Energy Efficient Routing with Mutual Information Accumulation

Tolga Girici, and Ahmet Cihat Kazez*
* Department of Electrical and Electronics Engineering
TOBB University of Economics and Technology
Email: {tgirici, ackazez}@etu.edu.tr

***Abstract*—We consider minimum-energy routing in a wireless network. We assume the use of ideal rateless codes, so that a node can *accumulate* transmission *rates* from the transmission of previous nodes on the routing path. Mutual information accumulation has significant advantages when compared with classical cooperative schemes that use energy accumulation. However, the resource allocation problem becomes more complex, as it involves the determination of 1) Routing path, 2) Transmission duration of each node, and 3) Transmission power of each node. We formulated the problem as an optimization problem, where the objective function is the total energy expenditure and the constraints are minimum mutual information for each node and the maximum total transmission time. We make a slotted-time assumption, and given the routing path and transmission duration, power optimization problem becomes convex. The optimal routing path and transmissions durations are found using a Branch-and-Bound technique. A distributively implementable greedy algorithm is also found and performance are compared by numerical simulations.**

I. Introduction

Wireless environment is characterized by rapidly fading noisy channel conditions and energy-limited mobile devices. In this environment achieving certain data rate requirements subject to the battery limit requires special techniques. Multihop transmission [1] is one such technique. There is a large literature on multihop routing protocols. In multi-hop transmission, receivers can combine the transmissions from the previous hops, forming virtual antenna arrays, which is called cooperative communication [2]. Cooperative diversity provides robustness against fading, increases the data rate and provides energy efficiency. Finding optimal routing paths in the presence of cooperative transmissions is a problem that recently received interest [3], [4], [5], [6]. The underlying principle is that the receivers combine signals coming from multiple sources either simultaneously [4] or at different times [3], [5], [6]. The effective SNR at the receiver is the sum of SNRs of coming from each source. Therefore this type of routing is called *energy accumulation*.

In fact, if the nodes could accumulate *mutual information* instead of energy, it would be more energy-efficient. This is becoming a reality with rateless (Fountain) codes [7] , [8]. The source has a number of data packets and sends each time a randomly selected and XORed combination of those packets. Here there is no need to receive each and every transmitted packet. Receiver only needs to accumulate a number of coded packet in order to decode the original data. The term *rateless* comes from the fact that there are potentially limitless combinations of packets. In a multihop scenario a node can accumulate packets that are transmitted by the nodes in previous hops of the routing path. If we idealize this situation we can assume that mutual information is accumulated instead of packets.

Recent works such as [9], [10] , [11], [12] study optimal routing in the presence of mutual information accumulation. The work in [9] considers a two hop system with one source, one destination and several relays. The authors make a performance analysis for simple cooperation schemes and show that mutual information accumulation results in significant improvement in delay. The work in [10] minimize delay subject to bandwidth and energy constraints, where the nodes use fixed power level. The paper [12] also considers delay minimization, however in the presence of random packet arrivals. The authors in [11] consider the same delay minimization problem as in [10], but also find some important results that decreases the complexity of the optimal solution. Firstly, the source starts to transmit and it stops once a relay node in the network accumulates enough mutual information. After that, this node becomes the transmitter and starts to transmit. When the destination node gets enough mutual information for decoding the packet, transmission finishes. They proved that for a given routing path, this greedy algorithm results in optimal delay. In order to simplify the routing path determination [11] also proposed two heuristics. Moreover , authors in [11] also address the problem of energy minimization subject to delay constraints. However, they solve the problem after making a low-SNR assumption. With this assumption $\log(1+SNR)$ is approximated as SNR , but the difference in between can be significant at high SNR.

In this work we consider the open problem of minimum-energy routing and resource allocation for a wireless network that utilizes mutual information accumulation. We assume that each node can accumulate mutual information from the previous two nodes on the routing path. The constraints are the minimum required mutual information for each node on the path and the total transmission time. Routing process involves determining the routing path and transmission powers/times for all nodes on the path. We assume the time is slotted and each transmission duration must a multiple of time slots. We follow an convex optimization based approach for the power allocation and exhaustive search for the joint routing path/time determination. The next section explains the system model.

