Opportunistic Spectral Usage: Bounds and a Multi-band CSMA/CA Protocol

Ashutosh Sabharwal, Ahmad Khoshnevis and Edward Knightly

***Abstract*— In this paper, we study the gains from opportunistic spectrum usage when neither sender or receiver are aware of the current channel conditions in different frequency bands. Hence to select the best band for sending data, nodes first need to measure the channel in different bands which takes time away from sending actual data. We analyze the gains from opportunistic band selection by deriving an optimal skipping rule, which balances the throughput gain from finding a good quality band with the overhead of measuring multiple bands. We show that opportunistic band skipping is most beneficial in low signal to noise scenarios, which are typically the cases when the node throughput in single-band (no opportunism) system is the minimum. To study the impact of opportunism on network throughput, we devise a CSMA/CA protocol, Multi-band Opportunistic Auto Rate (MOAR), which implements the proposed skipping rule on a per node pair basis. The proposed protocol exploits both time and frequency diversity, and is shown to result in typical throughput gains of 20% or more over a protocol which only exploits time diversity, Opportunistic Auto Rate (OAR).**

I. Introduction

A significant characteristic of wireless channels is time-varying *fading* caused by multiple transmission paths between a source and the destination. Though traditionally viewed as a source of unreliability which needs to be mitigated, the modern view is to exploit the channel fluctuations *opportunistically* when and where the channel is strong [1], [2], [3], [4], [5].[1] In many wireless systems, the available spectrum is more than what a single-device can use for transmission (e.g., IEEE 802.11). Thus, the system has multiple frequency bands available for transmission. In this paper, we study the opportunistic use of multi-band diversity.

Our contributions in this paper are two-fold. First, we derive bounds on the throughput of multi-band wireless systems. If the transmitter and receiver have perfect knowledge of channel SNR in each frequency band, then the optimal strategy is to choose the band with highest SNR. For the genie-aided system, the throughput of a K-band system is only $\log\log K$ more than the single-band system for medium to large SNRs. However, for low SNRs, the K-band throughput is $\log K$ times more than a single-band system. Hence, the biggest gain is in low-SNR regimes.

However, in practical systems, channel quality is unknown to either the transmitter or receiver, and has to be measured periodically, thereby incurring a resource overhead. The resource overhead is fundamental for measurement-based systems and increases with the number of bands K. To characterize the throughput gain of a K band system, we derive the optimal finite-horizon stopping rule which balances the measurement overhead with expected throughput. Using the metric of throughput gain over a single-band measurement based system, we characterize the regimes in which opportunistic selection is most beneficial. Much like in the genie-aided system, the gains from opportunistic selection are significant at low SNRs. For example, a 10-band system can have twice the throughput of a single-band system. However, as the average signal to noise ratio of each band increases, then a single-band system performs almost as well as any K band system.

Second, we propose a medium access control (MAC) protocol in the context of IEEE 802.11 standards, all versions (a/b/g) of which have multiple bands (commonly known as channels) for transmission. The protocol, termed, Multi-band Opportunistic Auto Rate (MOAR), allows nodes to opportunistically find the bands with the best channel quality and seeks to optimally balance the throughput gain with measurement overhead. MOAR combines multi-band frequency diversity with time-diversity as exploited in OAR [7], which sends multiple back-to-back packets in better channel conditions. MOAR nodes make a run-time decision as to whether they should continue to probe additional bands in search of a higher quality channel, or use the current band. The other key aspect of the MOAR protocol is ensuring that the transmitter and receiver stay synchronized in their

Ashutosh Sabharwal (ashu@rice.edu), Ahmad Khoshnevis (farbod@rice.edu) and Edward Knightly (knightly@rice.edu) are with the Department of Electrical and Computer Engineering (MS-380), Rice University, 6100, S. Main St., Houston, TX 77005. This research is supported by NSF Communication Theory Grant CCR-0311398, NSF ITR Grants ANI-0331620 and ANI-0325971, the TI DSP Innovation Fund, and by the Cisco ARTI program.

[1]The change of design philosophy can also be attributed to increases in signaling bandwidths. Newer systems have much wider bandwidths, which ensures that same-channel variations *appear* to occur much more slowly; see coherence time expressions in [6].

band skipping and do not end up alone on a new band. At the same time, the protocol has to ensure carrier-sense for other nodes in the system such that access is as fair as IEEE 802.11 in access probability. Finally, we explore the performance of MOAR via extensive *ns-2* simulations and study factors impacting the performance of MOAR. Our experiments show that MOAR outperforms state-of-the-art multi-rate protocols by 20% to 25%. We note that MOAR is compared with multi-rate protocols [7] which already give large gains over current IEEE 802.11 implementations, and hence actual gains over current systems are much larger than this range.

In many wireless LAN networks (e.g., campus or enterprise networks), frequency planning is performed to maximize throughput under full load. Under heavy loads, all frequency bands may be fully utilized and spectral opportunism may not possible; in these cases, single band rate-adaptive protocols suffice. However, almost all wireless networks show extended periods of low activity [8] or hot spots, in which case some or all access points can switch to a MOAR mode and exploit the available spectrum.

Multi-band communication (often referred as multi-channel in the literature) has been used in various forms in different systems. For example, some cellular systems use multi-bands to reduce inter-cell interference by assigning different bands to neighboring cells. In contrast to cellular systems, we are proposing self-managed frequency planning and usage by different nodes, while respecting other nodes who are sharing the same set of frequency bands. In the context of random access systems, our usage of multiple frequency bands contrasts [9], [10, and the references therein], which have used multiple bands for either reducing contention or increasing spatial reuse (and neither of them opportunistically). We also note that there has been little work in systematically characterizing the overhead in opportunism; see [11] in the context of multi-user diversity. Our initial work in [12] was recently generalized in [13] to allow channels which can have potentially different statistics; in contrast, we assume the same statistics for all the channels in our work.

The remainder of this paper is organized as follows. In Section II, we present the channel and measurement model. Sections III and IV are devoted to throughput analysis of opportunistic multi-band systems with and without channel information at the transmitter and receiver. We present the Multi-channel Opportunistic Auto Rate (MOAR) protocol in Section V and also discuss the challenges encountered while designing an efficient channel skipping protocol within the IEEE 802.11 channel access framework. The results of simulation experiments are presented in Section VII. Finally, we summarize in Section VIII.

II. Preliminaries

We consider a wireless system where the total available bandwidth is greater than what can be used for any single transmission, which is common in many wireless systems built to operate in non-licensed bands. For example, IEEE 802.11a/b/g devices use only a part of total available spectrum for any single transmission.

A. Channel Model

We assume that the total available bandwidth is W Hz, and any transmission uses only B Hz where $B \leq W$. Thus, the total spectrum of W Hz is divided into K frequency bands of B Hz each, where no two bands overlap in frequency domain (see Figure 1). The assumption of non-overlapping bands is to keep the analysis simple and allows us to explore key issues in opportunism; the analysis can be easily generalized to overlapping bands. Without loss of generality, we label the bands according to their center frequency. The frequency band with the smallest center frequency is labeled *Band 1*, the band with the next higher center frequency as *Band 2* and so on.

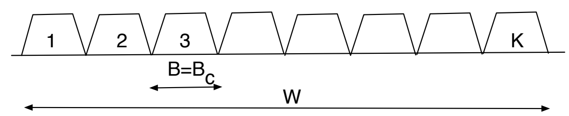

Fig. 1. Division of total available spectrum into smaller bands.

Throughout the paper, we assume that the channel encountered in each frequency band is flat and quasi-static, which implies that the received signal can be written as [6]

$$Y = H_i X + Z \tag{1}$$

where H_i is a complex constant, which is assumed to remain constant for T_c consecutive symbols before changing into a new independent constant drawn from the complex Gaussian distribution $\mathcal{CN}(0, 1)$. The additive noise Z is assumed to be i.i.d. complex Gaussian with zero mean and unit variance. The transmitter uses power P for each transmission and the received SNR is represented by $\mathrm{S}NR_i = P|H_i|^2$. Since H_i are assumed to be $\mathcal{CN}(0, 1)$, the average received SNR is $\overline{\mathrm{S}NR} = \mathbb{E}[\mathrm{S}NR_i] = P$. The constant T_c is known as the *coherence interval* and denotes the time period over which the channel gain and phase are highly correlated; in our model, they are perfectly correlated and hence the channels remain constant for T_c consecutive symbol periods. At moderate velocities, the coherence interval is on the order of multiple packet transmission times for systems like IEEE 802.11, which motivated the design of the Opportunistic Auto Rate (OAR) protocol [7].

A complementary constant which characterizes the channel behavior is the *coherence bandwidth*, B_c, which measures the maximum separation over which the fading coefficients for two frequencies are highly correlated. Since the channels in each frequency band are assumed to be flat and independent of each other, we have implicitly assumed $B = B_c$. Coherence bandwidth is inversely related to the *root mean square delay spread*, and can be well approximated [6]

$$B_c \approx \frac{1}{50 \cdot \sigma_\tau}, \tag{2}$$

where σ_τ represents the rms delay spread. Using the values of rms delay spread from measurement studies [14], [15], [16], [17], typical values of coherence bandwidth for IEEE 802.11 standards can be computed to be in the range 1-3 MHz in an indoor environment. Since several bands in all three popular variations, IEEE 802.11a/b/g, are orthogonal to each other with B greater than coherence bandwidth B_c, they fade independent of each other.

