Cross-layer Optimal Decision Policies for Spatial Diversity Forwarding in Wireless Ad Hoc Networks

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Abstract— **In order to adapt to the time-varying nature of wireless channels, various channel-adaptive schemes have been proposed to exploit inherent spatial diversity in wireless ad hoc networks where there are usually alternate forwarding nodes available at a given forwarding node. However, existing schemes along this line are designed based on heuristics, implying room for performance enhancement. Thereby, to seek a theoretical foundation for improving spatial diversity gain, we formulate the selection of the next-hop relay as a sequential decision problem and derive a general "Optimal Stopping Relaying (OSR)" framework for designing such spatial-diversity schemes. As a particular example, assuming Rayleigh fading channels, we implement an OSR strategy to optimize information efficiency (IE) in a protocol stack consisting of Greedy Perimeter Stateless Routing (GPSR) and IEEE 802.11 MAC protocols. We present an analysis of the algorithm for a single node. In addition, we perform extensive simulations (using QualNet) to evaluate the end-to-end performance of the proposed forwarding strategy. The results demonstrate the superiority of OSR over other existing schemes.**

I. INTRODUCTION

The time-varying nature of underlying wireless links has been generally regarded as a negative factor in wireless networking and neglected by higher layer protocols for a long time. In order to combat these adverse channel variation effects, recent works (e.g., [3], [6], [14], [18]) exploit spatial diversity inherent in multihop wireless networks due to the presence of alternate next-hop relays. In such a multiple candidate next-hop relays environment with mutually independent wireless links, it is highly probable that the channel condition at one of the candidate next-hop receivers has a high signal-to-noise ratio (SNR). Notice that this spatial diversity is similar to multiuser diversity described in [10].

Nevertheless, several design challenges must be first overcome so that we can leverage the possible performance improvements due to this type of spatial diversity, particularly regarding the design of a *strategy for selection of the next-hop relay*, and the design of low-overhead routing and MAC layers that jointly leverage the spatial diversity *in the presence of rapid fluctuations in the quality of the channel at the receivers*. This is due to the fact that acquiring channel state information (CSI) in such an environment is costly. Since CSI is only valid at the scale of channel coherent time [13], channel probing overheads may negate the gains achieved by diversity. On the other hand, a strategy that selects the next-hop relay (among a set of candidate relays) would work best if the CSI information is kept up to date. Thus, there exists a critical trade-off between the quality of the selected next-hop relay (and hence the achieved spatial diversity gain) and the amount of information obtained from the physical/link layer. Notice that current works in the literature along this line explore only the two extreme cases, where [14] requires the maximum feedback/information from the physcial/link layer and [6], [18] require the minimum feedback. It is natural then to investigate whether a better trade-off could be achieved by combining the advantages of the two extremes through a formally defined stochastic decision framework, as we consider here.

In this paper, we formulate the next-hop relay selection problem as a sequential decision problem and derive an Optimal Stopping Relaying (OSR) strategy that maximizes the average reward, defined as a function of the network performance. One of the practical advantages of this formulation is that, by only requiring long-term channel statistics, the forwarding node can calculate a threshold-based (and hence low complexity) policy based on optimal stopping theory [4] which guarantees the selected relay can optimize a design-defined performance metric. Equally important is the fact that a low-overhead implementation exists by conveying such a policy to the set of candidate next-hop relays, so that each candidate relay can decide whether it can be "the selected one" independently without explicitly feeding back the channel measurements (i.e., no exchange of channel states between the candidate relays and the forwarding node). In case more than one node qualifies under the policy, a priority-based scheme (e.g., [6], [18]) or the well studied splitting algorithm (e.g., [12]) is incorporated to ensure that the desired relay in the original decision problem is selected within a short resolution delay.

The contribution of this paper is threefold. First, we establish a general framework of optimal stopping relaying (OSR), which can optimize an arbitrarily specified performance metric and can be integrated with almost any deployed MAC and routing protocol. Second, as a particular example, assuming Rayleigh fading channels, we implement OSR to optimize information efficiency [2] in a setting of Greedy Perimeter Stateless Routing (GPSR) [9] and IEEE 802.11 MAC protocols. Moreover, unlike previous works, we also incorporate instant rate adaptation on the selected link in OSR. Third, as to the above realization of OSR, we not only analyze the forwarding capability of a single node but also evaluate end-to-end performance via extensive simulations in QualNet [1] under various network configurations. The results demonstrate the superiority of OSR over other existing schemes.

The rest of the paper is organized as follows. The next section summarizes the related work. Section III presents the general framework of OSR, followed by two sections each of which addresses its underlying optimal stopping theory and implementation in the setting of GPSR and IEEE 802.11 MAC protocols, respectively. Then, we evaluate the performance of the above realized OSR from two aspects: Section VI uses an analytical approach to examine the optimality of OSR in terms of the expected information efficiency achieved by a single node; Section VII presents extensive simulation results on evaluating end-to-end performance of OSR under various network configurations. Finally, Section VIII concludes the paper.

II. RELATED WORK

We review the related work with respect to two aspects; (a) the objectives of the proposed spatial diversity forwarding schemes and (b) the technical approach used to formulate the problem.