II. System Model

We consider a wireless network , where N nodes are randomly located in an area. The type of area will be circular in the simulations. There is a single source (node 1) and destination (node N) which are located on opposite ends of the area. Figure 1 illustrates a sample network topology. Channel condition among the nodes consist of a fixed attenuation (or very slow varying) and a fast-changing part. Fixed attenuation is caused by pathloss and shadowing, while the fast changing part consists of Rayleigh fading. For the optimal solution, we assume that channel state information is exactly available. Let $g_{i,j}$ be the total amount of channel attenuation between nodes i and j. We assume that channel coefficients stay fixed throughout the transmission session. Let us also define a new variable $h_{i,j} = \frac{g_{i,j}}{N_o W}$, where $N_o W$ is the noise power. The duration of the transmission is T_{max}, which is divided into equal time slots of duration T_s. This is illustrated in Figure 2. A single node transmits in each time slot.

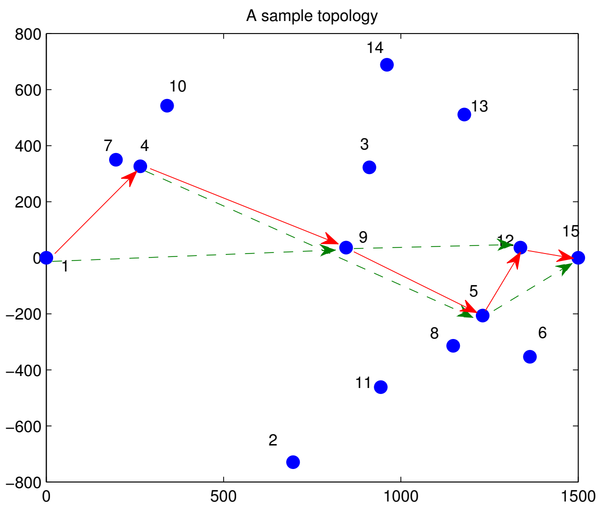

Fig. 1. A sample topology of 15 nodes. Routing path is shown by the solid lines. Each node is also able to accumulate mutual information from the links shown by the dashed lines.

In this paper we consider ideal Rateless codes and mutual information accumulation. Let us assume a routing path (i.e order of transmissions) $1, 2, \ldots, n-2, n-1, n, \ldots, N$. Let P_n and T_n be the transmit power and duration of node n , respectively. Then, the accumulated mutual information at node n is $T_{n-2}\log(1+P_{n-2}g_{n-2,n}) + T_{n-1}\log(1+P_{n-1}g_{n-1,n})$ nats/Hz. Each node on the path has to accumulate I_{max} nats/Hz mutual information in order to be able to decode the

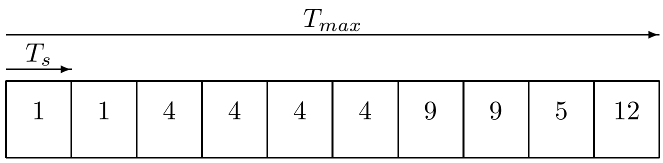

Fig. 2. A sample transmission schedule. Time is divided into slots. At each time slot, a node transmits. Nodes 1,4,9,5 and 12 on the routing path transmit in 2,4,2,1 and 1 time slots, respectively. Distant links are allocated more slots.

message successfully. [1]. In other words we assume that each node accumulates mutual information only from the latest two transmitters. This is also illustrated in Figure 1 Of course, the second node only accumulates from the first node. With this simplifying assumption coordination among the nodes (in real implementations) and mathematical analysis becomes easier. Besides, channel reuse becomes possible, that is, as node $n-2$ is transmitting , nodes ... $n-5$, $n+1$, $n+4$ ... can transmit other data using the same channel (with some added interference). Channel reuse is a subject for future research.

The routing problem we consider involves 1) determining the path that the packets follow from source to destination, 2) determining the transmission duration (i.e. number of slots) of each node on the path and 3) determining the transmission power for each node.

