DRS: Distributed Deadline-Based Joint Routing and Spectrum Allocation for Tactical Ad-hoc Networks

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***Abstract*—In this paper, we propose a novel distributed deadline-based routing and spectrum allocation algorithm for tactical ad-hoc networks. The proposed algorithm will enable nodes to adapt to various deadline requirements unique to each traffic classes. A tactical ad-hoc network needs to handle a variety of data flowing through the network including voice, surveillance video, threat alert among others. Each of these traffic classes may have different quality of service (QoS) based deadline requirements. It is critical to receive these packets before the deadline expires to make crucial decisions in the battlefield. Therefore, the network should be able to adapt to these requirements and maximize the effective throughput. Accordingly, a distributed deadline-based routing and spectrum allocation algorithm is designed to maximize the utilization of the available resources to ensure delivery of packets within the deadline constraints. The simulations show up to 35 % improvement in effective throughput and 26 % improvement in reliability as compared to the routing and spectrum allocation algorithm (ROSA) [1].**

I. Introduction and Background

In a tactical ad-hoc network, there exists a constant tension between available resources and the required QoS performance. Along with spectrum agility, a military network is required to handle various traffic classes with substantially different QoS based deadline requirements. For example, periodic surveillance data might have looser deadline constraints when compared to a video or threat alert message. In these delay-intolerant networks, only packets that arrive at the destination within the specified deadline are viable and will contribute to the *effective throughput*. In these scenarios, it becomes beneficial to examine the interaction between spectrum management, routing and session management to develop a cross-layer control algorithm capable of maximizing the effective throughput of the network.

Queue-length based backpressure scheduling algorithm was first proposed in [2] and was shown to be throughput optimal in terms of achieving network stability under any feasible load but suffers from last packet problem. In practical networks, when a finite flow has the last packet in the queue, it is starved for an extended period of time due to the presence of other queues with larger queue length. This is referred to as the last packet problem. Accordingly, there has been considerable work on delay-based scheduling [3]–[5] to improve delay performance of the network and eliminate last packet problem. In [3], the authors use shadow queuing architecture so that each node maintains only one queue per neighbor (irrespective of sessions) to reduce the complexity of the queuing structure and improve the delay performance at the cost of throughput. Maintaining a single queue per neighbor is only beneficial in scenarios where number of flows through a node is much greater than the number of neighbors. In [4], a throughput optimal scheduling is proposed using largest weighted delay first algorithm. Although this algorithm is an easy and distributed way to achieve throughput optimality, unlike the proposed algorithm, [3] and [4] does not take into account the possibilities of dynamic opportunistic routing. In [5], the authors propose a delay-limiting algorithm to control the burstiness and delays at the expense of throughput. Also, in cases when traffic reduces or traffic is spread spatially, the delay limiting approach becomes ineffective. It has been shown in [6] that factors contributing to inefficiency of back-pressure algorithm are inefficient spatial reuse, failure to opportunistically exploit better link rates, underutilized link capacity and inefficient routing due to insufficient path information. Deadline-based routing has been recently studied in [7]–[9]. In [7], an utility-based algorithm is proposed for cyclic mobile social network under the assumption that nodes follow cyclic mobility, periodically encountering each other with high probability. It is difficult to extend [7] to tactical ad-hoc network without the knowledge of encounter probability. To increase packet delivery ratio, [8] adopts an epidemic based routing and [9] proposes a capacity constrained routing algorithm that decides which packets have to be replicated. Since [8] and [9] aim to improve packet delivery ratio by using different replication strategies, it reduces the achievable throughput.

In previous work [1], an optimization algorithm (ROSA) is proposed to jointly select route and spectrum such that overall network throughput is maximized. This algorithm combines the idea of backpressure algorithm with channel dependent opportunistic routing but still suffers from the last packet problem. In this work, we extend [1] by designing and evaluating a distributed deadline-based joint routing and spectrum allocation algorithm for tactical ad-hoc networks. The capabilities of the proposed deadline-based algorithm include, (i) carefully managing multiple sessions to meet the deadline requirement; (ii) collaborative resource allocation procedure, (iii) adapting to broken routes by choosing alternative paths, (iv) selecting jointly optimal route, spectrum, power and session to maximize effective throughput of the network. To the best of our knowledge, this is the first work that combines

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the interaction of opportunistic routing, spectrum allocation and various deadline constraints together to maximize the network throughput of tactical ad-hoc networks.