Up to our knowledge, exploiting spatial diversity based forwarding in wireless ad hoc networks was first addressed in [11]. Larsson [11] presented the Selection Diversity Forwarding (SDF) scheme, in which a node first multicasts data to a set of candidate next-hop relays and then performs a forwarding decision in terms of positive forward progress based on multiple responses subsequently returned from that set of nodes. In [19], Zorzi and Rao proposed the Geographic Random Forwarding (GeRaF) scheme where the relay is randomly selected among receivers in a contention-based manner, where a node is given a higher priority if it is closer to the destination. Notice that, unlike the treatment in this paper, none of the previous works explicitly considered the characteristics of wireless channels, but rather they considered only the position information.

In contrast, [6], [18] solely considered the characteristics of the wireless channels. Moreover, as an improvement to [11], they attempted to decrease the protocol overheads by reserving the order of the control phase (multicast) and data phase. Thereby, when a node intends to forward a packet, the node first multicasts a polling message to a set of candidate next-hop relays. The node which is able to respond first is selected as the next-hop relay. Note that each possible response is sent in a predetermined time frame assigned in the polling message to avoid collisions. Once the node gets any feedback from the set of candidate next-hop relays, it will immediately transmit the data to the relay where the response came from. For convenience, we refer to this class of strategies as the *First Stopping Relaying (FSR)* scheme from now on. While this scheme has the advantage of inducing a short decision delay, the main drawback of FSR is that its extreme (min delay) decision rule may result in missing a better channel which may decrease the link outage probability or improve data rates especially when multi-rate radios are available.

In [14], Souryal and Moayeri investigated the Channel-Adaptive Relaying (CAR) scheme with joint consideration of the position and channel information (i.e., the maximum expected progress (MEP) strategy). In CAR, when a node intends to forward a packet, the node first multicasts a polling message to a set of candidate next-hop relays; then it makes a forwarding decision with respect to the different values of MEPs. Notice that this strategy collects responses from all candidate nodes. Thus, we refer to this class of strategies as the *Last Stopping Relaying (LSR)* scheme from now on. This scheme intends to select "the best" relay based on full information collected about all the relaying nodes, but the main drawback of LSR is that its extreme (max overhead) decision rule may result in invalidation of the collected CSI by the time the forwarding node selects the channel due to the large decision delay. In addition, as a side effect, to reach consensus on the forwarding decision of the node, all candidate relays have to wait for the message from the relay node to clarify the selection, which may also block the nearby traffic. The OSR strategy proposed in this paper can be viewed as one that combines the advantages of FSR and LSR while overcoming their drawbacks.

Lastly, from the problem formulation standpoint, Multi-channel Opportunistic Auto-rate (MOAR) [8] comes closest to our work in the sense that it also uses optimal stopping rules. Their work is different in that their objective is to exploit *frequency* (rather than time) diversity with multi-channel radios (i.e., no forwarding nodes). MOAR searches for a channel with a favorable SNR while keeping the non-negligible channel skipping costs in mind, which can be exactly mapped to the classic house selling problem without recall in optimal stopping theory. However, it can not be adapted to exploit spatial diversity studied in this paper because: a) the channels to the set of candidate next-hop relays dispersed in space can no longer be assumed as identical and independently distributed (i.i.d.); b) it is inefficient for a forwarding node to acquire CSI of each candidate next-hop relay sequentially in terms of both communication and delay. Notice that these differences manifest themselves in both the OSR problem formulation as well as implementation.

III. OPTIMAL STOPPING RELAYING FRAMEWORK

In this section, we show how the next-hop selection problem can be formulated as a sequential decision problem that attains a better trade-off between the achieved spatial diversity gain and costs of obtaining physical/link layer information from the next-hop candidate relays.

In this paper, we solve such a sequential decision problem based on optimal stopping theory which provides a solid theoretical foundation for designing such schemes. In conventional settings of an optimal stopping problem, a decision maker observes a sequence of random variables, given their joint probability distribution and associated real-valued reward functions. For each time step, after observing a random variable and calculating the obtained reward up to that point in time, the decision-maker takes an action to stop or continue the procedure in hope for a better reward. The goal of the problem is to derive an optimal policy in order to maximize the expected reward. In wireless ad hoc networks, this general framework arises as a collaboration among multiple protocol layers in a distributed manner as follows.

We assume cross-layer communication whereby a node's physical layer overhears the channel and provides CSI to upper layers if necessary. Thereby, the MAC layer is able to maintain the long-term channel statistics (e.g., mean) for every neighbor it hears. Recall that wireless links are generally assumed to be mutually independent, the node can obtain an estimation on a joint probability distribution of wireless links for any subset of its neighbors.

When a node intends to forward a packet, the routing layer is first responsible to select a set of candidate next-hop relays according to the design-defined performance metric. Then, based on available information (i.e., the set of candidate nodes and related channel statistics) provided by PHY/MAC and routing layers, the node can calculate its optimal stopping policy. In order to minimize the delay and communication costs, our design opts to perform the policy *on the relay side*. The MAC layer multicasts a polling message which carries the policy parameters to the set of candidate relays and each receiver can perform the policy to decide whether it is "the selected one" independently.

In case more than one node qualifies under the policy (we will discuss later how/if the policy will provide multiple results), there are two options to tackle the potential collisions and ensure the selection of the desired relay in the original decision problem within a short resolution delay. When the number of candidate nodes is small and collision detection cost is high, we can use the priority-based scheme (e.g., [6], [18]) in which each response by a node is prioritized in time in an order specified in the polling message. Notice that such a priority-based scheme guarantees that the relay will be selected and maximum resolution delay is bounded by the number of candidate relays. When the number of candidate nodes is large and collision detection cost is low, we can use the splitting algorithm (e.g., [12]) to filter out the desired relay via a tree-like mechanism.

