ACHIEVING WIRELINE RANDOM ACCESS THROUGHPUT IN WIRELESS NETWORKING VIA USER COOPERATION*

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ABSTRACT

Well appreciated at the physical layer, user cooperation is introduced here as a diversity enabler for wireless random access (RA) at the medium access control sub-layer. This is accomplished through a two-phase protocol in which active users start with a low power transmission attempting to reach nearby users, and follow up with a high power transmission in cooperation with the users recruited in the first phase. We show that such a cooperative protocol yields a significant increase in throughput. Specifically, we prove that for networks with a large number of users, the throughput of a cooperative wireless RA network operating over Rayleigh fading links approaches the throughput of a RA network operating over additive white Gaussian noise (AWGN) links. As a result, user cooperation migrates diversity benefits to the wireless RA regime, thus bridging the gap to wireline RA networks, without incurring a bandwidth or energy penalty.

1. INTRODUCTION

Offering well-documented counter-measures against fading, diversity techniques find widespread applications in modern wireless systems. User cooperation is a recently introduced diversity technique in which many single-antenna users share their information to construct a distributed virtual antenna array – an idea that has gained rapid acceptance as a sensible compromise between dependability and deployment cost [8]. User-collaborative diversity in *fixed access* point to point links is by now well understood (see e.g., [3]). Recent works have also pursued user cooperation in multiple access channels [5, 7].

In the present paper, we introduce user cooperation in random access (RA) channels by drawing from two different sources. On the one hand, we draw from well-established spread spectrum random access (SSRA) protocols; see e.g., [2, 4] and references therein. And on the other hand, we draw from the observation that user cooperation can be viewed as a form of multipath, a type of diversity for which SS with long pseudo-noise (PN) sequences used as spreading codes is particularly well suited [5].

An intuitive notion underlying the main results of this paper is that user cooperation is a form of diversity well matched to the very nature of RA networks. Indeed, the random nature of RA dictates that at any given time only a fraction of potential users is active, the others having either empty queues or their transmissions deferred. Accordingly, given that only a few out of the total number of transmitters are active at a given time, transmission hardware resources are inherently under-utilized in wireless RA networks. As we will show, user cooperation can exploit these resources to gain a diversity advantage, without draining additional energy from the network, and without bandwidth expansion. Reinforcing this intuitively reasonable notion, the number of temporarily idle users increases with the size of the network. Building on this intuition, we will establish that as the network size increases, there is an increasing diversity advantage to be exploited leading to a limiting scenario in which *the throughput of cooperative RA over wireless fading channels approaches that of an equivalent system operating over an AWGN channel.*

2. PRELIMINARIES

Consider a set of J users, $\mathcal{J} = \{U_j\}_{j=1}^{J}$, communicating with an access point (AP) in a wireless RA network as depicted in Fig. 1. User j and its position in a coordinate system centered at the AP will be denoted by U_j. With these positions considered random and uniformly distributed within a circle of radius R, we express the probability of the distance U_j-AP being smaller than r as

$$\Pr\{\|U_j\| < r\} = \frac{r^2}{R^2}, \qquad 0 \le r \le R, \tag{1}$$

where $\|U_j\|$ denotes the 2-norm of the position vector U_j. User positions are further assumed independent.

The average power received at U_{j_1} from a source U_{j_2} transmitting with power $P(U_{j_2})$ is given by an exponential pathloss model

$$P(U_{j_2} \to U_{j_1}) = \frac{\xi\, P(U_{j_2})}{\|U_{j_1} - U_{j_2}\|^{\alpha}}, \tag{2}$$

with ξ, and $\alpha \ge 2$ constants. As a special case, the power received at the AP from U_{j_2} is $P(U_{j_2} \to AP) = \xi P(U_{j_2})/\|U_{j_2}\|^{\alpha}$.

