A Multi-Hop Routing Scheme for Wireless Ad-Hoc Network

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Abstract: In this paper, a distributed adaptive opportunistic routing scheme for multi-hop wireless ad-hoc networks is proposed. The proposed scheme utilizes a reinforcement learning framework to opportunistically route the packets even in the absence of reliable knowledge about channel statistics and network model. This type of scheme is shown to be optimal with respect to an expected average per packet reward criterion. Then the proposed routing scheme is jointly addresses the issues of learning and routing in an opportunistic context where should be the network structure is characterized by the transmission success probabilities. In the particular, this learning of framework leads to a stochastic routing scheme which optimally “explores” and “exploits” the opportunities in the network.

Keywords: Opportunistic Routing and Reward Maximization, Wireless Ad-Hoc Networks.

I. INTRODUCTION

Opportunistic routing for multi-hop wireless ad-hoc networks has seen recent research interest to overcome deficiencies of conventional routing [1]–[6] as applied in the wireless setting. It is motivated by the classical routing solutions in the Internet, conventional routing attempts to find a fixed path along which the packets are forwarded [7]. Such fixed path schemes fail to take advantages of broadcast nature and opportunities provided by the wireless medium and result in unnecessary packet re-transmissions. The opportunistic routing decisions are made in an online manner by choosing the next relay based on the actual transmission outcomes as well as a rank ordering of neighboring nodes. These are opportunistic routing mitigates the impact of poor wireless links by exploiting the broadcast nature of wireless transmissions and the path diversity.

The authors in [1] and [6] provided a Markov decision theoretic formulation for opportunistic routing. In particular, it is shown that the optimal routing decision at any epoch is to select the next node based on the index summarizing the expected-cost-to-forward from that node to the destination. This index is shown to be computable in a distributed manner and with low complexity using the probabilistic description of wireless links. The study in [1], [6] provided a unifying framework for almost all versions of opportunistic routing such as SDF [2], Geographic Routing and Forwarding [3], and EXOR [4]. The variations in [2]–[4] are due to the authors’ choices of cost measures to optimize. For it can instance of optimal route in the context of EXOR [4] is computed so as to minimize the expected number of transmissions (ETX). Uses the smallest Geographical distance from the destination as a criterion for selecting the next-hop.

The opportunistic algorithms proposed in depend on a precise probabilistic model of wireless connections and local topology of the network. In practical setting, however, these probabilistic models have to be “learned” and “maintained”. In other words, a comprehensive study and evaluation of any opportunistic routing scheme requires an integrated approach to the issue of probability estimation. Authors in [8] provide a sensitivity analysis in which the performances of opportunistic routing algorithms are shown to be robust to small estimation errors. However, by and large, the question of learning/estimating channel statistics in conjunction with routing remains unexplored.

In this paper, we investigate the problem opportunistically routing packets in a wireless multi-hop network when zero or erroneous knowledge of transmission success probabilities and network topology is available. Then Using a reinforcement learning framework, we can propose an adaptive opportunistic routing algorithm which can minimizes the expected average cost for routing a packet from a source node to a destination. Our proposed reinforcement of learning framework allows for a low complexity, distributed asynchronous of implementation. The most significant of characteristics of the proposed solution are:

- It is oblivious to the initial knowledge of the network.

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It is distributed to each node will makes decisions based on its belief using the information obtained from its neighbors.

It is asynchronous at any time in subset of nodes can update their corresponding beliefs.

The idea of reinforcement learning has been previously investigated for conventional routing in Ad-hoc networks a ticket-based probing scheme is proposed for path discovery in MANETs to reduce probe message overhead. This heuristic can be viewed as a very special case of our work where the probabilistic wireless link model is replaced with a deterministic link model. In [10], the authors' attempts to find an optimal path dynamically in response to variations in congestion levels in various parts of the network. As discussed in the conclusion, the issue of congestion control remains open and entails further research.

We end this section with a note on the notations used. On the probability space \((\Omega, \mathcal{F}, P)\) let \(I: \Omega \rightarrow \{0,1\}\) denote the indicator random variable (with respect to \(F\)), such that for all \(\omega \in \Omega\) and \(\mathcal{F}\) element of the vector. Let \(x \in \mathbb{R}^d, d \geq 1\), denote the weighted max-norm with positive weight vector \(v\), i.e. \(\|x\|_v = \max_i \frac{|x_i|}{v_i}\). Let \(1 \in \mathbb{R}^d\) denote the vector with all components equal to 1. We also use the notation \(X^n\) to represent the first \(n\) random elements of the random sequence \(\{X_k\}_{k=1}^\infty\).

