Topology Control for Effective Interference Cancellation in Multi-User MIMO Networks

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***Abstract*—In Multi-User MIMO networks, receivers decode multiple concurrent signals using Successive Interference Cancellation (SIC). With SIC a weak target signal can be deciphered in the presence of stronger interfering signals. However, this is only feasible if each strong interfering signal satisfies a signal-to-noise-plus-interference ratio (SINR) requirement. This necessitates the appropriate selection of a subset of links that can be concurrently active in each receiver's neighborhood; in other words, a sub-topology consisting of links that can be simultaneously active in the network is to be formed. If the selected sub-topologies are of small size, the delay between the transmission opportunities on a link increases. Thus, care should be taken to form a limited number of sub-topologies. We find that the problem of constructing the minimum number of sub-topologies such that SIC decoding is successful with a desired probability threshold, is NP-hard. Given this, we propose MUSIC, a framework that greedily forms and activates sub-topologies, in a way that favors successful SIC decoding with a high probability. MUSIC also ensures that the number of selected sub-topologies is kept small. We provide both a centralized and a distributed version of our framework. We prove that our centralized version approximates the optimal solution for the considered problem. We also perform extensive simulations to demonstrate that (i) MUSIC forms a small number of sub-topologies that enable efficient SIC operations; the number of sub-topologies formed is at most 17% larger than the optimum number of topologies, discovered through exhaustive search (in small networks). (ii) MUSIC outperforms approaches that simply consider the number of antennas as a measure for determining the links that can be simultaneously active. Specifically, MUSIC provides throughput improvements of up to 4 times, as compared to such an approach, in various topological settings. The improvements can be directly attributable to a significantly higher probability of correct SIC based decoding with MUSIC.**

I. Introduction

In networks with multi-user MIMO capabilities, nodes can spatially multiplex multiple streams to simultaneously communicate with more than one neighbor. This capability has been shown to provide significant network capacity benefits [15], [3]. Multi-user MIMO communications can be facilitated at the PHY (physical) layer in two different ways; (a) precoding can be used at transmitters (with dirty paper codes [13]), and/or (b) successive interference cancellation (SIC) can be implemented at receivers [21]. Precoding requires transmitters to have an accurate estimate of the channel realization at the receivers. However, due to the prohibitive transmission overheads needed for feedback of this information from receivers to a transmitter, precoding is not widely employed in practice [14]. On the other hand, SIC only requires the knowledge of channel estimates at the receivers; since this can be provided in practice by the transmission of pilot tones [23], SIC is considered to be a more practical approach for multi-user MIMO systems.

SIC can enable the decoding of weak signals in the presence of strong interference: With SIC, the receiver tries to decode multiple received signals, typically each coming from a different transmitterusing an iterative approach. In each iteration, the strongest signal is decoded, by treating the remaining signals as interference. If a required SINR is satisfied, this signal can be decoded and *removed* from the received composite signal. In the subsequent iteration, the next strongest signal is decoded, and the process continues until either all the signals are decoded or a point is reached where an iteration fails. Note that after the removal of the strongest signal in an iteration, fewer interfering signals remain for the next iteration. With this process, nodes can receive signals from weaker transmitters in the presence of strong interferers. To illustrate with an example, consider that Jack wishes to decode Chloe's signal, in the presence of a stronger interfering signal that comes from Nina. Jack needs to first decode Nina's signal correctly, since it is the stronger one, treating Chloe's signal as noise. If the SINR is satisfied and Nina's signal is decoded in the 1st iteration, Jack can proceed with removing it from the composite signal and decoding Chloe's signal in the 2nd iteration. SIC can be cojoint with *selection diversity* at the transmitters. To facilitate this, Jack sends feedback to Chloe with regards to the channel attenuation experienced by Chloe's pilot tones, transmitted with different antennas. Chloe then uses the antenna element that yields the best reception at Jack's end [9], as we discuss later.

Challenges in rendering SIC efficient: There are two challenges that arise in harnessing the capacity benefits with SIC in a multi-hop wireless network. First, only up to a certain maximum number of strong interferers can be removed from a composite signal. This number is equal to $A-1$ where A is the number of antenna elements at the receiver. Second, the decoding in each successive iteration is successful only when signals are received with disparate power levels [16]. Indeed, if Chloe and Nina's signals both arrive at Jack with the same signal strength, the SINR requirement for decoding Nina's signal is unlikely to be satisfied and SIC will fail. Previous studies on realizing multi-user MIMO communications try to simply limit the number of links that simultaneously access the medium [3], [15], [12]. However, they do not account for the reception powers of the signals. In most of these studies, the communication model allows as many concurrent transmissions as the number of antenna elements in each contention region.

Addressing the challenges: In this paper, we ask the question: *How can we construct an environment that is conducive to SIC, in terms of a clean SINR separation between the target and the interfering signals?* To address this question, we propose a framework that performs topology control, by activating links in a way that favors the SIC functionality. Our framework identifies sets of links (sub-topologies), such that: (a) The simultaneous activation of the links in each sub-topology constructs signals with sufficiently disparate reception powers. Hence, the receivers are able to filter out stronger signals (perhaps unwanted) and detect the desired data stream(s) using SIC. (b) The links that cannot successfully co-exist are included in different topologies they are activated at different times. (c) The union of these topologies spans all the links in the multihop network. Note that there is a trade-off between the medium-access delay experienced by a link and the probability of successful reception. For each link to obtain frequent medium access, few sub-topologies should be constructed, each of which is packed with as many links as possible. On the other hand, a larger number of active links decreases the probability of successful detection with SIC. Our work is the first to consider this trade-off towards enabling multi-user MIMO communications. More specifically, our contributions are the following:

1. Designing MUSIC, a framework for constructing topologies that favor SIC: An ideal topology control solution would construct a minimum number of sub-topologies that are maximal: each of them would include as many links as possible, while maintaining a high decoding probability with SIC. However, we find that the problem of constructing the minimum number of sub-topologies wherein SIC decoding is always successful, is NP-hard. Given this, we design MUSIC, a framework that facilitates efficient multi-user MIMO-SIC enabled communications, through the greedy construction and scheduling of appropriate sub-topologies. The centralized form of our algorithm, C-MUSIC, constructs small populations of sub-topologies, wherein SIC decoding is successful with at least a certain probability. Specifically, given a link Chloe→Jack and a set of neighbor links, C-MUSIC successively adds into the same schedule: (a) the set of weaker links that can be scheduled together with Chloe→Jack while ensuring that Chloe's signal is successfully received by Jack with high probability; and (b) the set of stronger links than are scheduled with Chloe→Jack can be iteratively removed from the composite signal in order for Jack to extract Chloe's signal. We show that our topology control approach deviates from the optimal approach by a factor of $O(\Omega)$ in the worst case; Ω is a function of the number of maximum number of links that interfere with a given link (we provide an exact definition later). In addition, we propose D-MUSIC, a distributed topology control framework that leverages some of the functionalities of C-MUSIC. With D-MUSIC, each node requires only one-hop information towards making topology control decisions. Nodes exchange information with regards to their strong interfering links, towards enabling as many SIC-decodable sessions as possible.