Each of the J users has an infinite-length buffer for storing L-bit fixed length packets that arrive at a rate of λ packets per packet duration. The packet arrival processes are identically distributed (i.d.), not necessarily independent. The L bits of each packet are spread by a factor S (a.k.a. spreading gain) to construct a transmitted packet of $T := SL$ chips. Spreading is implemented using a long PN sequence $\mathbf{c} := \{c(t)\}_{t\in\mathbb{Z}}$ with period

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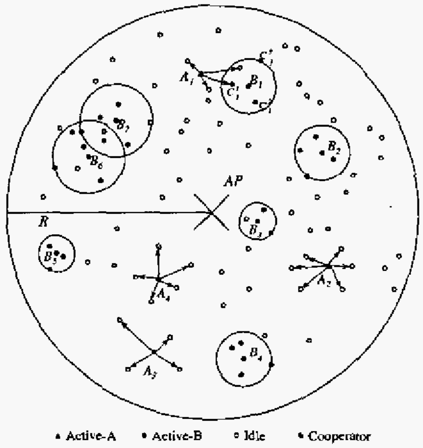

Fig. 1. A cooperative RA network snapshot.

$\mathcal{P}$. If $\mathbf{d}_{U_j} := \{d_{U_j}(l)\}_{l=0}^{L-1}$ denotes a *data* packet of user U_j, and $\mathbf{x}_{U_j} := \{x_{U_j}(t)\}_{t=0}^{T-1}$ the corresponding *transmitted* packet we have

$$x_{U_j}(Sl+s) = \sqrt{P(U_j)}\, d_{U_j}(l) c(Sl+s-\tau_{U_j}), \tag{3}$$

where $\mathbf{c}$ is a common long PN sequence *shared* by all users, τ_{U_j} is a user-specific shift applied to $\mathbf{c}$ and $P(U_j)$ is the power transmitted by node U_j.

2.1. Two-phase cooperation

Transmission in our cooperative RA protocol is done in two phases. In the first phase, "phase-A", the user sends a packet with sufficient power to be correctly decoded by nearby peers; while in the second phase, "phase-B", the set of peers that successfully decoded this packet transmit cooperatively with power sufficient to reach the AP. If we manage to balance conflicting power requirements, what happens in phase-A is that nearby users decode the original packet while the power received at the destination is negligible. This implies that: i) phase-A users do not interfere severely with concurrent phase-B nodes; and ii) phase-A locally disseminates information so that subsequent phase-B transmissions are enriched with a certain degree of user cooperation diversity.

Users are temporarily divided to a set of N_A "active-A" users, $\mathcal{A} = \{A_j\}_{j=1}^{N_A}$, operating in phase-A of their transmission trying to reach nearby users; a set of N_B active-B users, $\mathcal{B} = \{B_j\}_{j=1}^{N_B}$, communicating their packets to the AP; and N_I idle users $\mathcal{I} = \{I_j\}_{j=1}^{N_I}$ that either have empty queues or decided not to transmit. Clearly, $\mathcal{J} = \mathcal{A} \cup \mathcal{B} \cup \mathcal{I}$. A fourth class of users, comprises the sets of cooperators $\mathcal{C}_j = \{C_j^k\}_{k=0}^{K_j}$ associated with each active-B user B_j. The set $\mathcal{C}_j$ contains $C_j^0 = B_j$, and the K_j users that correctly decoded B_j's phase-A packet in the previous slot.

3. OPPORTUNISTIC COOPERATIVE RANDOM ACCESS

Since users transmit at random in RA networks, a number of users remain idle over any given slot. The Opportunistic Cooperative Random Access (OCRA) protocol introduced in this section exploits the good reception opportunities of this large set of idle

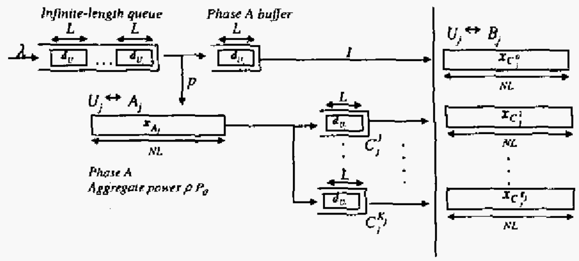

Fig. 2. OCRA is a two phase cooperative RA protocol.

users. OCRA is a two-phase protocol as described in Section 2 and is defined by the following operating conditions; see also Fig. 2.

[S0] Let κ be an upper bound on the achievable diversity. The period of the PN code $c(t)$ is chosen to be $\mathcal{P} = \kappa T + 1$.

