Coordinated Packet Transmission in Random Wireless Networks

S. Vanka and M. Haenggi
Department of Electrical Engineering
University of Notre Dame, Notre Dame, IN 46556
e-mail: (svanka, mhaenggi)@nd.edu.

***Abstract*—This paper studies the value of allowing multiple transmitters to share all of the available bandwidth to concurrently transmit to a single receiver with multi-packet decoding capability. While such coordination can be bandwidth-efficient, it increases the density of interferers when many such multiple-access clusters exist in the network. On the other hand, orthogonal schemes such as FDMA may not be as bandwidth-efficient but operate at lower interferer densities due to orthogonalization. We take the first step towards understanding this trade-off. In particular, we analyze equidistant transmitters sending data using a coordination scheme based on the optimum strategy for a Gaussian multiple access channel. In terms of the throughputs seen in a typical cluster in a Poisson network, this form of coordination has little or no benefit when compared to FDMA. We also find that the increased interference due to multiple coordinated transmissions reduces the efficacy of successive decoding.**

I. Introduction

Traditional scheduling algorithms assume a simple collision model to activate links. As a result, in a given time-slot or frequency band, no more than one transmitter can communicate with a given receiver. This restriction, however, can be relaxed for those receivers capable of multi-packet decoding (MPD) of transmissions from an intended *cluster* of transmitters. Such receivers can be built, for example, by receive MIMO processing [1], or by successive/joint decoding of concurrent transmissions.

When many such MPD-capable nodes exist in a network, the problem of scheduling becomes interesting. In [2] the authors study a random scheduling algorithm with MPD-capable nodes. While interesting, their packet reception model does not model interference from transmitters communicating to other MPD-capable receivers.

A more realistic model for an ad hoc setting needs to incorporate such inter-cluster interference which in turn depends on network geometry. When these inter-cluster interactions are factored in, the multiple-access scheme that each transmitter cluster adopts locally can have a network-wide impact in the form of interference. In a scheme such as Frequency Division Multiple Access (FDMA), transmissions within each cluster are orthogonalized, albeit at the cost of poorer bandwidth efficiency. However, coordinated transmissions improve the bandwidth reuse within a cluster at the cost of increasing the overall density of interferers. Consequently, unlike in a single multiple-access cluster, the benefits of coordinated transmission are not clear.

We compare orthogonal and coordinated transmission in a network made up of many randomly placed *symmetric* multiple-access clusters. Each cluster consists of a receiver and its set of equidistant transmitters. As a first step towards understanding the trade-off described above, we compare the local throughput seen on a set of typical links. The coordinated transmission scheme we study is inspired by the capacity-achieving scheme for a symmetric Gaussian MAC (GMAC). Combining analytical and numerical approaches, we find that for a given transmission rate, this scheme can provide modest gains over FDMA without power concentration for small link distances. The increased interference from coordinated transmissions also degrades the performance of the low-complexity successive decoding strategy.

II. System Model

A. Network Geometry

The set of receivers forms a unit intensity homogeneous Poisson Point Process (PPP) $\Phi = \{x_i\}$ on $\mathbb{R}^2$. For each receiver $x_i \in \Phi$, we place K transmitters marked $1, 2, \ldots, K$ respectively, at $x_i + r_{ik}$, $k = 1, 2, \ldots K$, where r_{ik} are iid random variables (in both i and k) drawn from a distribution F_r. The transmitter marked k in a cluster is called the k^{th} transmitter or user in the cluster. Denote the transmit decision of the k^{th} node attached to receiver node x_i by a binary variable t_{ik}. Thus the set of transmitters Φ_t is a clustered Poisson process [4] formed by the union of K unit-intensity, marked homogeneous PPPs $\Phi_t^{(k)} = \{x_i + r_{ik}, k, t_{ik}\}$, $k = 1, 2, \ldots, K$. In this paper, we assume $|r_{ki}| = r$ is known. We label the nodes in the *typical cluster* by $\{\mathrm{D}, \mathrm{S}_1, \mathrm{S}_2, \ldots, \mathrm{S}_K\}$, where D is the receiver node located at the origin and S_k is the k^{th} *typical* transmitter or user in the cluster located at r_{0k}. For ease of exposition we derive results for $K = 2$.

