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Topological Interference Management for Wireless Networks

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ABSTRACT Topological interference management (TIM) is considered under the condition that only topology-related information is available at the transmitters, but no accurate channel state information is fed back to them, which is capable of significantly reducing the overhead imposed on the network. TIM schemes can be classified into two broad categories, relying either on a fixed topology or on alternating connectivity. In this paper, we review the family of TIM schemes. Specifically, for the fixed topology, we discuss the attainable degrees of freedom (DoFs) under the condition that the channel coefficient values are either constant or time varying. For constant channel coefficients, we discuss the multiple groupcast networks/multiple unicast networks, interference channel networks, and interference broadcast channel networks; while for time-varying channel coefficients, we discuss interference channel networks and interference broadcast channel networks. Furthermore, in the context of alternating connectivity, we discuss the attainable DoF for interference channel networks, as well as X networks, vector broadcast channel networks, and interference broadcast channel networks. Finally, promising research directions are identified for TIM schemes.

INDEX TERMS Topological interference management (TIM), topology information, fixed topology, alternating connectivity, degrees of freedom (DoF).

I. INTRODUCTION

In support of the increasing demand for high-speed communication, the heterogeneous network (HetNet) concept was conceived for improving the spectral efficiency [1], which is achieved by relying both on micro cells and femto cells. However, interference management becomes a challenging task in this complex scenario relying on carefully developed frequency reuse patterns [2]. Hence various sophisticated interference management methods have been investigated, such as, interference alignment (IA) [3], interference cancellation [4] and so on. Traditional interference management techniques have predominantly been investigated based on the idealized simplifying assumption of having perfect channel state information knowledge at the transmitter (CSIT), which is impractical. Hence recently more realistic partial CSIT based interference management schemes have also been explored relying on both outdated and quantized CSIT [5], [6]. In [7], a novel concept referred to as topological interference management (TIM) was proposed, where only topology-related information[1] is available at the transmitters, but no CSIT. TIM beneficially reduces the accuracy requirement of CSIT, hence it has attracted a lot of research attention.

The family of TIM schemes can be broadly classified into two categories, namely TIM schemes designed for a fixed topology in this section and those conceived for alternating connectivity, as discussed in the next paragraph. Both of them are defined below with reference to the relevant literatures.

[1]In this paper, the concept of topology-related information refers to the knowledge of the connectivity states of the network. There are only two possible connectivity states for each link corresponding either to the presence or to the absence of connection, which hence uniquely and unambiguously determines the topology of the network constituted by the connected nodes [7].

TABLE 1. The DoF results of TIM with fixed topology for K-groupcast/K-unicast networks, where d_{sym} denotes the symmetric DoF per message.

System Configuration	Constraints		DoF Results
K-groupcast /K-unicast	[7]	No internal conflict	$d_{sym} = \frac{1}{2}$
		The demand graph is acyclic	$d_{sym} = \frac{1}{K}$
		Cycles and forks do not appear at the same time in each alignment set	$d_{sym} = \min\left(\frac{\Delta}{2\Delta+1}, \frac{1}{\Psi}\right)$
K-unicast	[7]	Cycles and forks do not simultaneously appear at the same time in each alignment set of the dual of K-unicast network	$d_{sym} = \min\left(\frac{\Delta}{2\Delta+1}, \frac{1}{\Psi}\right)$

