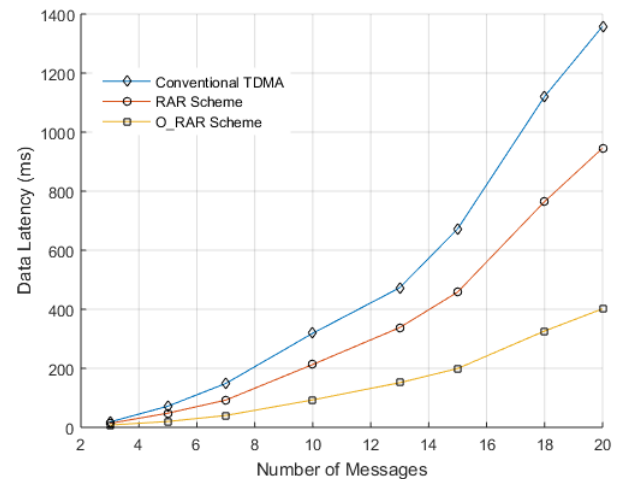
The brief demonstration of already proposed designs in section II specifies the novelty of our algorithm that none of the technique provides such solution having fully autonomous virtual sub-nets, operates in multi-channel environment for tactical radio communication. Therefore, it is not possible to mark fair comparison between other TDMA-based multi-channel MAC designs as each of them is mostly application or architecture specific. However, we performed a qualitative comparison with respect to the means of undertaking ad-hoc networks, depicted in Table 9.

2) QUALITATIVE COMPARISON WITH CONVENTIONAL TDMA

The quantitative comparison for control and data latency between proposed schemes and conventional TDMA is performed for different number of messages. For both packet types i.e. control and data, the proposed designs perform much better than TDMA when run for different number of messages. Fig. 27 shows that the O_RAR scheme performs

TABLE 9. Qualitative comparison of proposed design with other MAC protocols.

| Protocols and References | Application Area | Comments |
|--|-------------------------------------|--|
| SDR based DSA Network [10] | Tactical communication networks | A clustering based dynamic spectrum access network which switches frequency autonomously in response to jamming or interference, includes some frequency switching delays. Whereas, our proposed design responds to the issues by selecting different frequency channels for each transmission by the virtual groups of nodes without having any switching delays. |
| Dynamic TDMA Protocol [16] | Link-16 Tactical data link networks | The designs meets transmission requirements of nodes to send large number of messages and allocates slots accordingly. However, the slots are allocated using master node which contradicts with our distributed autonomous network behavior. |
| Voice Signaling Protocol for TDMA based MAC layer [21] | Tactical communication in MANETs | The signaling protocol utilizes TDMA based data transfer and requires the statistics from three layers for protocol operation i.e. application, network and MAC layer. Whereas, our designed scheme uses few information parameters to produce desired results and support multiple data type transmissions. |
| Sub-net based Hotspot Algorithm [22] | Wireless Sensor Network (WSN) | A sub-net based algorithm that discusses the strategy of network division and also verifies the proof of correctness. The design uses sub-net head for each sub-net to provide communication between source and sink. Though in our schemes, all decisions are taken on the basis of information provided during control frames transmission and there are no sub-net heads to govern the transmissions and resource distribution. |

**FIGURE 27.** Control latency comparison between proposed schemes and TDMA.**FIGURE 28.** Data latency comparison between proposed schemes and TDMA.

much better than TDMA and has low latency values. The scheme results even better than *RAR* scheme due to the addition of SYN phase in later scheme. This additional SYN phase turns the behavior of *RAR* scheme similar to the conventional TDMA for control frames transmission.

In case of data latency, TDMA consumes quiet high time for data transmission, as shown in Fig. 28. This happens because each SDR will have to wait for $2N$ number of data slots for its next data transmission as there are N cycles for *REQ_ACK* frames. The increase in latency lowers the maximum throughput for the channel and makes it comprehensible that the network performance diminishes with escalation of nodes.

C. OBSERVATIONS AND ALGORITHM CONSTRAINTS

Few important observations are made over analysis of performance measures

- 1) The diameter of sub-net depends on the number of TX and RX nodes. The worst case is when all nodes of network become members of single sub-net. In this case, the network operates as a single channel TDMA design.
- 2) Latency increases if large number of nodes transmit data with large data packets or if we increase size of data slot to accommodate more packets.
- 3) We assume that out of total number of nodes, first half nodes are TX and other half is RX and all these nodes send *REQ* frames in their respective time slots. When these *REQ* frames are sent from any SDR, for example after *SDR₁*, *SDR₅* sends its *REQ* frame rather *SDR₂*. In this case, *SDR₅* will have to wait for its slot and this effects on call setup time of other nodes as well as increases total control phase time. Hence, the scheme for *REQ* phase will start behaving as traditional TDMA

scheme and needs to have *REQ* slots equal to the number of nodes of the network which may later compensate in cumulative *REQ_ACK* frames of *O_RAR* scheme.

- 4) The protocol is limited to one-hop data transmission that is being extended to multi-hop transmission.