B. Communication Model

1) Medium Access: We assume packet queues at all transmitters are backlogged to ensure their participation in medium access. We extend conventional single-node ALOHA to transmitters within a cluster, which we term as *cluster-ALOHA* (c-ALOHA). The marks for each transmit cluster are drawn from a common $K-$dimensional joint distribution, independently from other clusters. The mark of the k^{th} transmitter in each cluster has a marginal distribution which is Bernoulli with parameter p_k.

A special case is when all links in a cluster are scheduled simultaneously, i.e., $t_{ik} \equiv t_i$ with some probability p. We call this *Joint* c-ALOHA. For orthogonal multiple access, the c-ALOHA protocol decouples into a set of K independent single-node ALOHA protocols.

2) Packet Transmission: Transmitters have a unit average power constraint per degree of freedom and use Gaussian signaling. The noise psd at each receiver is N_0 (in W/Hz). The path-loss follows a power law with exponent $\beta > 2$. The fading between any two nodes is iid block Rayleigh fading in time and flat fading in frequency. Each receiver has full CSI from all its intended transmitters. We further assume that transmitters have no CSI and do not use power control. All clusters use a common transmission scheme, the parameters of which are fixed during design time.

Packet transmissions are slotted and encoding and decoding are done on a per-slot basis, and immediate error-free ACK/NACK is available (i.e., we adopt a per-slot outage-based model). The number of channel uses during each time slot is large enough to permit the use of information-theoretic results. Each receiver treats inter-cluster interference as noise, which is optimum in the sum-rate sense for the weak-interference regime [5].

III. Multiple Access Strategies

When user k is assigned the entire bandwidth, it communicates using a capacity-achieving single-user AWGN channel code with an SNR threshold θ, which we call the *single-user threshold*.

A. Orthogonal Multiple Access

Users transmit in non-overlapping time slots (TDMA) or frequency bands (FDMA). This partition is common throughout the network. Without loss of generality, we assume FDMA-type multiple access, with a bandwidth partition $\{u_k\}_{k=1}^{K}$. If transmitters marked k use ALOHA with transmit probability p_k and encode their packets using a channel code with SNR threshold $\tilde{\theta}_k$, the transmission rate R_k, packet success probability $p_{s,k}$ and the local throughput T_k at the typical cluster are, respectively, defined as

$$R_k \triangleq C(\tilde{\theta}_k) \quad (1)$$
$$p_{s,k} \triangleq \mathbb{P}(\mathsf{SINR}_{\mathrm{S}_k \to \mathrm{D}} \geq \tilde{\theta}_k) \quad (2)$$
$$T_k \triangleq p_k p_{s,k} R_k \quad (3)$$

where $C(x) \equiv \log(1+x)$ for $x \geq 0$. Note that in general $\tilde{\theta}_k$ is a function of user k's bandwidth u_k. We study two approaches:

1) Naive FDMA, where all transmitters transmit with unit power spectral density (psd) in their allotted band and use Gaussian codes with the single-user threshold θ.
2) FDMA with Power Concentration (PC-FDMA), where transmitters marked k boost their psd in their allotted band to $1/u_k$ and use a Gaussian channel code with SNR threshold θ/u_k.

We use subscripts n and pc respectively for naive FDMA and PC-FDMA for the parameters defined in (1)-(3). Additionally for $K = 2$, let $u_1 \equiv u$ and $u_2 \equiv 1 - u$.

B. Coordinated Multiple Access

1) Coordinated Multiple Access in a Single Cluster Network: We use a scheme inspired by the capacity-achieving scheme for a two-user symmetric GMAC [3] with single-user threshold θ. The scheme has two modes:

1) Single-User Mode: Only one of the two users transmits at a rate $C(\theta)$.
2) Coordinated Mode: The transmitters communicate using the entire bandwidth, using the rate pairs

$$M_1' = (C(\theta), C(\theta/(1+\theta))) \quad (4)$$
$$M_2' = (C(\theta/(1+\theta)), C(\theta)) \quad (5)$$

We will call the user transmitting at the single-user rate as the *full-rate user* and the low-rate user as the *overlaid user*.