The rest of the paper is organized as follows. In Section II, we describe the system model. We discuss the design of deadline-based routing algorithm in Section III. Next in Section IV, we describe the performance evaluation. Finally, the conclusion and future work is presented in Section V.

II. System model

Consider a multihop tactical ad-hoc network with M primary users and N secondary users modeled as a directed connectivity graph $\mathcal{G}(\mathcal{U},\mathcal{E})$, where $\mathcal{U}=\{u_1,u_2,...,u_{N+M}\}$ is a finite set of wireless transceiver (nodes) of the graph, and $(i,j)\in\mathcal{E}$ represents unidirectional wireless link from node u_i to node u_j (for simplicity, we refer to them as node i and node j). We assume $\mathcal{G}$ is link symmetric, i.e., if $(i,j)\in\mathcal{E}$, then $(j,i)\in\mathcal{E}$. The nodes from the subset $\mathcal{PU}=\{u_1,...,u_M\}$ are designated as primary users, and nodes from the subset $\mathcal{SU}=\{u_{M+1},...,u_{M+N}\}$ are designated as secondary users. The secondary network is composed of cognitive nodes with objective to maximize spectrum utility but ensuring no interference to primary users. The primary user holds the license for the specific spectrum bands and have full access to the spectrum without interference from any other users. In military relevant scenarios, the primary user can also be a non-cooperative node (adversary). Let the set of neighbors for node i be given by $\mathcal{NB}_i\triangleq\{j:(i,j)\in\mathcal{E}\}$. The entire available spectrum is given by BW. The cognitive transceiver is capable of tuning to a set of contiguous frequency bands $[f,f+\Delta B]$, where ΔB is the bandwidth of the cognitive radio and $\Delta B<BW$. We define spectrum opportunity as the limited availability of a spectrum that might currently be used by nodes but can be further exploited by adjusting the transmit power without violating the bit error rate (BER) constraint of the existing transmission. This work is intended for any general physical layer but we assume that multiple transmissions can occur concurrently on the same frequency band, e.g., with different spreading codes.

The total spectrum, BW is divided into separate channels, a common control channel (CCC) and a data channel. All secondary nodes use CCC to share local information for spectrum negotiation and data channel is used exclusively for data communication. The data channel is divided into discrete set of carriers $\{f_{min},f_{min+1},...,f_{max}\}$, each of bandwidth w and identified by a unique discrete index. The cognitive radio of the secondary user can tune into consecutive set of carriers from $[f_{min},f_{max}]$. Let the traffic in the network consists of multiple sessions characterized by the source-destination pairs and the applications generating these sessions. The arrival rates of each session $s_i\in S_i$ at node i is given by $\lambda_i^s(t)$, and characterized by vector of arrival rates Λ. The overall objective of this paper is to maximize the *effective throughput* (η) defined as,

$$\eta=\frac{Rec_d\times Size_p}{t}, \tag{1}$$

where Rec_d is the number of packets received at the destination within the specified deadline, $Size_p$ is the packet size in bits and t is the time elapsed in seconds.

III. Deadline-based routing and spectrum allocation

In this section, we discuss the deadline-based distributed routing and spectrum allocation algorithm in detail. Here, we will define the utility function that has to be maximized to achieve the goal of the proposed solution.

A. Network Utility Function

Consider a tactical ad-hoc network that operates over a time slotted channel. The spectrum utility function is calculated by node i for every time slot t when node i is backlogged and not already transmitting or receiving packets. Each node i maintains a separate virtual queue (VQ) for each session. We define $Q_i^s(t)$ as the virtual queue length (VQL) formed by packets of session s in node i at time slot t. For each packet $q_i^s\in Q_i^s(t)$, a set of fields are defined, including,

- $L(q_i^s)$: length of the packet in bits,
- $T_r(q_i^s)$: remaining life time of the packet, which is based on the deadline $D(q_i^s)$ assigned to the packet at the source node, and
- $T_d(q_i^s)$: time to the destination as estimated at node i.