For the purpose of our analysis, we assume that the coherence interval T_c is much larger than the symbol period, $T_c \gg \frac{1}{B}$. Most wideband systems operate in the above mentioned regime of quasi-static fading. Thus, rates close to mutual information can be attained in a single coherence interval. The mutual information approximation is a good approximation of the performance of many practical error correcting codes, like turbo and low-density parity check codes [18], [19].

Finally, we comment on our choice of terminology. Often, both the portion of spectrum and the physical communication medium are referred as a "channel." For example, IEEE 802.11b has 11 channels, derived from the channelization of the total available spectrum. Instead, we will refer to these channels as bands to avoid confusion with the term channel used to describe H_i, which represents the impact of propagation on the transmitted signals.

B. The Channel Measurement Mechanism

In the next section, we consider achievable throughputs of wireless systems which use one of K bands for transmission. All of the schemes are based on measuring the current signal to noise ratio $\mathsf{S}NR_i$ for different channels and choosing the best among them. The channel measurement can be performed by nodes based on physical layer mechanisms such as existing physical layer training/preambles in packets. If a 4-way handshake mechanism is used such as the RTS/CTS mechanism in IEEE 802.11, then both the receiver and transmitter can obtain the $\mathsf{S}NR_i$ for a given band and use that information to adapt the rate or power for the data packet. However, knowledge about the channel conditions comes at the cost of using additional physical layer header (preamble) which requires additional transmission time.

Assume that T_m is the time needed to measure the channel at both the transmitter and receiver, which implies that one-sided channel measurement requires $T_m/2$ seconds. In this paper, we assume that T_m is sufficient to obtain near-perfect estimates of $\mathsf{S}NR_i$ (or the error in estimates is negligible). The channel measurement overhead can be computed in two different ways, depending on the choice of transmission policy. Two policies of interest are constant access time and constant data time. In the constant access time policy, node pairs are assumed to have fixed total time, T, to access and thus the effective fraction of time for sending data after k measurements is

$$\begin{aligned} c_k &= \left(1 - \frac{kT_m}{T}\right) \\ &= (1 - k\tau), \end{aligned} \tag{3}$$

where $\tau = \frac{T_m}{T}$. In the constant data time policy, nodes have a fixed time T for sending data irrespective of number of bands they have measured. Thus, the overhead constants c_j are given by

$$\begin{aligned} c_k &= \left(1 - \frac{kT_m}{T + kT_m}\right) \\ &= \frac{T}{T + kT_m} = \frac{1}{1 + k\tau} \end{aligned} \tag{4}$$

In either case, $c_k < 1$ and is a monotonically decreasing function of k for $T_m > 0$.

Even though the channel in any given band potentially remains constant for many back-to-back packets, the correlation in the observed channel gain over time for any node pair depends on the access mechanism. In a random access system, nodes contend after every packet (or every few packets as in OAR [7]). The probability of obtaining access to the channel after two of more contention cycles reduces geometrically. Specifically, if p is the probability for a node-pair to gain access to the channel, the probability that the same node pair has m consecutive accesses is p^m, which is small even for small m. For example, if $p = \frac{1}{n}$ in an n-flow system, then $p^m = \frac{1}{n^m}$ which decays relatively fast even for small networks ($p^m = 0.01$ for $m = 2$ and $n = 10$). Thus for any sender-receiver pair, with high probability, the received $\mathsf{S}NR_i$ for a given band are not correlated across time. In essence, random access tends to "decorrelate" the channel even in small user populations. As a result, the current $\mathsf{S}NR_i$ level cannot be predicted whenever two nodes gain access and thus has to be measured for each channel access.

III. Genie-Aided Bound

In this section, we quantify the maximum possible gain from having multiple bands in a system. Since the transmitter can use only one out of K bands, the problem of maximizing throughput translates to choosing the best possible band. To find the maximum possible gain in opportunistic selection of bands, we first analyze a system where a genie provides the transmitter with all $\mathsf{S}NR_i$ *without* any channel measurement overhead. The resulting throughputs serve as an upper bound to the performance of any practical system. Based on the knowledge of $\{\mathsf{S}NR_i\}_{i=1}^K$, the transmitter selects the best band and the accompanying rate of transmission. We further assume that the transmitter performs no power control and uses all its power for every transmission. Though power control can lead to better throughputs [20], it does not change the rate of throughput growth with SNR [21]. Thus, the throughput of the genie-aided system is given by

$$R^*(K) = \mathbb{E}\left[\max_{k=1,\ldots,K} \log\left(1+\mathsf{S}NR_k\right)\right] \quad (5)$$

$$= \mathbb{E}\left[\log\left(1+\max_{k=1,\ldots,K} \mathsf{S}NR_k\right)\right] \quad (6)$$

where the units of rate $R^*(K)$ is nats/s/Hz. Thus, to obtain actual throughput, $R^*(K)$ should be scaled by bandwidth B; the same applies to the analysis in the next section. The equivalence of (5) and (6) follows from the monotonicity of the $\log$ function. Thus if the channel for each of the K bands is known at the transmitter, the throughput optimizing solution is to use the band with the highest $\mathsf{S}NR_k$. Note that no spectral water-filling is possible since the transmitter can only use one band for any single transmission.

Given K circularly symmetric complex Gaussian variables, the growth of the extremum $\max_i \mathsf{S}NR_i$ can be obtained using the following result [22, Sec 9.3, Page 258] or [5].

Lemma 1: Let $z_1, z_2, \ldots, z_K$ be i.i.d. random variables with a common cumulative distribution function $F(\cdot)$ and probability density function $f(\cdot)$ satisfying $F(z)$ is less than 1 for all z and is twice differentiable for all z, and is such that

$$\lim_{z\to\infty}\left[\frac{1-F(z)}{f(z)}\right] = c > 0 \quad (7)$$

for some constant c. Then

$$\max_{1\le k\le K} z_k - l_K$$

converges in distribution to a limiting random variable with cdf $e^{-e^{-x/c}}$. In the above, l_K is given by $F(l_K) = 1-1/K$.

When $|H_k|$ are i.i.d. Rayleigh, $z_k = |H_k|^2$ is exponentially distributed with mean 1. In this case, the condition (7) is satisfied and $l_K = \frac{1}{c}\log K$ suffices. For some $\epsilon > 0$, there exists $\delta > 0$ and $\alpha > 1$ such that

$$\text{Prob}\left(\frac{\max_{1\le k\le K} z_k - \frac{1}{c}\log K}{\log\log K} > \epsilon\right) < \frac{\delta}{(\log K)^\alpha} \quad (8)$$

The above result states that with high probability, $\max_i \mathsf{S}NR_i$ grows as $\overline{\mathsf{S}NR}\log K$.

$$\begin{aligned} R^*(K) &\sim \log\left(\overline{\mathsf{S}NR}\log K\right) \\ &= \log(\overline{\mathsf{S}NR}) + \log\log K \\ &\sim R^*(1) + \log\log K \end{aligned} \quad (9)$$

Thus for large $\overline{\mathsf{S}NR}$, the gain in capacity from multi-band selection is only additive in capacity and the additive term grows as doubly logarithmic in number of bands K. On the other hand, for small $\overline{\mathsf{S}NR}$,

$$R^*(K) \sim \overline{\mathsf{S}NR}\log K = R^*(1)\log K, \quad (10)$$

which implies a multiplicative gain over a single-band system and the multiplicative factor grows logarithmically in K, in contrast to slow growth in (9). Thus, one can conclude that the maximum utility of multi-band transmissions is for small values of average SNR. In the next section, we show that the measurement based system also exhibits the maximum gain for low SNR but the gain does not increase monotonically with K for all cases.

IV. Measurement Based Systems

Next, we study the performance of a measurement based system which has K available bands to transmit in. The basic mechanism of band selection occurs *after* the nodes have gained access to the system; hence the results in this section only focus on the performance benefits during data transmission.

The search for a good channel is constrained by the fact that the transmitter-receiver pair cannot recall the bands they have already visited. In this case, the transmitter-receiver pair have to make a choice after measuring each band regarding using the current band or measuring another band. If the nodes choose to measure another band, then they cannot use any of the previously measured bands. Skipping without recall leads to a conservative design and could be improved upon if the nodes can recall all or some of the previously measured bands.

A. Optimal Stopping Rule

We use the theory of optimal stopping rules for finite horizons [23], [24] to derive the bounds without recall. The finite horizon problem can be solved by using the backward induction principle. Since the nodes cannot use more than K bands, we first obtain the optimal rule for band $K-1$. Knowing the stopping rule at band $K-1$, we can work backwards to find the stopping rule for band $K-2$ and so on. Without loss of generality, we assume first measurement is always made in band 1. Then the k^{th} measurement corresponds to measuring band k.