IV. OPTIMAL STOPPING RELAYING THEORY

In this section, we first provide some preliminaries on Rayleigh fading channel model used in our analysis/simulations. Next, we derive the optimal stopping rules for OSR based on the joint distribution of a sequence of observed random variables for the set of candidate next-hop relays and reward functions.

A. Rayleigh Fading Channels

In order to understand the behavior of higher layer protocols and design or finely tune their parameters in wireless networks, it is common to assume that the underlying channel is a flat Rayleigh fading channel. This model captures the fading phenomenon when there is no predominant line of sight between a transmitter and receiver. Hence, in the presence of additive white Gaussian noise (AWGN), the instantaneous SNR Γ conforms to an exponential distribution with probability density function (pdf)

$$f(\gamma) = \frac{1}{\overline{\gamma}} exp\{-\frac{\gamma}{\overline{\gamma}}\},\ \gamma \geq 0 \tag{1}$$

where $\overline{\gamma} = E\{\Gamma\}$ is the average SNR.

While the Rayleigh distribution describing the instantaneous statistics of signal envelope, the autocorrelation function of the envelope describes its statistics over time. Let f_m denote the maximum Doppler frequency defined as $f_m = \frac{v}{\lambda}$, where v is the speed of the mobile terminal and λ is the carrier wavelength, the correlation of two samples of a Rayleigh fading envelope taken at t and $t+\tau$ can be expressed as

$$\rho(\tau) = J_0^2(2\pi f_m \tau) \tag{2}$$

where $J_0(x)$ is the zero-order Bessel function of the first kind [16].

In general, the evolution of Rayleigh fading channels can be modeled as a Finite State Markov Chain (FSMC) (e.g., [17]). In an FSMC model, the SNR is partitioned into disjoint intervals and then mapped into a finite state space $\mathcal{S} = \{s_1, s_2, \ldots, s_K\}$. Suppose that SNR thresholds are $\vec{\gamma} = \{\gamma_1 = 0, \gamma_2, \ldots, \gamma_{K+1} = \infty\}$. If an instantaneous SNR Γ satisfies $\gamma_k \leq \Gamma < \gamma_{k+1}$, the channel is said to be in state k. Without loss of generality, in a multi-rate radio, we can specify a set of SNR thresholds so that each state is associated with a distinct supported data rate. Since the instantaneous channel SNR Γ conforms to an exponential distribution as expressed by eq. (1), when a node probes the channel, its steady-state probability of being in state s_k is given by

$$\begin{aligned} \pi_k &= \int_{\gamma_k}^{\gamma_{k+1}} f(\gamma) d\gamma \\ &= e^{-\frac{\gamma_k}{\overline{\gamma}}} - e^{-\frac{\gamma_{k+1}}{\overline{\gamma}}},\ k = 1, 2, \ldots, K \end{aligned} \tag{3}$$

Hence, the corresponding data rate denoted as $\mathcal{R}$ can be characterized as a discrete random variable with a probability mass function (pmf)

$$\mathcal{R} = R_k \quad w.p.\ \pi_k\ , k = 1, 2, \ldots, K \tag{4}$$

Notice that we set $r_1 = 0$ in state s_1 since we view γ_2 as the minimum SNR required by any effective reception.

B. *Optimal Stopping Rules*

Given the fading channel statistics, we define the sequence of random variables to be observed for the set of candidate next-hop relays and the reward functions for the forwarding node, which are the elements in an optimal stopping problem formulation.

Let Θ_i denote the reward (or utility) if node i is selected as the next hop relay[1]. For convenience, we drop the subscript since it is understood from the context. Define Θ as

$$\Theta = d\mathcal{R} \tag{5}$$

where d denotes the distance progress made by the transmission toward the destination and $\mathcal{R}$ denotes a discrete random variable representing the highest reliable data rate determined by the instantaneous channel SNR Γ at the candidate relay node. Progress d can be calculated via the location service provided by GPSR routing. Even in a high mobility environment, at the time scale of forwarding a packet, d can still be considered a constant. Hence, Θ is a discrete random variable with the same probability mass function as $\mathcal{R}$, given in eq. (4). Recall that, since fading on different channels is typically mutually independent, the random variables for the set of candidate next-hop relays are independent as well. Thus the joint distribution of the sequence of these random variables can be straightforwardly derived from the product of individual distribution functions.

The reward function for the forwarding node is defined as the value of the random variable Θ_i if the i-th candidate next-hop relay is selected. Notice that, as mentioned in Section III, due to the need to resolve potential collisions when more than one relay are qualified, there may exist a certain delay between the time the relay observes Θ_i and the time the forwarding node actually forwards the packet to the selected relay. At the time of forwarding, the actual value of Θ_i might have changed. However, the delay between observing Θ_i and the forwarding decision is within the coherence time of the channel. In this case, Θ_i can be considered constant within this small delay. We give a numerical example for this in Section V assuming Rayleigh fading (i.e., eq. (2)). This is because, typically, correlations of signal envelops between the time when a relay makes the decision and the time when the forwarding node starts to utilize that channel are above 0.95 for a wide range of configurations

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[1] Notice that our definition of the reward can be viewed as a generalized measure of information efficiency (e.g., [15]) which balances the need to minimize the number of hops along a path with the need to maximize the throughput on a given hop.