Any other operating point can be obtained by time-sharing between these points. A procedure of practical interest is Successive Decoding (SD), that achieves capacity for GMAC [3]. The receiver decodes the message encoded at the lowest rate first. If unsuccessful, an error is declared. Else the decoded bits are re-encoded, and their contribution to the receiving signal is removed. The message with the next lowest rate is decoded next, until messages from all users are decoded. It is also known that this is a capacity-achieving strategy for a $K-$user GMAC.

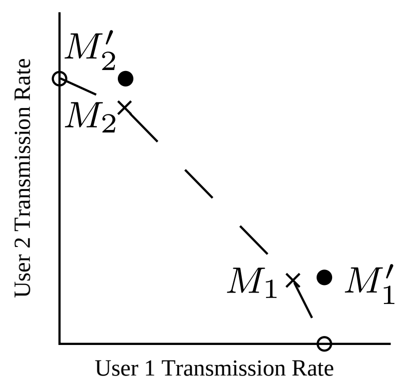

Figure 1: Transmission rates chosen for coordinated multiple access. The hollow circles represent the single-user mode. For the coordinated mode, we show the transmission rate-pairs chosen for a network with just one cluster (black circles), and with many clusters ($\times-$marks). The dashed line represents the set of effective transmission rates achievable by time-sharing among adjacent points.

2) Coordinated Medium Access in a Network with Many Clusters: We will capture the essence of the above scheme—that of overlaid transmission and successive decoding—to devise a scheme in a network with many clusters. As before, it has two modes:

1) Single-User Mode: Only one user per cluster transmits using a code with SNR threshold θ. The single-user mode for the k^{th} user corresponds to FDMA with $u_k = 1$.
2) Coordinated Mode:
   a) Corner Point 1: User 2 is the overlaid user. User 1 is called the *high-rate* user. $M_1 = (C(\xi_1), C(\xi_2))$.

b) Corner Point 2: User 1 is the overlaid user. User 2 is the high-rate user. $M_2 = (C(\xi_2), C(\xi_1))$.

As before, any other operating point can be obtained by time-sharing between these points. When every cluster operates in the coordinated mode, there will be a greater spatial density of interferers resulting in a higher level of interference. Unlike in the single-cluster case, single-user and coordinated modes operate at different levels of interference. This difference in the chosen transmission rates shown in Fig. 1.

We thus pose the question: Given a channel access mechanism across clusters, what is the throughput on each typical link $S_k \to D$, for $k = 1, 2$ in the coordinated mode? Without loss of generality, we analyze the first corner point M_1 where $R_1^{\rm c} \triangleq C(\xi_1)$, $R_2^{\rm c} \triangleq C(\xi_2)$.

If D adopts the SD procedure at this operating point, user 2 (the overlaid user) is decoded first before decoding user 1. Thus at the typical receiver D, the packet success probability from S_2 is

$$p_{s,2}^{\rm c} \quad \triangleq \quad \mathbb{P}(\mathsf{SINR}_{\rm S_2 \to D} \geq \xi_2). \tag{6}$$

If decoded correctly, the packets from $\rm S_1$ are decoded. Therefore

$$p_{s,1}^{\rm c} \quad \triangleq \quad q_{12}^{\rm c} p_{s,2}^{\rm c}, \tag{7}$$

where $q_{12}^{\rm c}$ is the conditional success probability for decoding high-rate user's packets given that overlaid user's packets have been decoded correctly.

IV. Average Throughput

A. Orthogonal Multiple Access

With orthogonal multiple access, the interference power I_k at the typical receiver $\rm D$ when decoding its $k^{\rm th}$ user $\rm S_k$ be written as

$$I_k = \sum_{x_i \in \Phi_t^{(k)} \setminus \{r_{0k}, k, 1\}} t_{ik} g_{ik} (x_i + r_{ik})^{-\beta}. \tag{8}$$

where $\{g_{ik}\}$ is a set of iid $\exp(1)$ random variables from Rayleigh fading. Since the Poisson property is unchanged by this conditioning of the typical transmitter's location (Slivnyak's theorem, see [4]), we can apply well-known results [6] to derive the packet success probabilities.