II. SYSTEM MODEL

We consider the problem of routing packets from a source node \(o\) to a destination node \(d\) in a wireless ad-hoc network of \(d + 1\) nodes denoted by the set \(\Theta = \{o, 1, 2, \ldots, d\}\). The time is slotted and indexed by \(n \geq 0\) (this assumption is not technically critical and is only assumed for ease of exposition). A packet indexed by \(m \geq 1\) is generated at the source node \(o\) at time \(m\) s according to an arbitrary distribution with rate \(\lambda > 0\). We assume a fixed transmission cost \(c_t > 0\) is incurred upon a transmission from node \(i\). Transmission cost \(c_t\) can be considered to model the amount of energy used for transmission, then the expected time to transmit a given packet and count when the cost is equal to unity. Given a successful transmission from node \(i\) to the set of neighbor nodes \(S\), the next (possibly randomized) routing decision includes 1) retransmission by node \(i\), 2) relaying the packet by a node \(j \in S\), or 3) dropping the packet all together. If a node \(j\) is selected, then it transmits to the packet at the next slot, while other nodes \(k \neq j, k \notin S\) expunge that packet.

We define the termination event for packet \(m\) to be the event that packet \(m\) is either received by the destination or is dropped by a relay before reaching the destination. We define termination time \(\tau_{\epsilon m}\) to be a random variable when packet \(m\)
is terminated. We can discriminate amongst the termination events as follows: We assume that upon the termination of a packet at the destination (successful delivery of a packet to the destination) a fixed and given positive reward \(R\) is obtained, while the reward is not obtained to the packet is terminated (dropped) before it reaches the destination. Let \(r_m\) denote, this is random reward obtained by the termination time \(\tau_{\epsilon m}\) i.e. it is either zero if the packet is dropped prior to reaching the destination node or \(R\) if the packet is received at the destination.

Let \(i_{n,m}\) denote the index of the node which transmits packet \(m\) at time \(n\). The routing scheme can be viewed as selecting a (random) sequence of nodes \(\{i_{n,m}\}\) for relaying packets \(m = 1, 2, \ldots\) As such, the expected average per packet reward associated with routing packets along a sequence of \(\{i_{n,m}\}\) up to time \(N\) is:

\[
J_N = E \left[ \frac{1}{M_N} \sum_{m=1}^{M_N} \left\{ r_m - \sum_{n=1}^{\tau_{\epsilon m} - 1} c_{i_{n,m}} \right\} \right]
\]

where \(M_N\) denotes a number of packets can terminated up to time \(N\) and the expectation is taken over the events of transmission decisions, successful packet receptions, and packet generation times.

Problems can choose a sequence of nodes \(\{i_{n,m}\}\) in the absence of knowledge about the network topology such that \(J_N\) is maximized as \(N \to \infty\). In the next section we propose d-Adapt OR algorithm which solves Problem (P). The nature of the algorithm allows nodes to make routing decisions in distributed, asynchronous, and adaptive manner. Remark The problem of opportunistic routing for multiple source-destination pairs can be effectively decomposed to the problem above where routing from one node to a specific destination is addressed.

III. DISTRIBUTED ALGORITHM

In this section we present the description of d-Adapt OR scheme. In the rest of the paper, we let \(N\) (i) to denote the set of neighbors of node \(i\) including node \(i\) itself. Let \(S\) denote the set of potential reception outcomes due to a transmission from node \(i\) i.e. \(S = \{S, S \subseteq N(i), i \notin S\}\). We refer to \(S\) as the state space for node \(i\) is transmission. Furthermore, let \(\Theta = \cup_{i \in S} \Theta_i\). Let \(A(S)\) denote the space of all allowable actions available to node \(i\) upon successful reception at nodes in \(S\), i.e. \(A(S) = S \cup \{f\}\) finally, for each node \(i\) we define a reward function on states \(S \in \Theta\) and potential decisions \(a \in A(S)\) as

\[
g(S, a) = \begin{cases} 
-c_a & \text{if } a \in S \\
R & \text{if } a = f \text{ and } d \in S \\
0 & \text{if } a = f \text{ and } d \notin S 
\end{cases}
\]
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A. Overview of d-Adapt OR

As discussed before, the routing decision at any given time is made based on the successful outcomes and involves retransmission, then choosing the next relay, or termination. Our proposed scheme makes such as a decision in distributed manner via the following three-way handshake between nodes i and its neighbors N (i).