III. Minimum Energy Transmission for a Given Path and Schedule

In this section we assume the routing path and number of slots for each transmitter is already determined. Assume the routing path is $\{1, 2, \ldots, N\}$ and their transmission durations are $\{T_1, T_2, \ldots, T_{N-1}\}$, which are all multiples of T_s and their sum is T_{max}. We optimize the transmission powers of transmitters on the path. The objective is to minimize total energy, which is the sum of the products of transmission durations and powers. The constraints are the required mutual information for each node on the path.

$$\min_{P} \left\{ \sum_{n=1}^{N} P_n T_n \right\} \quad (1)$$

$$\texttt{s.t.}\quad T_1 \log(1 + P_1 h_{1,2}) \geq I_{max} \quad (2)$$

$$T_{n-2}\log(1 + P_{n-2}h_{n-2,n}) + T_{n-1}\log(1 + P_{n-1}h_{n-1,n}) \geq I_{max}, n = 3, \ldots, N \quad (3)$$

The objective function is a convex (linear) function of powers. The constraints involve logarithms of powers, which are certainly concave. The sum of concave functions (weighted by transmission durations) is also concave. Therefore the

[1]In reality there are an integer number of packets, which are fountain-encoded (using Raptor or LT codes) at the application layer. These encoded packets are to be transmitted (possibly in a multihop manner) until the destination is able to successfully decode them. There is a packet reception probability for each link (depending on transmission power). Nodes decode the message if they are able to accumulate certain number of Fountain encoded packets. This more realistic scenario is a subject of future research.

constraint set is convex, which makes the problem convex. This problem can be solved by using standard interior point methods [17].

A. Solution

For the solution of the power power optimization problem we use Barrier Method, which is a type of interior point method [17]. In this method a logarithmic barrier function is used for each constraint. If a constraint is violated the barrier function becomes infinity, which necessitates satisfaction of all constraints. Again, assume the routing path is $\{1, 2, \ldots, N\}$ and their transmission durations are $\{T_1, T_2, \ldots, T_{N-1}\}$. We define the function to be minimized, $f(\overline{P})$, as in (4).

The parameters t is the weight of the barrier function. As it gets higher, the constraints tend to be satisfied with equality and the solution approaches the true optimum.

Algorithm 1 Power Optimization Using Barrier Method [17]

1: Start: any $\overline{P}$ that satisfies constraints (2), (3). $t = t^{(0)}$, $\mu > 1$, tolerance $\epsilon > 0$
2: **while** $m/t \leq \epsilon$ **do**
3: Compute $\overline{P}^*(t)$ that minimizes $f_t(\overline{P})$ in (4) starting at $\overline{P}$
4: Update $\overline{P} = \overline{P}^*(t)$
5: Increase $t = \mu \times t$
6: **end while**

Optimization by Barrier Method involves nested iterations. In the outer iteration the parameter t is increased (by multiplying with mu) step by step. In the inner iteration (Step 3) the problem $f_t(\overline{P})$ in (4) is solved using Newton method. Newton search requires the conputation of the gradient and Hessian at each iteration. Line search can be used in order to keep the power values always in the feasible region. The power values found in one iteration is used as the initial value of Newton search in the next iteration. As the parameter μ is increased, the number of inner (Newton) iterations decrease and the outer iterations increase. As $t^{(0)}$ increases, the duration of the first outer iteration increases.

Let us discuss about our slotted time assumption. Obviously it would result in less energy expenditure if we allowed transmission durations to be a continuous variable. However the problem becomes no more complex. If we look at (1) we see that the objective functions involves multiplication of time and power variables, which may result in multiple local minima. Let's we think of subproblem functions $f(\overline{T})$, $f(\overline{P})$ which are formed by considering the power and times fixed, respectively. For a given fixed set of powers, the objective becomes a linear function of time and the power constraint set becomes convex. Likewise, for a given time allocation the objective becomes a linear function of power and time constraints also become linear. Both subproblems are convex, therefore the joint time and power optimization problem becomes biconvex [14], [15]. Since each subproblem is convex, coordinate descent methods [16] can be used to find locally optimum solutions. In this method we first keep the times fixed and optimize powers, then we keep the powers fixed and optimize the times. This process goes on iteratively until a stopping criterion is satisfied. However those solutions are not guaranteed to be globally optimal. Therefore we chose to divide the time duration into slots, integrate the time optimization into route determination and solve it using a Branch and Bound technique. This assumption is not unrealistic, as many actual communication systems are time-slotted. Besides, time slot assumption also leads us to some greedy algorithms that can also be implemented in a distributed manner. In the next section we will study route and transmission duration optimization using a Branch and Bound technique.

