On the Wireless network coding with overhearing and index coding

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***Abstract*—We study the problem of Wireless Network Coding with imperfect overhearing, a joint coding/scheduling problem that arises naturally in multihop wireless networks and relates to multiple unicasts and intersession network coding. We show that the problem can be mapped to specific instances of index coding. In this direction, we provide a model that decouples the problem of scheduling and coding and ultimately results in comparison of different policies for evacuating packets from the system. Using this framework, we propose a heuristic approach that is based on rank minimization approaches proposed in the literature. We show that the proposed heuristic outperforms powerful schemes of the past like Random Linear Network Coding (RLNC) and COPE-like greedy Immediately Decodable Network Codes (IDNC).**

I. Introduction

We focus on a downlink problem where the transmitter (called relay in Fig. 1) receives stochastic arrivals of packets intended for N receivers and uses an error-free broadcast channel to transmit packets. The packets originate at source nodes whose transmissions are not studied here and are considered uncoded. There exist additional side information links, denoted with long dotted arrows in the Figure, that connect some sources to some receivers. The wireless network coding problem is to find a joint coding/scheduling policy that stabilizes this system whenever possible (i.e. it achieves maximum throughput). Note, that the maximum throughput for this problem is unknown because of the inclusion of coding policies in the admissible set. Our aim in this paper is to show that simple heuristics outperform existing state-of-the-art solutions.

The potential to increase throughput in a practical wireless system using side information and XOR coding is first proposed in [1], using *overhearing*. Prior work has shown that intersession network coding must be combined with scheduling in order to realize the throughput gain under fluctuating conditions (i.e. interference, erasures, random arrivals, etc), see for example [2]–[5]. In [6], the solution to the joint problem of coding/scheduling is given for the case of 2 receivers and it is shown that simple dynamic policies based on XORs are sufficient for capacity achievability. However, the problem becomes much more complicated when $N > 2$. In this paper, we show that the general problem for $N > 2$ relates to another interesting broadcast problem, called *index coding*.

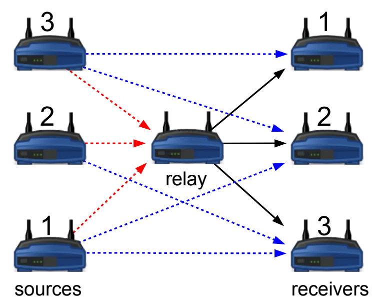

Fig. 1. An instance of the Wireless Network Coding problem for $N = 3$. Arrows show wireless links. Solid arrows show the broadcast channel under study; the relay/transmitter must choose a sequence of coded transmissions that guarantees the decoding of all the requested packets. The receivers can use side information obtained through overhearing (long dotted arrows).

A. Index Coding

The problem of finding the optimal *index code* was introduced in [7], where a base station attempts to minimize the number of transmissions such that all receivers have obtained one required message (or bit). In the simplest form of the problem, the base station is given a set of messages $\mathcal{W} \triangleq \{w_1, w_2, \ldots, w_N\}$ and each receiver i requires a different message w_i. The problem becomes interesting and complicated by the fact that each receiver has available side information $\mathcal{H}_i \subset \mathcal{W}$, where it is assumed that $w_i \notin \mathcal{H}_i$. This side information can by harnessed by a coding policy to reduce significantly the number of necessary transmissions in comparison to forwarding without coding, or even practical intersession network coding schemes proposed beforehand [1], [8].

The interest of the community in this problem has increased recently, mainly due to a number of important discoveries; we report some of them here. Every instance of the problem of finding an optimal network code on a Direct Acyclic Graph (DAG) and of the problem of finding a linear representation of a matroid were shown to be reduced to an instance of index coding in [9]. In [10], it was shown that the index coding problem is essentially an interference alignment problem, i.e. the coded transmissions must align with the side information on each receiver so that the decoding of the particular packet is guaranteed. Although there exist several results in the literature dealing with special cases, the general solution of the problem is not known and moreover it has been shown that linear coding is not in general sufficient for achieving the capacity, [11].

Recently it was shown that finding the optimal linear index code is equivalent to minimum rank completion of a partially sampled matrix, where the unsampled elements of the matrix correspond to the side information, [12]. Also, the same work shows that linear codes are sufficient for capacity in some special cases, though these do not apply to our problem. Note, that the low rank completion problem is known to be NP-hard.