1) At time n node i transmit a packet.

2) Set of nodes $S^n_i$ who have successfully received the packet from node i, transmit acknowledgment (ACK) packets to node i. In addition to the node’s identity, the acknowledgment packet of node $k \in S^n_i$ includes a control message known as estimated best score (EBS) and denoted by $\Lambda^k_{\text{max}}$.

3) Node i announces node $j \in S^n_i$ as the next transmitter or announces the termination decision f in a forwarding (FO) packet.

The routing decision of node i at time n is based on an adaptive (stored) score vector $\Lambda_n(i, \cdot , \cdot )$. The score vector $\Lambda_n(i, \cdot , \cdot )$ lies in space $R^v_i$, where $v_i = \sum_{a \in A} |A|$ and is updated by node i using the EBS messages $k \in S^n_i$ max obtained from neighbors k 2 S I n... Furthermore, node i uses a set of counting variables $n(i, S, a)$ and $N(i, S)$ and a sequence of positive scalars $f_n g 1 n=1$ to update the score vector at the time n. The counting variable $n(i, S)$ is equal to the number of times neighbor nodes S have received (and acknowledged) packets transmitted from node i and corresponding routing decision a in forwarding (FO) packet.

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For all nodes $k \in S^n_i$, the ACK packet of node k to node i include the EBS message $\Lambda^k_{\text{max}}$. Upon reception and acknowledgment, the counting random variable $N_n(i, S)$ is incremented as follows:

$N_n(i, S) =\begin{cases} N_{n-1}(i, S)+1 & \text{if } S = S^n_i \\ N_{n-1}(i, S) & \text{if } S \neq S^n_i \end{cases}$

3) Relay Stage: Node i selects a routing action $a_n^i \in A(S^n_i)$ according to the following (randomized) rule parameterized by $\epsilon_n(i, S) = \frac{1}{|A(S^n_i)|}$, with probability $1 - \epsilon_n(i, S^n_i)$, $a_n^i \in \arg \max_{a \in A(S^n_i)} \Lambda_n(i, S, a)$ is selected, 2 with probability $\epsilon_n(i, S^n_i)$, $a_n^i \in A(S^n_i)$ is selected at random.

Node i transmits FO, a control packet which contains information about routing decision a in at some time within the time slot $n^+$ and $(n + 1)^-$. If $a_n^i \neq f$, then node a $a_n^i$ prepares for forwarding in next time slot while nodes $j \in S^n_i$, $j \neq a_n^i$ expunge the packet. If termination action is chosen, i.e. $a_n^i = f$, all nodes in $S^n_i$ expunge the packet. Upon selection of action, then the counting variable is $n^+$ updated.

$\nu_n(i, S, a) =\begin{cases} \nu_{n-1}(i, S, a) & \text{if } (S, a) = (S^n_i, a_n^i) \\ \nu_{n-1}(i, S, a) & \text{if } (S, a) \neq (S^n_i, a_n^i) \end{cases}$

4) Adaptive Computation Stage:

Fig. 1. Flow of the algorithm. The algorithm follows a four-stage procedure: transmissions, updates, additions, and adaptations.
At time \((n+1)\), after being done with transmission and relaying, node \(i\) updates score vector \(\Lambda_n(i,\cdot,\cdot)\) as follows:

\[
\Lambda_{n+1}(i,S,a) = \Lambda_n(i,S,a) + a_{\nu_4(i,S,a)} \\
- \Lambda_n(i,S,a)+g(S,a)+\Lambda_{max}^n
\]

(2)

otherwise,

\[
\Lambda_{n+1}(i,S,a) = \Lambda_n(i,S,a).
\]

(3)

Furthermore, node \(i\) updates its EBS message \(\Lambda_{max}^i\) for future acknowledgments as:

\[
\Lambda_{max}^i = \max_{j \in A(S_n^i)} \Lambda_{n+1}(i,S_n^i,j).
\]

C. Computational issues

The computational of complexity and control overhead of the d-Adapt OR is low.