Based on these parameters, a weight $w_{q_i^s}[L(q_i^s),T_d(q_i^s),T_r(q_i^s)]$ can be defined for each packet $q_i^s\in Q_i^s(t)$ as follows (for simplicity, we removed q_i^s from all the parameters),

$$w_{q_i^s}(L,T_d,T_r)=\frac{L}{max(T_r,\tau)\,max(T_r-T_d,\tau)}. \tag{2}$$

As we can see in (2), $w_{q_i^s}$ assigned to each packet is directly proportional to L and inversely proportional to T_r and T_d. The τ in (2) is a very small value to avoid negative and infinite weights. The parameter T_r gets rid of the last packet problem by increasing the VQL as time elapses. This can be interpreted as the holding penalty imposed for packets being stagnant in the queue for extended period of time. Since T_r is dependent on the assigned deadline itself, it helps the nodes to manage different sessions by pushing critical packets faster even if the actual queue length is comparatively smaller. Considering just the deadlines alone will not help in cases where there are two sessions with the same deadline but one is further away from the destination than the other. In such cases, T_d will ensure that the session further away from the destination moves through the network at a faster rate compared to similar sessions closer to the destination. Therefore, T_d can be considered as a variable that either amplifies or diminishes the effect of T_r depending on the time required to reach the destination. T_d also encourages packets to take shorter routes if all other factors like queue length and spectrum are the same for the two different routes. The reasoning will become more evident when we discuss the network utility function used for the proposed algorithm. Among these three parameters, the exact value of T_d is not available at each node and has to be estimated at each hop. For a centralized network, assuming global knowledge of the network, T_d can be estimated using average queuing delays, transmission rate, propagation delays and average delays experienced previously by packets with same source-destination pairs. In a distributed network, where each node makes decision without global knowledge, this problem becomes challenging. One solution is to estimate T_d by using the queuing delay experienced by the packet in the node itself. We use this information and slightly overestimate the delay by assuming that the packet has to route through more than one node within its transmission range itself. Underestimating the T_d would increase the risk of packets not reaching the destination within the specified deadline. Therefore, slightly overestimate T_d according to the characteristics of the network. Since T_d is updated at every hop, the estimation error/margin decreases as the packet moves closer to the destination. This method does not cause any error propagation since the value is updated at each hop. A simple way to estimate T_d is based on distance to destination (d), communication range of the nodes deployed (R) and average time spent by the packet during each hop (T_h) (includes processing delay, queuing delay, transmission delay and propagation delay). The idea is to assume a hop is required every half range of a node and is given by $\alpha = R/2$. Accordingly, we estimate the time required to reach the destination as,

$$T_d = \frac{d\ T_h}{\alpha} = \frac{2d\ T_h}{R}. \tag{3}$$

The value of α can be varied according to the density of the network. Accordingly, we define the VQL of a session s in node i as follows,

$$Q_i^s(t) = \sum_{q_i^s \in Q_i^s(t)} w_{q_i^s}[L(q_i^s), T_d(q_i^s), T_r(q_i^s)]. \tag{4}$$

Now, let $a(q_i^s, j, t) = 1$ denote that packet $q_i^s \in Q_i^s(t)$ has been transmitted to node j at time slot t, and $a(q_i^s, j, t) = 0$ otherwise. The routing profile of node i is defined as $a_i^s(t) = [a(q_i^s, j, t)]_{q_i^s \in Q_i^s(t)}^{j \in \mathcal{N}}$, and $\mathbf{A}$ represents the vector of routing profile $a_i^s(t)$. We also define the transmission rate on link (i, j) during time slot t as $r_{ij}^s(t)$, and $\mathbf{R}$ as the vector of rates. Then the VQL of node i can be updated as,

$$Q_i^s(t+1) = \Bigg[Q_i^s(t) + \sum_{j \in \mathcal{N}/i} \sum_{q_j^s \in Q_j^s(t)} w_{q_j^s}(L, T_d, T_r) a(q_j^s, i, t) - \sum_{j \in \mathcal{N}/i} \sum_{q_i^s \in Q_i^s(t)} w_{q_i^s}(L, T_d, T_r) a(q_i^s, j, t)\Bigg]^+. \tag{5}$$

Accordingly, the network link utility function U_{ij} for link $(i, j) \in \mathcal{E}$ for session s can be defined as,

$$U_{ij}(a_i^s(t)) = C_{ij}[Q_i^s(t) - Q_j^s(t)]^+, \tag{6}$$

where $[Q_i^s(t) - Q_j^s(t)]^+$ represents the differential VQL and C_{ij} is the achievable channel capacity of the link $(i, j) \in \mathcal{E}$ at time slot t for a selected frequency (f). Accordingly, the transmission strategy can be given by,

$$C_{ij}(f, P_i(f)) \triangleq \sum_{f \in [f_i, f_{i+\Delta f_i}]} w.\log_2 \left[1 + \frac{P_i(f) L_{ij}(f) G}{N_j(f) + I_j(f)}\right]. \tag{7}$$

