Simple, Practical, and Effective Opportunistic Routing for Short-Haul Multi-Hop Wireless Networks

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***Abstract*—In this paper, we propose a simple and practical opportunistic routing algorithm, and we analyze its performance along a multi-hop wireless network path, while considering link-level interference among the network nodes. Through our analysis, we show that our algorithm results in significant improvement in throughput, especially for short-haul paths. The proposed algorithm can be easily integrated into most routing protocols with only minor modifications. Consequently, the algorithm provides a practical and effective approach for implementation of opportunistic routing in wireless networks.**

***Index Terms*—Opportunistic routing, throughput, capacity, link-level interference, hidden-terminal problem, multi-hop wireless network.**

I. INTRODUCTION

MUCH research has been published on multi-hop wireless networks due to their infrastructure-less, low-cost, and ease-of-deployment features. To improve the efficiency of hop-by-hop routing in a wireless network, the *Opportunistic Routing* scheme, which relies on the inherent broadcast nature of wireless transmissions, has been proposed and studied [1, 2].

In opportunistic routing, the receiver of a transmission is dynamically chosen from among all the nodes that are able to correctly receive the transmitted packet. Typically, this node will be one that is closest to the destination node. Thus, as opposed to regular multi-hop routing (which we term here the *Traditional Routing*), in opportunistic routing, a packet can advance larger distance towards the destination with each transmission.

Even though opportunistic routing has been discussed in numerous research papers, analytical studies of the performance of the opportunistic routing scheme have been rather scarce. Furthermore, such analytical studies of the opportunistic routing have primarily focused on the upper bound of packet propagation speed through the network and on the maximum achievable throughput of a single transmission. For example, Zeng *et al*. studied the upper bound of the expected one-hop throughput in [3], and Jacquet *et al*. [4] provided upper bound on the packet propagation speed in opportunistic routing. Li *et al*. [5] suggested a local scheduling scheme based on graph partition, instead of global scheduling; this scheme significantly reduces the end-to-end transmission latency and computational cost. Cacciapuoti, Caleffi, and Paura [6] derived a closed form expression for the average number of transmissions for a successful delivery of a packet with the knowledge of the delivery ratios between nodes and the nodes' priorities. Zeng, Lou and Zhai [7] formulated the problem of maximum end-to-end throughput of opportunistic routing as a maximum-flow linear programming problem using conflict graphs which express the relation of interfering links. However, most of the published analytical performance of opportunistic routing did not explicitly consider the link-level[1] interference among the nodes along a network path of a particular traffic flow. The importance of this observation is in the fact that this link-level interference among such nodes is <u>highly correlated</u> and, thus, could exhibits quite harmful effect on the performance of opportunistic routing [8].

As opposed to the traditional routing, there should be non-negligible improvement in throughput with opportunistic routing employed along a short-haul multi-hop network path, since the link-level interference from transmissions of the same traffic flow is limited in such a scenario. However, along a long-haul multi-hop network path, even though there might exist more opportunities for faster packet advancement towards the destination, throughput improvement (if any) is severely limited. This is due to the increased link-level interference among the nodes serving the same traffic flow. For example, in Fig. 1, the opportunistic delivery from node *0* to node *4* can be prevented by possible transmissions of nodes *3*, *5* or *6*.

Therefore in this paper, we focus on the use of opportunistic routing for a short-haul path in a multi-hop wireless network. For such a scenario, we propose a modified, but simple and practical, opportunistic routing algorithm, and we analyze its maximum achievable throughput (i.e., capacity) considering the effect of link-level interference. In this scenario, all the nodes belong to the same short-haul path in a wireless multi-hop network, along which a particular flow of packets is routed.

The network model that we assume for our analysis consists of a linear, one-dimensional network path. Although this model is somewhat limited as compared with a two- or even three-dimensional network, nevertheless, because of

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[1] We refer to "link-level interference" as the effect of one node's transmission preventing another node from transmitting.