1) Complexity To the execute stochastic recursion (2), the number of computations required per packet is order of \(O(\text{max}_{i \in [0,1]} |N(i)|)\) at each time slot.

2) Control Overhead of the number of acknowledgments per packet is in order of \(O(\text{max}_{i \in [0,1]} |N(i)|)\) independent of network size.

IV. OPTIMALITY OF D-A DAPTOR

We will now state the main result establishing the optimality of the proposed d-Adapt OR algorithm under an assumption of a time-invariant model of packet reception. More precisely, we have the following assumption.

Assumption1. The probability of successful reception of a packet transmitted by node \(i\) at set \(S \subseteq N(i)\) of nodes is \(P(S|i)\) independent of time and all other concurrent transmissions.

The probabilities \(P(S|i)\) in Assumption 1 thus characterize a packet reception model which we refer to as local broadcast model. Note that for all \(S \neq S'\), successful reception at \(S\) and \(S'\) are mutually exclusive and \(\sum_{i \in N} P(S|i) = 1\). Furthermore, logically node \(i\) is always a recipient of its own transmissions, i.e. \(P(S|i) = 0\) if \(i \notin S\).

The proposed local broadcast model is assumed to truly capture the coupling of the physical layer and the media access control (MAC) layer. In other words, the local broadcast model takes into account signal degradation due to path loss and multipath fading as well as captures the interference produced by other transmitting nodes. Note that, our model together with Assumption 1 imply an underlying MAC whose operation is controlled at a distinct layer and independently of the routing decisions. Furthermore, the implicit existence of a MAC scheme allows for a set of more advanced MAC schemes such as Zig-Zag. Finally, the identically distributed assumption on successful transmissions imposes a time-homogeneity on the operation of the network and significantly restricts the topology changes of the network. In Sections V and VII, we address the severity and implications of the above consequences of Assumption 1. In particular, we will show that d-Adapt OR exhibits many of its desirable properties and performance improvements in practice despite relaxation of the analytical assumptions.

Let \(\mathbb{P}\) be the sample space of the random probability measures for the local broadcast model. Specifically, \(\mathbb{P} = \{\mathbb{P} \mid \mathbb{P} \times \mathbb{R}^d : \mathbb{P}\) is a non-square left stochastic matrix. Moreover, let PP be the trivial \(\sigma\)-field generated by the local broadcast model \(P \in \mathbb{P}\) (sample point in \(P\), i.e. \(\mathbb{P} = \{P,P,P,P\}\). Let \(S_n^i\) be the set of nodes that have received the packet due to transmission from node \(i\) at time \(n\), while a in denotes the corresponding routing decision node \(i\) takes at time \(n\).

A distributed routing policy is a collection \(\phi = \{\phi^i\}_{i \in \Theta}\) of routing decisions taken at nodes \(i \in \Theta\) where denotes a sequence of random actions \(\phi^i = \{a^i_0,a^i_1,\ldots\}\) for node \(i\). The policy \(\phi\) is said to be admissible if for all nodes \(i \in \Theta\), \(S \subseteq \Theta\), a \(A(S)\) the event \(\{a^i_n = a\}\) belongs to the \(\sigma\)-field \(\mathcal{H}_n^i\) generated by the observations at node \(i\), i.e. \(\bigcup_{i \in \Theta} \{S_n^i\} \subseteq \mathcal{H}_n^i \subseteq \mathcal{H}_n\).

Let \(\Phi\) denote the set of such admissible policies. These policies are implementable in a distributed manner under the following assumption.

Assumption2. The successful reception at set \(S\) due to transmission from node \(i\) is acknowledged perfectly to node \(i\). With the above notations and assumptions, the following theorem establishes the optimality of d-Adapt OR, i.e. d-Adapt OR denoted \(\phi^* \in \Phi\) maximizes the expected average per packet reward obtained in (1) as \(N \to \infty\).

Theorem1. Suppose \(\sum_{n=0}^{\infty} a_n = \infty\), \(\sum_{n=0}^{\infty} a_n^2 < \infty\), and assumptions 1 and 2 hold. Then for all \(\phi \in \Phi\),

\[
\lim_{N \to \infty} \mathbb{E}^\phi \left[ \frac{1}{M_N} \sum_{m=1}^{M_N} \left( \sum_{n=1}^{\tau^N_n} c_{mn,\cdot} \right) \right] \\
\geq \lim_{N \to \infty} \sup_{\phi} \mathbb{E}^\phi \left[ \frac{1}{M_N} \sum_{m=1}^{M_N} \left( \sum_{n=1}^{\tau^N_n} c_{mn,\cdot} \right) \right]
\]
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Where $E^*$ and $E^\phi$ are the expectations taken with respect to policies $\pi^*$ and $\phi$ respectively.