In the above equation, $P_i(f)$ represents the transmit power of node i on the frequency f, $L_{ij}(f)$ is defined as the transmission loss due to path loss from i to j, G represents the processing gain, which would be the length of the spreading code when applicable, $N_j(f)$ is the receiver noise on frequency f and $I_j(f)$ is the interference experienced by the receiving node j. As we can see in (7), the achievable capacity primarily depends on selected frequency $\mathbf{F} = [f_i, f_{i+\Delta f_i}]$, power allocation $\mathbf{P} = [P_i(f)]$, $\forall i \in \mathcal{SU}$, $\forall f$ and the scheduling policy. Therefore, the overall notion of this network utility function is to couple the constraints of packet deadline to the traditional queue length used in the differential backlog algorithm which is then weighted by the dynamic spectrum availability information. The redefining of the queue length to form the new VQL is where the proposed algorithm extends [1]. We will discuss and evaluate the benefits of this in detail in section IV.

B. Optimization problem

Next, we define the overall optimization problem to maximize the the utility function discussed in (6). Let us denote the BER guarantees required for primary and secondary users as $BER_{\mathcal{PU}}$ and $BER_{\mathcal{SU}}$ respectively. Accordingly, we can represent the required signal-to-interference-plus-noise power ratio (SINR) thresholds required to achieve the target BER for the secondary and primary user as $SINR_{\mathcal{PU}}^{th}$ and $SINR_{\mathcal{PU}}^{th}$ respectively. Thus, the global objective of the optimization problem is to find the optimal global vectors $\mathbf{R}$, $\mathbf{F}$ and $\mathbf{P}$ that maximizes the sum of the network utilities, under the constraints of power and BER. The formulation of the optimization problem is as follows,

$$\begin{aligned}
\mathcal{P}_1: \text{Given}: &\ \mathcal{G}(\mathcal{U}, \mathcal{E}),\ P^{Bgt},\ Q_i^s,\ BER_{\mathcal{SU}},\ BER_{\mathcal{PU}} \\
\text{Find}: &\ \mathbf{R},\ \mathbf{F},\ \mathbf{P},\ \mathbf{A} \\
\text{Maximize}: &\ \sum_{i \in \mathcal{SU}} \sum_{j \in \mathcal{SU}ß} U_{ij}(a_i^s(t))
\end{aligned} \tag{8}$$

subject to:

$$\sum_{s \in S} r_{ij}^s \leq C_{ij}, \forall i \in \mathcal{SU}, \forall j \in \mathcal{SU} \tag{9}$$

$$SINR_k \geq SINR_{\mathcal{PU}}^{th}(BER_{\mathcal{PU}}), \forall k \in \mathcal{PU}, \forall f \tag{10}$$

$$SINR_l \geq SINR_{\mathcal{SU}}^{th}(BER_{\mathcal{SU}}), \forall l \in \mathcal{SU}, \forall f \tag{11}$$

$$\sum_{f \in [f_i, f_{i+\Delta f_i}]} P_i(f) \leq P_i^{Bgt}, \forall i \in \mathcal{SU} \tag{12}$$

In the above formulation, the objective is to maximize the network utility of all the active links. The constraint (9) restricts the total amount of traffic in link (i, j) to be lower than or equal to the physical link capacity. Constraints (10) and (11) impose that any transmission by secondary user should guarantee the required BER for the active primary users and secondary user respectively. Finally, P_i^{Bgt} is the instantaneous power available at the cognitive radio. We can see that the optimization problem requires global information about the feasible rates and the worst-case complexity of $\mathcal{P}_1$ is exponential. Due to these reasons and since scalability is important for tactical networks, we propose a distributed algorithm that can be implemented in a practical protocol.