(e.g., maximum velocity from 1 to 20m/s, and number of candidate relays from 2 to 8).

Based on the above discussion, the sequence of reward functions for the forwarding node is defined as

$$y_i(\theta_1, \theta_2, \ldots, \theta_i) = \theta_i, \ 1 \le i \le L \tag{6}$$

where L denotes the cardinality of the set of candidate next-hop relays. We can now formally state the decision problem in OSR as follows.

Problem: Given a forwarding node n_s which intends to forward a packet toward its destination and a set of L candidate next-hop relays $\{n_1, n_2, \ldots, n_L\}$ known at the routing layer, which can be characterized by L independent discrete random variables $\{\Theta_1, \Theta_2, \ldots, \Theta_L\}$ defined by eq. (5), what is the optimal policy at the forwarding node n_s to select the next-hop relay to which the packet is to be forwarded so as to maximize the expected reward $E\{\Theta\}$?

This problem is an L horizon optimal stopping problem which can be solved by the method of backward induction [4]. Regardless of implementation, we can divide the conceptual sequential observations into stages. Since we must stop at stage L, we first find the optimal policy at stage $L-1$. Then, given the optimal policy at stage $L-1$, we find the optimal policy at stage $L-2$ and so on back to the initial stage. Therefore, we define value functions at a forwarding node as follows. When $i = L$,

$$V_L^L(\theta_1, \theta_2, \ldots, \theta_L) = y_L(\theta_1, \theta_2, \ldots, \theta_L) = \theta_L. \tag{7}$$

Then inductively for $i = L-1$ backward to $i = 1$,

$$\begin{aligned} V_i^L &= \max\{y_i(\theta_1, \theta_2, \ldots, \theta_i), \\ & E\{V_{i+1}^L(\theta_1, \theta_2, \theta_i, \Theta_{i+1} | \Theta_1 = \theta_1, \Theta_2 = \theta_2, \ldots, \Theta_i = \theta_i)\}\} \end{aligned} \tag{8}$$

where V_i^L is short for $V_i^L(\theta_1, \theta_2, \ldots, \theta_i)$. Notice that V_i^L represents the maximum expected reward achieved by the forwarding node n_s starting from the stage i and having observed the random variables $\Theta_1 = \theta_1, \Theta_2 = \theta_2, \ldots, \Theta_i = \theta_i$.

Now we derive the optimal policy (OSR) from (7) and (8). The independence of Θ_i implies that V_i^L only depends on Θ_i and $T_{L-i} = E\{V_{i+1}^L(\theta_1, \theta_2, \theta_i, \Theta_{i+1} | \Theta_1 = \theta_1, \Theta_2 = \theta_2, \ldots, \Theta_i = \theta_i)\}$, which is a constant that depends only on $L - i$, the number of stages to go. Thus, the optimal policy for the forwarding node n_s is to select the i-th candidate next-hop relay if $\Theta_i \ge T_{L-i}$, where T_{L-i} can be computed inductively as follows:

$$\begin{cases} T_0 = -\infty & (9) \\ T_1 = E\{\Theta_L\} = \overline{\theta}_L = d_L \sum_{j=1}^{K} \pi_j^L R_j & (10) \\ T_{i+1} = E\{\max\{\Theta_{L-i}, T_i\}\} & \\ \quad = \sum_{j=1}^{K} \pi_j^{L-i} \max\{d_{L-i} R_j, T_i\}, \ 1 \le i \le L-1 & (11) \end{cases}$$

It is easy to see that the derived thresholds $T_0, T_1, \ldots, T_{L-1}$ in the optimal policy form a non-decreasing sequence. T_L (i.e., $E\{V_1^L\}$) gives the expected reward $E\{\Theta\}$ achieved by the forwarding node n_s under the optimal policy.

V. OPTIMAL STOPPING RELAYING IMPLEMENTATION

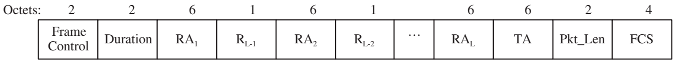
A. Selection of Candidate Next-Hop Relays in GPSR Protocol

OSR is implemented here assuming a GPSR protocol provides the set of of candidate next-hop relays. Notice that to avoid progress to be negative when selecting a node as the candidate next-hop relay, the selection procedure here is only considered for the greedy forwarding mode.

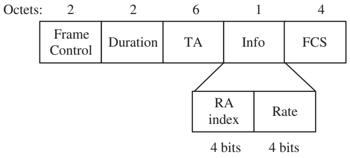
Let M denote a system parameter specifying the maximum order of spatial diversity that can be utilized by a forwarding node. In general, GPSR protocol returns top $L \le M$ candidate next-hop relays in terms of $\overline{\theta}_i$ (where $\overline{\theta}_i = E\{\Theta_i\}$). To obtain these metrics, apart from assuming that every node has the common knowledge of SNR thresholds of the FSMC model, progresses d_i and average channel SNR's $\overline{\gamma}_i$ are needed. Therefore, the forwarding node resorts to the location service to estimate the progresses d_i by acquiring locations of its neighbor and the destination nodes. Moreover, by setting its radio in the promiscuous mode, the forwarding node estimates the average channel SNR $\overline{\gamma}_i$ of its neighbor node i through an Exponentially Weighted Moving Average (EWMA) filter as in [7] with $\alpha = 0.2$ using $\overline{\gamma}_i = (1-\alpha)\overline{\gamma}_i + \alpha\gamma_i$ where γ_i is the SNR measurement on the latest received/overheard packet from node i and $\overline{\gamma}_i$ is the estimated average SNR for node i by the forwarding node.