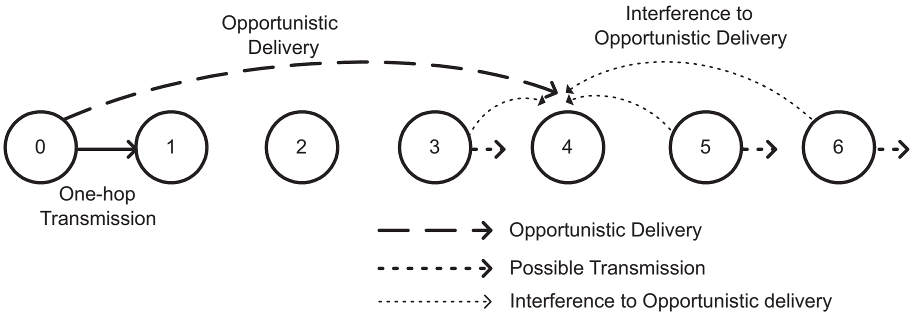

Fig. 1. Link-level interference from a traffic flow with opportunistic transmission.

its simplicity, this model allows us to gain comprehensive understanding of the effect of link-level interference on the network capacity. The followings are assumptions that we use in our analysis:

- Each node is equipped with a single transmitter/receiver and can, at any time, either transmit or receive, but not both.
- Transmissions are packetized and channel access is based on the *RTS/CTS/ACK* dialogue in the MAC-layer.
- For the simplicity of analysis, the ACK control packets are assumed to be correctly received by the sender.[2]
- The data rate used for sending data packets on the wireless channels between any two adjacent nodes is *C* [bps] and the probability of a packet being correctly received across one such hop is *p*.
- The system is in steady-state.
- In general, physical-level interference strongly depends on the actual topology of the network, the relative locations of the transmitters and the receiver node, and the radio propagation conditions. In our model, we capture the effect of the physical-level interference by assigning the probabilities, $p_{i,j}$, of a packet being correctly received at node j, while transmitted by node i. Although we consider the calculation of these probabilities to be outside the scope of this paper, we comment that these probabilities could be obtained either through radio propagation modeling tools, or by direct measurements.

II. SIMPLE AND PRACTICAL OPPORTUNISTIC ROUTING FOR SHORT HAUL MULTI-HOP PATHS

A. The maximum throughput of the traditional routing

Since the average number of transmissions required for one successful packet transmission between two adjacent nodes is $1/p$, the maximum throughput between two neighbors is $p \cdot C$. For a two-hop path, the maximum throughput is $p \cdot C/2$, because the source and the next node on the path cannot transmit at the same time. If the source and the destination are three or more hops apart, the maximum throughput degrades to $p \cdot C/3$. This is a result of the fact that, in this case, only one node among any three consecutive nodes on the path can transmit packets at any time. Referring to Fig. 2, if node *2* transmits to node *3*, then node *1* should not transmit, since node *2* cannot receive its transmission, and (to avoid the *hidden-terminal problem* [9]) node *0* should not transmit, since its transmission could collide with the transmission of node *2*. Note that in opportunistic routing the hidden-terminal problem plays a more significant role than in traditional routing.

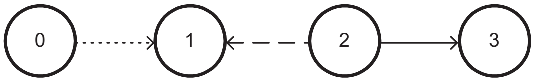

Fig. 2. An example of link-level interference, where transmission of node *2* prevents nodes *0* and *1* from transmitting.

B. The proposed algorithm

In this section, we propose a simple, practical, and effective modified opportunistic routing algorithm for short-haul multi-hop paths. As shown in Fig. 3(b), we assume that node *0* is the destination and node N is the source node. Using traditional routing, a packet would be forwarded along the path composed of the following sequenced nodes: *N-1, N-2, ... , 3, 2, 1, 0*. In the proposed algorithm, only the destination (node *0*) can opportunistically receive the packet by one of the transmissions of the nodes on the traditional routing path. If, at any time, the destination receives the packet opportunistically by overhearing the transmission of any prior node on the path[3], it sends a *destination ACK* to the other nodes on the path. When node *i* ($1 \leq i \leq N-1$) receives the destination ACK, it discards the packet that it received from node *i+1*. A node retransmits a packet only if it did not receive an ACK neither from the next node nor from the destination. A node that received a packet from the previous node, but did not hear an ACK from the destination, will send an ACK to the previous node (allowing the previous node to discard the packet) and will transmit the packet to the next node on the path. Each time that a node transmits the packet, the destination has an opportunity to receive the packet and, by sending the destination ACK, to stop further transmission of the packet by the other nodes on the path. Any duplicate packets received at the destination are discarded.