The resource allocation of the proposed algorithm consists of spectrum and power allocation similar to [1]. A spectrum opportunity for link (i, j) is a set of contiguous minibands where $O_{ij}(f) \geq 0$ and is given by,

$$O_{ij}(f) = P_i^{max}(f) - P_i^{min}(f), \tag{13}$$

where $P_i^{max}(f)$ is defined as the maximum power that can be used by the secondary node i on the frequency f such that it satisfies the BER constraints of primary and secondary users. On the other hand, $P_i^{min}(f)$ denotes the minimum power required to reach the required $SINR_{\mathcal{SU}}^{th}$ at the intended secondary receiver. In other words, $P_i^{min}(f)$ and $P_i^{max}(f)$ provides the lower bound and upper bound of transmit power respectively for node i on frequency f. The $P_i^{min}(f)$ and $P_i^{max}(f)$ values are determined by a node i by gathering spectrum and resource allocation information from its neighbors. This information is gathered using collaborative virtual sensing (CVS) using the control packets in the network. Due to lack of space, we do not include the details about resource allocation, CVS and the medium access control (MAC) protocol employed as they are similar to that in ROSA. We urge readers to refer [1] for further details.

C. Distributed Deadline-based Routing and Spectrum Allocation Algorithm.

In this section, we propose the distributed Deadline-based cross-layer Routing and Spectrum allocation algorithm (DRS) to maximize the effective throughput of the network. In the distributed network, each node makes adaptive decision to choose optimal session, next hop, power allocation and spectrum to use during the next time slot based on the information gathered from its neighbors using CVS. This decision will be different from traditional ROSA [1] because the network utility defined here is a function of VQL and not the actual queue lengths. Once a backlogged node senses an idle CCC, it performs Algorithm 1 to obtain the optimal resource allocation decision:

1) DRS assumes that location of the intended destination node is known to the source node. Accordingly, each node selects a feasible set of next hops for each backlogged session $j \in (u_1^s, u_2^s, ..., u_k^s)$, which are neighbors with positive advance towards the destination.
2) The maximum capacity for each node is calculated by considering all possible spectrum opportunities. The maximum capacity to each feasible neighbor is used along with the corresponding differential VQL to determine U_{ij}^s. The optimal decision is taken such that,

$$(s^{opt}, j^{opt}) = \arg\max(U_{ij}^s). \tag{14}$$

The sessions that have smaller deadline and/or are further away from the intended destination will be scheduled more often if the available spectrum for all sessions are comparable. The adaptive routing will also provide most traffic to VQs that are lightly backlogged.
3) The optimal frequency and power allocation $(f_i^{opt}, \mathbf{P_i^{opt}})$ correspond to the values that provide maximum Shannon capacity C_{ij} over (i, j^{opt}), where j^{opt} is the chosen hop.

Algorithm 1 Deadline-based Resource Allocation

$t = 1$, $\Delta = \infty$, $C_{ij} = 0$, $U_{ij}^* = 0$
for $s_i \in S_i$ **do** ▷ All Active sessions
  for $j \in u_1, u_2, ...u_k$ **do** ▷ Next feasible hops
    for $f_i \in [f_{min}, ..., f_{max-\Delta f_i}]$ **do**
      Calculate $P_i^t(f)$ similar to [1]
      Calculate C_{temp} as in (7)
      if $C_{temp} > C_{ij}$ **then**
        $C_{ij} = C_{temp}$
        $[f_{i,j}^*, \mathbf{P_{i,j}^*}] = [f_i, \mathbf{P_i^t}]$
      end if
    end for
    $U_{ij}^s = C_{ij} * [Q_i^{s_i} - Q_j^{s_i}]$
    if $U_{ij}^s > U_{ij}^*$ **then**
      $U_{ij}^* = U_{ij}^s$
      $[f_i^{opt}, \mathbf{P_i^{opt}}, s_i^{opt}, j^{opt}] = [f_{i,j}^*, \mathbf{P_{i,j}^*}, s_i, j]$
    end if
  end for
end for
Return $[f_i^{opt}, \mathbf{P_i^{opt}}, s_i^{opt}, j^{opt}]$

IV. PERFORMANCE EVALUATION

In this section, we compare the performance of DRS with ROSA in a multihop ad-hoc network. To evaluate DRS, we use an object-oriented packet-level discrete-event simulator similar to [1]. The metrics used for this evaluation are effective throughput (η) defined in (1) and reliability (ρ) which is defined as the percentage of packets received at the destination with respect to the number of packets generated at the source node. The evaluation is conducted on a grid topology in a 6000 m x 6000 m area. The sessions are initiated between disjoint random source-destination pairs and the size of the packets are set at 2500 bytes. The total available spectrum (BW) is set to be 54 MHz-72 MHz. The bandwidth usable by cognitive radios are restricted to be 2, 4 and 6 MHz. The bandwidth of the CCC is set as 2 MHz. Each session transmitted 500 packets at a data rate of 2 MHz and each result was obtained by averaging the values obtained from 50 random seeds.