2. Evaluating MUSIC: We evaluate C-MUSIC and D-MUSIC through OPNET simulations. We observe that with C-MUSIC, the number of sub-topologies created is at most 17% larger than those constructed through an exhaustive search (optimal) strategy. With D-MUSIC, this is number is at most 23% higher than the optimal. We also show that D-MUSIC scales well, in terms of bounding the SIC decoding error probability, in a large set of different topologies, SINR thresholds and numbers of antenna elements. We compare MUSIC against an approach which is agnostic to the SINR requirements and activates $A-1$ interfering flows in a contention region. We find that MUSIC outperforms such an approach by offering up to 4 times increase in the achievable aggregated network throughput.

The rest of the paper is structured as follows. In section II, we provide brief background on selective diversity and SIC, and we discuss related work. We state our assumptions, develop our models and postulate the considered problem in section III. In sections IV and V, we present the design of our framework, MUSIC. In Section VI we evaluate the performance of our approaches. Our conclusions form Section VII.

II. Background and Related Work

In this section, we first provide brief background on selection diversity and SIC. Subsequently, we discuss previous related studies and differentiate our work.

Selective diversity at transmitters: In multi-user MIMO communications, antenna array selection at the transmitter side is facilitated via a training process, which typically operates as follows. A transmitter X generates an array of A symbols (where A is the number of its antenna elements), and transmits one symbol with each antenna. A node Y that receives these training symbols maintains a moving average of the channel gain for each different antenna element. Node Y then identifies the antenna element that offers the best channel quality among the elements in the antenna array of X, and feeds this information back to X. Hence, after the session establishment, subsequent packet transmissions on the link $X \rightarrow Y$ use the chosen antenna element. Note that selection diversity incurs much lower transmission overheads than other multi-user MIMO transmission schemes where all antenna elements are simultaneously utilized. To elaborate, if all antenna elements are to be utilized, dirty paper coding has to be applied to enable multi-user MIMO[13]. With this, each antenna element will have to transmit with a given weight, which in turn is dictated by receiver feedback. However, due to the channel variability, these weights are frequently varying. As a consequence, receivers need to feedback channel state reports for each antenna much more frequently; this expectedly increases the long-term transmission overheads in the network. On the other hand, with selection diversity *an average channel gain* is estimated for each antenna element; this average is typically stable for prolonged periods of time (order of seconds). Hence, the (same) element that offers the highest average gain is used for extended durations, and this makes the transmission of channel state reports much more infrequent and thus, viable.

SIC: Successive Interference Cancellation at receivers: SIC allows receivers to extract an intended signal from a received composite signal; the composite signal is formed by a mixing of parallel transmissions in the receiver's neighborhood. SIC was first proposed in [21]. As discussed in section I, SIC is an iterative process. In each iteration, the strongest remaining signals in the composite signal is extracted, as long as the SINR is high enough for that signal to be decoded. The process continues until the signal of interest is extracted. In more detail, the receiver maintains an equalization matrix Q, which is used to "boost" the received power of the target signal, relative to the power of the remaining signals that are classified as interference, by filtering out stronger signals. Each node updates its locally-maintained Q with antenna weight coefficients, derived from pilot tones that are transmitted by neighbor nodes. A good approach for realizing Q is proposed in [17]. As per this approach, Q entries are chosen such that the expected estimation error in detecting a particular user's symbol is minimized. With this, a receiver with A antenna elements can successfully decode up to A signals, originated by A distinct neighbor transmitters (although there may be greater than A concurrent transmissions). A required condition here is that the A individual signals experience spatially uncorrelated fading.

Related work: There have been numerous previous studies on MIMO systems and on link scheduling. However, our work is the first to propose a topology control framework for facilitating efficient MIMO SIC operations.

Studies on multi-user MIMO networks: Sundaresan et al., [15] propose scheduling algorithms for giving medium access priority to MIMO links that belong to multiple contention regions. They demonstrate that the use of *stream control*, wherein different transmitters utilize different numbers of antenna elements, leads to significant network-wide throughput benefits. In a more recent study, Wang et al. [18] consider stream control in MIMO multi-hop networks; they propose a greedy centralized algorithm and quantify the theoretical upper bound on the achievable gains. However, unlike in our work, these efforts do not consider selection diversity or SIC decoding operations. Chu et al. in [3] propose TDMA-based algorithms to prioritize the scheduling of links based on QoS requirements imposed by the nodes in the network. However, they also do not consider selection diversity at transmitters. Mumey et al. [12], study the joint problem of stream control and link scheduling. Most importantly, unlike in our work all of the above studies assume that is able to decode as many interfering signals as the number of the utilized antenna elements.

Work on SINR-based link scheduling: Many prior studies have looked into the problem of TDMA link scheduling based on SINR information [1], [7], [11], [2], [22]. However, none of these studies considers MIMO networks. As examples, (a) Moscibroda et al. [11] find theoretical upper bounds on the scheduling complexity of arbitrary multi-hop topologies. and, (b) Santi et al. [2] propose a greedy heuristic algorithm for computationally-efficient link scheduling.

Applications of SIC on SISO networks: Several recent efforts examine performance benefits with SIC in SISO networks. Yi et al., [19] show that a particular distribution of received powers is needed for SIC systems to perform well in CDMA networks. Halperin et al., [8] propose a practical design of SIC in a SISO system. They prototype a simple version of their design. Their measurements demonstrate that SIC maintains fairness and promotes spatial reuse. However, these studies do not consider MIMO operations or multi-hop settings; with an antenna array, SIC decoding is typically more efficient.

III. Models, Problem Formulation and Approach

In this section, we describe our modeling assumptions and formulate the problem of interest. We also show that this problem is NP-hard.

Modeling assumptions: We consider an arbitrary multi-hop wireless network wherein, each node is equipped with an antenna array. All communications take place in a single frequency band, all transmitters use equal powers P, and the same combination of modulation and forward error correction coding schemes. As described in Section II, *selection diversity* is used for transmissions. The receivers use SIC decoding. In the rest of the paper, if the interference is stronger than the intended signal, we refer to it as *strong interference*; if it is lower than the intended signal we refer to it as *weak interference*.

Characterizing the network with a model: We model the above network as a directional graph G=(V, E). The set V includes all the nodes in the network. For a pair of nodes u,$v \in V$, a directional edge e=(u, v) is a member of E if node u's signals can be decoded at v in the absence of interference.