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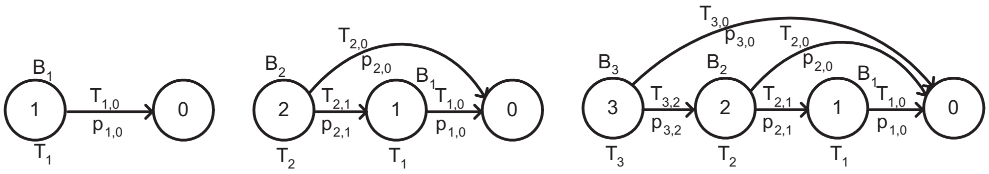
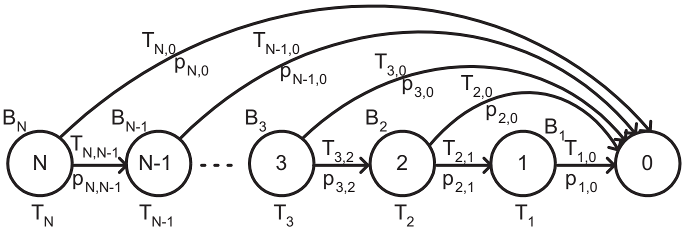
[2] This is a very reasonable assumption due to the small size of the ACK packets and the fact that the control packets should be transmitted at the lowest signaling rate. Thus, ACK control packets are unlikely to be lost.

[3] The ACK is also sent by the destination, if the packet is received through non-opportunistic reception from node 1.



(a) One-, two-, and three-hop paths



(b) N-hop path

Fig. 3. Reception model of the proposed opportunistic routing algorithm.

C. Maximum throughput analysis of the proposed algorithm

As per Fig. 3, we define T_i to be the throughput, excluding retransmission (often referred to as "goodput"), at node i and $T_{i,max}$ to be the maximum throughput, excluding retransmission (i.e., "maximum goodput"), at node i. We define $T_{i,j}$ to be the net throughput, excluding retransmission, from node i to node j. We also define B_i to be the throughput, including retransmissions, from node i and $p_{i,j}$ to be the probability of successful delivery of a packet transmitted by node i and received by node j, when there is no dominant physical-level interference from other nodes. We assume that the signal from node j at node *0* is significantly stronger than the signal from any node i at node *0*, for $i > j$. This means that, according to our model, when both nodes i and j ($i > j$) transmit to node *0* at the same time, the transmission from node j is received at node *0* with $p_{j,0}$, while the transmission from node i is lost. The idle probability of node i, F_i, is given by $F_i = (C - B_i)/C$.

The One-Hop Path Case

For one-hop path (the left scenario in Fig. 3(a)), $T_1 = T_{1,0}$ and $B_1 = T_1/p_{1,0}$. Since $0 \leq B_1 \leq C$, T_1 achieves its maximum value of $T_{1,max} = p_{1,0}C$ when $B_1 = C$.

The Two-Hop Path Case

Let us consider the two-hop path case (the middle scenario in Fig. 3(a)). When the source node (node *2*) transmits a packet, node *0* receives it correctly with probability $p_{2,0}$. The probability that node *0* does not receive the packet and node *1* receives it correctly is $(1 - p_{2,0})p_{2,1}$, in which case node *1* forwards the packet to node *0*. Note that when node *2* transmits a packet, node *1* should remain idle. Since the probability that a packet from node *2* is successfully forwarded is $p_{2,0} + (1 - p_{2,0})p_{2,1}$, then we have $B_2 = \frac{T_2}{p_{2,0}+(1-p_{2,0})p_{2,1}}$.