A. Scenario 1: Network performance as the number of session increases (All sessions started at same time)

In scenario 1, we evaluate the network performance as the number of active session in the network increases. The parameters used during the two experiments for scenario 1 is listed in Table I. The only difference between the two

TABLE I: Parameters of Experiments

Parameters	Scenario 1		Scenario 2		Scenario 3	
	Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5	Experiment 6
No. of Sessions	2, 4, 6, 8 10, 12, 14, 16	2, 4, 6, 8, 10, 12, 14, 16	2, 4, 6, 8,10, 12, 14, 16, 18, 20, 22	2, 4, 6, 8, 10, 12 14, 16, 18, 20, 22	2, 4, 6, 8, 10, 12, 14, 16	6 & 8
Session start	$t = 0$ s	$t = 0$ s	randomly from $t = [0,5]$ s	randomly from $t = [0,5]$ s	$t = 0$ s	$t = 0$ s
Deadline of each session	2 s	Odd sessions 1.5 s Even sessions 10 s	2 s	Odd sessions 1.5 s Even sessions 10 s	2 s	2 s

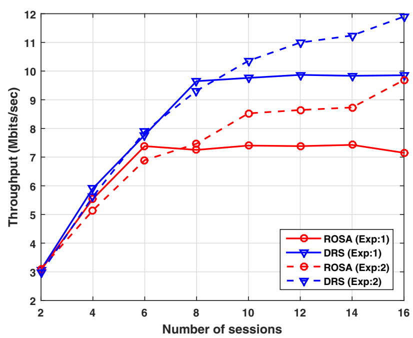

Fig. 1: Scenario 1: η vs No. of sessions.

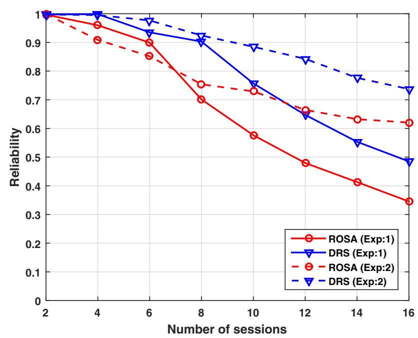

Fig. 2: Scenario 1: ρ vs No. of sessions.

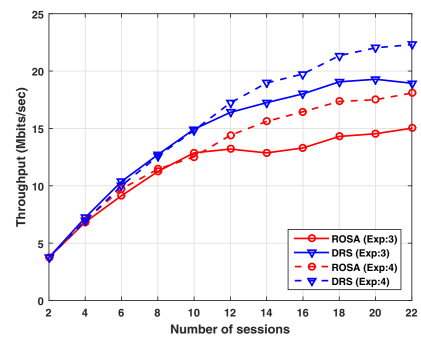

Fig. 3: Scenario 2: η vs No. of sessions.

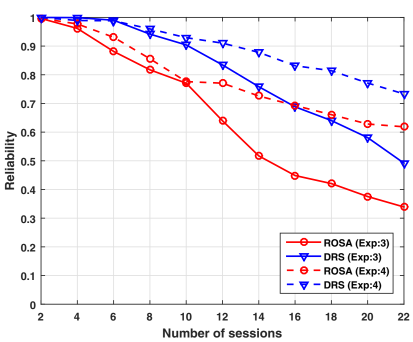

Fig. 4: Scenario 2: ρ vs No of sessions.

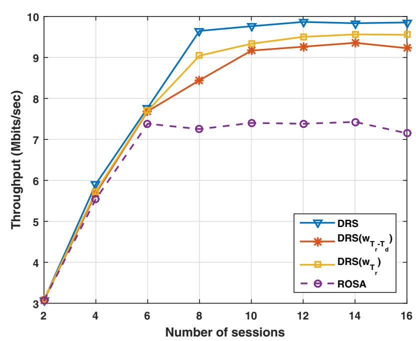

Fig. 5: Scenario 3: η vs No. of sessions.