IV. Optimal Routing and Time Optimization: Branch-and-Bound

As for finding the optimal routing path and transmission times, we use a Branch and Bound technique [13]. Branch and Bound is an exhaustive search technique that forms each possible solution as branches of a tree. By defining upper and lower bounds on the performance of each solution, it avoids searching branches that are guaranteed to result in suboptimal performance. Each branch includes the nodes that transmit at each time slot. Let's assume that the number of time slots is $T = \frac{T_{max}}{T_s} = 5$. We start with simplest route (root of the branch) $\{[1, 0, 0, 0, 0, N]\}$. It is certain that the source node needs to at least transmit in the first time slot. Then we form branches $\{[1, 1, 0, 0, 0, N]\}$, $\{[1, 2, 0, 0, 0, N]\}$,$\{[1, 3, 0, 0, 0, N]\}$, ..., $\{[1, 5, 0, 0, 0, N]\}$ (Line 8). We calculate the lower and upper bounds of energy expenditures for each branch. For example, the branch $[1, 1, 4, 3, 0, N]$ denotes that nodes 1,4,and 3 transmit in that order and for durations of 2,1 and 1 time slots. The last time slot is empty. The upper bound for energy expenditure of the route $\{1, 1, 4, 3, 0, N\}$ is defined by the energy expenditure of the path $\{1, 4, 3, N\}$ and time durations 2,1,1,2 slots (The last transmitter on the path (i.e. 3) takes the empty slots). The Algorithm 1 is run. Energy expenditure on the subbranches of this branch will always be smaller than or equal to this expenditure. The lower bound for $[1, 1, 4, 3, 0, N]$ is found taking the route $\{1, 4, 3\}$ (assuming node 3 is the destination) and time durations of 2 and 1 time slots. Energy expenditure on the subbranches of this branch will always be greater than or equal to this expenditure.

Line 8 adds a node to a branch. As for the branch $\{1, 1, 4, 3, 0, N\}$, nodes 1, 4 and N cannot be added to this branch. Node 1 could only be added as $\{1, 1, 1, 4, 3, N\}$ and node 4 as $\{1, 1, 4, 4, 3N\}$. Transmissions of a node should occur adjacently in time, as there is no gain in doing otherwise.

If the lower bound newly formed branch is greater than the upper bound of any of the existing branches, then it is immediately pruned. The reason is that this branch and its subbranches a guaranteed to be suboptimal. Likewise if the upper bound of the new branch is less than any of the existing lower bounds, then those branches are pruned (Lines 10-14). This branching and pruning procedure goes on until there is only one branch, which corresponds to the optimal solution (Line 17).

$$f_t(\overline{P}) = \sum_{n=1}^{N-1} T_n P_n - \frac{1}{t}\left[\log\left(T_1 \log(1+P_1 h_{1,2}) - I_{max}\right) + \log\left(T_1 \log(1+P_1 h_{1,3}) + T_2 \log(1+P_2 h_{2,3}) - I_{max}\right)\right.$$
$$+ \log\left(T_2 \log(1+P_2 h_{2,4}) + T_3 \log(1+P_3 h_{3,4}) - I_{max}\right) +$$
$$\left. \ldots + \log\left(T_{N-2} \log(1+P_{N-2} h_{N-1,N}) + T_{N-1} \log(1+P_{N-1} h_{N-1,N}) - I_{max}\right)\right] \quad (4)$$