B. Our Contribution

In this paper we focus on the problem of wireless network coding with imperfect overhearing and show, that under the assumption of symmetric (equal link capacities) error-free broadcast channel, this problem can be mapped to specific instances of the index coding problem. The optimal index code is shown to be a path-wise optimal *evacuation* policy for our system. Characterizing the throughput and providing an optimal dynamic policy requires solving arbitrarily large instances of the index coding problem, which is infeasible using the available solution of [12]. This motivates a heuristic; we decompose the problem into smaller problems which can be solved offline and stored on a lookup table.

The case of dynamic wireless network coding without overhearing is tackled in [13]. The following contribution is made in this paper towards this direction: we provide a tool for characterization of throughput of the wireless network coding problem with imperfect overhearing by using index coding-inspired solutions. Although our approach is similar to [13] in the sense that we analyze the dynamic properties of index coding, it provides an easy to use intermediate result and effectively decouples the scheduling problem from the coding problem. *Given any index code with known code length performance, the throughput performance in the problem with packet arrivals can be determined as optimal or suboptimal by looking at the performance for a large number of packets*. Note that two throughput optimal policies may have different evacuation time performance (cf. the example of input-queued switches in [14]).

An important question to ask at this point is: *how do the index coding-based solutions compare to prior schemes like RLNC and COPE-like greedy IDNC in the problem with arrivals?* For the case $N = 2$, RLNC and greedy IDNC are shown to be throughput optimal, [6]. Also, in slightly different context, it is known that a RLNC scheme achieves the maximum throughput of the *broadcast channel with erasures*, [15], where the difference is that initially there is no overhearing information but the broadcast transmissions are partially erased at different receivers. Consider the snapshot example of Figure 2; RLNC and IDNC require 4 slots to empty this system, while the optimal binary field index code is to transmit $1+3$, $3+4$ and $2+5$, which empties the system in 3 slots. This shows that index coding outperforms prior approaches in terms of evacuation and motivates further the question whether it also increases the throughput of this system. Our simulation results answer this question by showing that the proposed index coding-inspired heuristic strictly outperforms both RLNC and IDNC.

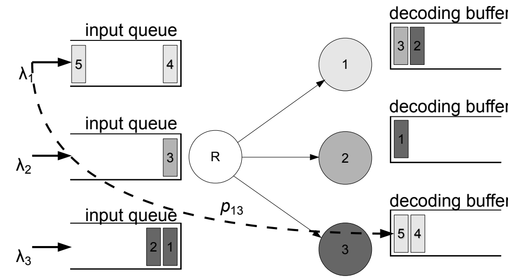

Fig. 2. The system under consideration for the case of three receivers; packets from three unicast flows arrive at the coding node *R* and are destined to three different receivers. Due to side overhearing channels, a copy of the arriving packet, destined to one receiver, may also arrive at another with a probability. We illustrate this for an arrival destined to receiver 1 that is also overheard by receiver 3.

II. System model

Consider a broadcast network with one transmitting node *R* (the relay) and a set of receivers $\mathcal{N} \triangleq \{1, \ldots, N\}$. The time is slotted, where slot t occupies the time interval $[t, t+1)$. Each slot fits exactly the transmission of one packet of L bits, either coded or native. This implies that the relay communicates through the broadcast channel with all receivers at the same unit rate. Incorporating integral rates is captured within this framework, but the problem of handling different transmission rates per receiver (as in [6]) is left for future work.

Erasures. We assume that the side information links, connecting the sources to the receivers, suffer from erasures. On the contrary, the broadcast transmissions made by the relay can be heard to all receivers erasure-free. Incorporating erasures in these links complicates the problem significantly and is left out of scope of this exposition. The links connecting the sources to the relay are also assumed to be erasure-free but the erasures on these links can be easily captured by adapting the values of the erasure probabilities in the side information links.

Arrivals. At the beginning of each slot, packets destined to receiver i arrive at *R* with the following property: *the same packet arrives at receiver* $j \neq i$ *with a probability* p_{ij}. This probability corresponds to a random overhearing event, that occurs whenever the side information link is not erased. We assume that each overhearing event is independent from the others and we are given the matrix of probabilities (p_{ij}), where $p_{ii} = 0,\ \forall i \in \mathcal{N}$. The packets arrive according to a stochastic arrival process with rate $\lambda_i, i \in \mathcal{N}$, see Fig. 2. We assume i.i.d. packet arrivals within each slot. The arriving packets destined to receiver i are stored in an infinite queue with a backlog denoted by $Q_i(t)$.