Proposition 1. *(Success Probabilities with naive FDMA, PC-FDMA). For a transmit probability p_k, the success probabilities $p_{s,k}^{\rm n}$,$p_{s,k}^{\rm pc}$ and for naive FDMA, PC-FDMA and are respectively*

$$p_{s,k}^{\rm n} \quad = \quad \exp(-p_k \gamma r^2 - \theta r^\beta N_0) \tag{9}$$

$$p_{s,k}^{\rm pc} \quad = \quad \exp(-p_k u_k^{-\delta} \gamma r^2 - \theta r^\beta N_0) \tag{10}$$

for $k = 1, 2$, $\delta \triangleq 2/\beta$ and

$$\gamma \quad \triangleq \quad \pi \theta^\delta \Gamma(1 + \delta) \Gamma(1 - \delta).$$

Proof: Readily obtained by specializing (2) to a homogeneous PPP (see e.g., [6], [7]). ■

Comparing PC-FDMA and naive FDMA, we find that interference limits the benefits of power concentration. In fact for homogeneous Poisson-distributed transmitter nodes with uncoordinated transmissions, naive FDMA can outperform PC-FDMA in average throughput at small bandwidth allocations, as shown in Corollary 2 below.

Corollary 2. *For any transmit probabilities $p_k^{\rm n}$ and $p_k^{\rm pc}$ chosen for naive FDMA and PC-FDMA respectively, there exists a $u_k^* > 0$ such that $T_k^{\rm n} > T_k^{\rm pc}$ for $u_k < u_k^*$.*

Proof: Using the expressions for success probabilities from Proposition 1 in the throughput expression (3) we can write for all $u_k > 0$

$$\frac{T_k^{\rm n}}{T_k^{\rm pc}} \propto \frac{\exp(\gamma r^2 (p_k^{\rm pc} u^{-\delta}))}{C(\theta_k / u_k)}.$$

Since $\lim_{u_k \to 0} T_k^{\rm n} / T_k^{\rm pc} = \infty$, $\exists u_k^* > 0$ such that $T_k^{\rm n} / T_k^{\rm pc} > 1$ $\forall u_k < u_k^*$. ■

Corollary 2 also holds for the respective throughput-maximizing transmit probabilities $\bar{p}_k^{\rm n}$ and $\bar{p}_k^{\rm pc}$. As a result, for fixed link distances and single-user theresholds, there exists $u^* = \min_k u_k^*$ for all classes of transmitters, where a Pareto improvement is possible if transmitters marked k switch to naive FDMA from PC-FDMA. Intuitively, this happens because at small u_k, PC-FDMA concentrates power in a very small band and allocates a correspondingly large transmission rate (SINR threshold) for this band. When thresholds become too large, outage events become frequent enough to negate the benefit of using a higher spectral efficiency. The average throughputs can now be evaluated from the definition (3).

B. Coordinated Multiple Access

1) Co-location Approximation: The interference I at the typical receiver due to transmitters do not belong to the typical cluster is D is

$$I \quad = \quad \sum_k \sum_{\Phi_t^{(k)} \setminus \{r_{0k}, k, 1\}} t_{ik} g_{ik} (x_i + r_{ik})^{-\beta}. \tag{11}$$

Thus different from (8) the interferers form a *clustered* point process $\Phi_t = \cup_k \Phi_t^{(k)}$. To retain the analytical simplicity of our treatment and yet gain insight into the effect of increased interference, we restrict our discussion to a regime where the intra-cluster transmitter node separation is small compared to the average distance between receiver nodes of the network (which is $1/2\sqrt{\lambda}$ for a homogeneous PPP of intensity λ). Here each transmitter cluster can be approximated by a single multi-antenna virtual transmitter node located at an arbitrarily chosen transmitter (say $x_i + r_{i1}$) in the cluster. The antenna separation at this virtual node is assumed to be sufficient to create independent fading paths. The resulting transmitter point process is thus a homogeneous PPP with unit intensity, resulting in the approximation

$$I \approx \sum_{\Phi_t^{(1)} \setminus \{r_{01}, 1, 1\}} t_i \left(\sum_k g_{ik} \right) (x_i + r_{i1})^{-\beta}, \tag{12}$$

assuming joint c-ALOHA. Although co-location of transmitters captures the increase in interference from concurrent transmissions, it does not precisely capture its effect in the vicinity of each interferer cluster where the geometry of interferer nodes also becomes important. This limits the utility of the co-location approximation in a more general case. In the next subsection we use this approximation to derive packet success probabilities for coordinated transmission with Joint c-ALOHA. A numerical validation of this approximation is presented in Section V-A (see Fig. 2)