The channel model: Transmitted signals are attenuated due to path loss. Furthermore, due to multipath, the signal experiences a fade that varies as per a Rayleigh-distribution; the channel coefficients $h_{u,v}$ in Eqn. 1 are generated using this model. The fading is independent among different transmitter-receiver antenna pairs, as well as at different time instances. Given these, the power of a signal transmitted by node u, at a receiver node v is given by:

$$P_{uv} = P \cdot |h_{uv}|^2 / d_{uv}^{\alpha} \,. \tag{1}$$

Multi-User MIMO Receptions using SIC: With SIC, the communication on a link (u, v) is successful **iff**:
(i) At v, signals from no more than A-1 other transmitters are received with a power that is greater than that of u's signal, **and** each stronger signal is successfully *removed* before decoding u's signal. For this, in each of the j=$\{1,2,...A$-$1\}$ SIC iterations, the following must be satisfied for detecting the j^{th} strongest transmitter's signal:

$$\frac{P_{uv}}{N + \sum_{z \neq u} P_{z,v}} > \gamma \tag{2}$$

(ii) After removing all stronger interferers, Eqn. 2 must be satisfied for u's signal.

As described earlier, satisfying these criteria in a multi-hop network is a challenge, which we address in this paper.

Problem Formulation: As discussed in Section I, in order to satisfy the above criteria, *we seek to partition the network into different sub-topologies* which time-share the medium. In each sub-topology, each active link has to satisfy Eqn. 2 with an arbitrarily small, predetermined probability δ. Note that the condition in Eqn. 2 is only probabilistically satisfied since temporal channel fluctuations can cause the decoding to fail. We seek to minimize the number of such topologies in order to ensure that each link is activated with the maximum frequency; indirectly, we seek to maximize the throughput under the conditions of max-min fairness.

In order to identify the links that can be grouped under the same sub-topology, we need to first infer the interference relationships among the links in the network. These interference relationships are defined not only in terms of whether a node is transmitting or not, but also with respect to which receiver is targeted by each transmitter. Interference relationships are typically represented using edge-based interference graphs (or conflict graphs) and we use a similar approach; conflict graphs have been used in the context of networks with single antenna elements in [10].

The Interference Graph: The directional, edge- and vertex-weighted interference graph G'=$(V', E', w_{V'}, w_{E'})$ is induced from the directional graph G=(V, E) that represents the network as follows. V' includes a vertex e for each directional edge (u, v) in E. The vertex e is weighted by the *mean* value of P_{uv} (Eqn. 1); the weight of edge e is denoted by $w_{V'}(e)$. Each pair of vertices e,f in V' is connected by a weighted directional edge in E'; the weight of the edge (e, f), denoted by $w_{E'}(e, f)$ is equal to the power measured at the receiver of link f when link e is active.

The problem of dividing the graph G' into a minimum number of sub-graphs G'_i (to represent each sub-topology) can be formally represented as follows:

minimize $\quad m, \;$ where $V' = V'_1 \cup V'_2 \cup .... \cup V'_m$
subject to $\quad \forall i, \forall e \in V'_i$:

$$\sum_{g \in V'_i} b_g < A \;\; , \;\; \text{where} \;\; b_g = \left\{ \begin{matrix} 1 \;, & w_{E'}(g,e) \geq w_{V'}(e) \\ 0 \;, & otherwise \end{matrix} \right\} \tag{3}$$

$$\underset{w_{E'}(g,e) \geq w_{V'}(e)}{\forall g \in V'_i \quad s.t.} \left[\sum_{\substack{h \in V'_i \\ w_{E'}(h,e) < w_{E'}(g,e)}} w_{E'}(h, e) < \frac{w_{E'}(g, e)}{\gamma} - N \right] \tag{4}$$

$$\sum_{\substack{f \in V'_i \\ w_{E'}(f,e) < w_{V'}(e)}} w_{E'}(f, e) < \frac{w_{V'}(e)}{\gamma} - N \tag{5}$$

This requires the minimization of the number of sub-topologies m. V'_j represents the set of links in the j^{th} sub-topology that is constructed. The constraint in inequality 3 mandates that the total number of strong interferers[1] should be less than the degrees of freedom A. The constraint in inequality 4 requires that for each communication link in a group, **each strong** interferer must be correctly decodable to be removed; the term within the summation inside the parentheses, essentially implies that the SINR for each strong interferer should be satisfied. Inequality 5 mandates that once the interference from the strong interferers is removed, the desired signal should be decodable i.e., should satisfy the SINR requirement. Note that the latter two inequalities are easily obtainable from the requirement postulated in Eqn. 2.

The Complexity of this problem: We prove that the problem of finding a minimum set of sub-topologies such that SIC is successful, is NP-hard. To this end, we simply show that a special case of the considered problem is the problem of scheduling in a SISO network.

Theorem 1. The topology control problem for multi-user MIMO networks using SIC, based on the SINR model is NP-hard.

Proof: When $A = 1$ in Eqn. 3, the considered problem reduces to the SISO scheduling problem with a single antenna per device. In this context, no SIC is considered. The SISO scheduling problem has been proven to be NP-hard [6]. Since, a special case of the considered problem is NP-hard, we conclude that the general problem is NP-hard. ■

Facilitating SIC under temporally varying conditions: Our approach relies on controlling the interference on each link. In what follows, we derive the necessary conditions for successful decoding with SIC.

Limiting weak Interference: In order for a signal to be decoded in the presence of only weak interferers, Eqn. 2 has to be satisfied. From this equation it is easy to see that the maximum interference that can be tolerated on link (u, v) for successful decoding under these conditions is $P_{uv}/\gamma - N$. We refer to this value as the *weak interference budget* of link (u, v). At the receiver node v, the aggregate power from all the weak interferers is the sum of the P_{uv} terms as defined in Eqn. 1. The $|h_{zv}|^2$ terms in this sum are exponentially distributed random variables (h_{zv} follows a Rayleigh distribution). Thus, the aggregate interference from the transmitters *at a given distance* can be modeled as an Erlang-distributed random variable with parameters n, the number of these transmitters, and σ, the variance of the Rayleigh distributed random variable. Our goal is ensure that the aggregate weak interference on each link does not exceed its weak interference budget with a probability greater than δ i.e., we require that:

$$Pr\left\{\sum_{z\neq u} P(z,v) > \frac{P(u,v)}{\gamma} - N\right\} < \delta. \tag{6}$$

Assuming that all weak interferers are received with the same power as that of the strongest (a conservative condition) among these interferers (say P'_{max}) and using the cumulative distribution function (CDF) of the Erlang-distribution, we define a function $ErlangFeasible(\sigma, n)$. This function outputs the tuple (n,P'_{max}), where n is the maximum number of interferers that can be tolerated by the target link, if each of these n interferers projected an interference equal to P'_{max}. Simply put, the $ErlangFeasible()$ function is used to bound the weak interference. With the above assumption, Eqn. 6 reduces to:

$$Pr\left\{ErlangFeasible(\sigma,n) > \frac{\frac{P(u,v)}{\gamma} - N}{P_{max}}\right\} < \delta. \tag{7}$$

With MUSIC, this condition is used to bound the number of weak interferers for a link (to be described later).