Storage. The receivers store overheard packets useful for decoding in the decoding buffers. Also, any additionally received packet (coded or native) from the transmissions of the relay is also stored in the buffer.

Transmissions and coding. At each slot t, *R* transmits exactly one packet. We assume that the packet is a linear function of the available packets, where the coefficients are drawn from a finite field $\mathbb{F}_q$ and they are applied bit-by-bit on existing packets. This is restrictive; more general operations such as allowing arbitrary linear operations on bits (e.g. shifting bits and then add them) which is known as *vector linear coding* or even non-linear operations are not considered here.

Decoding and Departures. When a receiver has successfully decoded an intended packet, then the corresponding packet is considered departed from the input queue. When all input queues are empty we also flush all buffers, thus, finite busy periods guarantee buffer stability.

III. Stability considerations

Denote the sum of input backlogs under coding/scheduling policy σ at the end of time slot t as $X_i^\sigma(t) \triangleq \sum_i Q_i(t)$. As in [14], we say that the system is stable if

$$\lim_{q\to\infty} \limsup_{t\to\infty} \Pr\left(X_i^\sigma(t) > q\right) = 0.$$

Consider the set of all arrival vectors $\boldsymbol{\lambda} \equiv (\lambda_i)$ for which the system is stable under policy σ; the closure of this set denoted by Λ^σ is called the *stability region* of the policy σ. The region $\Lambda \triangleq \cup_\sigma \Lambda^\sigma$ characterizes the system and is called the *throughput region*. A policy that achieves the throughput region of a system is called *throughput optimal*.

A. Evacuation Times and Stability

In order to study the throughput of the described system, we consider a different operation, which is based on evacuating system snapshots. Each snapshot is represented by a vector $\mathbf{w} \equiv (W_i)$, where W_i denotes the number of packets destined to receiver i. The packets arrive at the input queues following the rules explained above regarding overhearing. Thus, every one of the W_i packets may also reside at the buffer of receiver j with probability p_{ij}. Then, the system operates as it would normally do with the difference that no extra arrivals are introduced in the system. An admissible *evacuation policy* π is a sequence of (possibly coded) transmissions at the end of which all packets have departed from the system.

Let Π be the set of all evacuation policies (this includes policies that perform different types of codes). We denote with $T^\pi(\mathbf{w})$ the *evacuation time* of policy $\pi \in \Pi$, which is the minimum number of slots required to empty the system under policy π when $\mathbf{w}$ packets reside in the input queues at time zero. We denote with $\overline{T}^\pi(\mathbf{w}) \triangleq \mathbb{E}[T^\pi(\mathbf{w})]$ the average evacuation time of this policy, where the expectation is taken over the random overhearing events. We denote with $\overline{T}^\star(\mathbf{w}) \triangleq \inf_{\pi\in\Pi}\{\overline{T}^\pi(\mathbf{w})\}$ the infimum of the average evacuation time over all the policies in the set. Let $\lceil t\mathbf{x}\rceil$ denote the vector $(\lceil tx_1\rceil, \ldots, \lceil tx_N\rceil)$, where $\mathbf{x}$ is a real vector and

$$\hat{T}(\mathbf{x}) \triangleq \lim_{t\to\infty} \frac{\overline{T}^\star(\lceil t\mathbf{x}\rceil)}{t}.$$

Note, that each evacuation policy π can be mapped to an *epoch-based* coding/scheduling policy $\sigma(\pi)$, which is admissible in the system with arrivals defined above. This $\sigma(\pi)$ evacuates all packets present in the system at the beginning of each epoch using π and treats all new arrivals in the next epoch, see [14]. Additionally, as shown in [14], for every policy σ in the system with arrivals, we can construct a *randomized* evacuation policy $\pi(\sigma)$ that evacuates $\mathbf{w}$ as follows: Initially all packets $\mathbf{w}$ are kept in memory and the input queues are empty. Every time slot, random arrival RVs are generated that transport some of these packets from the memory to the inputs queues while at the same time, σ is used on the input queues.