B. Selection of the Next-Hop Relay via a MAC Layer Anycast Scheme

When there are more than one candidate next-hop relays, the forwarding node utilizes a MAC layer anycast scheme, implemented here as an extension of IEEE



(a) Multicast Request-To-Send (RTS) frame.



(b) Clear-To-Send (CTS) frame.

Fig. 1. MAC frame formats used by OSR.

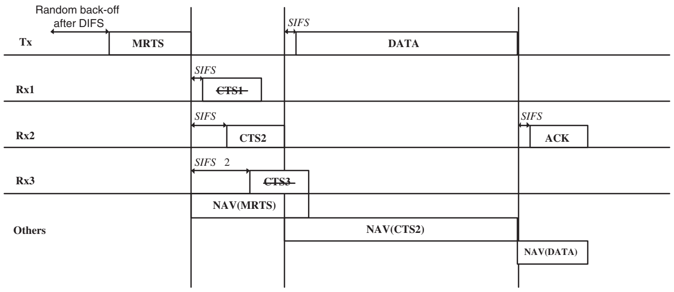


Fig. 2. A sample timeline of the OSR scheme for three candidate next-hop nodes.

802.11 MAC DCF, to perform the optimal policy. The policy parameters, i.e., the thresholds, are contained in the polling message, in this case a multicast RTS (MRTS) frame, as shown in Fig. 1(a). In contrast to the standard RTS frame, MRTS frame carries additional L node addresses (6 bytes), $L-1$ thresholds (1 byte) and two bytes for the length (payload) of the packet to be forwarded. In order to minimize the size of the MRTS frame, we do not include the destination address. Instead, we replace the threshold T_{L-i} by an encoded data rate as $\lceil \frac{T_{L-i}}{d_i} \rceil$. Thereby, getting rid of the need for computing the progress toward the destination, a candidate relay only needs to determine whether the observed channel state can support the data rate specified in the MRTS frame. The reply message, the CTS frame, is shown in Fig. 1(b). The CTS frame here is different from the standard CTS frame in that it carries one additional information byte. The upper four bits (supporting up to sixteen candidate next-hop relays) specify the index of next-hop relay that replies in the list presented in the MRTS frame. The lower four bits (supporting up to sixteen different data rates) encode the data rate supported by the selected next-hop relay.

Now we describe the MAC layer anycast scheme. When a node seizes the medium and intends to forward a packet toward its destination, it first multicasts an MRTS frame to the set of candidate next-hop relays selected by GPSR protocol. Upon reception of an MRTS frame with zero Network Allocation Vector (NAV), a candidate next-hop relay completes a channel measurement and accesses the received policy to obtain its threshold. To decide whether to be "the selected relay," it compares the highest reliable data rate supported by the measured channel state with the threshold. In case more than one node qualifies under the policy, it needs a mechanism to resolve the potential collisions. We implement a priority-based scheme for resolution here since the number of candidate next-hop relays would not be large in exploiting spatial diversity in wireless ad hoc networks and collision detection cost in delay would be at least $T_{CTS} + T_{SIFS}$. Specifically, the CTS reply frames are prioritized in time in the same order specified in the MRTS frame: if the i-th candidate next-hop relay qualified, it schedules the transmission of its CTS frame after a period equal to $T_{SIFS} + (i-1)T_{\sigma}$. Notice that any frame sent by a candidate next-hop relay will reach all other relays within a slot time T_{σ} with high probability since the carrier sensing range is normally two times of the transmission range. This ensures that a CTS frame scheduled by a relay will be suppressed due to a CTS frame sent by the relay with a higher priority. Next, when the forwarding node receives any CTS frame, it starts to transmit the DATA frame to the relay where this CTS frame comes from after a SIFS interval. Finally, similar to the standard DCF, the DATA frame will be acknowledged by an ACK frame shortly after. Notice that the MRTS and CTS frames are transmitted at the base data rate while the DATA and ACK frames are transmitted at the data rate specified by the relay that replies as any other rate-adaptive MAC protocol does (e.g., [5]).

To take the advantage of rate adaptation on the DATA/ACK frame and to avoid resorting to a medium reservation in the MRTS frame (as e.g., in [5]), we modify the Virtual Carrier Sensing (VCS) scheme in IEEE 802.11 MAC DCF as follows. Each frame intends to reserve the medium only for the immediate next frame instead of reserving the medium for all remaining frames. Thereby, any node, except the node which actually replies with a CTS frame, that overhears the MRTS frame, sets its NAV as $T_{SIFS}+(L-1)T_{\sigma}+T_{CTS}$, the maximum time needed to wait for response from any next-hop relay. Any node that overhears a CTS frame sets its NAV as $T_{SIFS} + T_{DATA}$, where T_{DATA}

is calculated based on the length of the DATA frame carried in the MRTS frame and the data rate indicated by the selected relay itself. Any node that overhears the DATA or ACK frame updates its NAV as usual (i.e., $T_{SIFS} + T_{ACK}$ or zero).