Algorithm 2 Route Optimization Using Branch and Bound

1: Starting with a single branch $\mathcal{B} = \{B_1\}$, $\mathcal{LB} = \{LB_1\}$, $\mathcal{UB} = \{UB_1\}$
2: where $B_1 = [1000...N]$, its lower bound $LB_1 = 0$, and upper bound $UB_1 = T_{max}(e^{I_{max}/T_{max}} - 1)/h_{1,N}$
3: **while** not stop **do**
4: Find branch $b^* = \arg\min_{UB \in \mathcal{UB}} \{\mathcal{UB}\}$
5: $\mathcal{B} = \mathcal{B} - B_{b^*}$, $\mathcal{UB} = \mathcal{UB} - UB_{b^*}$, $\mathcal{LB} = \mathcal{LB} - LB_{b^*}$
6: **for** n=1:N-1 **do**
7: **if** $n \notin B_{b^*}$ or $n = L(B_{b^*})$ **then**
8: ADD node n to B_{b^*} forming B_{new}. $\mathcal{B} = \mathcal{B} \cup B_{new}$
9: Calculate Lower and Upper Bounds LB_{new}, UB_{new}. $\mathcal{UB} = \mathcal{UB} \cup UB_{new}$, $\mathcal{LB} = \mathcal{LB} \cup LB_{new}$
10: **if** $\exists B_i$ s.t. $UB_i < LB_{new}$ **then**
11: Prune the new branch, $\mathcal{B} = \mathcal{B} - B_{new}$, $\mathcal{LB} = \mathcal{LB} - LB_{new}$, $\mathcal{UB} = \mathcal{UB} - UB_{new}$
12: **else**
13: $\forall B_i$ s.t. $LB_i > UB_{new}$, Prune B_i, $\mathcal{B} = \mathcal{B} - B_i$, $\mathcal{LB} = \mathcal{LB} - LB_i$, $\mathcal{UB} = \mathcal{UB} - UB_i$
14: **end if**
15: **end if**
16: **end for**
17: **if** $|B| = 1$ **then**
18: stop
19: **end if**
20: **end while**

V. A Greedy Algorithm

We devised a greedy algorithm that has an extremely low complexity when compared with the Branch-and-Bound approach. As shown in Algorithm 3 the algorithm first starts with a noncooperative route where each node only accumulates from the previous transmitter. At this stage (Lines 1-6) we assume each node has transmission duration of one time slot. Link costs (energy expenditures) are calculated in Line 1, and based on them, a noncooperative route is found using Bellman-Ford algorithm. Then in Line 5, power of each node on the path is recalculated according to cooperative routing, where each node accumulates from the last two transmitters. If the resulting total transmission duration is less than T_{max}, then we can add more transmissions in order to decrease the energy expenditure (Lines 8-17). The node π_{n^*} with highest power on the path is found. Either the transmission time of this node is increased, or a node in the "Decoding set" set is added to the path by making its transmission duration T_s. Decoding set $D(\pi_{n^*})$ is the set of nodes in the network, that are able to accumulate I_{max} mutual information before the node π_{n^*} starts to transmit. The most energy efficient decision is made, and it is continued until all slots are allocated.

It is also possible that as a result of Bellman-Ford algorithm more slots than $\frac{T_{max}}{T_s}$ is allocated. Then Lines 19-26 decrease the transmission durations by finding the node with least power at each iteration. At each iteration powers are recalculated as in Line 5. If transmission duration of a node becomes zero, then its power also is set to zero and the node is excluded from the path.

A. Distributed Implementation

The above algorithm can also be implemented distributively. Bellman-Ford algorithm is amenable to distributed implementation. Once a path is formed Line 5 can be implemented on the routing path starting from the first node on the path. Finding the node with highest (lowest) power on the path can be found by control signaling along the routing path. Once the highest-power node is found, it can use its two-hop information in order to add a new transmission , or increase its own transmission duration.

VI. Simulations

We consider a number of nodes randomly located in a circular area of radius of 750 meters. Nodes 1 and N are located on the opposite ends. Bandwidth is 1MHz, and the AWGN noise power spectral density is -174dBm. For simplicity, we only consider pathloss as the channel attenuation effect and our pathloss model is $-38.4 + 35log_{10}(d_{i,j})$, where $d_{i,j}$ is the distance between two nodes i and j. Fading and shadowing could easily been incorporated into the model. The total transmission time constraint is 10 msec and the mutual information requirement is 0.002 nats/Hz.

In the first case we consider a network of 15 nodes. The topology can be seen in Figure 3 and 4. Total time is divided into 10 time slots of 1msec. The figures show the results of Branch-and-Bound based solution and the result of the greedy algorithm, respectively. The result of the branch-and-bound and coordinate descent procedure is the route $\{1, 10, 12, 3, 11, 7, 14, 15\}$, with transmission times $1, 1, 1, 1, 3, 2$ time slots. Transmission powers are $65.4, 19.5, 4.42, 16, 59.6, 1.55, 2.22$ mW. The resulting energy expenditure is 0.000370.