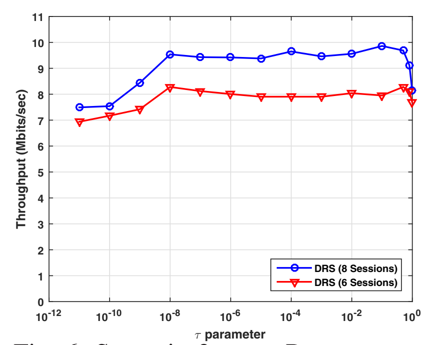

Fig. 6: Scenario 3: η vs Parameter τ.

experiments are the deadlines assigned to different sessions. In experiment 1, all the sessions have a deadline of 2 s, which represents a highly constrained network. Instead, in experiment 2, the odd numbered sessions have a deadline of 1.5 s and even numbered sessions have a deadline of 10 s. Experiment 2 can be considered as a scenario where one session carries periodic weather monitoring data through the network. These sessions are delay tolerant to an extent, hence have a longer deadline. The second type of data can have extremely small deadline consisting of delay-intolerant data like threat detection or incoming missile alert. The effective throughput and reliability of the network is depicted in Fig. 1 and 2. As we can see, DRS performs better than ROSA as the number of sessions increases. The overall effective throughput of DRS and ROSA is higher for experiment 2 because there are sessions that have longer deadlines. DRS is able to adapt to the requirements by expediting packets with smaller deadline while holding back packets that have longer deadlines. This is also the reason why the difference in reliability between DRS and ROSA is evident even at smaller number of sessions in experiment 2 (see Fig. 2). Thus, DRS is able to manage sessions carefully to maximize the number of packets being delivered to the destination node within the specified deadline.

B. Scenario 2: Network performance as the number of session increases (All sessions started at random time)

The second scenario is similar to scenario 1 with the exception that each session starts randomly any time between start of the simulation ($t = 0$ s) and session duration ($t = 5$ s). This ensures that all sessions are active at some point during the simulation but the number of active sessions will vary throughout the simulation. The two experiments in scenario 2 are similar to the ones of scenario 1 as they only vary in the deadlines assigned to individual sessions. The parameters of both the experiments (3 and 4) are enlisted in Table I. It is evident comparing Fig. 1 and 2 to Fig. 3 and 4 that the overall effective network throughput and reliability in scenario 2 is higher compared to scenario 1 because the sessions are spread over longer duration reducing network congestion. Examining Fig. 3 and Fig. 4 show that DRS performs much better than ROSA in terms of reliability and effective throughput with respect to experiments 3 and 4. In these scenarios, traditional backpressure based algorithm may suffer from the last packet problem. Since DRS is formulated based on VQL which takes into account the deadlines of each packet in the queue, the penalty for holding packets in the queue grows as time elapses eliminating the last packet problem.

C. Scenario 3: Examining the effect of different components of DRS

Here, we try to evaluate the effect of different components used during the formulation of DRS. Firstly, in experiment 8, we evaluate how T_r and $T_r - T_d$ affect the proposed algorithm individually. Accordingly, we run the simulation with the parameters shown under experiment 8 in Table I using two different weight definitions as shown below,

$$w_{T_r} = \frac{L}{max\,(T_r, \tau)}, \tag{15}$$

$$w_{T_r - T_d} = \frac{L}{max\,(T_r - T_d, \tau)}. \tag{16}$$

Figure 5 shows that both DRS using weights seen in (15) and (16) performs considerably better than ROSA but does not maximize the effective throughput like original DRS. This is because original DRS that uses the weight shown in (2) derives the benefits of both weights shown above. Hence, this shows why it is advantageous to have both T_r and $T_r - T_d$ in the denominator of the weight used to calculate VQL. Further, it is interesting to note that in cases where it is difficult to estimate T_d, one can still achieve moderately good performance by using weight shown in (15). Next, we evaluate the effect of the parameter τ on the effective throughput of the network. The weight in (2) uses a very small value τ to ensure correctness, such that instances with infinite value do not occur.