The proposed schemes favor simultaneous transmissions over multiple channels without disrupting each other's transmissions. Therefore, the designed scheme gives many benefits with less control signaling and can schedule bi-directional communication among peer nodes. Using the schemes, network can support different transmission methods i.e. broadcast and multi-cast by just referring sub-nets address.

VI. CONCLUSION AND FUTURE RECOMMENDATIONS

A. CONCLUSION

A virtual sub-net based architecture for multi-access environment is proposed on the basis of transmission patterns. The paper presented a novel distributed virtual sub-nets based protocol for tactical networks. The main objective of our work was to develop an efficient mechanism that improves network throughput and reduces call setup delays. The design is based on an adequate adaptive formation of sub-nets according to the transmission requirements relatively to their two-hop neighbors. The design uses only two control frames for protocol operation. It provides promising results in tactical settings as compared to other protocols which usually incorporate data channels and time slot decisions that not only increases control signaling overhead, call setup delays, but also reduce throughput of the system. The proposed protocol reduces call setup delays by incorporating both TDMA and FDMA approaches, where instead of waiting for their slot nodes communicate simultaneously on different frequency channels. The experimental results demonstrate a gain of 76.8% as compared to other conventional MAC protocols with increase in network throughput yield by the co-existence of multiple transmissions in tactical networks. It is proven that the protocol is suitable for tactical networks with time sensitive and continuous data communication.

B. FUTURE RECOMMENDATIONS

Tactical networks use MANETs in which radios are mobile and many times create different transmission patterns with the properties of having less access delay and control overhead which are non-trivial requirement for time critical military communication. In our protocol, there are many operational requirements which we did not explicitly highlight, consent it to be extended to make use of efficient slot and frequency scheduling methods that can improve fairness among nodes. The focus in duration of TDMA frame may incorporate more transmissions with combination of bi-directional communication method. The scheme can privilege sub-nets to inter-link if channel frequencies are distributed appropriately. The interleaving of control and data slots can open many ways

to get better results as well as integrates mobility related challenges.

REFERENCES

- [1] S. H. Cha, M. Shin, J.-H. Ham, and M. Y. Chung, "Robust mobility management scheme in tactical communication networks," *IEEE Access*, vol. 6, pp. 15468–15479, 2018.
- [2] K. Poularakis, Q. Qin, E. M. Nahum, M. Rio, and L. Tassiulas, "Flexible SDN control in tactical ad hoc networks," *Ad Hoc Netw.*, vol. 85, pp. 71–80, Mar. 2019.
- [3] J.-S. Shin, M. Kang, J. Park, D. Kwon, and J. Kim, "Conceptual design of networking node with real-time monitoring for QoS coordination of tactical-mesh traffic," *Korean Inst. Smart Media*, vol. 8, no. 2, pp. 29–38, Jun. 2019.
- [4] J. B. Evans, S. G. Pennington, and B. J. Ewy, "Named data networking protocols for tactical command and control," *Open Archit./Open Bus. Model Net-Centric Syst. Defense Transformation, Int. Soc. Opt. Photon.*, vol. 10651, May 2018, Art. no. 106510C.
- [5] A. Karalis, D. Zorbas, and C. Douligieris, "Collision-free advertisement scheduling for IEEE 802.15.4-TSCH networks," *Sensors*, vol. 19, no. 8, p. 1789, 2019.
- [6] Z. Niu, T. Ma, N. Shu, and H. Wang, "Identification of critical nodes in ad hoc network based on the analysis of network partition," in *Proc. IEEE 19th Int. Conf. Commun. Technol. (ICCT)*, Oct. 2019, pp. 1048–1052.
- [7] J. H. Chongoushian, "Multiple access wireless network with low latency subnet," U.S. Patent 10 237 885, Mar. 19, 2019.
- [8] L. Yajun, W. Muqing, and Z. Min, "Network-balanced algorithm based on hierarchical subnet space for software-defined wireless sensor networks," in *Proc. IEEE 4th Int. Conf. Comput. Commun. (ICCC)*, Dec. 2018, pp. 894–898.
- [9] K. Kishor, P. Nand, and P. Agarwal, "Subnet based ad hoc network algorithm reducing energy consumption in manet," *Int. J. Appl. Eng. Res.*, vol. 12, no. 22, pp. 11796–11802, 2017.
- [10] S. Watson and J.-B. Larouche, "Design of a software defined radio-based tactical DSA network," in *Proc. IEEE Mil. Commun. Conf. (MILCOM)*, Oct. 2017, pp. 738–743.
- [11] W. Huitao, Y. Ruopeng, Wufan, and Z. Xiaofei, "Research on IP address allocation of tactical communication network," *J. Phys., Conf. Ser.*, vol. 1187, no. 4, Apr. 2019, Art. no. 042105.
- [12] S. Jiangwei, W. Muqing, and Z. Zhihao, "Clustering algorithm based on extending dynamic subnetwork scheme for software-defined wireless sensor networks," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC Workshops)*, Aug. 2018, pp. 190–195.
- [13] J. S. Lee, Y.-S. Yoo, H. S. Choi, T. Kim, and J. K. Choi, "Energy-efficient TDMA scheduling for UVS tactical MANET," *IEEE Commun. Lett.*, vol. 23, no. 11, pp. 2126–2129, Nov. 2019.
- [14] S. Saleem and S. A. Khan, "Slot assignment protocol for narrow band waveform for tactical MANETs," in *Proc. 25th Int. Conf. Softw., Telecommun. Comput. Netw. (SoftCOM)*, Sep. 2017, pp. 1–6.
- [15] G. Selvakumar *et al.*, "Throughput optimization methods for TDMA-based tactical mobile ad hoc networks," in *Integrated Intelligent Computing, Communication and Security*. Singapore: Springer, 2019, pp. 323–331, doi: 10.1007/978-981-10-8797-4.
- [16] L. Liu, Y. Liu, Z. Wang, and C. Liu, "Design of dynamic TDMA protocols for tactical data link," in *Proc. 12th Int. Conf. Commun. Netw. China (ChinaCom)*, Xi'an, China, Switzerland: Springer, Oct. 2017, pp. 166–175, doi: 10.1007/978-3-319-78130-3.
- [17] H. Idoudi, O. Mabrouk, P. Minet, and L. A. Saidane, "Cluster-based scheduling for cognitive radio sensor networks," *J. Ambient Intell. Humanized Comput.*, vol. 10, no. 2, pp. 477–489, Feb. 2019.
- [18] G. F. Elmasry, *Tactical Wireless Communications and Networks: Design Concepts and Challenges*. Hoboken, NJ, USA: Wiley, 2012.
- [19] C.-F. Shih, A. E. Xhafa, and Z. Jianwei, "Techniques for generation of a frequency hopping sequence," U.S. Patent 9 614 579, Apr. 4, 2017.
- [20] I. Nosheen, S. A. Khan, and F. Khalique, "A mathematical model for cross layer protocol optimizing performance of software-defined radios in tactical networks," *IEEE Access*, vol. 7, pp. 20520–20530, 2019.
- [21] N. K. Patel, P. Saxena, R. Singh, and S. Kumar, "A novel voice signaling protocol for tactical broadcast voice communication in mobile ad hoc network," in *Proc. 10th Int. Conf. Comput., Commun. Netw. Technol. (ICCCNT)*, Jul. 2019, pp. 1–4.