After measuring band k, assume that the nodes use rate R_k for transmission. Then the "reward" (throughput) for band $k < K$ can be written as

$$\lambda_k = \begin{cases} c_k R_k, & c_k R_k > \Lambda_{k+1} \\ \Lambda_{k+1}, & \text{otherwise} \end{cases}. \quad (11)$$

In (11), Λ_{k+1} represents the expected reward if the nodes skip band k and use one of the remaining unmeasured bands. The constants c_k represent the total reduction in throughput due to k channel measurement, and depends on the choice of transmission policy (see Section II-B).

The stopping rule is completely specified by $\{\Lambda_k\}_{k=1}^{K}$. Since there are a finite number of bands, K, the nodes have to stop at band K and use the available rate to send the packet. Thus the resulting reward is

$$\lambda_K = c_K R_K,$$

where R_K is the available rate in band K at the time of measurement and c_K is the total overhead suffered in measuring K bands. Then the expected reward for band K is

$$\begin{aligned} \Lambda_K &= \mathbb{E}\left[\lambda_K\right] & (12) \\ &= c_K \mathbb{E}\left[R_K\right]. & (13) \end{aligned}$$

Thus, Λ_K gives the expected reward of using the channel in band K. Once Λ_K is available, $\Lambda_{K-1}, \Lambda_{K-2}, \ldots, \Lambda_1$ can be obtained using (11). In the next two subsections, we will study the behavior of Λ_k for two physical layers, one with continuously variable data rates based on information-theoretically optimal coding, and other with finite rate set, representative of practical systems like IEEE 802.11b.

B. Continuously Variable Rates

If the SNR in band k is $\mathsf{S}NR_k$, then the maximum possible data rate is $\log(1+\mathsf{S}NR_k)$. We first compute Λ_K as follows

$$\begin{aligned} \Lambda_K &= c_K \mathbb{E}\left[\log(1+\mathsf{S}NR_K)\right] \\ &= \frac{c_K}{\overline{\mathsf{S}NR}} \int_0^\infty \log(1+\mathsf{S}NR_K) e^{\frac{-\mathsf{S}NR_K}{\overline{\mathsf{S}NR}}} d\mathsf{S}NR_K \\ &= c_K e^{1/\overline{\mathsf{S}NR}} \mathrm{Ei}\left(1, \frac{1}{\overline{\mathsf{S}NR}}\right), & (14) \end{aligned}$$

where the function Ei is the exponential integral (Cauchy principle value integral) defined as $\mathrm{Ei}(1,x) = \int_x^\infty \frac{e^{-t}}{t} dt$ for $x > 0$. Given Λ_K, Λ_k for $k \in \{1, 2, \ldots, K-1\}$ can be computed using the following recursion (following (11))

$$\begin{aligned} \Lambda_k &= \mathbb{E}[\lambda_k] \\ &= \frac{c_k}{\overline{\mathsf{S}NR}} \int_{e^{\Lambda'_{k+1}}-1}^\infty \log(1+\mathsf{S}NR_k) e^{\frac{-\mathsf{S}NR_k}{\overline{\mathsf{S}NR}}} d\mathsf{S}NR_k \\ &\quad + \frac{\Lambda_{k+1}}{\overline{\mathsf{S}NR}} \int_0^{e^{\Lambda'_{k+1}}-1} e^{\frac{-\mathsf{S}NR_k}{\overline{\mathsf{S}NR}}} d\mathsf{S}NR_k \\ &= c_k \left[\Lambda'_{k+1} e^{\frac{(1-e^{\Lambda'_{k+1}})}{\overline{\mathsf{S}NR}}} + e^{\frac{1}{\overline{\mathsf{S}NR}}} \mathrm{Ei}\left(1, \frac{e^{\Lambda'_{k+1}}}{\overline{\mathsf{S}NR}}\right)\right] \\ &\quad + \Lambda_{k+1}\left(1 - e^{\frac{(1-e^{\Lambda'_{k+1}})}{\overline{\mathsf{S}NR}}}\right) \\ &= c_k e^{\frac{1}{\overline{\mathsf{S}NR}}} \mathrm{Ei}\left(1, \frac{e^{\Lambda'_{k+1}}}{\overline{\mathsf{S}NR}}\right) + \Lambda_{k+1} & (15) \end{aligned}$$

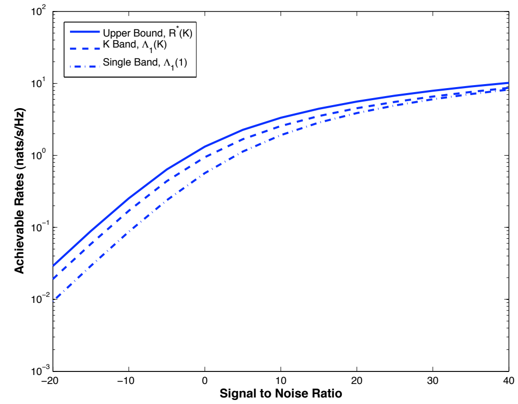

Fig. 2. Achievable rates as a function of SNR for the upper bound with $K = 10$ bands, multi-band system with $K = 10$ bands and a single-band system. Constant access time policy is used with $\tau = 0.05$.

where $\Lambda'_{k+1} = \frac{\Lambda_{k+1}}{c_k}$. The total expected throughput available from using K bands is then given by Λ_1. Whenever necessary, we will show explicit dependence of Λ_1 on the number of bands as $\Lambda_1(K)$. Figures 2 and 3 show the achievable rates as a function of SNR and number of bands K. For a fixed number of bands $K = 10$ and using the constant access time policy in (3) with $\tau = 0.05$, Figure 2 shows that the biggest gain from multi-band skipping is at low to medium SNRs. Using the metric of throughput gain, we will show that the above conclusion is in fact true in general. Furthermore, the same analysis will also show that the rate of growth as a function of $\overline{\text{SNR}}$ is $\Lambda_k \sim c'_k \log(\overline{\mathsf{S}NR})$ for high SNRs and $\Lambda_k \sim c''_k \overline{\mathsf{S}NR}$ for low SNRs.

The behavior as a function of K is remarkably different for a fixed SNR, as shown in Figure 3 for SNR = 20dB and the constant access time policy with $\tau = 0.05$. As K increases, the upper bound $R^*(K)$ has a throughput increase of $\log\log(K)$. On the other hand, $\Lambda_1(K)$ saturates because of increasing overhead. In fact, the overhead of measuring 20 bands equals the total access time ($20 \times 0.05 = 1$) leaving no time for actual data. Thus, it is clear that the throughput of measurement based system cannot increase unboundedly like the upper bound $R^*(K)$. Though the throughput does not grow unboundedly in multi-band systems, it is higher than a single-band system, which is the bottom-most curve in Figure 3. Hence, even with finite measurement overheads, there is a gain in skipping from one band to another in search of a better channel.

Next we study some of the properties of the adaptive system based on the optimal skipping rule as a function of SNR and number of bands. To study the behavior of the system throughput, we study thoughput gain, which is rate of growth (or decay) of throughput when compared to a single-band rate-adaptive system ($K = 1$ in the optimal skipping based system). For the K-band system without recall, the throughput gain of the expected reward at band k is defined

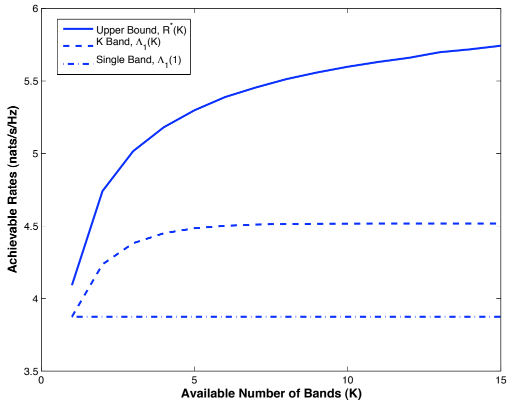

Fig. 3. Achievable rates as a function of number of bands K for the upper bound, multi-band system and a single-band system for SNR=20 dB. Constant access time policy is used with $\tau = 0.05$.

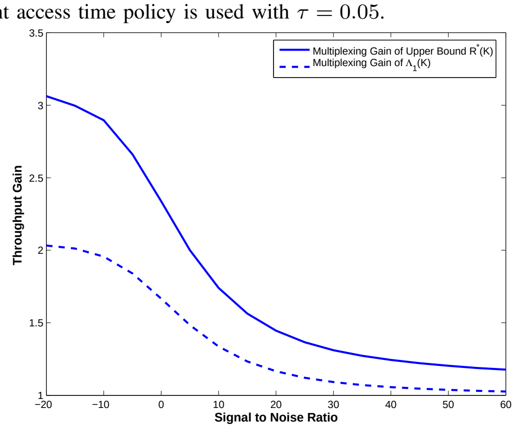

Fig. 4. Throughput gain as a function of SNR for the upper bound with $K = 10$ bands, multi-band system with $K = 10$ bands and a single-band system. Constant access time policy is used with $\tau = 0.05$.

as

$$r_k(\overline{\mathsf{SNR}}) = \frac{\Lambda_k(K)}{\Lambda_1(1)},$$

which measures the gain of using K bands over the system which uses only one band. We study the behavior of throughput gain in two SNR regimes, $\overline{\mathsf{SNR}} \to 0$ and $\overline{\mathsf{SNR}} \to \infty$.