The ratio of probabilities $p_{2,0}$ to $(1 - p_{2,0})p_{2,1}$ equals the ratio between the following two throughputs: the throughput from node *2* to node *0* and the throughput from node *2* to node *1*. Therefore,

$$T_{2,0} = \frac{p_{2,0}}{p_{2,0} + (1 - p_{2,0})p_{2,1}} T_2 \quad \text{and}$$
$$T_{2,1} = \frac{(1 - p_{2,0})p_{2,1}}{p_{2,0} + (1 - p_{2,0})p_{2,1}} T_2. \tag{1}$$

Since node *1* forwards to node *0* all the packets received from node *2*, therefore $T_{2,1} = T_1$. Thus B_2 can be expressed in terms of T_1 as $B_2 = \frac{T_1}{(1-p_{2,0})p_{2,1}}$. Furthermore, since $0 \leq B_1 + B_2 \leq C$, T_2 achieves its maximum value of $T_{2,max} = p_{1,0} \cdot \frac{p_{2,0}+(1-p_{2,0})p_{2,1}}{p_{1,0}+(1-p_{2,0})p_{2,1}} \cdot C$ when $B_1 + B_2 = C$.

The Three-Hop Path Case

Let us consider the three-hop path case (the right scenario in Fig. 3(a)). When the source node (node *3*) transmits a packet, node *0* receives it correctly with probability $p_{3,0}$. The probability that node *0* does not receive the packet and node *2* receives it correctly is $(1 - p_{3,0})p_{3,2}$, in which case node *2* forwards the packet. Note that when node *3* transmits, node *2* and node *1* should remain idle to allow node *2* to receive the transmission. Since the probability of successful forwarding of a packet from node *3* is $p_{3,0} + (1 - p_{3,0})p_{3,2}$, therefore, we have $B_3 = \frac{T_3}{p_{3,0}+(1-p_{3,0})p_{3,2}}$.

The ratio of probabilities $p_{3,0}$ to $(1 - p_{3,0})p_{3,2}$ equals the ratio between the following two throughputs: the throughput from node *3* to node *0* and the throughput from node *3* to node *2*. Therefore,

$$T_{3,0} = \frac{p_{3,0}}{p_{3,0} + (1 - p_{3,0})p_{3,2}} T_3 \quad \text{and}$$
$$T_{3,2} = \frac{(1 - p_{3,0})p_{3,2}}{p_{3,0} + (1 - p_{3,0})p_{3,2}} T_3. \tag{2}$$

Since node *2* forwards all the packets received from node *3*, therefore $T_{3,2} = T_2$. Thus B_3 can be expressed in terms of T_1 as $B_3 = \frac{p_{2,0}+(1-p_{2,0})p_{2,1}}{(1-p_{3,0})(1-p_{2,0})p_{3,2}p_{2,1}} T_1$. Furthermore, since $0 \leq B_1 + B_2 + B_3 \leq C$, T_3 achieves its maximum value as $T_{3,max}$ when $B_1 + B_2 + B_3 = C$.

The Case of a Path Over Three-Hops Long

We consider now the case when $N \geq 4$, as in Fig. 3(b). First, we assume that $Q_n = F_{n-3}F_{n-4}...F_1$ to approximately denote the probability that nodes *1* through *n-3* are all idle when node *n* transmits a packet. When node *n* ($n > 3$) transmits a packet, node *0* receives the packet correctly with probability $p_{n,0} \cdot Q_n$. The probability that node *0* does not receive the packet and node *n-1* receives it correctly is $(1 - p_{n,0}Q_n)p_{n,n-1}$, in which case node *n-1* forwards the packet to node *n-2*. Note that when node *n* transmits a packet, nodes *n-1* and *n-2* should remain idle to allow node *n-1* to receive the packet. Since the probability of a successful forwarding of a packet from node *n* is $p_{n,0}Q_n + (1 - p_{n,0}Q_n)p_{n,n-1}$, therefore, we have $B_n = \frac{T_n}{p_{n,0}Q_n+(1-p_{n,0}Q_n)p_{n,n-1}}$.