[S1] At the beginning of each slot, if U_j's queue is not empty, U_j enters phase-A with probability p and moves the first packet in the queue, $\mathbf{d}_{U_j} := \{d_{U_j}(l)\}_{l=0}^{L-1}$, to a single packet buffer that we term phase-A buffer.

[S2] **Phase-A**: When in phase-A, we say that $U_j \leftrightarrow A_j$ is an active-A user and transmits a packet $\mathbf{x}_{A_j} := \{x_{A_j}(t)\}_{t=0}^{T-1}$ spread according to (3) with PN-shift and power given by

$$\tau_{A_j} = 0, \qquad P(A_j) = \rho P_0 \|A_j\|^\alpha / \xi, \tag{4}$$

with $\rho \in (0,1)$. The PN shift is deterministically chosen and the transmission power is so that the packet is received at the AP with fractional power ρP_0. A random integer, $\tau_{B_j} \sim \mathcal{U}[1,T]$, uniformly chosen over $[1,T]$ is included in the packet header to coordinate PN-shifts during phase-B.

[S3] **Phase-A handshake**: Any idle user I_k that decodes $\mathbf{x}_{A_j}$ becomes a cooperator $I_k \leftrightarrow C_j^k$ and places $\mathbf{d}_{U_j}$ in a single-packet buffer designated for cooperation purposes. This successful decoding is acknowledged to A_j who collects a total of K_j acknowledgments and feed-forwards this number K_j to the cooperators. Similar to e.g., [2, 4], this handshake is assumed to be instantaneous and error free.

[S4] User U_j enters phase-B in the slot immediately after entering phase-A.

[S5] **Phase-B**: Let $\mathcal{C}_j = \{C_j^k\}_{k=0}^{K_j}$ be the set of cooperators as defined in Section 2 comprising $C_j^0 = B_j \leftrightarrow U_j$ and the K_j cooperators recruited in phase-A. Each of the C_j^k transmits the packet $\mathbf{d}_{U_j}$ spread according to (3) using

$$\tau_{C_j^k} = \tau_{B_j} + \tau_k T, \qquad P(C_j^k) = \frac{P_0}{K_j+1}\|C_j^k\|^\alpha/\xi, \tag{5}$$

with τ_{B_j} the number received in phase-A's packet header, and the integer $\tau_k \sim \mathcal{U}[0, \kappa-1]$. The power scaling is so that the total received power at the destination is P_0. Let $\mathbf{x}_{C_j^k} := \{x_{C_j^k}(t)\}_{t=0}^{T-1}$ denote these transmitted packets.

The number of cooperators K_j is termed the *"cooperation order"* of B_j and the number κ_j of PN shifts chosen by at least one cooperator is called the *"diversity order"* of B_j.

[S6] **AP acknowledgement**: The AP acknowledges successful reception of the superposed phase-B packets corresponding to B_j through a feedback channel. If an acknowledgement is not received, the packet $\mathbf{d}_{B_j}$ is placed back in B_j's queue; cooperators discard this packet in any event.

[S7] Idle operation: When not transmitting, $U_j \leftrightarrow I_j$ correlates the received signal with $\{c(t)\}_{t=0}^{T-1}$ to detect phase-A packets transmitted by other (nearby) users.

By rule [S2], U_j becomes the active-A user A_j and transmits $\mathbf{x}_{A_j}$ with low power so as to reach nearby users while not interfering with the AP (if $\rho \ll 1$). Phase-B is defined by rule [S5] in which the packet is transmitted with κ_j-order diversity by $U_j \leftrightarrow B_j$ plus K_j cooperators corresponding to the K_j idle users that successfully decoded U_j's transmission during phase-A. The opportunistic nature of the protocol manifests in the random diversity order κ_j which depends on the number K_j of cooperators recruited and the random selection of shifts τ_k.

Rules [S1], [S4] and [S6] govern the transition between idle, and active-A/B states. Users move from idle to active-A with probability p as per [S1]; after entering phase-A, the user moves deterministically to phase-B in the first upcoming slot ([S4]), and back to idle in the second one ([S6]). A lost packet does not alter this transition but only determines whether the packet is put back in queue or not. Also, [S6] dictates that cooperators discard B_j's packet regardless of the transmission success.

