Optimization of packet forwarding scheduling in wireless ad-hoc networks: Deployment on a 3D environment

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Abstract. The key aim of a multi-hop wireless network is to increase service efficiency in terms of transmission scheduling, packet transfer volume, and other factors. In a practical deployment of Ad-Hoc wireless network in three-dimensional (3D) environments, we study the optimizing transmission scheduling problem by end-to-end latency minimization using the signal-to-interference-and-noise rate (SINR) mechanism. Two strategies are considered. The former directly deals with end-to-end latency and eliminates the constraint of frame periodicity. The latter combines two cooperative transmission and transmission interference suppression models. The properties of both strategies are analyzed, and mixed-integer programming (MIP) models and solution heuristics are developed. Simulation results are presented to clarify the end-to-end latency performance of strategies, especially in 3D environments.

1 Introduction

An Ad Hoc Wireless Network (AHWN) consists of a variety of units that can establish seamless, active connections in the network with no need for physical infrastructure. Each communication node can work as both a transceiver and an intermediary to theoretically guarantee the connection between all source-destination couples using the multi-hop transmission model. Among the issues that have been addressed by extensive research, we find the packet forwarding scheduling problem in multi-hop networks, which has different characteristics in AHWN. Moreover, the topology of these networks relies on many influences such as the position of nodes, spreading conditions, environmental considerations, etc [1]. Recently, the focus was on enhancing the efficiency of parallel transmission employing a shortest-length scheduling approach that satisfies a certain collection of packets to forward via the fewest number of slots feasible in a supposedly periodic time frame [2]. Traditional shortest length scheduling simply guarantees that an adequate number of forwards are planned for each connection, regardless of the order in which coherent collections appear in the frame [3]. Given that a characteristic hypothesis in shortest-length scheduling is flow periodicity by duplicating the frame over the high haul, all connection transmissions planned inside the frame will be completely used. Then again, if the objective is to forward a collection of packets with no periodicity, shortest-length scheduling is not suitable at this point.

For services demanding timely delivery of a collection of packets, minimizing the end-to-end latency problem during delivering those packets is studied in [4]. The authors develop two strategies to minimize the overall number of time slots needed when forwarding a certain collection of packets without frame periodicity. The first strategy is based on the Standard Packet Forwarding (SPF) model, in which every time slot in the frame imposes a coherent collection. The second strategy combines two cooperative packet transmission (CPT) and transmission interference suppression (TIS) models. CPT allows the same packet to be transmitted by multiple transmitters, and a receiver can collect the signals generated by the packet to achieve a higher SINR. TIS enables a node to remove the interference induced by the forwarding of a packet that it successfully received and buffered earlier. Through presenting variables that usually depict packet propagation, the MIP formulation for two strategies has been provided to consistently combine transmission scheduling and routing. It is shown that this problem is NP-complex, and a solution heuristic for planning and routing on a slot-by-slot level is proposed accordingly. However, the performance of transmission scheduling and packet routing in a realistic AHWN relies on many influences such as spreading conditions, environmental specifications, and node positions [1]. The solution to this issue is quite challenging, particularly in 3D environments. Therefore, in this paper, we have taken up the challenge of studying the end-to-end latency minimization problem, which has already been addressed in [4], by considering a practical deployment of AHWN on 3D environments instead of two-dimensional (2D) ones.

2 Environment structure and propagation model

In this paper, we use Digital Terrain Elevation Data (DTED) maps to built a reasonable simulation terrain for the deployment of AHWNs. This model is in the form of an environmental altitude database determined by the associated latitude and longitude coordinates [5].The propagation loss was predicted empirically by many approaches [6,7]. The propagation loss prediction

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approach using environment profile information is shown in [8] and given as:

$$PL = max\,(L_{FS}\,, L_{PE}) + L_D \qquad (1)$$

where L_{FS}, $L_{PE,}$ and L_D denote the free space, flat earth, and diffraction losses, respectively.

In addition, inter-symbol interference between nodes is disregarded. In [7], the free-space loss is expressed as:

$$L_{FS} = 20log(d) + 20log(f) + 32{,}45 \qquad (2)$$

where d is the distance between mobile units in kilometers and f denotes the transmitting frequency in megahertz. Flat earth loss is defined as follows:

$$L_{PE} = 118{,}7 - 20log(h_t \cdot h_r) + 40log(d) \qquad (3)$$

where h_t and h_r are the antenna lengths of transceiver units.