Next we prove the optimality of d-Adapt OR in two steps. In the first step, we show that $\Lambda_n$ converges in an almost sure sense. In the second step we use this convergence result to show that d-Adapt OR is optimal for Problem (P).

A. Convergence of $\Lambda_n$

Let $U : \Pi \rightarrow \Pi$ be an operator on vector such that,

\[
U^\alpha(i, \pi, \alpha) = g(i, \pi) + \sum_{j \in A(i)} P(j | i, \pi) \max_{j \in A(i)} \Lambda^\alpha (j, \pi, \alpha)
\]

\hspace{1cm} (4)

Let $\Lambda^\alpha(i, \pi, \alpha)$ denote the fixed point of operator $U$, $U^\alpha$, i.e.

\[
\Lambda^\alpha(i, \pi, \alpha) = g(i, \pi) + \sum_{j \in A(i)} P(j | i, \pi) \max_{j \in A(i)} \Lambda^\alpha (j, \pi, \alpha)
\]

\hspace{1cm} (5)

When the following lemma we can establishes the convergence of recursion (2) to the fixed point of $U, \Lambda^\alpha$.

**Lemma 1.** Let

(I) $\Lambda^{\alpha}(i, \pi, \alpha) = 0, \Lambda^{\alpha}_{\max} = 0$ for all $i \in \Theta$,  

(II) $\sum_{n=0}^{\infty} \alpha_n = \infty, \sum_{n=0}^{\infty} \alpha_n^2 < \infty$.

Then iterate $\Lambda_n$ obtained by the stochastic recursion (2) converges to $\Lambda^\alpha$ almost surely. Then the proof uses known results on the convergence of the certain recursive stochastic process as presented.

B. Proof of optimality

Using this convergence of $\Lambda_n$ we can show that the expected average per packet reward under d-Adapt OR is equal to the optimal expected average per packet reward obtained for a genie-aided system where the local broadcast model is known perfectly. In proving the optimality of d-Adapt OR, we take cue from known results associated with a closely related Auxiliary Problem (AP). In the Auxiliary Problem (AP), there exists a centralized controller with full knowledge of the local broadcast model as well as the transmission outcomes across the network [1], [6]. For Auxiliary Problem (AP), a routing policy is a sequence of routing decisions taken for nodes $i \in \Theta$ at the centralized controller, where $\pi_i^d$ it can be denotes the solution of random actions $\pi_i = \{a_i, a_1, \ldots \}$ for node $i$. The routing policy $\pi$ is said to be admissible for Auxiliary Problem (AP) if the event $\{a_n = a\}$ belongs to the product $\sigma$-field $\mathcal{F}_n = \mathcal{P} \times \Pi, \mathcal{H}_n$.

In this Auxiliary Problem (AP), let denote the set of admissible policies for Auxiliary Problem (AP). The reward associated with policy $\pi \in \Pi$ for routing a single packet $m$ from the source to the destination is then given by

\[
f^\pi([m]) = E^{\pi}[\sum_{i=1}^{m-1} c_{i,i+1}]
\]

\hspace{1cm} (6)

Where $F_0 = P_0$. Now, in this setting, we are ready to formulate the following Auxiliary Problem (AP) as a classical shortest path Markov Decision Problem (MDP).

Auxiliary Problem (AP) Find an optimal policy $\pi^*$ such that,

\[
f^\pi([m]) = f^\pi([0]) = \sup_{\pi \in \Pi} f^\pi([m])
\]

\hspace{1cm} (7)

**Remark 1.** The existence of an admissible policy $\pi^* \in \Pi$ achieving the supremum on the right hand side of (7) is a result of Theorem 7.1.9 in [12].