Proposition 2 (Throughput Gain in Low SNR): Let r_k represent the limit $\lim_{\overline{\mathsf{SNR}}\to 0} r_k(\overline{\mathsf{SNR}})$, then the throughput gain for the system using optimal skipping rule in the low SNR regime is given by

$$r_k = \frac{c_k}{c_1} e^{-\frac{c_1 r_{k+1}}{c_k}} + r_{k+1},$$

where $r_{K+1} = 0$.

Proof: We prove the first part using induction on k, starting from $k = K$. First note that for small SNR,

$$\begin{aligned}\Lambda_K(K) &= c_K e^{1/\overline{\mathsf{SNR}}} \mathrm{Ei}\left(1, \frac{1}{\overline{\mathsf{SNR}}}\right) \\ &\approx c_K \overline{\mathsf{SNR}},\end{aligned}$$

using the small SNR approximation for the exponential integral. Also, the same approximation can be used to obtain $\Lambda_1(1) \approx c_1 \overline{\mathsf{SNR}}$. This immediately implies that $r_K = \frac{c_K}{c_1}$. Using the approximation for $\Lambda_K(K) \approx c_1 r_K \overline{\mathsf{SNR}}$ in $\Lambda_{K-1}(K)$, we obtain

$$\begin{aligned}\frac{\Lambda_{K-1}(K)}{\Lambda_1(1)} &\approx \frac{c_{K-1} e^{1/\overline{\mathsf{SNR}}} \mathrm{Ei}\left(1, \frac{e^{c_1 r_K \overline{\mathsf{SNR}}/c_{K-1}}}{\overline{\mathsf{SNR}}}\right) + c_1 r_K \overline{\mathsf{SNR}}}{c_1 \overline{\mathsf{SNR}}} \\ &\to \frac{c_{K-1}}{c_1} e^{-c_1 r_K / c_{K-1}} + r_K = r_{K-1}\end{aligned}$$

The above result further implies that for small $\overline{\mathsf{SNR}}$, $\Lambda_{K-1} \approx c_1 r_{K-1} \overline{\mathsf{SNR}}$. Thus, r_{K-2} can be obtained using the same steps as above with r_K replaced by r_{K-1}, giving the recursive relation for throughput gain r_k. ■

From the recursive relation of r_k, it is clear that $r_k \geq r_{k+1}$ since the first term on the right hand side is non-negative. Figure 4 shows the typical behavior of throughput gain as a function of SNR for the upper bound $R^*(K)$ and $\Lambda_1(K)$ for $K = 10$ bands with an overhead of $\tau = 0.05$ for the constant access time policy. As can be seen, the throughput gain reduces monotonically with increasing SNR and shows that the biggest gains are at low to medium SNRs. In fact, as the SNR increases, the throughput gain of $\Lambda_1(K)$ approaches one as shown in the next proposition.

Proposition 3 (Throughput Gain in High SNR): The throughput gain for the system using optimal skipping rule in the high SNR regime is given by

$$\lim_{\overline{\mathsf{SNR}}\to\infty} r_k(\overline{\mathsf{SNR}}) = \frac{c_k}{c_1}.$$

Proof: We again use induction starting from Λ_K in (14). As $\overline{\mathsf{SNR}} \to \infty$, $e^{1/\overline{\mathsf{SNR}}} \to 1$ and

$$\mathrm{Ei}\left(1, \frac{1}{\overline{\mathsf{SNR}}}\right) \approx \log(\overline{\mathsf{SNR}}) + o\left(\overline{\mathsf{SNR}}^{-1}\right),$$

which implies that $\Lambda_1(1) \approx c_1 \log(\overline{\mathsf{SNR}})$. Thus, $\lim_{\overline{\mathsf{SNR}}\to\infty} \frac{\Lambda_K}{\Lambda_1(1)} = \frac{c_K}{c_1}$. As a result, Λ_{K-1} can be approximated as

$$\begin{aligned}\Lambda_{K-1} &\approx c_{K-1}\left[\frac{c_K \log(\overline{\mathsf{SNR}})}{c_{K-1}} + \left(1 - \frac{c_K}{c_{K-1}}\right)\log(\overline{\mathsf{SNR}})\right] \\ &= c_{K-1} \log(\overline{\mathsf{SNR}})\end{aligned}$$

which implies $\lim_{\overline{\mathsf{SNR}}\to\infty} \frac{\Lambda_{K-1}}{\Lambda_1(1))} = \frac{c_{K-1}}{c_1}$. To arrive at the above approximation, we have used the fact that

$$\lim_{\overline{\mathsf{SNR}}\to\infty} e^{\frac{(1-e^{\Lambda_K/c_{K-1}})}{\overline{\mathsf{SNR}}}} = 1$$

The above steps apply for Λ_{K-2} by replacing K with $K-1$, and hence the result is proved. ■

Thus, the throughput gain of $\Lambda_1(K)$ is one for all K, which implies that the rate of throughput growth for the measurement based method is the same as a single band system for *any* number of bands. In other words, there is no gain in having many available bands when the average SNR is high in each band. The result is intuitive since good channel conditions on average imply that nodes need not skip to other bands in search of better channels. We further strengthen that intuition with the following result on the probability of skipping in the two SNR regimes.

Proposition 4 (Probability of Skipping): As $\overline{\mathsf{S}NR} \to 0$, the probability of skipping band k after measuring it, Π_k, converges to

$$\lim_{\overline{\mathsf{S}NR}\to 0} \Pi_k = 1 - e^{-\frac{c_1 r_{k+1}}{c_k}}.$$

On the other hand, for large $\overline{\mathsf{S}NR}$, the probability of skipping band k after measuring it decays as

$$\Pi_k \approx \frac{1}{\overline{\mathsf{S}NR}^{1-\frac{c_{k+1}}{c_k}}}. \quad (16)$$

Since $\frac{c_{k+1}}{c_k} < 1$ for all j for both constant access time and constant data time policies, the probability of skipping any band goes to zero for large $\overline{\mathsf{S}NR}$.

Proof: The probability of skipping *after* having measured band k, Π_k for $k \in \{1, \ldots, K-1\}$ can be computed as follows,

$$\begin{aligned} \Pi_k &= \text{Prob}\left[\log(1+\mathsf{S}NR_k) < \frac{\Lambda_{k+1}}{c_k}\right] \\ &= \text{Prob}\left[\mathsf{S}NR_j < e^{\Lambda_{k+1}/c_k} - 1\right] \\ &= 1 - e^{\frac{1-e^{\Lambda_{k+1}/c_k}}{\overline{\mathsf{S}NR}}} \end{aligned} \quad (17)$$

For small SNR, $\Lambda_{k+1} = c_1 r_{k+1}\overline{\mathsf{S}NR}$ from Proposition 2. Thus,

$$\begin{aligned} \Pi_k &\approx 1 - e^{\frac{1-e^{c_1 r_{k+1}\overline{\mathsf{S}NR}/c_k}}{\overline{\mathsf{S}NR}}} \\ &\to 1 - e^{-\frac{c_1 r_{k+1}}{c_k}} \end{aligned}$$

For large SNR, $\Lambda_{k+1} \approx c_{k+1}\log(\overline{\mathsf{S}NR})$ from Proposition 3. Thus,

$$\begin{aligned} \Pi_k &\approx 1 - e^{\frac{e^{c_{k+1}\log(\overline{\mathsf{S}NR})/c_k}}{\overline{\mathsf{S}NR}}} \\ &= 1 - e^{\frac{\overline{\mathsf{S}NR}^{\frac{c_{k+1}}{c_k}}}{\overline{\mathsf{S}NR}}} \\ &\approx \frac{1}{\overline{\mathsf{S}NR}^{1-\frac{c_{k+1}}{c_k}}}, \end{aligned}$$

which proves the result. ■

Once the probability of skipping a band is known, the average number of band skips can be easily calculated using the following relation. Define $\Pi_0 = 1$ and $\Pi_K = 0$, then the expected number of steps $\overline{K}$ can be found as follows

$$\overline{K} = \sum_{j=1}^{K}\left[j(1-\Pi_j)\prod_{l=0}^{j-1}\Pi_l\right] \quad (18)$$

C. Finitely Variable Rates

In actual networks, neither the channel distribution is known nor can the nodes use an arbitrary number of rates for transmission. In this section, we derive the optimal stopping rule for networks which have arbitrary distribution for the channel SNR and the nodes can use only a finite number of rates. Let the set of possible rates be denoted by R_l where $l = 0, 1, \ldots, L$ such that $R_0 = 0$. Denote the probability of getting rate R_l by p_l, such that $\sum_{l=0}^{L} p_l = 1$. Then the expected throughput for band K is given by

$$\Lambda_K = c_K \sum_{l=0}^{L} p_l R_l. \quad (19)$$

Once Λ_K is available, then using (11), Λ_k for all $k < K$ can be computed the following recursion. Define the indicator set $\mathbf{1}_l(k) = \{l : c_k R_l \geq \Lambda_{k+1}, l \in \{0, \ldots, L\}\}$ and its complement $\overline{\mathbf{1}}_l(k) = \{l : c_k R_l < \Lambda_{k+1}, l \in \{0, \ldots, L\}\}$. Then

$$\Lambda_k = c_k \sum_{l\in\mathbf{1}_l(k)} p_l R_l + \Lambda_{k+1}\sum_{l\in\overline{\mathbf{1}}_l(k)} p_l. \quad (20)$$

By defining $\Lambda_{K+1} = 0$, then (20) also leads to Λ_K in (19). Note that the second summation is the probability of skipping band k, Π_k.