- [22] T. Ali, S. Yasin, U. Draz, and M. Ayaz, "Towards formal modeling of subnet based hotspot algorithm in wireless sensor networks," *Wireless Pers. Commun.*, vol. 107, no. 4, pp. 1573–1606, Aug. 2019.



RUKAIYA received the B.S. degree in computer engineering from the Sir Syed University of Engineering and Technology (SSUET), Karachi, Pakistan, in 2011, and the M.S. degree in computer engineering with specialization in computer networks from the Sir Syed University of Engineering and Technology, in 2015. She is currently pursuing the Ph.D. degree in computer engineering with the National University of Sciences and Technology (NUST), Islamabad, Pakistan.

From 2011 to 2015, she was a Junior Lecturer with the Sir Syed University of Engineering and Technology, where she has been serving as a Lecturer with the Department of Computer Engineering since 2016. She has worked as a Research Associate at office of research, innovation and commercialization (ORIC), SSUET. Her research interests include MAC and routing protocols, wireless ad-hoc networks, mission critical tactical networks, and network security.

Ms. Rukaiya awards and honors include a gold medal in the B.S. degree and an indigenous scholarship from higher education commission (HEC), Pakistan for her Ph.D. studies.



SHOAB A. KHAN received the Ph.D. degree in electrical and computer engineering from the Georgia Institute of Technology, Atlanta, GA, USA, in 1995. He has more than 22 years of industrial experience in companies in USA and Pakistan. He is currently a Professor of computer and software engineering with the College of Electrical and Mechanical Engineering, National University of Sciences and Technology.

He is an Inventor of five awarded U.S. patents, and he has more than 260 international publications. He has published a book on digital design by John Wiley & Sons. He is being followed in national and international universities. He has also founded the Center for Advanced Studies in Engineering (CASE) and the Center for Advanced Research in Engineering (CARE). The CASE is a prime engineering institution that runs one of the largest post graduate engineering programs in the country and has already graduated 50 Ph.D. and more than 1800 M.S. students in different disciplines in engineering, whereas, under the leadership of the CARE, has risen to be one of the most pro-found high technology engineering organizations in Pakistan developing critical technologies worth millions of dollars for organizations in Pakistan. The CARE has made history by winning 13 PASHA ICT awards and 11 Asia Pacific ICT Alliance Silver and Gold Merit Awards while competing with the best products from advanced countries like Australia, Singapore, Hong Kong, and Malaysia. He has received the Tamgh-e-Imtiaz (Civil), the National Education Award 2001, and the NCR National Excellence Award in Engineering Education. He has served as the Chair for the Pakistan Association of Software Houses. He has served as a member for the Board of Governance of many entities in the Ministry of IT and Commerce. He has also served as a member for the National Computing Council and the National Curriculum Review Committee.

...