Theorem 1 [From [14]]: *The following hold:*

1) *The throughput region of the system is the set of vectors $\boldsymbol{\lambda} \geq \mathbf{0}$ satisfying*
$$\hat{T}(\boldsymbol{\lambda}) \leq 1.$$
2) *Suppose that for an evacuation policy π we have*
$$\limsup_{t\to\infty} \frac{\overline{T}^\pi(\lceil t\mathbf{x}\rceil)}{t} = \hat{T}(\mathbf{x}), \forall\ \mathbf{x}, \tag{1}$$
then, the epoch-based policy $\sigma(\pi)$ is throughput optimal.
3) *Suppose that a policy σ is throughput optimal. Then the randomized evacuation policy $\pi(\sigma)$ is asymptotically optimal in terms of evacuation in the sense that*
$$\limsup_{t\to\infty} \frac{\overline{T}^{\pi(\sigma)}(\lceil t\mathbf{x}\rceil)}{t} = \hat{T}(\mathbf{x}), \forall\ \mathbf{x}. \tag{2}$$

Theorem 1-(i) states that given a direction $\boldsymbol{\lambda}$, the maximal point of the throughput region can be determined by the asymptotic growth of the minimal evacuation function, or else, by examining how fast can the system evacuate packets when the packets grow to infinity at proportions dictated by $\boldsymbol{\lambda}$. By evaluating the above condition in all possible directions, the throughput region is obtained. Theorem 1-(ii) states that if an evacuation policy π is identified with optimal asymptotic growth, then its epoch-based version $\sigma(\pi)$ is a throughput optimal policy. Also, Theorem 1-(iii) states that the randomized evacuation version $\pi(\sigma)$ of any throughput optimal policy σ should have the same asymptotic growth with the optimal. *Thus, we have reduced the original problem of determining the system stability region and proposing a throughput optimal coding/scheduling policy to a different problem of finding an evacuation policy that evacuates a large number of packets in asymptotically optimal number of transmissions.*

IV. Throughput Region of WNC and Index Coding

In this section we study the problem of optimal evacuation of the Wireless Network Coding system and we show that this problem is an instance of index coding. Then we propose a heuristic solution based on this formulation.

A. Mapping to an instance of index coding

First, observe that finding the minimum evacuation time of the system is equivalent to minimizing the number of required transmissions so that all receivers have obtained the requested packets. Suppose we are interested to evaluate the quantity $\overline{T}^\star(\mathbf{w})$ for some $\mathbf{w}$ and for some random realization of the overhearing events ω. Let $\mathbf{s}^p(\omega) = (s_i^p)$ be a binary vector for each packet p with $s_i^p = 1$ if packet p is overheard at receiver i and 0 otherwise. We collectively refer to a realization of all overhearing events of packets $\mathbf{w}$ using $\mathbf{s}(\omega)$. Below we describe an instance of the index coding problem whose minimum code length is equal to $T^\star(\mathbf{w}, \mathbf{s}(\omega))$.

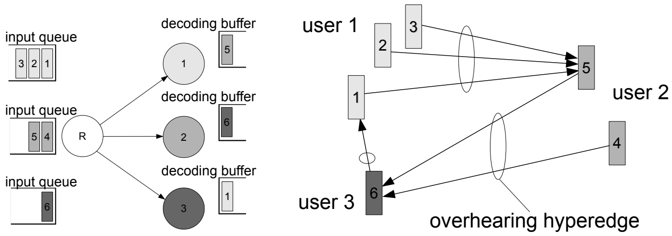

Fig. 3. An example with three receivers and six packets, where three packets are overheard and they reside on the corresponding decoding buffers (left). The corresponding overhearing SIG is shown (right).

$$\begin{array}{cc} & \begin{array}{ccc|cc|c} & \text{rec. 1} & & \text{rec. 2} & & \text{rec. 3} \end{array} \\ \mathcal{A}(G) = & \left[\begin{array}{ccc|cc|c} 1 & 0 & 0 & 0 & * & 0 \\ 0 & 1 & 0 & 0 & * & 0 \\ 0 & 0 & 1 & 0 & * & 0 \\ \hline 0 & 0 & 0 & 1 & 0 & * \\ 0 & 0 & 0 & 0 & 1 & * \\ \hline * & 0 & 0 & 0 & 0 & 1 \end{array}\right] \end{array}$$

Fig. 4. Set of matrices that fit the SIG of Figure 3 (right). '$*$' indicate entries to be completed with "0" and "1".