**Fact 1:** There exists a function $\phi^*: \Theta \cup \{d\} \rightarrow \mathbb{R}^+$ such that $\pi^* = \{a_0, a_1, \ldots \}$ is an optimal policy for Auxiliary Problem (AP), where $a_n = \pi^*(S_n)$. Furthermore, $\pi^*$ is such that

\[
\pi^*(s) \in \arg \max_{j \in A(s)} V^*(f)
\]

\hspace{1cm} (8)

Where (value) function $V^* : \Theta \cup \{f\} \rightarrow \mathbb{R}^+$ is the unique solution are the following fixed point equation:

\[
V^*(d) = R
\]

\hspace{1cm} (9)

\[
V^*(i) = \min \{c_i + \sum_{j, \pi} P(j | i) V^*(j)\}
\]

\hspace{1cm} (10)

\[
V^*(f) = 0
\]

(11)

Moreover, $V^*(j)$ is the maximum expected reward for routing a packet from node $j$ to the destination $d$, i.e. $V^*(j) = \sup_{\pi \in \Pi} f^\pi([j])$.

Lastly,

**Fact 2:** function $V^* : \Theta \cup \{f\} \rightarrow \mathbb{R}^+$ is unique. Lemma 2 below states that the relationship between the solution of Problem (P) and that of the Auxiliary Problem (AP). More specifically, Lemma 2 shows that $V^*(0)$ is an upper bound for the solution to Problem (P).

**Lemma 2.** Consider any admissible policy $\phi \in \Phi$ for Problem (P). Then for all $N = 1,2,\ldots$,

\[
E^{\phi} \left[ \frac{1}{M_N} \sum_{n=1}^{M_N} \left\{ p_{n-1} - \sum_{m=n}^{M_N} c_{n,m-1} \right\} \right] \leq V^*(0)
\]

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Proof: The proof is given in Appendix B. Intuitively the result holds because the set of admissible policies in (P) is a subset of admissible policies in (AP), i.e. $\Phi \subset \Pi$.

Lemma 3 gives the achievability proof for Problem (P) by showing that the expected average per packet reward of d-Adapt OR is no less than $V^*(\alpha)$

**Lemma 3.** For any $\delta > 0$,

$$\lim_{N \to \infty} E^{\Phi_{\delta}} \left[ \frac{1}{M_N} \sum_{m=1}^{M_N} \left\{ E \left[ r_m - \sum_{n=1}^{e_m} c_{n,m} \right] \right\} \right] \geq V^*(\alpha) - \delta.$$ 

Proof: The proof is given in Appendix C. Lemmas 2 and 3 imply that

$$\lim_{N \to \infty} E^{\Phi_{\delta}} \left[ \frac{1}{M_N} \sum_{m=1}^{M_N} \left\{ E \left[ r_m - \sum_{n=1}^{e_m} c_{n,m} \right] \right\} \right]$$

can exist and it is equal to $V^*(\alpha)$ establishing the proof of Theorem 1.

V. PROTOCOL DESIGN AND IMPLEMENTATION ISSUES

In this section we describe an 802.11 compatible implementation for d-Adapt OR.

A. 802.11 compatible implementation

Implementation of d-Adapt OR, analogous to any opportunistic routing scheme involves the selection of a relay node from a candidate set of nodes that have received and acknowledged a packet successfully. One of the major challenges in devising d-Adapt OR algorithm is the design of 802.11 compatible acknowledgment mechanisms at the MAC layer. Below we propose a practical and simple to implement acknowledgment architecture.

For each neighbor node $j \in \mathcal{N}(i)$ the transmitter node $i$ reserve a virtual time slot of duration $\text{TACK} + \text{T SIFS}$, where $\text{TACK}$ is the duration of the acknowledgment packet and $\text{T SIFS}$ is the duration of Short Inter Frame Space (SIFS) [15]. The transmitter $i$ then piggy-backs a priority ordering of nodes $\mathcal{N}(i)$ with each data packet transmitted. The priority ordering determines the virtual time slot in which a candidate node transmits an acknowledgment. Nodes in the set $\mathcal{S}_i$ that have successfully received the packet then transmit acknowledgment packets sequentially in the reserved virtual time slots in the order determined by the transmitter node. For example, in the linear network shown in Fig. 2, if node 0 piggy-backs the order $1,2,g$, then node 1 transmits an ACK first and later node 2 transmits an ACK. If node 1 does not receive the packet successfully from node 0, node 1 does not transmit an ACK and duration of $\text{TACK} + \text{TSIFS}$ corresponding to node 1 is not utilized.