Controlling strong interference: Consider an example where a node receives a composite signal with K different signals. Further, assume that the signal from its desired transmitter is the second *weakest* from among these K signals. P_i represents the power of the i^{th} strongest signal in a sorted order; thus, $P_{(K-1)}$ represents the power of the desired signal. In order for the desired signal to be correctly decoded, first, it is required that $K \leq A$. Second, each of the $K - 2$ strong interference terms must be correctly decoded and removed. This implies that the SINR requirements at each of the following steps need to be satisfied:

$$\begin{aligned}
&\text{if} \quad P_1/(N + P_2 + P_3 + ... + P_K) > \gamma \Rightarrow \text{decode and subtract 1st interferer.}\\
&\text{if} \quad P_2/(N + P_3 + ... + P_K) > \gamma \Rightarrow \text{decode and subtract 2nd interferer.}\\
&\quad \dots\\
&\text{if} \quad P_{K-1}/(N + P_K) > \gamma \Rightarrow \text{desired transmitter is correctly decoded.}
\end{aligned} \tag{8}$$

In the set of requirements listed above, the strong interference P_{K-2} must be at *least* equal to $(P_{k-1} + P_K + N).\gamma$. This condition has to be satisfied in the worst case when P_K has its maximum value of $(P_{K-1}/\gamma) - N$. Simplifying, it is easy to see that $P_{(K-2)}$ must be at least equal to $P_{(K-1)} \cdot (\gamma + 1)$. Following through these equations iteratively backwards, each j^{th} strongest interferer must satisfy the property relative to the intended signal:

$$P_j \geq P_{(K-1)} \cdot (\gamma + 1)^{K-1-j}, \forall j \in [1, K-2] \tag{9}$$

For correct decoding at every step, there can be at most one strong interferer for a specific value of $l = K - 1 + j$. In other words, if a link (y, z) experiences interference from transmitter u, then

$$\forall u \in V: \ P_{uz} > P_{yz}, \qquad P_{uz} \geq P_{yz} \cdot (\gamma + 1)^k, \quad k \in [1, A-1]. \tag{10}$$

and for each value of k, there can be just a single interferer. If this is not the case, one or more of the requirements in Eqn. 8 are violated.

Communications that block each other: Given the above requirements on the interferers, we define the link pairs that cannot be activated simultaneously (i.e., **block** each other). We say that links $\ell_1 = (u, v)$ and $\ell_2 = (x, y)$ block each other if:
(a) $P_{xv}<P_{uv}$ but $P_{xv}\geq P_{uv}/\gamma$: the weak interferer causes more interference than the weak interference budget.
(b) $P_{xv}>P_{uv}$ but if $P_{xv}\leq\{P_{uv}+N\}\cdot\gamma$: strong interferer cannot be removed. (k=0 in Eqn. 10)
(c) x=u : these links have the same transmitter.
(d) x=v or y=u : a node is the transmitter of one link and the receiver of the other.

Note here that, if a link ℓ_1 is activated, a link that blocks ℓ_1 cannot be activated simultaneously. However, this does not imply that a link (say ℓ_j) that does not block ℓ_1 can be activated with probability 1; it depends on (a) whether there are other links of similar interference power as ℓ_j has already been activated at that time and (b) whether its weak interference budget is satisfied.

[1]If the incoming edge weight $w_{E'}(g, e)$, at a node e of the interference graph, is larger than node weight $w_{V'}(e)$, link g projects interference that is stronger than the desired signal strength at the receiver of link e.

IV. Our Centralized Approach: C-MUSIC

Since the general problem for finding the minimum number of sub-topologies for disjoint activation (as discussed in the previous section) is NP-hard, we propose a centralized approximate approach that we call Centralized MUSIC (or C-MUSIC) for this purpose. C-MUSIC takes as input the interference graph $G'(V', E')$. It maintains a dynamically changing set of nodes R' which initially contains the nodes in G' (i.e., V'). R' is updated as new sub-topologies are formed. We describe C-MUSIC in a sequence of steps. For ease of presentation, we primarily describe how the links that are included in the first sub-topology are chosen. Later, we discuss how the same procedure can be used with minor modifications, for other sub-topologies.

Step 1: Adding nodes that do not require SIC to a sub-topology: First, C-MUSIC identifies a set S of vertices from R', whose (vertex) weights are greater than all incoming edge weights. The elements of S represent the communication links whose receivers do not need SIC to decode their target signals. C-MUSIC then finds a maximally feasible subset[2] of S; this subset is called S'. S' is added to a newly formed set R'_1; the links corresponding to these vertices are included in the first sub-topology. Elements of $\{S - S'\}$ are no longer under consideration for being included in the first sub-topology. This step is represented by instructions $2-5$ in Algorithm 1.

Algorithm 1: Finding sub-topology R'_i of R'

Input: R', (copy of) $G' - (R'_1 \cup R'_2 \cup \ldots \cup R'_{i-1})$
Output: R'_i, i^{th} sub-topology
begin
1 **init:** $R'_i = \emptyset$
2 $S \leftarrow$ {Nodes in R' that do not have strong interferers in R'}
3 $R' \leftarrow R' \setminus S$
4 $S' \leftarrow$MaxFeasibleSubset(S, δ)
5 $R'_i \leftarrow R'_i \cup S'$
6 Update weak and strong interference budgets
7 Refine R' based on R'_i
8 **while** R' *is not empty* **do**
9 $S \leftarrow$ {Nodes in R', which do not have strong interferers in R'}
10 $R' \leftarrow R' \setminus S$
11 $S' \leftarrow$ MaxFeasibleSubset(S)
12 $R'_i \leftarrow R'_i \cup$ FeasibleWeakInterferers(R'_i, S', δ)
13 Updates and refining of (R', S', R'_i)
end
14 **return** R'_i
end

Step 2: Updating weak and strong interference budgets: First, nodes that are blocked by the elements of S' are removed from R'. Next, the elements of R'_1 are considered one by one; if any other element (say u) in R' projects weak interference on the considered element (say v) the weak interference budget of v is decremented by $w_{E'}(u, v)$, and similarly for u. This step decreases the "maximum additional weak interference" that can be tolerated on link v. In addition, the strong interference is handled as described in Section III (Line 6 of Algorithm 1).