Rules [S0], [S3] and [S7] guarantee logical consistency of the protocol. Rule [S0], provides sufficient number of PN shifts to enable the selection rule in phase-B [c.f. (5)]; [S3] disseminates the number of cooperators recruited to allow proper power scaling during phase-B as required by (5); and [S7] ensures that idle users are listening for phase-A packets.

A delicate issue in OCRA's description is the use of PN shifts, that is judiciously chosen to satisfy the following requirements:

Remark 1 The PN shifts during phases A and B are selected to:

[a] Facilitate decoding of phase-A's packet by idle users. Indeed, since phase-A packets use a fixed shift ($\tau_{A_j} = 0$), the idle users just need to correlate with a fixed sequence.

[b] Let the AP combine different cooperative copies of the same packet. If $\tau_{B_{j_1}} \neq \tau_{B_{j_2}}$, then $\tau_{C_{j_1}^{k_1}} \neq \tau_{C_{j_2}^{k_2}}$ $\forall k$ as can be seen from (5). Thus, the AP knows that if

$$\tau_{C_{j_1}^{k_1}} - \tau_{C_{j_2}^{k_2}} = \kappa_0 T \tag{6}$$

for some integer $\kappa_0 \in [0, \kappa - 1]$, then they correspond to the same packet.

Packets in OCRA are not correctly decoded either when two users choose the same PN shift, $\tau_{B_{j_1}} = \tau_{B_{j_2}}$; or; when the interference is too high. This motivates the following definition:

Definition 1 *Soft and hard collisions*

[a] *We say that B_{j_1} experiences a "hard collision" (HC) if $\tau_{B_{j_1}} = \tau_{B_{j_2}}$ for some $j_2 \neq j_1$; the HC event is*

$$\mathrm{HC} := \bigcup_{j_2 \neq j_1} \left\{ \tau_{B_{j_1}} = \tau_{B_{j_2}} \right\}. \tag{7}$$

[b] *Given that B_{j_1} does not experience a hard collision, we say that it experiences a "soft collision" (SC) when the packet is lost due to interference:*

$$\mathrm{SC} := \{\hat{\mathbf{d}}_{B_{j_1}} \neq \mathbf{d}_{B_{j_1}} \mid \mathrm{HC}^c\}, \tag{8}$$

where HC^c denotes the complement of HC and $\hat{\mathbf{d}}_{B_{j_1}}$ the packet estimate.

A third consequence of the selection of PN shifts is given in the following proposition.

Proposition 1 *Given a slot with N_B active-B users, OCRA's hard collision probability for any reference user B_{j_1} is*

$$P_{\mathrm{HC}}(N_B) = \left(1 - \frac{1}{T}\right)^{N_B - 1}, \tag{9}$$

independently of N_A and the sets of cooperators recruited[1].

OCRA's hard collision probability given in (9) coincides with non-cooperative SSRA collision probability results in [6]. This design goal is made possible by the increase in the PN sequence period $\mathcal{P}$ as per [S0]. The fact that this period must satisfy $\mathcal{P} \leq 2^S$, effectively limits the achievable diversity order of OCRA to

$$\kappa = \frac{2^S - 1}{T}. \tag{10}$$

Since $2^S \gg 1$, the constraint in (10) is not severe in practice.

4. OCRA'S THROUGHPUT

Mimicking steps for non-cooperative SSRA in [6] we can try to evaluate the aggregate throughput of OCRA. The hard collision probability coincides with the non-cooperative SSRA protocol and is given by Proposition 1. The soft collision probability, depends on both the number of active-A and active-B users and is given by

$$P_{\mathrm{SC}}(N_A, N_B - 1) = P_e(N_A, N_B - 1)[1 - P_{\mathrm{HC}}(N_B - 1)], \tag{11}$$

with $P_e(N_A, N_B - 1)$ a function that maps the number of interferers to the packet error probability.