The ratio of probabilities $p_{n,0}Q_n$ to $(1 - p_{n,0}Q_n)p_{n,n-1}$ equals the ratio between the following two throughputs: the throughput from node *n* to node *0* and the throughput from node *n* to node *n-1*. Therefore,

$$T_{n,0} = \frac{p_{n,0}Q_n}{p_{n,0}Q_n + (1 - p_{n,0}Q_n)p_{n,n-1}} T_n \quad \text{and}$$

$$T_{n,n-1} = \frac{(1 - p_{n,0}Q_n)p_{n,n-1}}{p_{n,0}Q_n + (1 - p_{n,0}Q_n)p_{n,n-1}} T_n. \qquad (3)$$

Since node *n-1* forwards all the packet received from node *n*, therefore, $T_{n,n-1} = T_{n-1}$. By iterative procedure for $n = 4, 5...$ and by using the above results for one-, two-, and three-hop path cases, we can express B_n in terms of T_1.

For any *n*, such that $3 \leq n \leq N$, the following inequality holds: $0 \leq B_{n-2} + B_{n-1} + B_n \leq C$. Using a simple search algorithm, we can determine the value of T_1 that maximizes $B_{n-2} + B_{n-1} + B_n$. Then, the value of T_N that corresponds to this value of T_1, is the maximum throughput of node *N*; i.e., $T_{N,max}$. Using the above analysis, we compare in Table I the maximum throughputs of the traditional routing and the opportunistic routing schemes and show the ratio of the two throughputs. For this example, we set *C* to 1 and assumed for simplicity[4] that $p_{n,n-1} = p$ and $p_{n,0} = p/2^{n-1}$ ($n > 0$).

D. Simulation and discussion

From the "$\frac{PROP}{TRAD}$" sub-column of the "***Analytical Results***" column in Table I, we observe that the proposed opportunistic routing algorithm achieves some degree of throughput improvement for short-haul paths in multi-hop wireless network, as compared with the traditional routing scheme. For $N = 3$, the improvement is maximized, since there is no link-level interference from other nodes within the same path. We also see that the improvement becomes more significant with the decrease in the probability of a packet reception. As N increases, the maximum throughput of the proposed opportunistic routing algorithm converges to the throughput of the traditional routing.

To validate our analytical model, we performed a simulation study. The followings are the assumptions that we used in our simulation:

- Slotted operation: all that nodes that have a packet to transmit, contend for the channel access by transmitting their packets at the beginning of a slot.
- Only the source node generates packets and sends the packets to the destination through the intermediate nodes.
- The source node always has packets to transmit.
- Throughput is calculated by $\frac{\text{Total number of packets from the source node delivered to the destination node}}{\text{Total number of slots}}$.

We developed two simulation models, one is "pre-arranged node selection model" which is to get the maximum throughput and the other is "random node selection model" which reflects the actual channel access operation.

The Pre-Arranged Node Selection Model

To achieve the maximum throughput and to allow for some randomness in selecting the transmitting nodes, the channel access by nodes is made as follows:

1) During each time-slot, a node with the most packets to transmit from among the first three nodes (including the source) - lets call them nodes k, $k+1$, and $k+2$ - is selected to transmit. The other two nodes (from among the three) are disabled from accessing the channel. Also, the two nodes that follow the selected node are disabled from channel access, as well. For example, if node $k+1$ is selected to transmit, then nodes k and $k+2$, as well as $k+3$ are disabled.
2) From among the next three nodes, following the last node that was disabled from transmission in step 1), step 1) is repeated. In our above example, these will be nodes $k+4$, $k+5$, and $k+6$.
3) The source node is set to always have a fixed number of packets to transmit (as an example, we set to 10 in our simulation).

The results of the above simulation model are listed in the "***Simulation Results (Pre-Arranged Node Selection)***" column in Table I. From the results, we see that the maximum throughput results of the simulation agree well with the analytical results (the "***Analytical Results***" column) in the table, providing validation of our analysis.