Step 3: Refining the candidate vertices for the next round of SIC: From the updated set R', C-MUSIC next tries to find a set of vertices that can perform SIC to eliminate strong interference from the current set R'_1. It considers each element in R' sequentially. Consider one such link e. C-MUSIC checks, for each element (say v) in R'_1, whether $w_{E'}(v, e) > w_{V'}(e)$. If this condition holds, v is a strong interferer. It then finds the highest value of k such that $w_{E'}(v, e)/w_{V'}(e) > (1+\gamma)^k$. After this process, C-MUSIC checks whether the following conditions hold for e: (i) For no element in R'_1, the value of k (found above) is zero and (ii) The values of k for each element of R'_1 is unique. (Recall that these requirements were derived in Section III). If the conditions do not hold, e is removed from R' (Line 7 of Algorithm 1).

Algorithm 2: Algorithm MaxFeasibleSubset

Input: Set of Links S that do not need SIC, Error Margin δ
Output: S', subset of S in which each link's SINR is satisfied w.p. 1-δ
begin
init: $S' = \emptyset$
repeat
$\ell \leftarrow$ the most-blocking link in S
$S \leftarrow S \setminus \{\ell\}$
$S' \leftarrow S' \cup \{\ell\}$
$r_{V'}(\ell) = w_{V'}(\ell)$ // residual interference of ℓ
$S \leftarrow S \setminus \{\psi \in S$: ℓ blocks ψ (or ψ blocks ℓ)$\}$
foreach $z \in S$ *s.t.* $(\ell, z) \in E'$ **do**
$r_{V'}(z)$ -= $w_{E'}(\ell,z)$
$S \leftarrow S \setminus \{v\}$ if $r_{V'}(z) < 0$
end
until $S = \emptyset$;
return S'
end

Step 4: Adding more links that use SIC to sub-topology $\mathbf{R'_1}$: The elements that remain in R' at the end of Step 3 are candidates for SIC. From those vertices in R', C-MUSIC again finds a set S where SIC is not needed (when only considering the other vertices in R' at this time[3]). It then finds the maximal feasible subset S' of S using Algorithm 2 as in Step 1.

Next, C-MUSIC checks whether all the vertices in S' can be activated together with R'_1. For this, it considers each element in R'_1 and determines if the weak interference budget of any of these elements is exceeded by the elements in S', to ensure that the condition in Eqn. 7 is satisfied (Line 5 of Algorithm 3). If the interference budged is not exceeded for any link in R'_1, all links in S' are added to R'_1, and the links in R' that are blocked due to this addition are eliminated from consideration. If the interference budget is exceeded for a link in R'_1, C-MUSIC removes the link that causes the maximum weak interference (considering all links $e \in S'$ and $v \in R'_1$) from S' and Step 4 is repeated. At the end of this process, all links that remain in S' are safely included in R'_1. Step 4 is captured by instructions 8-13 in Algorithm 1. Line 13 is used to update the set R'_1 by including the set of links that were successfully included in this round, and to find the set of candidates for the next round considering the updated R'_1.

Algorithm 3: Algorithm FeasibleWeakInterferers

Input: Sub-topology R'_i, Candidate Links S', Link Error Margin δ
Output: F', the subset of S' that can be added to R'_i
begin
1 **init:** $F' = S'$
2 **while** S' *is not empty* **do**
3 $\ell \leftarrow \{z \in R'_i$ that blocks most links in $S'\}$ //ℓ is the hardest to schedule more links with
4 $n_\ell = |\psi|$, where $\psi \in S' : w_{E'}(\psi,\ell) < r_{V'}(\ell)$
5 $(n'_\ell, w_{max_{E'}}(\ell, z)) \leftarrow$ErlangFeasible$(n_\ell, r_{V'}(\ell))$
6 $S' \leftarrow S \setminus \{v \in S' : w_{E'}(v, \ell) > w_{max_{E'}}(\ell, z)\}$
7 **foreach** $z \in S'$ **do** update residual capacity (i.e. remaining affordable interference) of z now that $\ell \in S'$
end
8 **return** S'
end

The steps above are repeated and in each round, a subset of vertices from R' are added to R'_1 and a new subset is eliminated from contention. The process terminates if R' is empty at this time; *i.e.,* each link is either included in R'_1 or is eliminated

[2]Note that a maximal feasible subset is not the same as the *maximum* subset that satisfies the desired properties (using Algorithm 2); finding the maximum feasible subset (a maximal subset of the highest cardinality) is NP-hard [20].

[3]These links will use SIC to remove interference from links that were already included in the previous steps; Steps 2-3 determine whether this is feasible.

from consideration for R'_1. If not, the process returns to Step 3 above.

Constructing subsequent sub-topologies: Once the first set of links (R'_1) is determined, R' is updated to remove these vertices and the links incident on them; now it contains those links that could not be included in the first sub-topology. These links are considered for the second sub-topology and the above steps are repeated. At the end of the process, R'_2 is determined. If there are links in R'_1 that can be activated in addition, in the second sub-topology (they do not violate the requirements of the R'_2 links that are already included), they are included as well using a procedure similar to the above (not described in detail due to space constraints). Similarly, when links are chosen for sub-topology i (R'_i) links that are in $R'_1 \cup R'_2 \ldots R'_{i-1}$ are considered for reactivation in sub-topology i. In other words, after fulfilling the fairness constraints the algorithm tries to *pack* as many links as possible into each sub-topology.

Approximation bound of proposed algorithm: Next, we show that our approach has a *performance efficiency* that is within Ω of the optimal, where Ω is the *maximum opportunity cost* in the network. We first define a few key terms (including performance efficiency and opportunity cost) and later, prove the performance bound.

Interfering Links: Eqn. 2 determines whether two distinct links can be active simultaneously without SIC. If the SINRs measured at the two receivers are simultaneously higher than γ, the two links can be active together; if not, the two links are classified as *interfering* links. Note that *interfering links* have an edge between them in the interference graph. Let $\mathbf{T}_l$ denote the set of interfering links for link l. If link l is active, none of the links in $\mathbf{T}_l$ can be active.

The opportunity cost: The *opportunity cost* O_l for link l is the maximum number of links in $\mathbf{T}_l$ that can be active simultaneously if l is deactivated. From among the opportunity costs of all the links in the network, we denote the maximum opportunity cost[4] by Ω.

Definition 1. We define the *performance efficiency* of an algorithm as the ratio of number of links selected at the end of the algorithm to the total number of candidate links at the beginning of the algorithm.