To compute the optimal skipping rule, the nodes need to only know p_l, which is location dependent and channel type dependent. The channel type depends on the amount of scattering in the environment and the extent of mobility, and is often modeled by a different K-factor in Ricean channel models. The decision to skip can be made by only one of the nodes, sender or receiver, and hence only one of the nodes needs to estimate the probabilities p_l. In the sequel, we propose a multi-band protocol and present a performance evaluation of the above case with finitely variable rates.

V. Multi-band Opportunistic Auto Rate (MOAR) Protocol

In this section, we present a CSMA/CA protocol based on the IEEE 802.11 DCF mechanism to exploit multi-band opportunism. The authors proposed OAR in [7] which can be characterized as opportunistic across users, exploiting periods of high quality channel to achieve throughput gains. Using OAR as one mechanism, the proposed multi-band protocol naturally exploits both temporal and spectral opportunism. We first present the challenges in designing a CSMA/CA protocol that senses different portions of spectrum in search of good channels and follow that discussion with an actual protocol to address the main design challenges.

Measuring channel conditions before and after each skip: For realistic systems, channel conditions on all the bands are not known *a priori*. Moreover, since channel conditions are continually changing, past channel measurements (beyond several packet transmission times, i.e., the coherence time interval) are not a useful predictor of current channel conditions. Hence, there is a need to introduce a mechanism to measure the current conditions in the present band before making the decision whether to skip to another band or not.

Coordinating a channel skip decision between the transmitter and the receiver: Prior to skipping, the transmitter and the receiver of a flow need to mutually decide the band to skip to. Since a wireless ad hoc network does not have a central entity to coordinate skip decisions, there is a need for a distributed mechanism to coordinate the skip decision between the transmitter and receiver.

Maintaining carrier sense for all overhearing nodes: A potential problem with band skipping in wireless ad hoc networks is the need to maintain carrier sense for all overhearing nodes to avoid the hidden terminal problem [25]. This involves making sure that all overhearing nodes are able to correctly set their defer timers so as to allow the transmitter-receiver pair sufficient time to skip to better quality channels.

Limiting the number of times nodes skip in search of a better quality channel: Potentially, a transmitter-receiver pair can continue skipping multiple times in search of the highest quality channel. However, due to the overhead of channel measurement and estimation incurred at every skip, throughput gains of sending data on a better quality frequency channel are diminishing with each skip (as discussed in Section IV-A). The optimal skipping rule devised in Section IV-A allows a MOAR node to limit the number of times it skips in search of better quality channels, to optimally balance the tradeoff between the opportunistic throughput gain and the overhead of channel skipping and channel measurement.

A. MOAR Protocol Description

In this section we describe how MOAR employs a band skipping technique within the IEEE 802.11 framework.[2] All nodes initially reside on a single common frequency band, known as the *home band*. DATA transmission is preceded by the sender transmitting an RTS packet to the receiver on the home band. On reception of the RTS frame, the receiver makes the decision to skip by comparing the measured SNR to a channel skip threshold.[3] If the measured SNR is low, the sender and receiver skip to a new channel in search of a better quality channel, whereas if the measured SNR is high, data is transferred on the current frequency channel as in the OAR protocol, in which nodes transfer multiple back-to-back packets in proportion to their channel quality.

On making the decision to skip, the receiver selects a band to skip to and piggy-backs this channel on the CTS packet. After transmitting the CTS frame, the receiver immediately skips to the new frequency channel and waits for another RTS from the receiver for a time equal to the CTS timeout value as mandated by the IEEE 802.11 standard. Since we assume that in a realistic setting channel conditions on other frequency channels are unknown, the band to which the receiver decides to skip is selected *randomly* among the available frequency bands. Yet, if information regarding channel conditions or interference on some other band is known (e.g, in a wireless LAN scenario where the Access Point (AP) may have information regarding interference on other bands), the receiver can take that into account to make a better decision about which band to skip to. However, for the purpose of this discussion we do not require the existence of such information.

If after skipping to a new band, the receiver does not receive another RTS from the sender within a CTS timeout period, the receiver node switches back to the home band and starts contending for channel access as mandated by the IEEE 802.11 standard.

Once the sender receives confirmation of the choice of band to skip to from the receiver (via a CTS frame), it immediately skips to that band. Note that the time elapsed for switching channels is $\sim 1 \mu s$ [28] and has negligible overhead. After skipping to the selected channel, the transmitter and receiver renegotiate the data rate via another RTS/CTS exchange which also serves the dual purpose of measuring the channel. In case the channel quality on the new band is measured to be below the skip threshold, the sender-receiver pair can choose to skip again in search of a better quality channel.

Since RTS/CTS exchange prior to any channel skip is done at the base rate on the home band, all nodes within radio range of the receiver and the transmitter can also decode these packets. However, some nodes (including nodes within radio range of the sender but outside the radio range of the receiver) may be unable to hear the CTS packet and are unable to detect whether a decision to skip bands was made or not. Moreover, even though nodes within radio range of the receiver can correctly decode a CTS packet and infer that a decision to skip has been made, they are unable to set a correct defer time since it is not known *a priori* how many times the sender-receiver pair may skip in search of a better quality channel. This can lead to problems similar to the hidden terminal problem [25].

To solve the problem mentioned above, all MOAR nodes upon reception of an RTS/CTS packet defer (via the Network Allocation vector, NAV) for a fixed amount of time corresponding to a maximum time, D_{skip}, necessary for the

[2] Although our discussion of MOAR is within the context of the RTS/CTS mechanism within the DCF mode of IEEE 802.11, the concepts are equally applicable to other RTS/CTS based protocols such as SRMA [26], and FAMA [27].

[3] A reasonably accurate estimate of the received SNR can be made from physical-layer analysis of the PHY layer preamble to each packet.

transmitter and receiver to skip (multiple times, if required) to a better quality channel and finish the DATA/ACK transmission. D_{skip} is given by

$$D_{skip} = K \cdot T_{overhead} + T_D, \quad (21)$$

where, K is the maximum number of allowed channel skips, $T_{overhead}$ is the time taken for RTS/CTS exchange at base rate, including all the defer timers (EIFS, SIFS, DIFS etc) as mandated by the IEEE 802.11 standard. The time period T_D represents the time to send data packet at the base rate.

We refer to D_{skip} as a *temporary reservation*, to denote the fact that the reservation is not an actual reservation but represents a maximal amount of reservation time. A temporary reservation serves to inform the neighboring nodes that a reservation has been requested but the duration of the reservation is not known. Any node that receives the temporary reservation is required to treat it the same as an actual reservation with regard to later transmission requests; that is if a node overhears a temporary reservation it must update its NAV so that any later requests it receives that would conflict with the temporary reservation must be denied. Thus the temporary reservation serves as a placeholder until either a new reservation is received or is canceled. If the sender-receiver pair decide not to skip bands then they can proceed with the DATA/ACK exchange on the home band as dictated by OAR in which case other nodes can replace the temporary reservation with the exact reservation, as carried in the DATA/ACK packets.

Once the transmitter and the receiver conclude the DATA/ACK transmission by skipping to one or more bands, they return to the home band. The ACK for the final packet (recall in OAR, nodes can send multiple back-to-back packets) is sent in the home band at base rate by the sender, and the sender rebroadcasts the same ACK. The two-way ACK in the home-channel is necessary to ensure that all the nodes within the range of either the sender and/or the receiver can correctly infer the end of channel skipping and cancel the temporary reservation timer. In case a node is unable to hear either the updated reservation or the DATA/ACK transmission signalling the end of the temporary reservation, it would be able to contend for the channel again after the temporary reservation has expired.

In the next section we discuss issues in implementing the optimal stopping rule in actual networks.

VI. Implementation Issues for Optimal Stopping Rule

The optimal stopping rule derived for finite rates (Section IV-C) depends the distribution of possible data rates which in turn depends on the distribution of the channel. Thus, for a node to compute the optimal stopping thresholds Λ_k, we need the probabilities of different data rates p_l in Equations (19) and (20) and the cost of measurement c_k.