The Random Node Selection Model

At the beginning of each time-slot, transmitting nodes are selected randomly from among nodes that have packets to transmit on the path from the source to the destination. The selection is done in a way as not to violate the interference conditions; i.e., that only one node from among any three consecutive nodes can be selected for transmission. The simulation results are listed in the "***Simulation Results (Random Node Selection)***" column in Table I. From the table, we see that in the random node selection model, the proposed opportunistic routing algorithm still achieves some degree of throughput improvement, as compared with the traditional routing scheme for short-haul paths. The maximal improvement occurs when $N = 3$, since then there is no link-level interference from other nodes within the same path.

From the simulation results in the random node selection case, we see that when $p = 1$, the throughput approaches 0.25 as N increases for both, the traditional and the proposed

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[4] This model was chosen for exemplary use only, and one can assume other models for degradation of loss probability with distance.

TABLE I

MAXIMUM THROUGHPUT OF THE TRADITIONAL ROUTING AND THE PROPOSED OPPORTUNISTIC ROUTING SCHEMES

		Analytical Results			**Simulation Results (Pre-Arranged Node Selection)**			**Simulation Results (Random Node Selection)**		
	N	*TRAD*	*PROP*	$\frac{PROP}{TRAD}$	*TRAD*	*PROP*	$\frac{PROP}{TRAD}$	*TRAD*	*PROP*	$\frac{PROP}{TRAD}$
p=1	1	1	1	1	1	1	1	1	1	1
	2	0.5	0.6667	1.3333	0.5	0.6667	1.3333	0.5	0.6667	1.3334
	3	0.3333	0.4706	1.4118	0.3333	0.4705	1.4116	0.3333	0.4706	1.4117
	4	0.3333	0.3907	1.172	0.3333	0.3837	1.1511	0.3	0.3806	1.2687
	5	0.3333	0.3561	1.0682	0.3333	0.3474	1.0421	0.2748	0.3308	1.2038
	6	0.3333	0.3418	1.0255	0.3333	0.3363	1.009	0.262	0.2983	1.1388
	7	0.3333	0.3363	1.009	0.3333	0.3338	1.0013	0.2543	0.2772	1.0897
	8	0.3333	0.3344	1.0031	0.3333	0.3334	1.0001	0.2503	0.2641	1.055
p=0.9	1	0.9	0.9	1	0.8999	0.8999	1	0.9	0.9002	1.0002
	2	0.45	0.6097	1.3548	0.45	0.6098	1.3553	0.45	0.6096	1.3547
	3	0.3	0.4303	1.4342	0.3	0.4302	1.434	0.3	0.4304	1.4347
	4	0.3	0.3593	1.1976	0.3	0.3523	1.1742	0.27	0.3492	1.2935
	5	0.3	0.3243	1.0809	0.2999	0.3162	1.0541	0.2474	0.302	1.2211
	6	0.3	0.3094	1.0312	0.2999	0.3038	1.013	0.2357	0.2716	1.152
	7	0.3	0.3034	1.0113	0.2998	0.3006	1.0025	0.2288	0.2515	1.0992
	8	0.3	0.3012	1.0039	0.2998	0.3	1.0008	0.2252	0.239	1.0611
p=0.8	1	0.8	0.8	1	0.8001	0.7999	0.9997	0.8	0.7999	1
	2	0.4	0.55	1.375	0.3999	0.55	1.3751	0.4	0.55	1.3748
	3	0.2667	0.3882	1.4559	0.2667	0.3883	1.456	0.2667	0.3883	1.4561
	4	0.2667	0.3261	1.2228	0.2666	0.3192	1.1972	0.24	0.3162	1.3178
	5	0.2667	0.2916	1.0933	0.2666	0.2841	1.0655	0.2199	0.2722	1.2382
	6	0.2667	0.2765	1.0368	0.2666	0.2711	1.0171	0.2095	0.2441	1.1655
	7	0.2667	0.2703	1.0136	0.2665	0.2674	1.0035	0.2033	0.2253	1.1084
	8	0.2667	0.2679	1.0048	0.2664	0.2668	1.0014	0.2	0.2135	1.0674
p=0.7	1	0.7	0.7	1	0.7001	0.7002	1.0001	0.7003	0.7001	0.9997
	2	0.35	0.4879	1.3939	0.35	0.4878	1.3936	0.35	0.4879	1.3941
	3	0.2333	0.3446	1.4769	0.2333	0.3446	1.4769	0.2334	0.3446	1.4766
	4	0.2333	0.2911	1.2475	0.2333	0.2844	1.2187	0.21	0.2818	1.3417
	5	0.2333	0.258	1.1056	0.2333	0.2512	1.0768	0.1924	0.2414	1.2549
	6	0.2333	0.2432	1.0423	0.2332	0.2382	1.0213	0.1833	0.2159	1.1777
	7	0.2333	0.237	1.0159	0.2332	0.2342	1.0046	0.1778	0.1986	1.1172
	8	0.2333	0.2346	1.0056	0.233	0.2334	1.0017	0.1749	0.1877	1.0729
p=0.6	1	0.6	0.6	1	0.6001	0.6001	1.0001	0.5999	0.5998	0.9999
	2	0.3	0.4235	1.4118	0.3	0.4235	1.4117	0.3	0.4235	1.4114
	3	0.2	0.2994	1.4972	0.2	0.2994	1.4967	0.2	0.2995	1.4974
	4	0.2	0.2544	1.2718	0.2	0.2482	1.2407	0.18	0.2457	1.3648
	5	0.2	0.2235	1.1177	0.1999	0.2175	1.088	0.1649	0.2096	1.2709
	6	0.2	0.2096	1.0478	0.1999	0.205	1.0257	0.1571	0.187	1.1901
	7	0.2	0.2036	1.0182	0.1998	0.201	1.0062	0.1524	0.1715	1.1255
	8	0.2	0.2013	1.0065	0.1998	0.2001	1.0017	0.1498	0.1617	1.0791