For receiving ACKs, each transmitting node $i$ waits for a duration of $T_{\text{wait}} = |\mathcal{N}(i)| |\text{TACK} + \text{T SIFS}|$. After each node in the set $\mathcal{S}_i$ has acknowledged or $T_{\text{wait}}$ timer has expired, node $i$ transmits a forwarding control packet (FO). If timer $T_{\text{wait}}$ has expired and no ACK has been received, then node $i$ either drops the packet or retransmits. If priority of node $j \in \mathcal{S}_i$ is $l$, $1 \leq l \leq |\mathcal{N}(i)|$, then it waits for a duration of $T_{\text{wait FO}} = |\mathcal{N}(i)| - l + 1 |\text{TACK} + \text{T SIFS}|$ to receive a FO. If $T$ wait FO expires and no FO packet has been received, then the corresponding candidate nodes drop the received data packet. Fig 3 shows a typical sequence of control packets for topology in Fig 2.

![Fig. 2. With probability $p_{ij}$, a packet transmitted by node $i$ is successfully received by node $j$.](image)

![Fig. 3. Typical packet transmission sequence for d-Adapt OR.](image)

In addition to the acknowledgment scheme, d-Adapt OR requires modifications to the 802.11 MAC frame format. Fig. 4 shows the modified MAC frame formats required by d-Adapt OR. The reserved bits in the type/subtype fields of the frame control field of the 802.11 MAC specifications are used to indicate whether the rest of the frame is a d-Adapt OR data frame, a d-Adapt OR ACK, or a FO. This enables the d-Adapt OR to communicate and be fully compatible with other 802.11 devices.
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The data frame contains the candidate are set in the priority order, the payload, and then the 802.11 frame check sequence. The acknowledgment frame includes the data frame senders address and the feedback EBS. The FO packet is exactly the same as a standard 802.11 short control frame, but uses different subtype value.

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<th>Addr 1</th>
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<th>Addr 3</th>
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<tr>
<td>Payload</td>
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\[ d-\text{AdaptOR data packet format} \]

<table>
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<th>Frame Control</th>
<th>Duration ID</th>
<th>Receiver Addr</th>
<th>EBS</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

\[ \text{ACK packet format} \]

<table>
<thead>
<tr>
<th>Frame Control</th>
<th>Duration ID</th>
<th>Receiver Addr</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

\[ \text{FO packet format} \]

Fig. 4. Frame structure of the data packet, acknowledgment packet, and FO packet

B. d-Adapt OR in non-idealized setting

1) Loss of ACK and FO packets: Interference or low SNR can cause loss of ACK and FO packets. Loss of an ACK packet results in an incorrect estimation of nodes that have received the packet and thus affects the performance of the algorithm. Loss of FO packet negatively impacts the throughput performance of the network. In particular, loss of FO packet can result in the drop of data packet at all the potential relays and then reducing the performance throughput.

2) Increased Overhead: d-Adapt OR adds a modest additional overhead to this standard 802.11 due to the added acknowledgment/handshake structure. Assuming a 802.11b physical layer operating at 11 Mbps with a SIFS time of 10 preamble duration of 20, Physical Layer Convergence Protocol (PLCP) header duration of 4 and 512 byte frame payloads, the overhead of an d-Adapt OR data frame with three candidates is compared with unicast 802.11 in Table I. It is clear that the overhead increases linearly with the number of neighbors.

<table>
<thead>
<tr>
<th>Overhead Comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Frame</td>
</tr>
<tr>
<td>802.11 unicast</td>
</tr>
<tr>
<td>d-AdaptOR</td>
</tr>
</tbody>
</table>

Note that the overhead cost can be reduced by restricting the number of nodes in the candidate list of MAC header to a given number, MAX-NEIGHBOUR. The unique ordering for the nodes in the candidate set is determined by prior itizing the nodes with respect to \(\Lambda_n(i, \{i, j\}, j \in N(i))\) and then choosing the MAX-NEIGHBOUR highest priority nodes. 8 Needless to say that such limitation will sacrifice the optimality of d-Adapt OR for a lower overhead.

3) Choice of parameters: To ensure an acceptable through put, the value of reward, R, must be chosen sufficiently high. However, beyond a given threshold (depending on the network topology), the value of R does not affect asymptotic performance of the algorithm. The convergence rate of stochastic recursion (2) strongly depends on choice of sequence \{\alpha_n\}. It converges slowly with slowly decreasing sequence \{\alpha_n\} and results in less variance in the estimates of \(\Lambda_n\). while fast decreasing sequence \{\alpha_n\} causes large variance in the estimates of \(\Lambda_n\).