The cost of channel measurement via RTS/CTS, c_k, is a constant and for a fixed RTS/CTS packet size can be computed as in Equation (3) or (4). The key challenge for the nodes is to compute p_l, which is the probability of data rate R_l. Alternatively, if the underlying distribution of signal to noise ratio, SNR and its parameters (mean, variance, etc.) are known, the nodes can compute p_l indirectly rather than requiring it to be provided explicitly. However, in practice, the parameters of the SNR distribution or the distribution itself may not be known *a priori*. Moreover, for mobile nodes, the parameters of the channel fading distribution (and hence the distribution of data rates) may also change with time as the distance between the sender and the receiver changes. In such cases, in order to make a skipping decision in accordance with the optimal skipping rule, a node may need to estimate either the parameters of the underlying distribution of channel fading or the distribution of data rates.

In case the underlying distribution of the channel fading is known but the exact parameters of the distribution are unknown, a MOAR node can choose to estimate the unknown parameters. Various point estimation techniques such as the method of moments and maximum likelihood estimation (among others [29], [30]) have been proposed and well studied in the literature. In particular, [31] compares the efficiency of different techniques for estimating the unknown parameters for a Rayleigh distribution. However, estimating the unknown parameters of a Ricean distribution is computationally expensive [32]. Moreover, in certain scenarios the exact distribution of the received SNR may be unknown which makes estimating p_l infeasible. Thus rather than estimating the underlying distribution of the received SNR we choose to directly estimate the distribution of achievable data rates by measuring p_R from samples of received SNR.

To estimate the distribution of the transmission data rates, we propose that each MOAR node transmits the first N_{est} packets without channel skipping in an effort to estimate p_l. We denote N_{est} as the *estimation window*. Each transmitted data packet (and the accompanying control packets RTS/CTS/ACK) contributes towards the samples needed to estimate the needed parameters. We estimate the probability $\hat{p}_l$, that the feasible data rate is R_l by

$$\hat{p}_l = \frac{\sum_{i=1}^{N_{est}} 1(\mathsf{S}NR_{l-1} < \mathsf{S}NR_i < \mathsf{S}NR_l)}{N_{est}}, \quad (22)$$

where, N_{est} denotes the size of the estimation windows over which p_l is being estimated, $1(\cdot)$ is the indicator function, $\mathsf{S}NR_i$ denotes the received SNR for sample i and $(\mathsf{S}NR_{l-1}, \mathsf{S}NR_l)$ denotes the SNR thresholds between which rate R_l is feasible.

After enough samples have been collected to estimate the distribution of the transmission rates within certain confidence, MOAR nodes may start opportunistic channel skipping. Since the distribution of data rates may change over time, MOAR nodes continuously update the estimated values of p_R by using only the last N_{est} samples of the received SNR. In this way, MOAR is still able to perform well for scenarios where the channel conditions change (for example, due to mobility) at a time scale greater than the time required to accurately estimate the distribution of data rates.

Note that the accuracy of the estimation scheme described above depends on the size of the estimation window, N_{est}. If the size of the estimation window is large then p_l can be estimated with greater confidence which in turns increases the accuracy of the optimal skipping rule for MOAR. However, longer estimation windows mean that the estimates are less responsive to changes in the probability distributions. On the other hand, a small estimation window can lead to more responsive but less accurate estimate of p_l which in turn could reduce the throughput gains of MOAR. Thus, there is an inherent tradeoff between the speed of adaptation of estimates and the resulting accuracy.

In Section VII, we investigate the effect of estimation window size on the throughput performance of MOAR via simulations and suggest a suitable value of the estimation window size for which MOAR is able to extract maximal throughput gains available from opportunistic skipping.

VII. Performance Analysis of MOAR

In this section, we use *ns-2* simulations to evaluate the performance of MOAR as compared to OAR. Our key performance metric is aggregate throughput while maintaining the same time share as IEEE 802.11. All experiments use the fast fading model with the Ricean probability density implemented in the *ns-2* extension [33]. Although the *ns-2* extensions implemented in [33] result in an accurate simulation of the wireless channel for each individual flow, the fading components of channels for different flows are *identical*, a scenario not encountered in practice. This arises due to the fact that the index into the pre-computed channel table is chosen based on the simulator's time instant, which is identical for all flows. Thus, to realistically model the wireless channel for multiple users in a manner consistent with [6], we modified the extensions of [33] such that channel lookup indexes are a function of the flow, time, and IEEE 802.11 band. This allows us to accurately model independent fading suffered by the different frequency channels. As in [33], background noise is modeled with $\sigma = 1$.

The available rates for both MOAR and OAR, based on IEEE 802.11b, are set to 2 Mb/sec, 5.5 Mb/sec, and 11 Mb/sec, so that with OAR, nodes can respectively transmit 1, 3, or 5 consecutive packets depending on their channel condition. The values for received power thresholds for different data rates were chosen based on the distance ranges specified in the Orinoco™802.11b card data sheet. For *only* the path loss component (no channel fading) of the received power, the threshold received power for 11 Mb/sec, 5.5 Mb/sec, and 2 Mb/sec correspond to distances of 100 m, 200 m, and 250 m respectively. As specified by the IEEE 802.11 standard, we set the rate for sending physical-layer headers to 1 Mb/sec for all packets. Each transmitter generates constant-rate traffic such that all nodes are continuously backlogged. Moreover, packet sizes are set to 1000 bytes and all reported results are averages over multiple 50-second simulations.

Here, we study the factors that impact the performance of MOAR in fully connected topologies in which all nodes are within radio range of each other. Such topologies are representative of a wireless LAN scenario. The performance factors we study are location distribution, Ricean parameter K, error in channel measurement and the impact of estimating channel distribution while employing the optimal skipping rule within MOAR. Finally we combine all these factors to explore the performance of MOAR for random fully connected topologies.[4]

A. Location Distribution

The opportunistic gain that can be achieved by skipping bands is dependent upon the temporal channel quality which has two components, a random fading component and a constant line of sight propagation loss component. In this experiment, we study the impact of the node location distribution by considering a scenario where there is a single flow and the distance (and hence the strength of the line of sight component) between the sender and the receiver is varied. The random channel fading is kept constant by setting the Ricean fading parameter, $K = 4$.

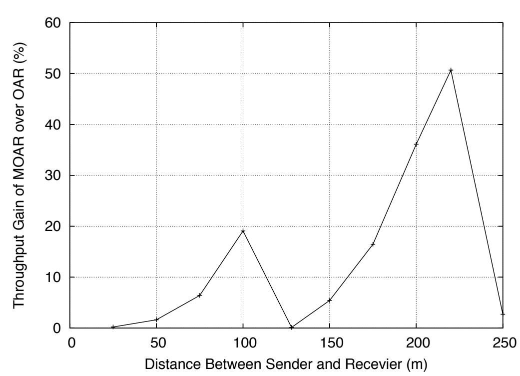

Fig. 5. Throughput gain of MOAR as a function of distance between the sender and the receiver node

Figure 5 depicts the average throughput gain of MOAR over OAR as the distance between the sender and the

[4]More extensive simulation results are available in [34], and are not presented in this paper for lack of space.

receiver of a flow is varied. The throughput gain has two peaks corresponding to distance between the sender and the receiver of 100 m and 225 m respectively. This is due to the fact that the path loss component of the received power has distance thresholds for 11 Mb/sec, 5.5 Mb/sec, and 2 Mb/sec of 100 m, 200 m and 250 m respectively. Thus for distances less than 100 m, the average channel condition corresponds to a data rate of 11 Mb/sec, distances between 100 m and 200 m correspond to a data rate of 5.5 Mb/sec and distances between 200 m and 250 m correspond to a data rate of 2 Mb/sec. Whenever the two mobile nodes are close to each other, the line of sight component dominates resulting in minimal available channel diversity gains over and above what OAR can achieve. However, as the distance between the two mobile nodes approaches the thresholds where the average data rate is often switched, random channel variations become comparable with the line of sight component. Finally, we note that the increasing height of the peaks with larger distance matches the predictions made in Section IV-B, that the largest throughput gain from channel skipping is in the low-SNR regime (see also Figure 4).

B. Impact of Ricean Parameter, K

In this section we explore the effect of the Ricean parameter K on the throughput performance of MOAR relative to OAR. For lower values of K, the contribution of the line of sight component to the received SNR is weaker, and hence overall channel quality is poor. With increasing K, the line of sight component is stronger such that the overall SNR increases and a higher transmission rate is feasible. We study the effect of K on the throughput gain of MOAR relative to OAR. To isolate the effect of K, we simulate one flow with the distance between the source and the destination fixed thereby keeping the line of sight component constant.