We employ the approach of propagation by diffraction adopted by the International Telecommunication Union [9] to estimate the diffraction loss. This approach is derived from the Bullington design. In this recommendation, diffraction loss is given as:

$$L_D(\sigma) = 6{,}9 + log\,(\sqrt{(\sigma - 0{,}1)^2 + 1} + \sigma - 0{,}1 \qquad (4)$$

where σ is the diffraction coefficient that joins all the path-related geometrical variables. It may be estimated by the procedure shown in [9].

3 Network model

Bidirectional graph $G = (\boldsymbol{V}; \boldsymbol{E})$ is generally exploited to construct the links between communication units in an AHWN. Units in the network compose the collection of intersections, $\boldsymbol{V}$, and the connections between the units compose the collection of borders, $\boldsymbol{E}$ [10]. A unit-to-unit received power matrix $P = [p_{nm}]$ is built. p_{nm} represents the power received from unit n by unit m and is calculated as: $p_{nm} = P_n - PL_{nm}$ where the transmission power of unit n and the propagation loss from unit n to unit m are represented by P_n and PL_{nm}, respectively. A couple of units $(n; m)$, where n and m are members of $\boldsymbol{V}$, is in $\boldsymbol{E}$ if, and only if, the signal-to-noise rate (SNR) demand is verified, that is:

$$SNR_{nm} = \frac{p_{nm}}{\mu} \geq \gamma \qquad (5)$$

where μ is the noise intensity and γ is the chosen SNR limit.

The network's connection status is given by a physical link matrix $C = [c_{nm}]$, in which c_{nm} entries of the matrix rely on the SNR_{nm} and the SNR limit γ for a secure connection, respectively. Hence, the elements of C can be defined as follows:

$$c_{nm} = \begin{cases} 1\,, & if \quad n \neq m \quad and \quad SNR_{nm} \geq \gamma \\ 0\,, & if \quad n = m \quad or \quad SNR_{nm} < \gamma \end{cases}$$

4 Approved transmission models

4.1 Standard packet forwarding model (SPF)

We suppose Ω signifies a collection of units sending in a time slot t that is belonging to a sequence of $T = \{1,2,\ldots\ldots,\tau\}$, the status of each node is being either transmitting, receiving, or inactive over at the most one link in a time slot t [4]. Generally, not all transmissions can be forwarded simultaneously due to the interference constraint. We denote a group of active nodes belonging to a matching collection $\xi \,\epsilon\, \boldsymbol{E}$ by $\Omega(\xi) = \{\mathrm{n} : \exists m, (n; m)\,\epsilon\,\xi\}$. Thus, the SINR demand is applied to each link $(n; m)\,\epsilon\,\xi$:

$$SINR_{nm} = \frac{p_{nm}}{\mu + \sum_{k \epsilon \Omega(\xi)\backslash\{n\}} p_{km}} \geq \gamma \qquad (6)$$

Each packet s belonging to a set of packets S needs to be forwarded over a link at one time slot and is to be delivered to its receiver $D(s)$ from its source node $O(s)$ by passing through several relaying nodes on its path.

4.2 Cooperative packet transmission model (CPT)

With the CPT model, a group of nodes can send in parallel or receive the same packet, and each end node can join the transmitting signals from several transmitters [4,11]. Moreover, the nodes will send packets several times after receiving and storing them the first time. The CPT model described in [4] is adopted, and the SINR demand for $m \in \boldsymbol{V}$ to successfully accept packet $s \in S$ is:

$$SINR_{nm} = \frac{\sum_{n \epsilon \Omega(s)} p_{nm}}{\mu + \sum_{k \epsilon \Omega\backslash\Omega(s)} p_{km}} \geq \gamma \qquad (7)$$

where $\Omega(s) \subseteq \Omega$ represents the subgroup of transmitter packet s.

4.3 Transmission interference suppression model (TIS)

The TIS model was proposed in [12]. Its basic premise is that a receiver will cancel the intervening signal created by the transmission of a packet that it had previously received successfully and buffered. The SINR demand for node $m \in \boldsymbol{V}$ receiving packet $s \in S$ from node n with TIS is:

$$SINR_{nm} = \frac{p_{nm}}{\mu + \sum_{k \epsilon \Omega\backslash\Omega(m)\cup\{n\}} p_{km}} \geq \gamma \qquad (8)$$

where $\Omega(m) \subseteq \Omega$ present the sub-group of transmitters of packets that were buffered in node m.