Figure 4 shows the result of the greedy algorithm. The figure shows that the resulting route is $\{1, 10, 12, 3, 11, 7, 4, 14, 15\}$, with transmission times $1, 1, 1, 1, 3, 1, 1$ time slots. This is

Algorithm 3 Greedy Routing Algorithm

1: Calculate link costs $C_{i,j} = T_s(e^{I_{max}/T_s} - 1)\frac{1}{h_{i,j}}, \forall i \neq j$
2: Run the Distributed Bellman-Ford algorithm based on the above costs. Let π be the resulting path. Let $\pi_1, \pi_2, ...$ be the nodes on the path (e.g. $\pi_1 = 1$). Let $|\pi|$ be the number of nodes on the path (e.g. $\pi_\pi = N$).
3: Set $T_n = T_s, \forall n \in \pi$. Set $P_{\pi_1} = P_1 = C_{1,\pi_2}$,
4: **for** $n = 2 : |\pi| - 1$ **do**
5: $\quad P_{\pi_n} = (e^{\frac{I_{max} - T_s \log(1 + P_{\pi_{n-1}} h_{\pi_{n-1},\pi_{n+1}})}{T_s}} - 1)\frac{1}{h_{\pi_n,\pi_{n+1}}}$
6: **end for**
7: **if** $|\pi| < \frac{T_{max}}{T_s}$ **then**
8: $\quad$ **while** $\sum_{n=1}^{N} T_n < T_{max}$ **do**
9: $\quad\quad$ Find $n^* = \arg\max_{n=1...|\pi|-1} P_{\pi_n}$
10: $\quad\quad$ Find the Decoding Set $D(\pi_{n^*})$
11: $\quad\quad$ **for** $i \in D(\pi_{n^*})$ **do**
12: $\quad\quad\quad T_i' = T_i + T_s$
13: $\quad\quad\quad$ Set $\pi = [\pi_1, \pi_2, ...\pi_{n^*}, i, \pi_{n^*+1}, \ldots, N]$ if $T_i = 0$
14: $\quad\quad\quad$ Compute new power expenditures $P_{\pi_n'}, \forall n = 1...|\pi'|$ as in Line 5
15: $\quad\quad$ **end for**
16: $\quad\quad$ Find the energy-minimizing node i^*. Set $T_{i^*} = T_{i^*} + T_s$, Set $\pi = [\pi_1, \pi_2, ...\pi_{n^*}, i^*, \pi_{n^*+1}, \ldots, N]$ if $T_{i^*} = T_s$, and compute new power expenditures as in Line 5.
17: $\quad$ **end while**
18: **else**
19: $\quad$ **while** $\sum_{n=1}^{N} T_n > T_{max}$ **do**
20: $\quad\quad$ Find $n^* = \arg\min_{n=1...|\pi|-1} P_{\pi_n}$
21: $\quad\quad T_{\pi_{n^*}} = T_{\pi_{n^*}} - T_s$.
22: $\quad\quad$ **if** $T_{\pi_{n^*}} = 0$ **then**
23: $\quad\quad\quad$ Set $P_{\pi_{n^*}} = 0$ and delete node π_{n^*} from the path π
24: $\quad\quad$ **end if**
25: $\quad\quad$ Calculate node powers as in Line 5.
26: $\quad$ **end while**
27: **end if**

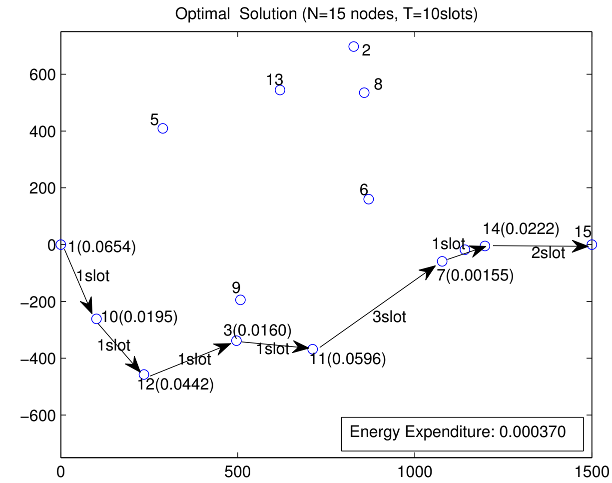

Fig. 3. A sample topology and the result of optimal routing and resource allocation.