Notice that in IEEE 802.11 MAC any node that initiates a use of wireless medium will defer by a T_{DIFS} which is larger than T_{SIFS}, so all nodes that may potentially interfere on the ongoing frame exchange sequence can also defer properly depending on Physical Carrier Sensing (PCS). Even if all frames can not be overheard clearly as assumed above, we can resort to EIFS by setting it as $T_{SIFS} + (L-1)T_\sigma + \max\{T_{CTS}, T_{ACK}\} + T_{DIFS}$, which is long enough for the transmission of any control frame. For example, when a node detects an erroneous frame corresponding to the MRTS frame, it will defer by an EIFS interval, which is large enough to allow the CTS frame to go through. This is also true when a node detects an erroneous frame corresponding to the DATA or ACK frame. In the worst case, if none of the CTS frames are received, the forwarding node goes into a random back-off and then retries.

Fig. 2 illustrates an example of utilizing anycast extension based on IEEE 802.11 MAC DCF described above. Specifically, the timeline of a sample scenario begins with the forwarding node multicasting an MRTS frame to its three candidate next-hop relays. The first relay withdraws its response since it is not qualified due to an unfavorable channel. The second relay is qualified and schedules a CTS frame at the time $T_{SIFS} + T_\sigma$ after reception of the MRTS frame. Regardless the state of underlying channel, the third relay schedules a CTS frame with a $T_{SIFS} + 2T_\sigma$ interval later as long as it received the MRTS frame. However, it is suppressed by the second relay's CTS frame sent T_σ earlier. The remaining events are similar to the standard DCF, so when receiving a CTS frame, the forwarding node transmits the DATA frame to the second relay and then receives an ACK frame from it later on.

VI. PERFORMANCE ANALYSIS ON FORWARDING CAPABILITY OF A SINGLE NODE

In this section, to examine the optimality of OSR in terms of the expected reward, we first introduce an enhanced FSR scheme, which is in the same spirit of [6], [18] enhanced with link adaptation. Then we compare the between FSR and OSR with respect to the forwarding capability of a single node.

A. First Stopping Relaying

To compare our scheme against FSR on the same grounds, we assume that FSR shares the same implementation as OSR, described in Section V, except that in FSR any next-hop relay is qualified as long as it received the MRTS frame. As a result, the forwarding node always selects the first relay that replies. In order to evaluate the expected reward achieved by a forwarding node via FSR, we first calculate the probability p_i that the i-th candidate next-hop relay is selected.

$$p_i = 1 - \pi_1^i \tag{12}$$

Next, let Y be an indicator random variable for the selection of the i-th candidate next-hop relay. Then the probability mass function of Y can be expressed as

$$Y = \begin{cases} i & \text{w.p. } \prod_{j=1}^{i-1}(1-p_j)p_i,\ 1 \le i \le L \\ 0 & \text{w.p. } \prod_{j=1}^{L}(1-p_j) \end{cases} \tag{13}$$

Now, the expected reward given that the i-th candidate next-hop relay is selected can be computed as

$$E\{\Theta | Y = i\} = \frac{d_i \overline{R}^i}{p_i} \tag{14}$$

where $\overline{R}^i = \sum_{j=1}^{K} \pi_j^i R_j$. Finally, to sum up all cases, the expected reward for the forwarding node via FSR is

$$\begin{aligned} E\{\Theta\} &= E\{E\{\Theta|Y\}\} \\ &= \sum_{i=1}^{L} d_i \overline{R}^i \prod_{j=1}^{i-1} \pi_1^j \end{aligned} \tag{15}$$

B. Performance Comparison of FSR and OSR

Here we compare the forwarding capability of a single node for the cases of FSR and OSR in terms of the expected reward[2]. In the following evaluations, we assume that the SNR thresholds are set as $\{0, 1, 3, 7, 15, +\infty\}$ and the corresponding set of data rates are $\{0, 1, 2, 3, 4\}$. Without loss of generality, we assume that there are L candidate next-hop relays for the forwarding node with equal progress d_i toward the destination and i.i.d. channel SNRs Γ_i, where L varies from 2 to 8 (inclusive) and the average channel SNRs $\overline{\gamma}_i$ increases from 0.1 to 20 with step of 0.5.

Fig. 3 shows $E\{\Theta\}$ achieved by a forwarding node via FSR with different number of candidate next-hop relays

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[2] We ignore the overheads in terms of decision delays of FSR and OSR since they are very close in an expected sense due to their similar decision procedures. Particulary, it is easy to verify in the simulations that the expected decision delays of FSR and OSR are equal to $T_{SIFS} + \frac{L}{2}T_\sigma$.

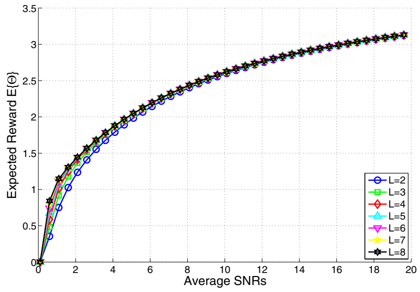


Fig. 3. The expected reward gained by a forwarding node via FSR.

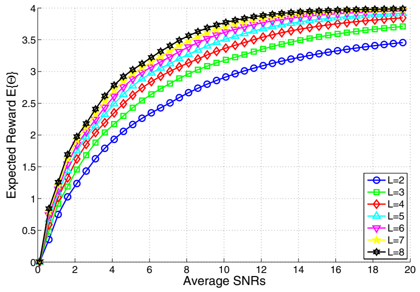


Fig. 4. The expected reward gained by a forwarding node via OSR.