5 Reduced latency scheduling problem (RLSP)

We discuss the optimization problem considered in [4], which aims to decrease global end-to-end latency by optimizing packet transmission scheduling. Principally, RLSP selects, for every time slot, specific packets to be forwarded and the connections to be employed by forwards, to utilize the least number of time slots to send all the packets to their corresponding recipients. Two RLSP strategies are explored in the following subsections: the first with SPF (S-RLSP), and the second with the incorporation of CPT and TIS (I-RLSP), exploiting MIP models.

5.1 1st strategy: Improvement of transmission scheduling with SPF

In [3, 4, 13], the authors studied and proved the problem's NP-hardness. Since the solution of latency minimization for S-RLSP is and will continue to be NP-hard, the authors in [4] proposed a heuristic algorithm to yield an optimal solution within a minimum of time. The algorithm divides packet transmissions into time slots and schedules them in order. The progress of the algorithm is explained in **Algorithm 1**. Notations considered by the algorithm are listed in Table 1.

Before the beginning of the first time slot $t = 1$, **Algorithm 1** gives the first state of all packets inserted into the network. The $line - 4$ formulation aims to reduce the total path followed by all packets to their receivers in the time slot t. The $line - 5$ constraint guarantees that a unit can only transmit or receive a packet in the slot t. The $line - 6$ constraint guarantees that a packet may be transmitted by only one unit in the slot t. The $line - 7$ constraint ensures that if $Z_{ms} = 0$, the packet s must not reach the unit m. The $line - 8$ determines the unit that can be reached by the packet s, i.e., $Z_{0s} = 0$. The $line - 9$ calculates the shortest path taken by the packet s from all units with s to its receiver $D(s)$. Formula $line - 10$ presents the SINR demand for delivery of the packet s from unit n to unit m.

Algorithm 1: For *S-RLSP* [4]

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1: Initializing sets at the first slot $t = 1$
2: $S(t) = S$;   $S(n,t) = \{s \in S : O(s) = n\}, n \in V$;
   $V(s,t) = \{O(s)\}$;   $L(s,t) = l(s, O(s))$;
3: Stage 1: Solve MIP formulation
4:          $min \sum_{s \in S(t)} z_s$
5: s. t:    $\sum_{s \in S(n,t)} X_{ns} + \sum_{s \in S'(n,t)} Y_{ns} \leq 1$,   $n \in V$
6:          $\sum_{n \in V(s,t)} X_{ns} \leq 1$,   $s \in S(t)$
7:          $Z_{ms} \leq Y_{ms}$,   $s \in S(t)$, $m \in V'(s,t)$
8:          $Z_{0s} + \sum_{m \in V'(s,t)} Z_{ms} = 1$,   $s \in S(t)$
9:          $z_s = L(s,t)Z_{0s} + \sum_{m \in V'(s,t)} l(s,m)Z_{ms} = 1$,
                                                      $s \in S(t)$
10:         $\frac{\sum_{n \in V(s,t)} p_{nm}X_{ns} + M(m)(1-Y_{ms})}{\mu + \sum_{k \in V\{m\}} \sum_{r \in S(t)\{s\}} p_{km} \cdot X_{kr}} \geq \gamma$,
                                        $m \in V$,   $s \in S'(m,t)$
11:         $X, Y, Z$  binary;  $z$ continuous
12: Stage 2: Updating of the sets
13:         $V(s,t+1) = V(s,t) \cup \{m \in V'(s,t): Y^*_{mp} = 1\}$,
                                                      $p \in P(t)$
14:         $S(t+1) = \{s \in S(t) : D(s) \notin V(s,t+1)\}$
15:         $S(n,t+1) = \{s \in S(t+1): n \in V(s,t+1)\}$,
                                                      $n \in V$
16:         $L(s,t+1) = min_{n \in V(s,t+1)} l(s,n)$,   $s \in S(t+1)$
17: Stage 3: If $S(t+1) = \emptyset$ stop. Else, define $t = t+1$
            and return to Stage 1
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The related sets are updated in Stage 2. The nodes getting the packet s ($Y^*_{mp} = 1$) are integrated in $V(s; t+1)$, i.e., $line - 13$. Packets that hasn't yet arrived at intended receivers in time slot t are registered in $S(t+1)$ (see $line - 14$). The $line - 15$ updates the set of packets saved in each node. The algorithm is terminated with Stage 3 in which the procedure stops if all packets have been arrived at their receivers in t slots, else it returns to Stage 1 by setting $t = t+1$.