Specifically, TIM schemes conceived for a *fixed topology* and relying on different system configurations have been investigated in [7]–[15]. Specifically, Jafar [7] revealed the intricate relationship between the TIM problem and the so-called index coding problem. The optimal symmetric degrees of freedom (DoF) was defined as that achieved by each user benefitting from TIM and relying either on single input single output (SISO) networks or on symmetric multiple input multiple output (MIMO) networks, where each node has the same number of antennas. Furthermore, a specific asymmetric MIMO scenario was also considered for characterizing a TIM scheme. Additionally, Hassibi [8] proposed a compelling scheme, which he referred to as a matrix completion based TIM scheme relying on SISO networks. As a further development, Sun and Jafar [9] quantified the optimal symmetric DoF based on TIM schemes designed for a scenario described as a 4-to-1 1×2 single input multiple output (SIMO) interference channel (IC) network, where the above-mentioned compact representation implies that four pairs of users are supported and each transmitter has one antenna, while each receiver has two antennas. Receiver one is interfered by all the other three transmitters, while the remaining receivers only receive the desired signals. Both the upper bound of the symmetric DoF of $(1 \times R)$ SIMO IC networks, as well as the DoF regions of multiple input single output (MISO) IC networks managed by TIM schemes were quantified. Moreover, Gao *et al.* [10] considered the downlink of hexagonal cellular networks relying on TIM schemes in two scenarios, namely when the channel coefficients were either constant or time-varing. Additionally, Yang *et al.* [11] considered SISO IC networks relying on a single reconfigurable antenna at each receiver. Moreover, the family of transmitter/receiver cooperation based TIM schemes has been explored by Yi and Gesbert [12] and Yi and Caire [13] for SISO IC networks and by Liu *et al.* [14] for MIMO IC networks. Finally, Naderializadeh *et al.* [15] investigated the symmetric DoF attained by SISO IC networks when the channel coefficients were time-varying.

On the other hand, TIM schemes designed for *alternating connectivity* have been explored in [16]–[18]. Specifically, in [16], the DoF of a 2-user SISO IC network, as well as a so-called 2-user SISO X network and a 2-user vector broadcast channel based network was investigated. A pair of examples related to a 3-user SISO IC network was also investigated by Sun *et al.* [16]. Each of the examples considered both the presence and absence of connectivity. Moreover, in [17], the DoF of a 3-user SISO IC network was considered, which consists of seven specific alternating connectivity states. Furthermore, Aquilina and Ratnarajah [18] considered a 2-cell 2-user-per-cell interference broadcast channel, where the associated TIM schemes were characterized by quantifying the DoF bounds in the context of SISO, MISO and MIMO configurations. Below we will discuss the TIM problem of these two categories in a little more detail. The definitions used in this paper are detailed in the Appendix.

Notations: $\boldsymbol{A}_{ij}$ represents the element of the ith row and the jth column of the matrix $\boldsymbol{A}$

II. TIM FOR FIXED TOPOLOGY

In this section, the DoF results of TIM for fixed topology are concluded from two aspects depending on the channel coefficient values are constant or time-varing.

A. THE CHANNEL COEFFICIENT VALUES ARE CONSTANT

When the channel coefficient values are constant, the scenarios of multiple groupcast networks/multiple unicast networks, IC networks, interference broadcast channel (IBC) networks are summarized.

1) MULTIPLE GROUPCAST NETWORKS/MULTIPLE UNICAST NETWORKS

The DoF results of TIM invoked for fixed topology for both mutliple groupcast networks and mutliple unicast networks when the channel coefficient values are constant are summarized in Table 1. For TIM schemes, Jafar [7] investigated different scenarios in SISO K-groupcast/K-unicast settings where there are K messages and each message has a unique source, and each message can be desired by more than one destination for mutliple groupcast networks or by one destination for mutliple unicast networks. It is proved that the optimal symmetric DoF per message [7]

$$d_{sym} = 1/2 \tag{1}$$

is achieved if and only if no internal conflict exists. Surprisingly, this DoF result is the same as that under perfect CSIT knowledge. Moreover, if the demand graph is acyclic, the optimal symmetric DoF per message [7]

$$d_{sym} = 1/K \tag{2}$$

is achievable. Furthermore, for each alignment set, if no cycles and forks[2] appear at the same time, the optimal symmetric DoF per message [7] is

$$d_{sym} = \min\left(\frac{\Delta}{2\Delta+1}, \frac{1}{\Psi}\right) \tag{3}$$

where Δ is the minimum internal conflict distance, and Ψ is the maximum cardinality of an acyclic subset of messages. Remarkably, the DoF results above are obtained via the existing results for the corresponding index-coding problems.