2) Success Probabilities using the Co-location Approximation:

Proposition 3. *(Success Probability with Coordinated Transmissions and c-ALOHA). If every cluster operates at the first corner point M_1 for Joint c-ALOHA with transmit probability p, the success probabilities (6) and (7) at the typical receiver are respectively*

$$p_{s,2}^{\mathrm{c}} = \frac{\exp(-p\gamma_2 r^2 - \xi_2 r^\beta N_0)}{1+\xi_2} \tag{13}$$

$$p_{s,1}^{\mathrm{c}} = \frac{\exp(-p\gamma_1 r^2 - (\xi_2+\xi_1+\xi_1\xi_2) r^\beta N_0)}{1+\xi_2} \tag{14}$$

where $\gamma_1 \triangleq |b(0,1)|\Gamma(2+\delta)\Gamma(1-\delta)(\xi_1+\xi_2+\xi_1\xi_2)^\delta$, $\gamma_2 \triangleq |b(0,1)|\Gamma(2+\delta)\Gamma(1-\delta)\xi_2^\delta$.

Proof: Suppose g_k $(k=1,2)$ denote the fading gains from each of the typical transmitters. Recall from (7) that

$$\begin{aligned} p_{s,2}^{\mathrm{c}} &= \mathbb{P}(\mathsf{SINR}_{\mathrm{S}_2\to\mathrm{D}} \geq \xi_2) \\ &= \mathbb{P}\left(\frac{g_2 r^{-\beta}}{g_1 r^{-\beta} + I_{\Phi_t\setminus\{S_1,S_2\}} + N_0} \geq \xi_2\right). \end{aligned}$$

Since $g_2 \sim \exp(1)$, using standard arguments (see e.g., [6] for single-user decoding) we can show that $p_{s,2}^{\mathrm{c}}$ can be written as the Laplace transform evaluated at $\xi_2 r^\beta$ of the sum distribution of the three denominator terms. Given that these random variables are mutually independent, the Laplace transform of their sum distribution is the product of the Laplace transforms of the marginal distributions. The latter are known to be respectively:

$$\begin{aligned} \mathcal{L}_1(s) &= 1/1+sr^{-\beta} \\ \mathcal{L}_2(s) &= \exp(-\pi p\mathbb{E}[h_2^\delta]\Gamma(1-\delta)s^\delta) \\ \mathcal{L}_3(s) &= \exp(-sN_0), \end{aligned}$$

where h_2 is the fading variable representing Nakagami-2 fading. Using the properties of gamma functions it is easy to show that $\mathbb{E}[h_2^\delta] = \Gamma(2+\delta)$[1]. Setting $s = \xi_2 r^\beta$ we get (13). From (6) we know that $p_{s,1}^{\mathrm{c}} = q_{12}^{\mathrm{c}} p_{s,2}^{\mathrm{c}}$. Writing $\tilde{I} = I_{\Phi_t\setminus\{S_1,S_2\}} + N_0$, we expand this using Bayes' rule as the joint probability

$$p_{s,1}^{\mathrm{c}} = \mathbb{P}\left(\frac{g_1 r^{-\beta}}{\tilde{I}} \geq \xi_1, \frac{g_2 r^{-\beta}}{g_1 r^{-\beta} + \tilde{I}} \geq \xi_2\right).$$

Utilizing the mutual independence of g_1, g_2 and $\tilde{I}$, the right hand side can be expressed as

$$\int_0^\infty \underbrace{\mathbb{P}(g_2 r^{-\beta} \geq \xi_2(g_1 r^{-\beta} + x), g_1 r^{-\beta} \geq \xi_1 x)}_{\mathrm{Term1}} d\mathbb{P}(\tilde{I} \leq x). \tag{15}$$

[1]For coordinated transmission with K users, this can be generalized to $\mathbb{E}[h_K^\delta] = \Gamma(K+\delta)$ (Nakagami$-K$ fading).