5.2 2nd strategy: Improvement of transmission scheduling with CPT and TIS

We consider the 2nd strategy for minimal latency scheduling, which implies that the CPT and TIS models are used. The I-RLSP heuristic algorithm is the same as the S-RLSP heuristic. The difference lies only in the **Stage 1** of **Algorithm 1**, as expressed in the following MIP formulation. A given node can send a packet in several time slots. The problem is a one-slot variant of S-RLSP.

$$\min \sum_{s \in S(t)} z_s - \mathcal{E} \sum_{s \in S(t)} \sum_{n \in V} Y_{ns} \tag{9}$$

$$s.t: \qquad lines: (5), (7), (8)\ \ (9)\ in\ \ \boldsymbol{Algorithm\ 1}$$

$$\frac{\sum_{n \in \boldsymbol{V}(s)} p_{nm} \boldsymbol{X}_{ns} + \boldsymbol{M}(\boldsymbol{m})(\boldsymbol{1} - Y_{ms})}{\boldsymbol{\mu} + \sum_{r \in S'\{m,t\}\{s\}} \sum_{k \in V(\boldsymbol{r},\boldsymbol{t})} p_{\boldsymbol{km}} \cdot \boldsymbol{X}_{\boldsymbol{kr}}} \geq \boldsymbol{\gamma}, \qquad m \in \boldsymbol{V}, \quad s \in S'(m, \boldsymbol{t}) \tag{10}$$

$$\boldsymbol{X},\ \boldsymbol{Y},\ \boldsymbol{Z}:\ \ \boldsymbol{binary};\ \ \boldsymbol{z},\qquad \boldsymbol{continuous} \tag{11}$$

The last term of the formula (9) uses a positive constant to define the goal of the secondary optimization, (more details in [4]). Remark that the constraint mentioned in $line - 6$ is missed in the above formulation which allows a packet to be transmitted by multiple nodes.

Table 1. Table of Notations.

$\boldsymbol{S(t)}$	Collection of packets that have not yet reached their receivers at the starting of slot t
$\boldsymbol{S(n,t)}$	Collection of packets available at unit $n \in V$ (i,e,. $S(n,t) \subseteq S(t)$)
$\boldsymbol{S'(n,t)}$	Collection of packets absent at unit $n \in V$ (i,e,. $S'(n,t) = S(t) \backslash S(n,t)$)
$\boldsymbol{V(s,t)}$	Collection of units that contain packet s at the starting of the slot t (i,e,. $V(s,t) \subseteq V$)
$\boldsymbol{V'(s,t)}$	Collection of units without packet s at the start of slot t (i,e,. $V'(s,t) = V \backslash V(s,t)$)
$\boldsymbol{O(s), D(s)}$	Origin and destination units of packet $s \in S$
$\boldsymbol{l(s,n)}$	Path length from unit $n \in V$ to $D(s)$
$\boldsymbol{L(s,t)}$	Length of the actual path of s to its receiver $D(s)$ (i,e,. $L(s,t) = min_{n \in V(s,t)} l(s,n)$)
$\boldsymbol{X_{ns}}$	Logic variable becomes 1 if unit $n \in V(s,t)$ sends packet s, and 0 else
$\boldsymbol{Y_{ms}}$	Logic variable becomes 1 if unit $m \in V'(s,t)$ receives packet s, and 0 else

Z_{ms}	Logic variable becomes 1 if unit $m \in V'(s,t)$ is the nearest unit to $D(s)$
Z_{0p}	Secondary logic variable for the packet s
z_s	Variable computing the length path of s to its $D(s)$ after transmission in slot t

6 Results and discussion

In all the experiment simulations presented below, the AHWN units are deployed in environment provided by the DTED $level - 1$ map, which is approximately covering an area of $111.2\,km \times 111.2\,km$. Fig. 1. illustrate a concrete representation of this environment, referred to as $Level - 1$, which has a maximum elevation of $702\,m$.

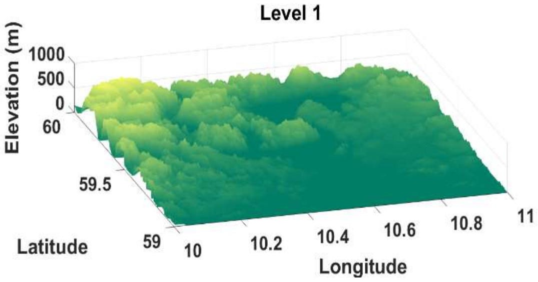

Fig. 1. Deployment terrain.