Using (11), we can compute the packet success probability conditioned on the number of interferers, namely $P_s(N_A, N_B - 1) := 1 - P_{\mathrm{HC}}(N_B) - P_{\mathrm{SC}}(N_A, N_B - 1))$. Using the latter along with (9) and (11), we find

$$P_s(N_A, N_B - 1) = \left(1 - \frac{1}{T}\right)^{N_B - 1} [1 - P_e(N_A, N_B - 1)]. \tag{12}$$

Averaging (12) over the joint distribution of (N_A, N_B), we obtain an expression for the average departure rate

$$\mu^{\mathrm{OCRA}} = p \sum_{n_B = 0}^{J-1} \Pr\{N_B - 1 = n_B\} \left(1 - \frac{1}{T}\right)^{n_B} \times \sum_{n_A = 0}^{J} \Pr\{N_A = n_A\}[1 - P_e(N_A, N_B)], \tag{13}$$

where we used the independence of N_A and N_B [6]. Next, we consider a dominant system for OCRA after replacing [S1] with:

[S1'] At the beginning of each slot, U_j enters phase-A with probability p and moves the first packet in its queue, $\mathbf{d}_{U_j} := \{d_{U_j}(l)\}_{l=0}^{L-1}$, to the phase-A buffer. If U_j's queue is empty, it moves a dummy packet.

This modification renders the departure process stationary and, using an argument introduced in [1], we can claim that $\eta^{\mathrm{OCRA}} = \mu^{\mathrm{OCRA}}$, with μ^{OCRA} given as in (13). However, this will require evaluation of $P_e(N_A, N_B - 1)$, which appears to be intractable and motivates the asymptotic approach of the next section.

[1] Proofs of the claims in this paper are omitted due to space limitations, but can be found in [6].

4.1. OCRA's asymptotic throughput

Since OCRA's throughput $\eta^{OCRA}(J, N_0/P_0, S, \kappa, p, \rho)$ depends also in (κ, ρ), it is convenient to differentiate the maximum stable throughput (MST) depending on whether we optimize over ρ or not. For ρ fixed, we define the ρ-conditional MST as

$$\eta_{\max}^{OCRA}(J, N_0/P_0, S, \kappa \mid \rho) = \max_{p} \{\eta(J, N_0/P_0, S, p, \kappa, \rho)\}, \tag{14}$$

with the maximum achieved at $p_{\max}(\rho) = \arg\max_p(\eta)$. If we jointly optimize over (p, ρ), we define the MST as:

$$\eta_{\max}^{OCRA}(J, N_0/P_0, S, \kappa) = \max_{p,\rho} \{\eta(J, N_0/P_0, S, p, \kappa, \rho)\}, \tag{15}$$

with the maximum achieved at $(p_{\max}, \rho_{\max}) = \arg\max_{(p,\rho)}(\eta)$.

Having made this distinction, we can introduce the main results of this paper in the following two theorems.

Theorem 1 *Consider the OCRA dominant system defined by rules [S0], [S1'] and [S2]-[S7] operating over a fading channel; and functions $\rho = \rho(J)$ and $K = K(J)$ such that $\lim_{J\to\infty} \rho = 0$ and $\lim_{J\to\infty} K = \infty$. Let $\mathcal{C}_j := \{C_j^k\}_{k=1}^{K_j}$ be the set of cooperators of the active-B user B_j for $j \in [1, N_B]$. If*

- **[h1]** $\lim_{J\to\infty}(\rho^{2/\alpha} J/K) = \infty$, *with α being the pathloss exponent in (2); and*
- **[h2]** *the transmission probability $p = p_{\max}(\rho)$ is chosen to achieve the ρ-conditional MST [c.f. (14)];*

then

$$\lim_{J\to\infty} \Pr\{K_j \geq K/2, \ \ \forall j\} = 1. \tag{16}$$

Theorem 1 establishes that every active-B user is receiving cooperation by at least $K/2$ users; moreover, as long as the convergence rates of $\rho(J)$ and $K(J)$ satisfy [h1], the cooperation order K_j becomes arbitrarily large while the active-A transmitted power vanishes. Consequently, the seemingly conflicting requirements of recruiting an infinite number of cooperators with a vanishingly small power *are* compatible as $J \to \infty$ implying that very large diversity orders are achievable by OCRA.