We first consider the phase where, the set of nodes that cannot apply SIC are chosen. At the end of this phase, a sub-set of such nodes (that cannot perform SIC given this chosen set) are *blocked* i.e., removed from consideration. In addition, the SIC condition is applied to choose a set of candidate nodes, that are considered for the subsequent phase. Let us call this Phase 1. Let α' and α^* be the performance efficiencies of the algorithm that performs Phase 1 (consisting of the MFS selection and the selection of nodes for the next phase) and and the optimal algorithm for Phase 1, respectively. Then, the following lemma is holds.

Lemma 1. The algorithm that performs Phase 1 achieves a performance efficiency [5] of $1/\Omega$. In other words, $\alpha^* \leq \Omega \cdot \alpha'$ is satisfied.

Proof: Consider link l, the link that blocks the most links; this is the link that is chosen first by Algorithm 2 when finding a maximal feasible subset. If this link is added to the sub-topology, then no link that is blocked by this link from among the subset of nodes that are considered by Algorithm 2 can be active simultaneously. Furthermore, the activation of this link (perhaps jointly with other links in this subset) can block links not in this subset, from performing SIC. If link l were to be deactivated, at most Ω additional links can be active in lieu of link l, where Ω is defined as above; note that Ω being an upper bound subsumes the possibility of SIC on links that have an edge to link l in the interference graph. Applying the same argument inductively, the proof is established. ∎

The following theorem provides a performance bound on our proposed algorithm.

Theorem 1. Algorithm 1 has a performance efficiency of Ω.

Proof: For each sub-topology, the proposed algorithm (Algorithm 1) executes in two phases. Phase 1 was define above. In Phase 2, the algorithm checks if, for the set of candidate nodes, the weak interference budgets of nodes already selected are violated. The set of procedures in Phase 2 are similar; an MFS is selected from the candidate set, and nodes that block the already selected nodes are removed. Leveraging Lemma 1, it is easy to see that the performance efficiency of Phase 2 and the optimal algorithm are simply α' and α^*, respectively.

Let S^* and C^* (or S' and C') denote the outputs achieved at the end of Phase 1 and Phase 2 by the optimal algorithm (or by Algorithm 1), respectively. Then, in order to prove the theorem, we need to show that:

$$\frac{|S^*| + |C^*|}{\Omega} \leq |S'| + |C'|. \tag{11}$$

We denote R^* and R' to be the number of candidate links for a sub-topology at the beginning of the optimal algorithm and Algorithm 1, respectively. Since the optimal algorithm finds at least as many links as the proposed algorithm for a sub-topology, the set of candidate links for forming the subsequent sub-topology, is smaller. In other words, $|R^*| \leq |R'|$. With this:

$$\begin{aligned} \frac{|S^*| + |C^*|}{|S'| + |C'|} &= \frac{\alpha^*|R^*| + \alpha^*(|R^*| - \alpha^*|R^*|)}{\alpha'|R'| + \alpha'(|R'| - \alpha'|R'|)} \\ &= \frac{|R^*|}{|R'|} \cdot \frac{2\alpha^* - (\alpha^*)^2}{2\alpha' - (\alpha')^2} \leq \frac{2\alpha^* - (\alpha^*)^2}{2\alpha' - (\alpha')^2}. \end{aligned} \tag{12}$$

Using Lemma 1 reduces the last term in Eqn. 12 to

$$\frac{2\alpha^* - (\alpha^*)^2}{2\alpha' - (\alpha')^2} = \frac{\alpha^*}{\alpha'} \cdot \frac{2 - \alpha^*}{2 - \alpha'} \leq \Omega$$

∎

V. Our Distributed Approach: D-MUSIC

The centralized version of our approach requires information to be collected at a central controller for determining the different sub-topologies. In this section, we propose D-MUSIC, a distributed approach for constructing these sub-topologies. While D-MUSIC does leverage some of the features of C-MUSIC, there are modifications to enable distributed operations. The key property of D-MUSIC is that nodes exchange local messages and determine the links that can be activated concurrently in their neighborhoods. Thus, while the sub-topologies are determined on a global scale, the process of determination is performed in a distributed manner, in parallel, and locally in the different parts of the network.

[4] In [2], for the SISO case, Ω is shown to follow $O(|V|^{1-\frac{2}{\varphi(\theta)+\epsilon}}(\log|V|)^{\frac{2}{\varphi(\theta)+\epsilon}})$, where θ is the path loss exponent, $\varphi(\theta)$ is a constant which depends on θ, and ϵ is an arbitrarily small positive constant.

[5] This is the maximum ratio by which the results of an approximation algorithm may differ from the optimal solution.

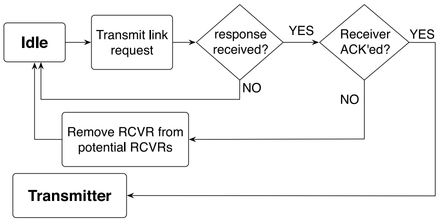

Fig. 1. The operations of the transmitter in a sub-topology with D-MUSIC.

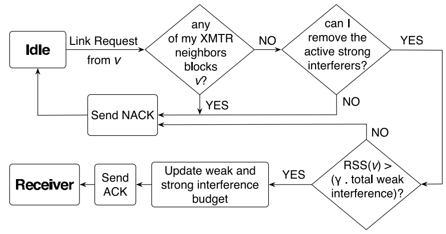

Fig. 2. The operations of the receiver in a sub-topology with D-MUSIC.

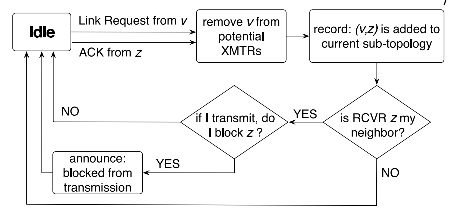

Fig. 3. The operations of the overhearer in a sub-topology with D-MUSIC.

Recall that each sub-topology corresponds to a time-period. All the links that belong to a sub-topology can be activated in the assigned time period, without violating the requirements on the probability of successful decoding on any of the links.

Assumptions: We assume that nodes are aware of their one-hop neighborhoods. In particular, using a neighbor discovery process of some sort (such as HELLO messages [4]), we assume that a node knows who its neighbors are and the signal power on the link to each of these neighbors. We also assume that a potential transmitter uses this information towards selecting the best antenna in order to communicate with a specific receiver.

For ease of presentation, we assume that every node has packets to send i.e., can be a transmitter. It can choose any of its neighbors as a receiver; given this, every node in the network can assume the role of a receiver as well. The approach can be easily modified to accommodate the case where only a sub-set of the nodes have packets to send, i.e., are transmitters.

We assume that nodes transmit their packets using either a SISO transmission or using the MIMO diversity mode during the topology control phase. Multi-user MIMO communications with selection diversity and SIC are activated during a data packet exchange phase that follows the sub-topology formation. In this paper, we simply allow nodes to transmit packets at random, using an ALOHA-like protocol during the data packet exchange phase; the design of a smart MAC protocol for this is beyond the scope of this paper.