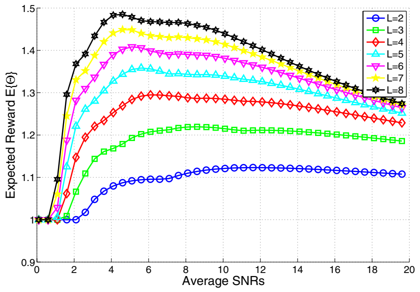


Fig. 5. The gain of OSR over FSR in terms of the expected reward at a forwarding node.

and average channel SNRs. A significant characteristic of the forwarding capability of a single node in FSR is that when average channel SNRs are extremely low (i.e., ≈ 0) or high (i.e., ≥ 5), $E\{\Theta\}$ almost does not change with L, which is the order of spatial diversity exploited. On the other hand, when average channel SNRs are in the intermediate region (i.e., $0 < \overline{\gamma}_i < 5$), the larger the L, the larger the $E\{\Theta\}$ achieved. However, notice that the more the average channel SNRs are close to zero or five, the less the increasement is due to a larger L for any given average channel SNRs.

Fig. 4 shows $E\{\Theta\}$ achieved by a forwarding node via OSR with different number of candidate next-hop relays and average channel SNRs. In contrast to FSR, only when channel SNRs are extremely low (i.e., ≈ 0), $E\{\Theta\}$ varies slightly with L. Beyond that, OSR always achieves a larger $E\{\Theta\}$ with a larger L, though the rate of such increase becomes slower as L becomes larger for any given average channel SNRs. In that sense, OSR is especially useful when the number of relaying nodes is low.

To better compare the performance of OSR and FSR, Fig. 5 depicts the gains of OSR over FSR by computing $\frac{E\{\Theta\}_{OSR}}{E\{\Theta\}_{FSR}}$. When average channel SNRs are low, the gain of OSR over FSR is negligible (i.e., ≈ 1). Above a certain threshold, OSR starts to outperform FSR; for any given average channel SNRs, the larger the L, the larger the achievable gain. The rate of the increase in gains becomes slower for larger L. Moreover, with further increase of average channel SNRs, gains, regardless of L, tend to decrease. Though not shown in the figure (due to scale difference), gains converge to one when average channel SNRs become extremely large (i.e., > 50). This is because when channels are fairly good, no matter what selection policy is used (i.e., OSR or FSR), virtually any reasonable decision policy will achieve equally well performance.

VII. END-TO-END PERFORMANCE EVALUATION WITH TCP AND UDP FLOWS USING QUALNET

A. Simulation Model

In this section, we compare end-to-end performance of OSR with LSR [14] in terms of thoughput/packet delivery ratio (PDR), end-to-end delay and jitter in QualNet 3.7 [1] simulation environment. The common simulation settings are as follows. Routing is GPSR protocol with average beacon interval of 1.5 seconds. MAC is the anycast extension on IEEE 802.11 MAC DCF described in Section V-B. The physical layer is 802.11b supporting multiple data rates (i.e., 2/5.5/11 Mbps). The radio transmission power is 4.145 dBm and the radio reception sensitivities are -85 dBm (11 Mbps), -87 dBm (5.5 Mbps), -89 dBm (2 Mbps) and -93 dBm (carrier sense), respectively. The antenna for each node is omnidirectional and the propagation is modeled as a combination of two-ray path loss and time-varying correlated fading.

For OSR, the design parameters, SNR thresholds in FSMC, are set to values that ensure that the data transmission in every channel state (except s_1) achieves at least 10^{-5} BER. Thereby, when assuming quasi-static fading channels, it is expected to obtain $FER < 0.05$ for a frame as long as 5000 bits.

B. Grid Topology, A Single TCP Flow

We first evaluate the performance of OSR and LSR[3] in a simple setting as follows: an 8×8 grid topology where nodes are 100 m apart, a single File Transfer Protocol (FTP) session transmits 512-byte data packets from the source to the destination nodes , with total 900 seconds

[3] Compared to the prototype of LSR in [14], we have further incorporated the adaptive modulation scheme when making a forwarding decision so as to enhance the spectrum efficiency of LSR.

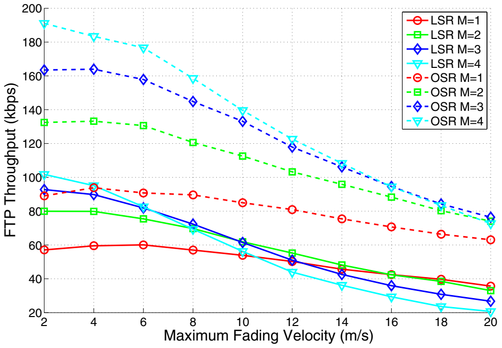


Fig. 6. Average FTP throughput vs. maximum fading velocity for 8×8 grid topology with Rayleigh fading.

simulation time, the file transfer starts at 6th second and ends at 880th second.

The average FTP throughput for LSR and OSR with $M = 1, 2, 3, 4$ as a function of the maximum fading velocity v_m are depicted in Fig. 6. In a coarse view, OSR, even with $M = 1$, outperforms LSR for most of maximum fading velocities. This is due to different overheads induced by the decision-making procedure. We explain this point as follows. Although LSR simplifies the decision-making procedure at the forwarding node, the overheads incurred by gathering CSI can negate the achieved spatial diversity gain, which results in that curves for various M for LSR cross each other from $v_m = 4$ to 6 m/s. The larger the M, the more the performance drops. Consequently, the $M = 4$ case behaves the worst starting from $v_m = 10$ m/s and the $M = 1$ case behaves the best starting from $v_m = 16$ m/s among LSR. While in OSR, due to its theoretical founded and decentralized decision-making procedure, it is generally true that OSR with larger M obtains better performance.