$\mathrm{Term1}$ can be expressed as

$$\mathrm{Term1} = \int_{\xi_1 x}^\infty \mathbb{P}(g_2 r^{-\beta} \geq \xi_2(y+x)) \exp(-yr^\beta) r^\beta dy,$$

since $g_1 r^{-\beta}$ is $\exp(r^\beta)$. But $g_2 \sim \exp(1)$, so the integrand reduces to $\exp(-\xi_2 r^\beta(y+x))$. Combining the two exponentials in y we obtain

$$\begin{aligned} \mathrm{Term1} &= \exp(-\xi_2 r^\beta x) \int_{\theta x}^\infty \exp(-(1+\xi_2) r^\beta y) r^\beta dy \\ &= \frac{\exp(-(\xi_2+\xi_1+\xi_1\xi_2) r^\beta x)}{1+\xi_2}. \end{aligned}$$

Plugging this result into the first step (15) yields

$$p_{s,1}^{\mathrm{c}} = \frac{\mathcal{L}_{\tilde{I}}((\xi_1+\xi_2+\xi_1\xi_2)r^\beta)}{1+\xi_2}.$$

Since Φ_t is well approximated by a homogeneous PPP with intensity p, we get (14). ■

V. Numerical Results

A. Validating the Co-location Approximation

Suppose transmitter orientations are uniformly random relative to their intended receivers. Clearly, conditioned on the location of one transmitter (at a distance $r_1 = r$), its partner transmitter is located uniformly randomly inside a ball of radius $2r$ centered at its location. In general if an angular spread of $\omega \leq \pi$ is permitted between the transmitter orientations within a cluster (i.e., the orientations are longer iid), the radius of this ball is $2r\sin(\omega/2)$. The co-location approximation assumes that the distance between transmitters in a cluster is small.

To validate the approximation, we create realizations of $\Phi_t^{(1)}$, with unit intensity without loss of generality. We fix a small link distance $r \ll 0.5$ and an ω. Centered at each point in this process, we place the point marked 2 uniformly randomly inside a ball of a radius $2r\sin(\omega/2)$. These latter points correspond to the second transmitter point process $\Phi_t^{(2)}$.

For each realization, we measure the interference at the origin using the exact locations from (11) and from the approximation (12), and compare the empirical complementary (cumulative) distribution functions (CCDFs) of interference for both these cases. Some results are shown in Fig. 2 for $r = 0.1, \omega = \pi$ (independent orientations). We find that the approximation is a good fit as long as r remains much smaller than the distance scale $1/2\sqrt{\lambda}$ of the network.

B. Comparing Orthogonal and Coordinated Transmission

We present numerical results to gain insights into the results presented in Section IV. Due to space limitations we discuss only the interference-limited regime ($N_0 \to 0$). We study a system of two-user symmetric multiple-access clusters with link distance $r = 0.05, 0.1$ ($\ll$0.5) for two values of a single-user threshold $\theta = 0\,\mathrm{dB}$. The path-loss exponent $\beta = 3$. For the coordination scheme we let $\xi_1 = \theta$ and $\xi_2 = \theta/(1+\theta)$.

We use the throughput maximizing transmit probability for both users for FDMA. Using results from Proposition 1 in (3), the optimum transmit probability is $\min(1, a^{-1})$, where a depends on the link distance, the path-loss exponent and the

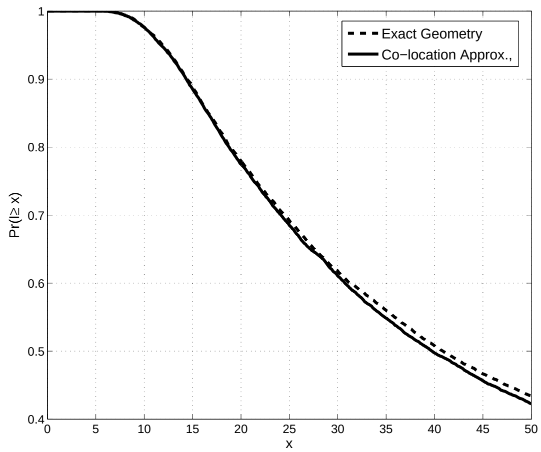

Figure 2: CCDF with and without Co-location Approximation for $r = 0.1$, $\omega = \pi$, $\lambda = 1$.