Transmitter functions: If a node is not a priori chosen to be a receiver, it can be a transmitter. The node determines whether its transmission violates the following constraints in the considered sub-topology: (i) the chosen receiver is a transmitter (ii) the transmission causes the weak interference capacity of an already activated neighbor link to exceed its budget and (iii) the transmission causes strong interference at a neighbor receiver, which leads to SIC decoding failure (a different strong receiver with the same value of k with respect to that receiver, has already been activated or, $k = 0$). If any of these conditions hold, the transmitter is precluded from initiating the transmission process.

Let us now assume that the transmitter determines that it is allowed to perform a transmission. After a randomly chosen time period, it transmits a packet to its best (in terms of signal strength) possible neighbor (that does not violate the above constraints) to which it intends to send packets. In this packet, it includes its ID, the ID of the receiver, and the sub-topology in which it wishes to communicate with the receiver. The process starts out with sub-topology 1 and if no links can be activated in this topology (given other links that were activated), it proceeds to try sub-topology 2 and so on. The transmitter functionalities are depicted in Fig. 1.

If the transmitter does not hear messages corresponding to the current sub-topology for a pre-defined time period, it may try to reactivate some of its links which were included in a prior sub-topology. The action is based on an implicit understanding that there are no additional links being activated in the current sub-topology in the transmitter's neighborhood; the weak interference and strong interference constraints need to be satisfied in order for a transmission to be initiated.

Receiver functions: Upon the receipt of the above packet, the receiver determines if the proposed transmission is in fact viable. First, it checks whether this packet can be decoded in the indicated sub-topology given its knowledge of the links that are already included in that sub-topology, in its local neighborhood. If the reception requires SIC, the receiver determines if this is viable; note that the transmitter may not be aware of all the strong interferers in the receiver's neighborhood. If it can indeed decode the packet, it transmits an acknowledgement to the transmitter, confirming the activation of the link in the proposed sub-topology. The acknowledgement message contains: (i) the residual weak interference budget of the receiver given this reception and (ii) the value of k if this transmitter is a strong interferer to a different transmitter from which the receiver intends to receive in the same sub-topology (note that with multi-user MIMO the receiver can receive a plurality of signals concurrently). We capture the receiver functionalities in Fig. 2.

Overhearing nodes: Nodes that are neighbors of the transmitter take a conservative approach and assume that the communication will take place.

Nodes that are neighbors of the receiver hear the ACK message, and determine whether or not they can initiate a new transmission in the announced sub-topology given the new link in the sub-topology. For this, these nodes determine whether they project (a) strong interference that can be tolerated with SIC at the receiver or (b) weak interference that do not violate the receiver's weak interference budget. If either (a) or (b) hold, they can potentially be a transmitter in the considered sub-topology. If they cannot initiate new transmissions (due to this newly activated link), they are precluded from being transmitters for that sub-topology. These nodes can only initiate new transmissions in the next sub-topology (time period). We show these functions in Fig. 3.

Termination of the process: After a node is able to activate all of its outgoing links (perhaps in different sub-topologies) it transmits a message announcing that it is ready for the data transfer phase. From the perspective of a node, the data transfer phase does not begin until all of its neighbors have announced that they are ready as well. Inductively, one can easily see that this phase can begin only when all the nodes in the network are ready.

VI. Performance Evaluation

We evaluate the performance of C-MUSIC and D-MUSIC on both specific and random topologies via extensive simulations. In small topologies, we compare the performance of C-MUSIC and D-MUSIC with that of optimal activation (exhaustive search). We also compare the performance of our approaches with an approach where, A-1 other links are allowed to be simultaneously active in a neighborhood of a receiver; as discussed earlier, many MAC protocols are based on allowing these many concurrently active links [15], [12]. We call this the degree of freedom based approach or simply DoF-based topology control.

Simulation Setup: We implement all the algorithms on the OPNET v.14 simulator; we provide the details below.

Phases of operation: There are two phases that are simulated. First, we have a topology control phase where the specific, considered approach (either C-MUSIC, D-MUSIC, Exhaustive Search or DoF-based topology control) is invoked. At the end of this phase, the sub-topologies that are formed are activated sequentially in time. The second phase is a data transfer phase. This phase includes the activation periods for each sub-topology. Here, data packets are transmitted between randomly chosen source destination pairs that are active within the corresponding period. Nodes generate data packets destined to all of their neighbors. The load generated at a node varies between 10 and 30 packets/sec; each packet is 1500-bytes long. In addition to the achieved throughput, the performance in terms of the metrics defined later in this section, is evaluated with each approach.

Channel Models: We assume that packets experience path loss with a path loss exponent of 4. During the topology control phase, we assume that the MIMO diversity mode [5] is used to increase the reliability of packet transmissions; due to the increased reliability, we assume that the transmissions are lossless. Lossy transmissions due to fading (if SISO were used) would affect all the topology control algorithms in terms of convergence times. Packets in the data transfer phase are subject to both path loss and temporally varying Rayleigh fading.

SIC implementation: When decoding a data packet, we consider all other packets that interfere with the considered packet due to either full or partially overlapped receptions. For a target packet if (a) the strong interference from all such interfering packets can be removed in distinct SIC iterations (have different k values as per Eqn. 10) and, (b) the total weak interference from such packets can be accommodated (is below the packet's weak interference budget), the packet is successfully decoded.

Scenarios of Interest: We primarily vary the node density in the network; we use the average node degree as a measure of this density. We consider cases where nodes have 3,4, or 8 antenna elements. We also consider the impact of varying the SINR threshold; we consider two different threshold values, 5 and 12 dB. We repeat every simulation experiment for 40 times.

Metrics: We evaluate C-MUSIC and D-MUSIC in terms of the *number of topologies formed* as compared to the optimal (using exhaustive search) in small scenarios. In large scenarios, the exhaustive search takes a long time and does not converge. We also compute the *average decoding success probability*; note that due to temporal variations in channel conditions there will be decoding failures. This could be both due to a signal getting attenuated due to fading or due to an interfering signal having a higher than average power[6]. We also measure the achieved throughput in the data transfer phase with all the considered approaches.

Results: Next we discuss the results from our simulation experiments.

[6]Recall that the sub-topologies were all formed based on mean signal power criteria.