Figure 6 depicts the effective throughput of the network as τ varies from 10^{-11} to 0.99 while keeping the number of sessions and source data rates constant. The other parameters of experiment 9 are depicted in Table I. The result shows that the effective throughput of the network using DRS is consistently high for values of τ over a range between 10^{-8} to 10^{-1}. Any value greater than 10^{-1} takes away the effect of deadlines and has a degrading effect on effective throughput. As the value of τ moves closer to 1, the VQL becomes more and more equivalent to traditional queue length. On the other hand, choosing τ to be smaller than 10^{-8} also affects the algorithm adversely since it bloats the VQL to an extent where the capacity component of the network utility function becomes insignificant. This lower bound would depend on the characteristics of the network, specifically, the achievable capacity determined by the bandwidth of the transceiver. Figure 6 also shows that the range of values for τ outside which the effective throughput of the network starts declining is same for both 6 and 8 sessions. This shows that the acceptable value for τ does not change according to the number of active sessions in the network. Since we have shown that DRS performs consistently well over a large range of values of τ, one can choose any value within the acceptable range depending on the network setup.

V. Conclusions

We proposed a novel distributed deadline-based joint routing and spectrum allocation algorithm to maximize the effective throughput of the network. DRS adapts according to available resources and is capable of handling sessions with different deadline requirements. DRS enables every node in the network to choose optimal session, next hop, frequency and transmit power with an objective to deliver maximum number of packets to their intended destination before the specified deadline. Though DRS is designed for tactical ad-hoc networks, its application can be extended to any wireless ad-hoc network that handles sessions with different QoS based deadline requirements. Simulations comparing the performance of DRS with ROSA showed up to 35 % improvement in the effective throughput and up to 26 % improvement in reliability of the network. As a next step, we will implement and evaluate DRS on a software defined radio based testbed [10] to corroborate the improvement achieved in simulation on a software defined network.

References

[1] L. Ding, T. Melodia, S. Batalama, J. Matyjas, and M. Medley, "Cross-layer Routing and Dynamic Spectrum Allocation in Cognitive Radio Ad Hoc Networks," *IEEE Transactions on Vehicular Technology*, vol. 59, pp. 1969–1979, May 2010.

[2] L. Tassiulas and A. Ephremides, "Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks," in *Proc. of IEEE Conference on Decision and Control (CDC)*, Honolulu, HI, December 1990.

[3] L. Bui, R. Srikant, and A. Stolyar, "A Novel Architecture for Reduction of Delay and Queueing Structure Complexity in the Back-Pressure Algorithm," *IEEE/ACM Transactions on Networking*, vol. 19, no. 6, pp. 1597–1609, December 2011.

[4] M. Andrews, K. Kumaran, K. Ramanan, A. Stolyar, P. Whiting, and R. Vijayakumar, "Providing quality of service over a shared wireless link," *IEEE Communications Magazine*, vol. 39, no. 2, pp. 150–154, February 2001.

[5] M. Kurth and J.-P. Redlich, "Delay properties of opportunistic back-pressure routing in CSMA-based wireless mesh networks," in *Proc. of IEEE Intl. Symp. on Personal, Indoor and Mobile Radio Communications Workshops (PIMRC)*, Istanbul, Turkey, September 2010.

[6] B. Ji, C. Joo, and N. Shroff, "Exploring the inefficiency and instability of Back-Pressure algorithms," in *Proc. of IEEE Conference on Computer Communications (INFOCOM)*, Turin, Italy, April 2013.

[7] M. Xiao, J. Wu, H. Huang, L. Huang, and W. Yang, "Deadline-sensitive opportunistic utility-based routing in cyclic mobile social networks," in *Proc. of IEEE Intl. Conf. on Sensing, Communication, and Networking (SECON)*, Seattle, WA, June 2015.

[8] C. Lee and K. I. Kim, "A Deadline Aware DTN Approach Based on Epidemic Routing," in *Proc. of IEEE Intl. Symp. on Network Computing and Applications (NCA)*, Cambridge, MA, August 2014.

[9] Q. Fu, B. Krishnamachari, and L. Zhang, "DAWN: A density adaptive routing for deadline-based data collection in vehicular delay tolerant networks," *Tsinghua Science and Technology*, vol. 18, no. 3, pp. 230–241, June 2013.

[10] J. Jagannath, H. Saarinen, W. Timothy, J. O'Brien, S. Furman, T. Melodia, and A. Drozd, "COmBAT: Cross-layer Based Testbed with Analysis Tool Implemented Using Software Defined Radios," in *Proc. of IEEE Conf. on Military Communications (MILCOM)*, Baltimore, MD, November 2016.