Given $\mathbf{w}$ and $\mathbf{s}(\omega)$, denote the set of all packets $\mathcal{W}$, (i.e. $|\mathcal{W}| = \sum_i W_i$), the "want" sets $\mathcal{W}_1, \ldots, \mathcal{W}_N$ and the "has" sets $\mathcal{H}_1, \ldots, \mathcal{H}_N$ for the N receivers. We have $|\mathcal{W}_i| = W_i$ and $w_j \in \mathcal{H}_i$ if $s_i^{w_j}(\omega) = 1$. The sets satisfy these standard conditions:

$$\begin{aligned} &\mathcal{W}_i \cap \mathcal{W}_j = \emptyset, \ \forall i, j \in \mathcal{N} \text{ and } i \neq j \\ &\cup_{i=1}^{N} \mathcal{W}_i = \mathcal{W}, \\ &\mathcal{H}_i \cap \mathcal{W}_i = \emptyset, \ \forall i \in \mathcal{N}. \end{aligned}$$

There are different ways to define the Side Information Graph (SIG), e.g. [16] connects users to packets in a bipartite graph. We define the SIG to be a special case of [12] where vertices are packets and edges indicate side information.

DEFINITION 1 [OVERHEARING SIG]: *The Overhearing SIG $G \equiv (\mathcal{W}, E)$ is a multipartite directed graph with vertices the packets (elements of $\mathcal{W}$) and edges constructed as follows: If $v \in \mathcal{H}_i$, we construct the set of directed edges $O_v^i \equiv \{(w, v) : w \in \mathcal{W}_i\}$. We call this set an **overhearing hyperedge**, i.e the set of edges that correspond to a single overhearing event. Then $E \triangleq \cup_{(v,i)} O_v^i$.*

Note that for every packet v overheard by receiver i, we are to draw W_i directed edges to node v from all nodes $w \in \mathcal{W}_i$, see the clarifying example in Figure 3. G is called multipartite because there exist no edges connecting nodes belonging to the same set $\mathcal{W}_i$. Next, we define the set of *all binary matrices that fit a SIG*:

DEFINITION 2 [FITTING CONDITION]: *Let $G \equiv (\mathcal{W}, E)$ be any SIG. We say that the matrix $\mathbf{A} \in \mathbb{F}_2^{|\mathcal{W}| \times |\mathcal{W}|}$ **fits** G if for all $i, j = 1, \ldots, |\mathcal{W}|$:*

$$a_{ij} = \begin{cases} 1 & i = j, \\ 0 & (i, j) \notin E. \end{cases}$$

Let $\mathcal{A}(G)$ be the set of all matrices that fit G.

Consider now the case that packet v is overheard by receiver i. Then the elements (a_{jv}), $j \in \mathcal{W}_i$ correspond to the hyperedge of this overhearing. Note, that the elements that correspond to all overhearings are undefined in the above fitting condition. See Figure 4 for an example.

Let $\mathcal{I}_G$ be the set of all index codes for SIG G. We denote with $len(C), C \in \mathcal{I}_G$ the length of code C. We conclude from the above that the minimum evacuation time for the studied realization is equal to the minimum index code length of the corresponding overhearing SIG G, or in other words, *the minimum length index code of the overhearing SIG is a path-wise optimal policy in terms of evacuation*,

$$T^\star(\mathbf{w}, \mathbf{s}(\omega)) = \min_{C \in \mathcal{I}_G} len(C). \tag{3}$$

B. Optimal Index Code

Let G be a SIG and $\mathcal{I}_G^\ell$ the set of all linear index codes for this SIG. Define:

$$minrk_2(G) \triangleq \min_{\mathbf{A} \in \mathcal{A}(G)} \{rank_2(\mathbf{A})\}.$$

THEOREM 2 [LINEAR INDEX CODING FROM [12]]: *If the encoding and decoding functions are constrained to be linear, the minimum index code length of a SIG G is*

$$\min_{C \in \mathcal{I}_G^\ell} len(C) = minrk_2(G). \tag{4}$$

The rank of the matrix $\mathbf{A}$ is calculated using field $\mathbb{F}_2$ operations. The optimal code is the following: Pick a rank-minimizer matrix $\mathbf{A}^*$, choose any $minrk_2(G)$ linearly independent rows of $\mathbf{A}^*$ and transmit the corresponding linear equations of packets using the elements of these rows as coefficients.

From (2), (3) and (4), we conclude that the throughput region can be determined by $minrk_2(G)$ as $\mathcal{W}$ scales to infinity. Unfortunately, low rank matrix completion is known to be a hard problem. Thus, we proceed by proposing a heuristic evacuation policy which is based on the above result.