Notice that we did not explicitly consider v_m in our optimal stopping policy though it is natural to be treated as an adverse factor to the network performance. We can observe that, as to OSR, the larger the M, the more vulnerable to the increase of v_m. When $v_m = 20$ m/s, the average FTP throughput achieved by OSR with different M becomes saturated and get close to each other .

C. Static Random Topology, Multiple UDP Flows

We then evaluate the impact of traffic on end-to-end performance of OSR and LSR. Two hundred static nodes are randomly and uniformly deployed in a 3000 m× 600 m rectangle area. v_m is fixed at 5 m/s, and we vary the network traffic in terms of the number of Constant Bit Rate (CBR) flows from 2 to 20. Each flow generates 512-byte data packets at the rate of 4 packets/s. Notice that, to avoid obvious bottleneck, we do not allow a node to be a source or destination in more than one CBR flow. Within total 900 seconds simulation time, the start times of CBR flows are randomly and uniformly distributed in the interval of $[6, 180)$ seconds and they all end at 880th second.

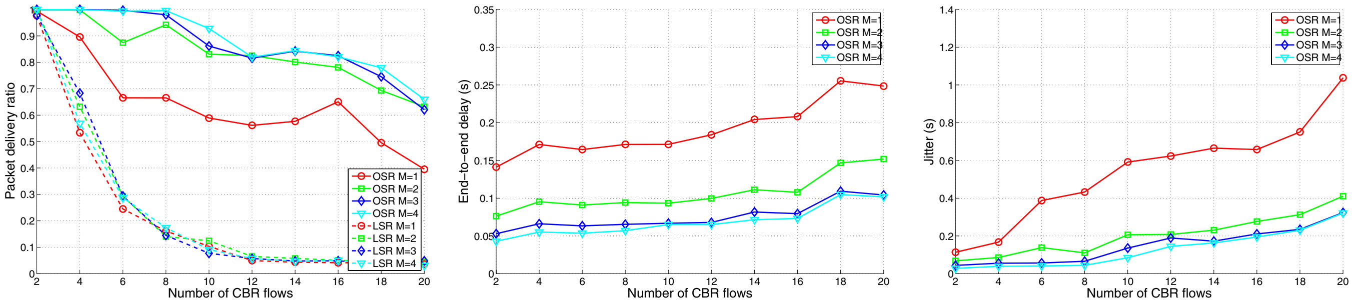
We plot PDR as a function of the number of CBR flows for OSR and LSR with different M in Fig. 7(a). For OSR, for a given M, PDR decreases gracefully with the increase of number of CBR flows; for a given number of CBR flows, it is generally true that OSR with a larger M achieves a greater PDR. The increase becomes less when M grows larger. Similar phenomena for OSR have also been observed in Fig. 7(b) and Fig. 7(c) in terms of end-to-end delay and jitter, respectively.

For LSR, for a given M, PDR decreases very sharply with the increase of number of CBR flows; for a given number of CBR flows, there is no obvious difference among various M. This is because with the increase of M, the implicated spatial blocking effects induced by the centralized decision-making procedure in LSR completely overwhelm the gain achieved in heavy loads. Notice that this is in contrast to OSR which does not have such a problem and is never degraded by a larger M. Accordingly, due to the poor PDR, end-to-end delays and jitters in LSR are several orders higher than OSR and thus not shown in Fig. 7(b) or Fig. 7(c).

Furthermore, we also conduct simulations with mobile topologies and also observe that OSR outperforms LSR within expectation. However, due to space limit, we omit those results here.

VIII. CONCLUSIONS

In this paper, we formulated the next-hop relay selection problem as a sequential decision problem. Hence, we derived an Optimal Stopping Relaying (OSR) policy for improving spatial diversity gain in wireless ad hoc networks. Compared to previous schemes, its key difference is that it optimizes its selection of the next-hop relay in terms of arbitrary specified performance metric based on optimal stopping theory while minimizing the channel probing overheads. Assuming Rayleigh fading channels, we implemented this policy with link adaptation to optimize information efficiency (IE) in a protocol stack of Greedy Perimeter Stateless Routing (GPSR) and IEEE 802.11 MAC protocols. The performance evaluation was conducted from two aspects. First, we analytically compared the forwarding capability of a single node of OSR



(a) Packet delivery ratio.

(b) End-to-end delay.

(c) Jitter.

Fig. 7. End-to-end performance of OSR vs. the number of CBR flows for random, static topology with Rayleigh fading $v_m = 5$ m/s.

with First Stopping Relaying (FSR), which is in the same spirit of [6], [18] while further considering link adaptation. Since OSR intelligently skips non-optimal next-hop relays, OSR outperforms FSR in terms of information efficiency. Second, we evaluated end-to-end performance of OSR with Last Stopping Relaying (LSR) [14] via extensive simulations in QualNet. The simulations show that OSR provides better services to upper-layer applications (i.e., FTP, CBR) than LSR in terms of throughput/packet delivery ratio, end-to-end delay and jitter, especially when utilizing more (i.e., above two) candidate next-hop relays.

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