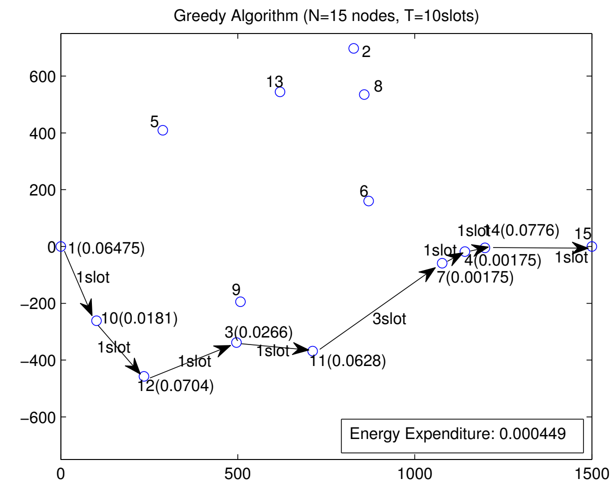

Fig. 4. Result of the greedy algorithm and resource allocation for the same topology

quite similar to the optimal route. The greedy algorithm seems to waste a time slot for a very short hop , resulting in an energy expenditure of 0.000449 . The optimal solution uses that slot for the link (14,15) , which results in 18% decrease in energy expenditure.

In the second set of simulations, we considered a 10-node network and 10 time slots. Table I shows the energy expenditures for the Greedy and Optimal solutions, for 8 different topologies. The results show that in most of the cases, Greedy algorithm performs very close to the optimal. Considering the simplicity of the greedy algorithm, this is an important result.

VII. Conclusions

In this paper we considered the problem of minimum-energy routing in the presence of ideal rateless codes and mutual information accumulation. The problem is quite complex, as it involves routing path determination, and joint power/time optimization. We indicated that for a given routing path the underlying optimization problem has a biconvex nature. Although coordinate-descent algorithms can be used in such cases, the result may not always be globally optimum. In order to find an optimal solution, we made a slotted time assumption and jointly considered the route and transmission time determination. With this formulaton, power optimization becomes a convex problem, which can be solved using interior point methods for a given route and transmission times. As for the routing path and transmission times, we used Branch-and-Bound technique as the solution method. Time slotted structure also led us to a much simpler greedy algorithm, which is based on Bellman-Ford algorithm and subsequent iterative improvements. This algorithm is also amenable to

TABLE I
ENERGY EXPENDITURES FOR THE OPTIMAL AND GREEDY SOLUTIONS, FOR 8 TRIALS. NETWORK OF 10 NODES AND 10 TIME SLOTS.

Trial	Greedy	Branch and Bound
1	0.00115213	0.00105177
2	0.00062995	0.00056099
3	0.00044979	0.00043553
4	0.00095683	0.00094714
5	0.00101207	0.00099972
6	0.00064664	0.00063047
7	0.00039214	0.00038377
8	0.00068374	0.00066423

distributed implementation. Simulation studies show that the greedy algorithm perform quite close to the optimal solution. Especially for small number of users, the performance are almost the same.

Branch-and-Bound based solution takes too much time even for moderate number of users and time slots. Determining the complexity of the problem and searching for ways to improve the run time of Branch-and-Bound is a subject of future research. Upper and lower bounds can be made tighter in order to effectively eliminate suboptimal branches. Better upper and lower bounds , on the other hand, require more computation time. Simulations should be carried out for more users, more time slots and more cases. Another subject for future work is finding better greedy algorithms.

The fact that a node uses last two transmitters , can lead to frequency reuse , where nodes are grouped into groups of three nodes, where each group transmits simultaneously. Although we mentioned this in the paper, we leave this topic as a future research. Finally, channel reuse is expected to significantly improve the performance.

Finally, instead of ideal rateless codes, more realistic scenarios (LT or Raptor codes) can be considered. In that cases , number of transmitted packets would take place of the transmission durations. Moreover, packet reception probability (power-dependent) and packet accumulation would take place of Shannon capacity and mutual information accumulation. The cases where the channel state information is unavailable or incomplete, also needs investigation.

VIII. ACKNOWLEDGEMENT

This research is supported by Turkish Scientific and Technical Research Council (TÜBİTAK) Career Award 110E256.

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