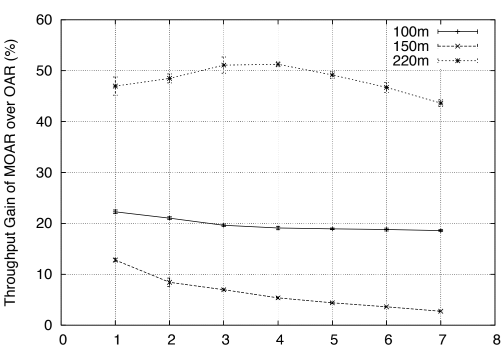

Fig. 6. Throughput gain of MOAR over OAR as a function of the Ricean parameter K

Figure 6 depicts the average percentage throughput gain of MOAR over OAR versus the Ricean fading parameter K for distance between the sender an the receiver fixed to 220 m, 150 m and 100 m respectively. 95% confidence intervals for 5 random simulation runs (each 50 seconds long) are also shown. Observe that MOAR outperforms OAR by 40% to 55% when the distance between the sender and the receiver is 220 m indicating that significant throughput gains can be obtained by opportunistically exploiting the temporal variations among the IEEE 802.11b bands. However, the throughput gain with increasing K is dependent on the distance between the sender and the receiver. In particular, when the distance between the sender and the receiver is 100 m or 150 m, the throughput gain of MOAR over OAR decreases with increasing K. This is due to the fact that a larger value of K represents a smaller variation in channel quality which reduces the probability that the channel conditions on one of the other IEEE 802.11 bands is better than the channel conditions on the home band. Thus the opportunity to skip bands opportunistically decreases leading to a decrease in throughput gain of MOAR over OAR with increasing K.

On the other hand when the distance between the sender and the receiver is 220 m, the throughput gain of MOAR over OAR *increases* with an increasing value of K. Note that MOAR can skip bands opportunistically only after the initial RTS/CTS on the home band takes place successfully. When the distance between the sender and the receiver is 220 m the line of sight component is already very weak and low values of K (denoting high channel variance) makes the transmission of RTS/CTS on the home band sometime impossible as the received power is below the threshold required to correctly decode packets. As K increases, channel variance decreases and RTS/CTS on the home band have a higher probability of being correctly received which allows MOAR greater opportunity to skip bands. Thus the throughput of both OAR and MOAR increases with increasing K. Lower values of K means that MOAR has lower probability of finding good channels. However, higher average channel quality provides *increased* opportunity to skip poor bands and find a higher data rate channel which dominates the fact that there is a lower probability of finding better quality channels. Thus the gain of MOAR over OAR increases for increasing K rather than showing a decrease as one would intuitively expect and as is shown when the distance between sender and receiver is 100 m or 150 m.

C. Channel Measurement Error

We next study the impact of error in channel quality measurement on the performance of MOAR (we previously considered perfect channel measurement). We consider the case that the measured channel SNR is the true SNR plus a Gaussian error process. The impact of channel estimation error is location dependent. For small distances (less than 100m), the system is very robust to even large errors primarily because the system does not skip very often.

However, the loss due to estimation error is the largest when the distance is greater than 100m, with largest loss in performance as the distance increases. Figure 7 depicts the average performance loss as a function of standard deviation of the measurement error, where the average is performed over the distance between the source and the receiver. On average, there is a significant loss in throughput gain even for small errors. Thus, it is important to develop accurate channel estimation procedures to extract the maximum possible from opportunistic band selection.

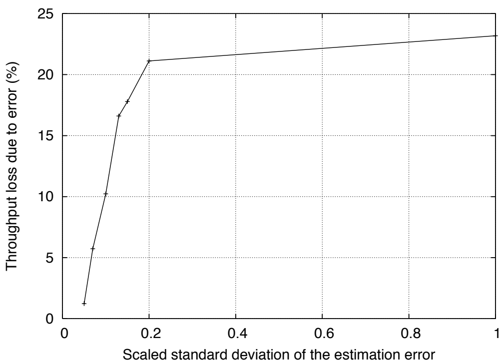

Fig. 7. Throughput loss of MOAR due to channel measurement error

D. Optimal Skipping Rule: Effects of Estimation

We discussed the challenges involved in implementing an optimal skipping rule in actual systems in Section VI. In particular we proposed a measurement based scheme to estimate p_R, the probability that data rate R is feasible. In this section we study the impact of the size of the estimation window (N_{est}) on the performance of MOAR and suggest a suitable value of the estimation window size in order to extract maximal throughput gain from MOAR. We consider a single flow with the distance between the sender and the receiver fixed to d. The random channel fading is kept constant by setting the Ricean parameter, $K = 3$.

Figure 8 plots the average throughput gain (over 3 runs of 25 sec each) of MOAR over OAR versus the estimation window size, N_{est}, for different values of d, the distance between the sender and the receiver. Observe that for each value of d, for a small value of N_{est} MOAR is not able to extract significant throughput gain due to opportunistic band skipping. However, for N_{est} greater than a critical value (for each value of d), MOAR outperforms OAR by 5%-50% depending on the distance between the sender and the receiver. The reason for this behavior is that for a smaller estimation window size, the proposed measurement based scheme to estimate the distribution of feasible data rates does not have enough samples to accurately estimate the distribution. Thus, in this regime the optimal skipping rule

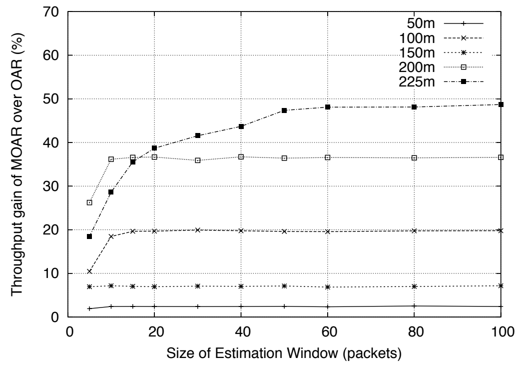

Fig. 8. Effect of estimation window size on throughput gain of MOAR

results in a conservative value of the skipping threshold which in effect causes MOAR to be conservative in band skipping and the throughput gain of MOAR over OAR is very small. However, for a larger estimation window size, the measurement based estimation scheme is able to estimate the channel rate distribution quite accurately which in turn implies that MOAR is able to aggressively skip bands as dictated by the optimal skipping rule. Hence, MOAR is able to extract the maximal throughput gains available via opportunistic band skipping. Figure 8 also indicates that the critical value of the estimation window is dependent on the distance between the sender and receiver. In particular, the minimum size of the estimation window for which MOAR outperforms OAR ranges from 5 to 50 packets.

In practical systems the distance between the sender and the receiver is either unknown *a priori* or can change due to node mobility. Thus it is important to set the value of the estimation window size such that MOAR is able to extract maximal gains from opportunistic band skipping independent of the distance between the sender and the receiver. It can be seen from Figure 8 that an estimation window size equal to 60 packets is able to achieve maximal throughput gain over OAR irrespective of the distance between the sender and receiver.

E. Random Fully Connected Topologies

Here we consider random topologies representative of a wireless LAN and consider a scenario where the link distance is uniformly distributed in a circular area with diameter 250 m. We fix the Ricean fading parameter to K=4 and also set the size of the estimation window to 60 packets as discussed in the previous section. Figure 9 shows the average throughput gain of MOAR over OAR (computed on a per-flow basis and then averaged over flows). The curve labeled "Look-ahead" represents the genie-aided protocol in which channel state information for all the 11 bands is known *a priori* and thus flows need to skip at a maximum of one time to the band with known higher rate than the present band. This serves as an upper bound to the gain that MOAR can extract over OAR. We also implement the optimal skipping rule (as derived in Section IV-A) and plot the throughput gains of MOAR with optimal skipping over OAR.

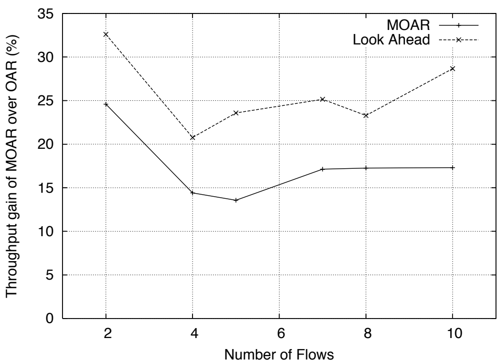

Fig. 9. Throughput gain of MOAR for random fully connected topologies

As discussed above, the opportunistic gain that MOAR can extract is dependent upon the distance between the sender and receiver of a flow. For a given random topology, some flows are located in a region where the opportunistic gain obtained by skipping bands is not significant. These nodes, besides contributing little to the net overall gain that MOAR can obtain, actually reduce the opportunistic gain for better located nodes. The reason can be attributed to the random nature of the MAC: Whenever nodes with lower opportunistic gain access the medium, nodes which are better located to exploit the opportunistic gain through band skipping defer medium access. Thus, the net opportunistic gain that can be obtained by exploiting channel diversity is reduced. However, on average MOAR still outperforms OAR by 14-24%. Also note that the gain of MOAR with optimal skipping is very close to the maximum gain achievable if the channel condition on all the 11 bands is known *a priori*. Thus, in realistic systems where channel state information on other channels may be unavailable, the optimal skipping rule can still enable MOAR to capture most of the performance gains available via opportunistic skipping.

VIII. Summary

In this paper we analyzed the gains from multi-band spectral opportunism via information theoretic bounds. The bounds show the value in opportunistically searching for better bands on a packet time-scale and also indicate the extent of gain available due to multiple band based spectral opportunism. We devised the Multi-band Opportunistic Auto Rate (MOAR) protocol to exploit these gains in random-access systems. MOAR allows nodes to opportunistically skip frequency channels in search of better quality channels to achieve higher throughputs. To balance the tradeoff between the time and resource cost of channel measurement/channel skipping and the throughput gain available via transmitting on a better channel, we also devised an optimal stopping rule for MOAR. Finally we explored the performance of MOAR via extensive simulations and showed that MOAR achieves a consistent gain in throughput of 20% to 25% over current state-of-the-art multi-rate MAC protocols.