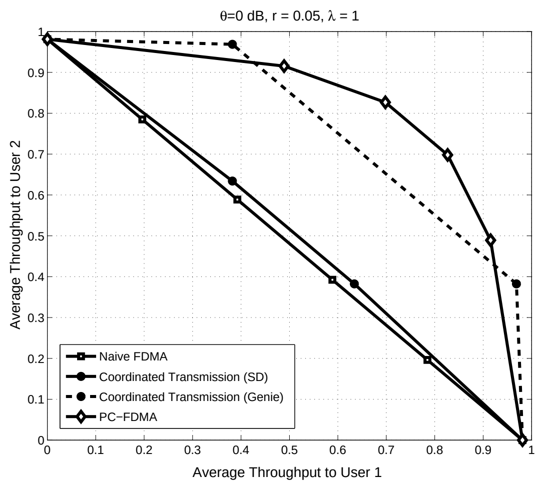

Figure 3: Average Link Throughputs for $\theta = 0\,\mathrm{dB}$, $r = 0.05$.

SNR threshold. For the chosen set of parameters $a^{-1} < 1$; hence the optimal transmit probability is 1.

When the users adopt the coordinated scheme described in Section III-B2, the optimum transmit probability depends on whether full-rate user's or the overlaid user's throughput is to be maximized. Since these users transmit at different rates, these probabilities are in general different. However, when both the link distances and the transmission rates are small (as in the present parameter set), both these probabilities will be equal to 1. We compare the average throughputs on each link for naive FDMA, PC-FDMA and coordinated transmission. For coordinated transmission we plot the throughputs obtained with SD and with genie-aided cancellation of the overlaid user. These results are shown for in Fig. 3 ($r = 0.05$) and Fig. 4 ($r = 0.1$). For small link distances (high SINR regime), a moderate increase in the transmission rate increases throughput without appreciable loss in reliability. This explains PC-FDMA's throughput gain over naive FDMA at reasonable bandwidth allocations. Error propagation from successive decoding restricts the gains from coordinated transmission to small link distances or SNR thresholds. Increasing the link distance reduces the received SIR, worsening the error propagation problem. We find this in Figs. 3 and 4. Even with perfect SD, for a wide range of throughputs there is a Pareto improvement by switching to PC-FDMA, i.e., trading bandwidth efficiency for lower interferer density is beneficial.

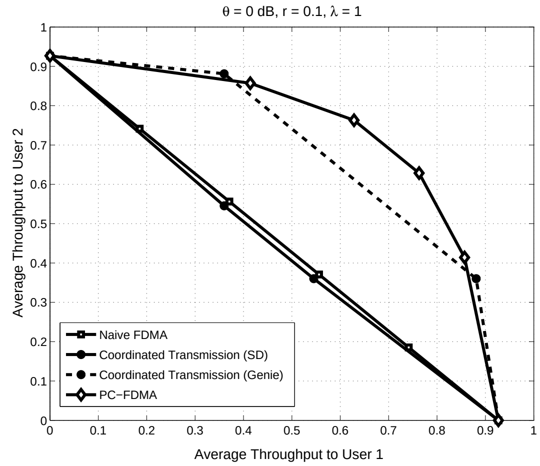

Figure 4: Average Link Throughputs for $\theta = 0\,\mathrm{dB}$, $r = 0.1$.

VI. Conclusion

We have studied orthogonal multiple access and a coordinated scheme inspired by the capacity-optimal scheme for the two-user Gaussian symmetric multiple access channel in a network consisting of randomly placed multiple-access clusters. Even without error propagation, increased interference from network-wide coordinated transmissions degrades the performance of this coordinated scheme compared to the single-cluster case; increased interference also reduces the efficacy of successive decoding strategy. Thus in terms of average link throughput, orthogonal schemes are a competitive design option.

Acknowledgements

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