TRAD. : TRADITIONAL ROUTING; *PROP.*: PROPOSED OPPORTUNISTIC ROUTING

schemes. We recall from Section II.A that the maximum throughput for the traditional routing is $p \cdot C/3 = 1/3$. The difference stems from the fact that in the random node selection case, the average hop distance between two adjacent transmitting nodes is 4, rather than 3, as is the case in the pre-arranged node selection. This can be demonstrated as follows. Suppose that node k is selected as one of the transmitting nodes. Then the next transmitting node can be either (k+3), (k+4), or (k+5). Thus, the average hop distance between two transmitting nodes is given by: 1/3·(3hops+ 4hops +5hops) = 4hops. Consequently, with 4 hops as the average hop distance between two adjacent transmitting nodes, the maximum throughput when p=1 is 0.25, which is consistent with our simulation results in the table. We add that the random node selection case is probably closer to real life scenario than the pre-arranged node selection case.

Although, in general, the proposed algorithm uses only some of the available opportunistic forwarding scenarios, *it utilizes almost all of such scenarios in short-haul multi-hop paths*. Furthermore, the proposed scheme essentially eliminates all duplicate packets, which are present in other opportunistic routing schemes. Finally, the proposed opportunistic routing algorithm is simple and can be easily integrated within the traditional multi-hop routing wireless network protocols with minor modifications only.

III. CONCLUSION

In this paper, we first observed that for long-haul paths, the increase in throughput from opportunistic routing is rather marginal and does not justify the increased complexity of implementation required to implement opportunistic routing. As an alternative to the schemes proposed in the technical literature, we proposed a simple and practical modified opportunistic routing algorithm, one that is especially well suited to short-haul paths. We analyzed numerically the performance of our algorithm, demonstrating the achievable increase in throughput. We also performed a simulation study to validate our numerical analysis. The algorithm essentially eliminates all duplicate packets, which are common occurrences in other opportunistic routing protocols, while exploiting most of the opportunities to increase throughput. The practicality of the proposed algorithm stems to the fact that it can be easily integrated into the existing routing protocols, requiring only minimal changes.

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