Acknowledgements

The authors thank the reviewers for their careful reviews and excellent suggestions which greatly improved the paper, especially the section on optimal stopping rules. Furthermore, we thank Jingpu Shi of Rice University for his extensive help with simulations. Finally, we thank Vikram Kanodia for several insightful discussions.

References

[1] S. Borst and P. Whiting, "Dynamic rate control algorithms for HDR throughput optimization," in *Proceedings of IEEE INFOCOM 2001*, Anchorage, Alaska, 2001.

[2] X. Liu, E. Chong, and N. Shroff, "Transmission scheduling for efficient wireless network utilization," in *Proceedings of IEEE INFOCOM 2001*, Anchorage, Alaska, 2001.

[3] Y. Liu and E. Knightly, "Opportunistic fair scheduling over multiple wireless channels," in *Proceedings of IEEE INFOCOM 2003*, San Francisco, CA, 2003.

[4] X. Quin and R. Berry, "Exploiting multiuser diversity for medium access control in wireless networks," in *Proceedings of IEEE INFOCOM 2003*, San Francisco, CA, 2003.

[5] P. Vishwanath, D. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *IEEE Transactions on Information Theory*, vol. 48, no. 6, pp. 1277–1294, June 2002.

[6] T. S. Rappaport, *Wireless Communications: Principles and Practice*, Prentice Hall, 1999.

[7] B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly, "Opportunistic media access for multirate ad hoc networks," in *Proceedings of ACM MobiCom 2002*, Atlanta, Georgia, Sept 2002.

[8] Tristan Henderson, David Kotz, and Ilya Abyzov, "The changing usage of a mature campus-wide wireless network," in *Proceedings of the Tenth Annual International Conference on Mobile Computing and Networking*. September 2004, ACM Press.

[9] Z. Yang and J. J. Garcia-Luna-Aceves, "Hop-reservation multiple access (HRMA) for ad-hoc networks," in *Proceedings of IEEE INFOCOM 1999*, New York, NY, 1999, pp. 194–201.

[10] J. So and N.H. Vaidya, "A multi-channel MAC protocol for ad hoc wireless networks," Tech. Rep., UIUC, 2003.

[11] D. Gesbert and M-S. Alouini, "How much feedback is multi-user diversity really worth?," in *Proceedings of IEEE ICC 2004*, Paris, France, 2004.

[12] V. Kanodia, A. Sabharwal, and E. Knightly, ""MOAR: A multi-channel opportunistic auto-rate media access protocol for ad-hoc networks"," in *Proc. Broadnets*, October 2004.

[13] Sudipto Guha, Kamesh Munagala, and Saswati Sarkar, "Jointly optimal transmission and probing strategies for multichannel wireless systems," in *Proc. Conference on Information Sciences and Systems (CISS)*, March 2006.

[14] Gerard J.M. Janssen and R. Prasad, "Propagation measurements in an indoor radio environment at 2.4 Ghz, 4.75 Ghz and 11.5 Ghz," in *Proceedings of VTS conference on frontiers of Technology*, 1992.

[15] H. Hashemi and D. Tholl, "Statistical modeling and simulation of the rms delay spread of indoor radio propagation channels," *IEEE Transactions on Vehicular Technology*, vol. 43, no. 1, pp. 110–120, Feb 1994.

[16] T.Wysocki and H.-J.Zepernick, "Characterisation of the indoor radio propagation channel at 2.4 GHz," *Journal of Telecommunications and Information Theory*, vol. 1, no. 3-4, pp. 84–90, 2000.

[17] C. Steger, P. B. Radosavljevic, and J. P. Frantz, "Performance of 802.11b wireless LAN under emulated channel conditions," in *Proceedings of IEEE Vehicular Technology Conference*, 2003.

[18] C. Berrou, "The ten-year-old turbo codes are entering into service," *IEEE Communications Magazine*, vol. 41, pp. 110–116, August 2003.

[19] T. Richardson and R. Urbanke, "The renaissance of Gallager's low-density parity-check codes," *IEEE Communications Magazine*, vol. 41, pp. 126–131, August 2003.

[20] A. J. Goldsmith and P. P. Varaiya, "Capacity of fading channels with channel side information," *IEEE Transactions on Information Theory*, vol. 43, no. 6, pp. 1986–1992, November 1997.

[21] S. K. Jayaweera and H. V. Poor, "Capacity of multiple antenna systems with both receiver and transmitter channel state information," *IEEE Transactions on Information Theory*, vol. 49, no. 10, pp. 2697–2709, October 2003.

[22] Herbert A. David, *Order Statistics*, Wiley Series in Probability and Mathematical Statistics, 1981.

[23] Y. S. Chow, H. Robbins, and D. Siegmund, *Great Expectations: The Theory of Optimal Stopping*, Houghton Mifflin Company, 1971.

[24] Tom Ferguson, "Optimal stopping time and applications," Online Text. *http://www.math.ucla.edu/ tom/Stopping/Contents.html*.

[25] V. Bharghavan, S. Demers, S. Shenker, and L. Zhang, "MACAW: A media access protocol for wireless LANs," in *Proceedings of ACM SIGCOMM 1994*, London, UK, 1994.

[26] F. A. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part III - polling and (dynamic) split-channel reservation multiple access," *IEEE Transactions on Communications*, vol. 24, no. 8, 1976.

[27] J. J. Garcia-Luna-Aceves and C. Fullmer, "Floor acquisition multiple access (FAMA) in single-channel wireless networks," *ACM Mobile Networks and Application (MONET), Special issue on Ad Hoc Networks*, vol. 4, pp. 157–174, 1999.

[28] R. Garces and J. J. Garcia-Luna-Aceves, "Collision avoidance and resolution multiple access for multichannel wireless networks," in *Proceedings of IEEE INFOCOM 2000*, Tel Aviv, Israel, 2000, pp. 595–602.

[29] G. Casella and R. Berger, *Statistical Inference*, Brooks Cole, 2001.

[30] W. L. Lehmann and G. Casella, *Theory of Point Estimation*, John Wiley and Sons, 1998.

[31] E. E. Afify, "Comparison of estimators of parameters for the rayleigh distribution," Online text. *http://jscs.stat.vt.edu/interstat/articles/2003/abstracts/ u03001.html-ssi*.

[32] C. Tepedelenlioglu, A. Abdi, and G. B. Giannakis, "The ricean K factor: Estimation and performance analysis," *IEEE Transactions on Wireless Communications*, vol. 2, no. 4, pp. 799–810, July 2003.

[33] R. Punnoose, P. Nikitin, and D. Stancil, "Efficient simulation of Ricean fading within a packet simulator," in *Proceedings of IEEE Vehicular Technology Conference, 2000*, 2000, pp. 764–767.

[34] A. Sabharwal, V. Kanodia, and E. Knightly, "Opportunistic spectral usage: Bounds and a multi-band CSMA/CA protocol," Tech. Rep., Rice University, 2004.

Ashutosh Sabharwal (S'90, M'99) is a research faculty of Electrical and Computer Engineering and the research director of Center for Multimedia Communications at Rice University. He received the B.Tech. degree from Indian Institute of Technology, New Delhi in 1993 and the M.S. and Ph.D. degrees from the Ohio State University in 1995 and 1999 respectively. He was the recipient of Presidential Dissertation Fellowship award in 1998. He served as technical co-chair of the wireless personal communication systems symposium at IEEE VTC 2005, and has served on the program committee of several conferences including IEEE INFOCOM, SIGCOMM Workshops, WinMee and GLOBECOM. His research interests are in the areas of information theory, protocols and algorithms for high-performance wireless systems.

Ahmad Khoshnevis (S'98) received his B.S. degree in Electrical Engineering from Amirkabir University of Technology (Tehran Polytechnic) in 96, B.S in computer science and B.A. in physics from Bloomsburg University of Pennsylvania in 99 and his M.S. degree in Electrical Engineering from Rice University in 2001. He is currently pursuing the PhD degree in Electrical Engineering at Rice University where he is a member of Center for Multimedia Communication. His current research focus is in the area of network information theory and cooperative communication with feedback and side information.

Edward Knightly (S'91, M'96, SM'04) is a professor of Electrical and Computer Engineering at Rice University. He received the B.S. degree from Auburn University in 1991 and the M.S. and Ph.D. degrees from the University of California at Berkeley in 1992 and 1996 respectively. He is an associate editor of IEEE/ACM Transactions on Networking. He served as technical co-chair of IEEE INFOCOM 2005 and served on the program committee for numerous networking conferences including ICNP, INFOCOM, IWQoS, MobiCom, and SIGMETRICS. He received the National Science Foundation CAREER Award in 1997 and the Sloan Fellowship in 2001. His research interests are in the areas of mobile and wireless networks and high-performance and denial-of-service resilient protocol design.