VI. SIMULATION STUDY

In this section, we provide simulation results in which the performance of d-Adapt OR is compared against suitably chosen candidates: Stochastic Routing (SR) [1] (SR is the distributed implementation of policy discussed in Section IV-B), EXOR [4] and a conventional routing algorithm Ad hoc On-Demand Distance Vector Routing (AODV) [15]. Both SR and EXOR are distributed mechanisms in which the probabilistic structure of the network is used to implement opportunistic routing algorithms. As a result, their performance will be highly dependent on the precision of empirical probability associated with link, \(p_{ij}\). In fact, authors in [8] have identified network topologies and examples in which small errors in empirical probabilities incur significant loss of performance. To provide a fair comparison, hence, we have considered modified versions of SR and EXOR in which the algorithms adapt \(p_{ij}\) to the history of packet reception outcomes, while rely on the updates to make routing decisions (separated scheme of estimation and routing). Our simulations are performed in Qual Net. Simulations consist of a grid topology of 16 nodes as shown in Fig. 5(a) each equipped with 802.11b radios transmitting at 11 Mbps. The wireless medium is modeled as to include Rician fading and Log-normal shadowing with mean 4dB and the path oss follows the two-ray
model in [16] with path exponent of 3. Note that the choice of indoor environment is motivated by the findings in [17] where opportunistic routing is found to provide better diversity of transmission outcomes.

Packets are generated according to a CBR source with rate 10 packets/sec. They are assumed to be of length 512 bytes equipped with simple CRC error detection. The acknowledgment packets are short packets of length 24 bytes transmitted at rate of 11 Mbps, while FO packets are transmitted at reliable lower rate of 1Mbps. When the lower transmission rate for FO packets is used as it increases the reliability of the packets to avoid issues discussed in Section V-B. Cost of transmission is assumed to be one unit, while reward for successfully delivering a packet to the destination is assumed to be 20.

![Fig. 6. Throughput comparisons for d-Adapt OR, SR, EXOR, AODV](image)

Fig. 6. Throughput comparisons for d-Adapt OR, SR, EXOR, AODV

Finally, we investigate the performance result for a random topology in Fig. 7(a), wherein 16 nodes are uniformly distributed over an area of 90m * 90m and all other parameters are kept the same as those in the grid topology of Fig. 5(a). Fig. 7(b), 7(c) plots the average reward and regret respectively for the candidate routing algorithms. The results are in line with conclusions for the grid topology in Fig. 5(a). It should be noted that, optimality of d-Adapt OR holds for all topologies, however it may not outperform other algorithms (SR, EXOR) in certain topologies.

**VII. CONCLUSIONS**

In this paper, we proposed d-Adapt OR, an adaptive routing scheme which maximizes the expected average per packet reward from a source to a destination in the absence of any knowledge regarding network topology and link qualities. D Adapt OR allows for a practical distributed implementation with provably optimal performance under idealized assumptions on stationary of network and reliability of acknowledgment scheme. The performance of d-Adapt OR is also investigated in practical settings via simulations. Simulation results show that d-Adapt OR outperforms the existing opportunistic protocols in which statistical link qualities are empirically built and the routing decisions are greedily adapted to the empirical link models.

The long term average reward criterion investigated in this paper is somewhat limited in discriminating among various adaptive schemes with optimal average reward per packet. This is mostly due to the inherent dependency of the long term average reward on the tail events. To capture the performance of various adaptive schemes e.g. convergence rate, it is desirable to study the regret as defined in (12). An important area of future work comprises of developing fast converging algorithms which optimize the regret as a performance measure of interest. The designs of routing protocols need consideration of congestion control along with the throughput performance [19], [20]. Our work, however does not consider the issue of congestion control. Incorporating congestion control in opportunistic routing algorithms to minimize expected delay in an oblivious network is an area of future research. Last but not least, the broadcast model used in this paper assumes a decoupled operation at the MAC and network layer. While this assumption seems reasonable for many popular MAC schemes based on random access philosophy, it ignores the potentially rich interplays between scheduling and routing which arise in scheduling TDMA-based schemes.

**VIII. REFERENCES**


A Multi-Hop Routing Scheme for Wireless Ad-Hoc Network