This suggests that as the number of users grows large, OCRA's throughput approaches the throughput of non-cooperative SSRA operating over a κ-order diversity channel. To formalize this notion, we define the asymptotic throughput of OCRA, η_∞^{OCRA}, and the asymptotic throughput of non-cooperative SSRA, operating over a κ-order diversity channel, η_∞^κ, as follows

$$\eta_\infty^{OCRA}(N_0/P_0, S, \kappa) := \lim_{J\to\infty} \eta_{\max}^{OCRA}(J, N_0/P_0, S, \kappa),$$
$$\eta_\infty^{\kappa}(N_0/P_0, S) := \lim_{J\to\infty} \eta_\infty^{\kappa}(J, N_0/P_0, S), \tag{17}$$

and introduce the following major conclusion about OCRA.

Theorem 2 *For any $\kappa \leq (2^S - 1)/T$, the asymptotic MST of OCRA operating over a Rayleigh fading channel η_∞^{OCRA} and the asymptotic throughput of non-cooperative random access over a κ^{th}-order diversity channel η_∞^κ are equal; i.e.,*

$$\eta_\infty^{OCRA}(N_0/P_0, S, \kappa) = \eta_\infty^{\kappa}(N_0/P_0, S) \tag{18}$$

Theorem 2 is the main result of this paper effectively stating that very high diversity orders are achievable by OCRA. Notice that the only constraint $\kappa \leq (2^S - 1)/T$, is not very restrictive in practice since we are interested in achieving diversity orders of no more than a few units, and $2^S/T \gg 1$. Thus, after recalling that very high order diversity approaches an AWGN channel (see also [6]), it is fair to state that with κ sufficiently large

$$\eta_\infty^{OCRA}(N_0/P_0 + 1/S, S, \kappa) \approx \eta_\infty^{G}(N_0/P_0, S)\,. \tag{19}$$

Surprisingly, user cooperation can improve throughput to the point of achieving wireline-like throughput in a wireless RA environment. This is a subtle but significant difference relative to point-to-point user cooperation in fixed access networks, where the diversity advantage typically comes at the price of bandwidth expansion [3, 8].

Remark 2 *Average power constraint.* It can be proved that cooperation is limited to nearby idle users and accordingly the total transmitted power by any active communication is

$$\sum_{k=0}^{K_j} P(C_j^k) \approx (K_j + 1)\frac{P_0}{K_j + 1}\|B_j\|^\alpha/\xi = P_0\|B_j\|^\alpha/\xi. \tag{20}$$

Comparing (20) with non-cooperative SSRA, we observe that the average transmitted power in non-cooperative SSRA is equal to OCRA's phase-B power. The sole power increase is due to the phase-A power used to recruit cooperators yielding the relation

$$P^{\mathrm{OCRA}}(U_j) \approx (1 + \rho)P^{\mathrm{SSRA}}(U_j) \tag{21}$$

between the power required by OCRA and non-cooperative SSRA. Since $\rho \to 0$, we deduce that OCRA enables high order diversity with a small increase in average transmitted power.

Remark 3 *Maximum power constraint.* A maximum power constraint $P(U_j) \leq P_{\max}$ determines the AP's coverage area, since power control dictates that $\|U_j\|^\alpha \leq (\xi P_{\max}/P_0) := R_c^\alpha$. But the power in OCRA is contributed by K_j cooperators and accordingly

$$R_c^{\mathrm{OCRA}} = (K_j)^{1/\alpha} R_c^{\mathrm{SSRA}}. \tag{22}$$

This increase in coverage stems from the fact that in OCRA users are transmitting less power during more time.

Remark 4 *Network Area.* The proofs rely on the asymptotic behavior of certain distance ratios. This behavior does not depend on the radius of the network, implying that we can make it arbitrarily large. Accordingly, our major claims in Theorems 1 and 2 are valid for a fixed area network with increasing user density as well as for a fixed user density network with increasing area.