C. A Proposed Heuristic

We construct a lookup table containing all instances of the problem such that each receiver requests *at most one packet*. Due to different possible overhearing event combinations, there exist $\sum_{i=1}^{N} 2^{i(i-1)} \binom{N}{i}$ such instances, many of which are, however, homomorphic. Also, note that this is exponential to the number of receivers but not the number of packets (as before). We compute the $minrnk_2$ for each of these. Then we order the elements in this table according to the efficiency metric $\frac{\#decoded\ packets}{minrnk_2}$. In case of tied metric, priority is given to the packets with the smaller out degree in the overhearing SIG. Yet another tie is solved arbitrarily. The proposed policy simply chooses the top element of the lookup table for which all involved packets appear in the input queues.

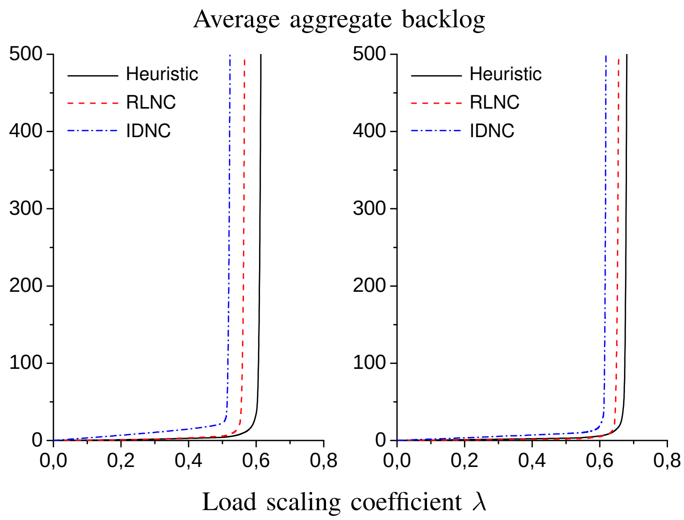

Fig. 5. Average aggregate backlog performance for a system with three receivers, in two chosen directions $\boldsymbol{\lambda} = (\lambda, \lambda, \lambda)$(left) and $\boldsymbol{\lambda} = (\lambda, .8\lambda, .6\lambda)$ (right). The overhearing probabilities are: $p_{12} = p_{23} = p_{31} = .8$, $p_{13} = p_{21} = p_{32} = .5$.

V. Comparison with state-of-the-art policies

In this section we consider two important state-of-the-art schemes that are used as solutions to the WNC problem and compare their performance to our $\mathsf{Heuristic}$ policy by use of simulation.

IDNC**:** we have in mind greedy immediately decodable policies like the one proposed in [1]; form the XOR sum of packets such that each packet can be immediately decoded at the corresponding intended receiver and choose the largest such sum (ties solved randomly). We expect this policy to be inefficient compared to the optimal because it fails to solve cycles in G, for example consider the example given in the introduction.

$\mathsf{RLNC} - g$**:** this policy considers the packets at the input in different generations of size g. In the each generation, g packets from each receiver are coded together forming Ng equations with randomly drawn coefficients. In some cases, some receivers do not participate if they do not have any packets. We assume an idealized version of the policy where the coefficients are pseudo-random and they result in linearly independent coded packets. These equations are transmitted until all receivers have decoded all Ng packets. Side information packets are also linearly independent equations that can be used to accelerate the decoding. However, the required transmissions are calculated based on the receiver with the smallest number of side information packets. When the first generation is decoded, the transmissions stop and we proceed to the second generation. When all the packets of the generation are decoded we move to the next generation. We expect this policy to be inefficient compared to the optimal because it requires all the receivers to decode all packets. On the contrary, optimal index codes transmit only the amount of information that is required so that each receiver obtains the packets it is interested in.

We compare the dynamic policies $\mathsf{IDNC}, \mathsf{RLNC} - 8$ to our proposed $\mathsf{Heuristic}$ in Figure 5. The Figure shows the average backlogs of the compared policies. In two chosen directions $\boldsymbol{\lambda} = (\lambda, \lambda, \lambda)$, $\boldsymbol{\lambda} = (\lambda, .8\lambda, .6\lambda)$ and for a specific overhearing probability matrix given in the caption, $\mathsf{Heuristic}$ outperforms prior approaches, showing a throughput increase.

VI. Conclusion

We proposed a methodology for solving a joint coding/scheduling problem using insights from the index coding problem. We also proposed policy $\mathsf{Heuristic}$ which outperforms prior approaches. This is evidence that index coding increases the throughput of this system and that $\mathsf{IDNC}, \mathsf{RLNC}$ are not throughput optimal.

Acknowledgments

The work of G. Paschos is supported by the WiNC project of the Action:Supporting Postdoctoral Researchers, funded by national and Community funds (European Social Fund).

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