All units in the network have the same transmit power as 5 W and the transmission and receive antennas are each 2 m long. The noise power μ, and the SINR demand γ, and the transmission frequency f are $10^{-20}\,W$, 1, and 400 MHz, respectively. In the following, the performance of both strategies will be evaluated. The latency values versus the amount of packets injected in the network, the number of hops between the transceivers of the packets, and the number of units deployed in the environment will be illustrated. The test networks we consider here are medium networks with 30 units. Each latency value is an average estimate for 10 instances.

Fig. 2. plots the end-to-end latency values of both strategies as a function of the amount of packets that are introduced into the network subject to the provision that the number of hops for every couple of units is 4. We can note the ratio variances grow as the amount of packets increases, and that I-RLSP performs much better than S-RLSP.

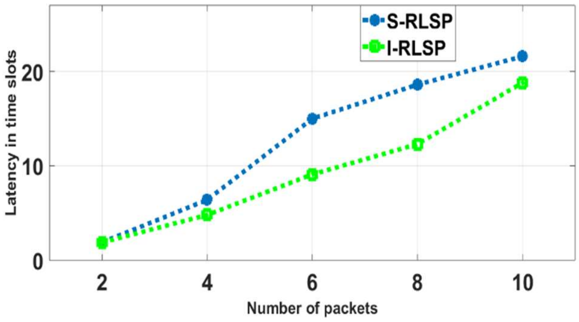

Fig. 2. Performance comparison of two strategies versus the amount of packets

Fig. 3. shows the end-to-end latency values of both strategies as a function of the number of hops between the transceivers per packet by setting the number of packets inserted into the network to 5. We can note that the relative variations to the second packet up to the 5^{th} packet increase significantly. It is obvious that I-RLSP provides a significantly better end-to-end latency than S-RLSP. For $hop = 5$, I-RLSP spares about 50% of the number of slots compared to S-RLSP. Comparing Fig. 2. and Fig. 3, we may also see that the latencies provided by S-RLSP and I-RLSP grow higher with the amount of packets than with the number of hops, because the insertion of a given packet into the network may make the transmission scheduling process more complicated, and thus it takes time to find an optimal solution.

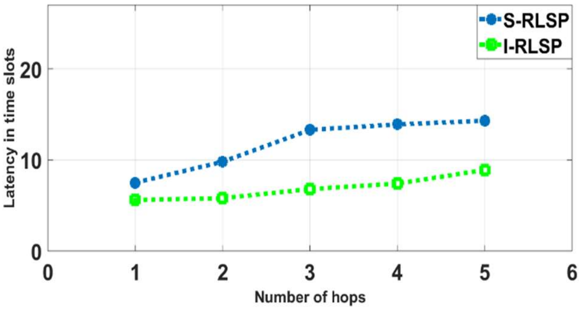

Fig. 3. Performance comparison of two strategies versus the number of hops

The performances of both strategies are also evaluated by varying the number of units deployed in the network as shown in Fig. 4. This test allows to study the influence of the increase of units deployed in the network on the overall end-to-end latency for 5 inserted packets. In Fig. 4, we note that the I-RLSP offers an efficient solution to the overall latency minimization problem compared to the S-RLSP. We can also observe that the relative variations reduce as the number of units in the network grows.

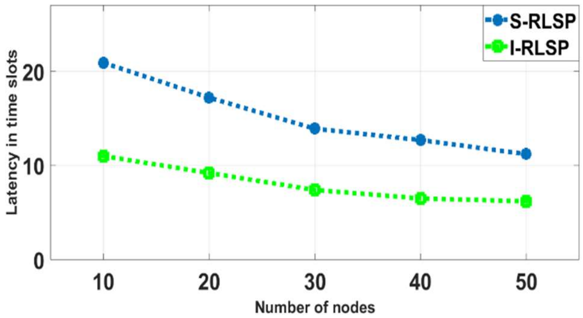

Fig. 4. Performance comparison of two strategies versus the number of units.

7 Conclusion

The present study addresses the end-to-end latency minimization problem in AHWNs using the physical interference model. Two strategies have been investigated. The first one, called S-RLSP, is a recent method in the literature for latency minimization scheduling. The second strategy called I-RLSP which integrates two interesting physical layer methods, namely cooperative packet transmission and transmission interference suppression. A series of calculation formulas are presented, and a characterization of the solution is provided. A real deployment of the network in 3D environment is considered. According to the results, the I-RLSP strategy outperforms the S-RLSP strategy in terms of minimizing overall end-to-end latency. However, the deployment of nodes and routing of packets in real 3D terrains still faces environmental hurdles that limit it to improve the performance of AHWNs compared to 2D terrains.

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