5. SIMULATIONS

A first question we address in this section is how large the number of users should be to achieve a significant throughput increase. For that matter, we refer to Fig. 3 where we depict OCRA's MST, η_{max}^{OCRA}, as a function of the number of users J in a network with spreading gain $S = 32$, packet length $L = 1024$, and a 215/255 BCH code capable of correcting $t = 5$ errors used for FEC. A quick inspection of Fig. 3 reveals that convergence to AWGN throughput is rather slow since for J as large as 512 there

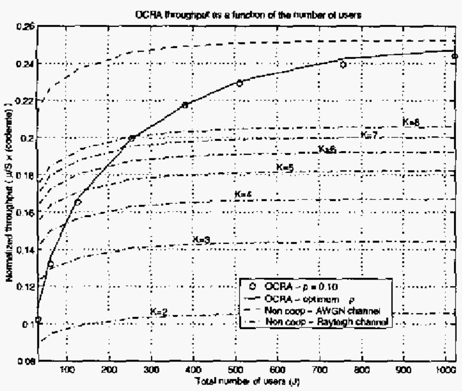

Fig. 3. The MST for $J = 128$ is $2/3$ the MST of SSRA over an AWGN channel ($\kappa = 10$, $S = 32$, $L = 1024$, 215/255 BCH code capable of correcting $t = 5$ errors).

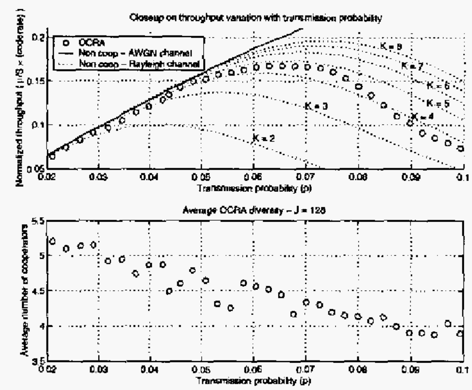

Fig. 4. OCRA's throughput is between the throughput of 4^{th} and 5^{th}-order diversity, consistent with the fact that the cooperation order is between 4 and 5 ($\rho = 0.01$, $J = 128$, same as in Fig, 3).

is still a noticeable gap. Notwithstanding, the throughput increase is rather fast; for $J = 64$ there is a threefold throughput increase ($\eta_{\max} = 0.04$ if the channel is Rayleigh), and for $J = 128$ OCRA's MST is $2/3$ of the MST achieved by non-cooperative SSRA over an AWGN channel. Thus, while collecting the full diversity advantage requires an inordinately large number of users, OCRA can collect a significant percentage of it in moderate size networks, with a ratio $J/S \approx 4$.

Similar conclusions can be drawn from the simulation with $J = 128$ users depicted in Fig 4. For this case study, we show throughput and average diversity as a function of the transmission probability p. For the range of probabilities close to the MST, OCRA's throughput remains between the curves for 4^{th} and 5^{th}-order diversity, consistent with the fact that the average degree of cooperation that users receive is between 4 and 5.

A second question addressed is how we select ρ which distinguishes between ρ-conditional MST in (14) and MST in (15). Interestingly, optimizing over (ρ, p) provides a small throughput increase with respect to optimizing over p only, as can be seen in Fig. 3. In this plot, the solid line depicts OCRA's MST and the circles depict the ρ-conditional MST when we set $\rho = 0.01$. In most of the operational range shown, there is no noticeable difference between these two approaches. This has the important practical implication that we do not need to optimize ρ, removing a significant part of the added complexity that OCRA incurs relative to non-cooperative SSRA.

6. CONCLUSIONS

With the goal of migrating user cooperation benefits to random access channels, we introduced the OCRA protocol which we showed capable of effecting a significant throughput increase with respect to equivalent non-cooperative random access protocols. Testament to this significant advantage is the fact that as the number of users in the network increases, OCRA's throughput over Rayleigh fading links approaches that of the corresponding SSRA protocol over AWGN links, without an energy penalty. Accordingly, *OCRA has the capacity of rendering a wireless RA channel equivalent to a wireline one* from the throughput perspective. This is a striking difference with point to point cooperation, where the diversity comes at the expense of bandwidth expansion. The price paid is a modest increase in complexity (and therefore cost) of the baseband circuitry. Simulations demonstrated that our asymptotic results can be perceived in realistic-sized networks since the asymptotic results manifest for moderate values of the total number of users.

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