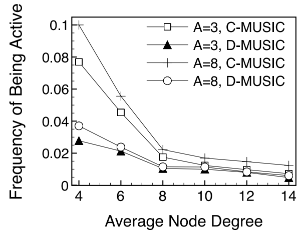

Fig. 4. The frequency with which sub-topologies are activated with C-MUSIC and D-MUSIC

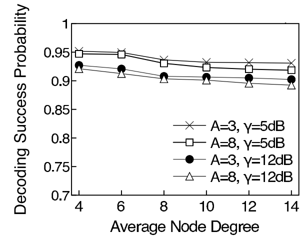

Fig. 5. The decoding probabilities are stable with C-MUSIC and D-MUSIC for a wide range of densities.

1. C-MUSIC and D-MUSIC are efficient in terms of the number of sub-topologies formed: We compare the number of sub-topologies formed with C-MUSIC and D-MUSIC to *the minimum* number of topologies found with exhaustive search. Due to the exponential growth with exhaustive search, we only perform our comparisons with small topologies consisting of 40 links (which correspond to either 7 or 8 nodes in different scenarios that we consider). We consider 30 such topologies. We find that the average number of sub-topologies found using C-MUSIC is 9.18, and the minimum feasible (on average) is 7.83. The average with D-MUSIC is 9.64. These results show that the MUSIC framework can efficiently find sub-topologies; the number found is only marginally higher than that with the optimal.

We also compare the frequency with which sub-topologies are activated with D-MUSIC in networks of different densities, with that using C-MUSIC. These results are shown in Fig. 4. In small networks, as one might expect, the activation frequencies are high; in larger networks more sub-topologies are formed and the activation frequencies decrease. As the number of antenna elements is increased, SIC is more effective and thus, more links can be grouped under a sub-topology. Consequently, the activation frequency increases with the number of antenna elements used. Most importantly, the performance of D-MUSIC is very similar to that of C-MUSIC.

2. The probability of successful decoding with D-MUSIC does not decrease to a significant extent as density increases: Next we assess the ability of D-MUSIC to provide high decoding success probabilities in scenarios with different levels of interference. For this, we perform simulations with different numbers of antenna elements at each node as well as with different SINR thresholds. Fig. 5 depicts the results. We observe that with D-MUSIC, the probability of successful decoding remains stable (varies by at most 2%) as the node density increases. This demonstrates that topology control with D-MUSIC in dense multi-user MIMO networks effectively bounds the probability of decoding error.

3. DoF based link activation cannot effectively exploit the benefits of multi-user MIMO: We compare the link activation based on SINR (as in MUSIC) with that simply based on the number of antenna elements (DoF based topology control). For this, we perform simulations on three random topologies of different sizes. We compare the efficiency of C-MUSIC, in terms of successful decoding, with the DoF based technique. DoF forms a sub-topology R_i as follows: (a) A link ℓ is selected as per line 3 of Algorithm 2 and is added into R_i. (b) A new link is added into R_i, as long as either (a) there is no link in R_i that has more than A-1 interfering links, where A is the number of antenna elements on each device, or (b) it does not interfere with any of the links in R_i. The results are depicted in

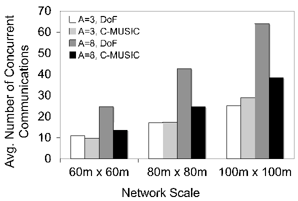

Fig. 6. The DoF method is liberal in allowing many links to be simultaneously active.

Probability of Decoding Error			
		A=3	A=8
60x60	**C-MUSIC**	**0.018**	**0.034**
	DoF-Method	0.616	0.748
80x80	**C-MUSIC**	**0.024**	**0.036**
	DoF-Method	0.643	0.753
100x100	**C-MUSIC**	**0.026**	**0.041**
	DoF-Method	0.680	0.754

Fig. 7. Links activated based on DoF-based topology control experience more decoding errors.

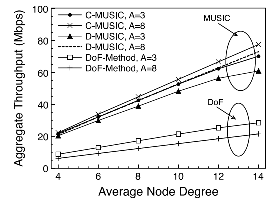

Fig. 8. MUSIC provides a better throughput compared to that with the DoF method.

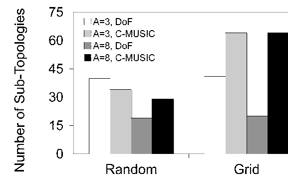

Fig. 9. The type of topology affects the ability of MUSIC to form limited numbers of sub-topologies.

Figs. 6, 7 and 8. First, we observe that the DoF method allows the concurrent activation of a much larger number of links, as compared to MUSIC (Fig. 6), in all the different topologies that we examine. In fact, as the size of the topology increases, DoF allows many more links to be active (as much as 66% more, compared to MUSIC). However, as we observe in Fig. 7, this leads to an excessive increase in the probability of decoding error. In particular, we observe that with 3 antenna elements per node, the application of DoF increases the probability of decoding error by as much as 28 times, while with 8 antennas the increase is 16 times. This expectedly has a direct impact on the total network throughput. In Fig. 8 we observe that MUSIC outperforms DoF in terms of total throughput in all considered network densities, by as much as 4 times.

4. The topological properties of the network affect the performance: We perform extensive simulations with both MUSIC and DoF with two types of topologies: a randomly generated topology and a grid. From Fig. 9 we see that the efficiency of C-MUSIC is higher with random topologies. With random topologies, fewer sub-topologies are formed, since many more links are amenable to inclusion in every sub-topology. On the other hand, in grid topologies, we observe that C-MUSIC is coerced into constructing a significantly larger number of sub-topologies (2.2 times more than with random topologies for A=8), each consisting of much fewer links. This is because in a grid topology each node is equi-distant from its neighbors. Hence, the signals of neighbors arrive at a receiver with similar powers; this increases the probability of decoding error with SIC. Due to this, it is also the case that in the grid deployment, the number of antennas does not affect the number of formed sub-topologies. Unlike C-MUSIC however, we observe that DoF constructs a similar number of sub-topologies with both the random and the grid deployments. This is because DoF takes into account the node degree (which is 7 on average in all simulated topologies) and not the SINR. However, due to this it suffers from degraded decoding probabilities. We observe that the decoding probability with the DoF-based approach was 0.73, while that with C-MUSIC was 0.013.

VII. Conclusions

In this paper, we propose MUSIC, a topology control framework for exploiting the benefits of multi-packet reception using SIC in multi-user MIMO networks. We determine the conditions that render SIC efficient; these are related to the maximum number and the strength of simultaneously interfering transmissions. These conditions are then used to drive our framework MUSIC. MUSIC, divides the network topology into sub-topologies, each of which includes links that can be activated together; the activation of these links leads to a high decoding probability with SIC. We provide both a centralized and a distributed version of MUSIC. Our extensive OPNET simulations, across multiple topologies and with different numbers of antenna elements, demonstrate that MUSIC forms sub-topologies that enable efficient SIC operations. We also show that MUSIC outperforms approaches that simply consider the number of antenna elements as a determining factor for allowing parallel transmissions.

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