Moreover, the DoF results achieved for the multiple unicast network can also be achieved for the dual of multiple unicast network where the roles of transmitters and receivers are switched [7]. It is claimed that if no cycles and forks simultaneously appear at the same time in each alignment set of the dual of multiple unicast network, the optimal symmetric DoF per message [7] of the muliple unicast network is

$$d_{sym} = \min\left(\frac{\Delta}{2\Delta+1}, \frac{1}{\Psi}\right) \tag{4}$$

where Δ is the minimum internal conflict distance for the dual of multiple unicast network, and Ψ is the maximum cardinality of an acyclic subset of messages for the dual of multiple unicast network. Similarly, the DoF results above are obtained via the existing results for the corresponding index-coding problems.

2) INTERFERENCE CHANNEL NETWORKS

The DoF results of TIM invoked for fixed topology based IC networks when the channel coefficient values are constant are summarized in Table 2.

In SISO IC networks, for TIM schemes, as IC networks is only specific scenario of multiple unicast networks, the results obtained for SISO multiple unicast networks in section "Multiple Groupcast Networks/Multiple Unicast Networks" are also applied for SISO IC networks [7].

In [8], the matrix completion based TIM philosophy was proposed for SISO IC networks, where a matrix $\boldsymbol{B}$ is defined by the elements $\boldsymbol{B}_{ij}$ assuming values of "1", "0" or "×". Explicitly, "1" indicates that the link between transmitter i and receiver j is the desired link, "0" represents that interference is imposed on receiver j by transmitter i, while "×" may be an arbitrary value. Hassibi [8] proved that the achievable DoF per user [8] is

$$d_{SISO\_sym} = 1/\text{rank}(\boldsymbol{B}) \tag{5}$$

[2]A fork is a vertex that is connected by three or more edges [7].

The matrix completion based TIM schemes fill in the values of "×"s by minimizing the rank of the matrix $\boldsymbol{B}$. An alternating projection based method was proposed in [8] in order to solve the matrix completion problem, while a Riemannian Pursuit (RP) matrix completion method was advocated in [19].

For SISO IC networks relying on a reconfigurable antenna at each receiver, a TIM scheme was designed in [11], where each receiver has the capability of switching amongst various preset modes during different channel access instances or time slots, but hence the effective channel coefficients become time-varying. If each reconfigurable antenna has at least two modes, the necessary and sufficient conditions of guaranteeing a symmetric DoF per user [11]

$$d_L = 1/2 \tag{6}$$

in case of having an infinite number of different channel uses is that there is at most one internal conflict at each vertex in the conflict digraph. Moreover, the symmetric DoF per user experienced in the presence of an infinite number of different channel uses is upper-bounded by [11]

$$d_L \le \frac{\Delta_{\min}+1}{2\Delta_{\min}+3} \tag{7}$$

where $\Delta_{\min}$ is the minimum internal conflict distance between the vertices, which have two or more internal conflicts in the conflict digraph. Furthermore, if the maximum number of the cochannel interferers is less than three, the optimal symmetric DoF $\frac{\Delta_{\min}+1}{2\Delta_{\min}+3}$ becomes achievable in the presence of an infinite number of channel uses [11].

Furthermore, transmitter cooperation based TIM schemes were proposed in [12] for the K-user SISO IC network relying either on interference avoidance or on IA. For interference avoidance, through a generator sequence, the symmetric DoF per user is upper-bounded by [12]

$$d_{SISO\_sym} \le \min_{\mathcal{S}\subseteq\mathcal{K}} \min_{\mathcal{I}_0\subseteq\mathcal{J}(\mathcal{S})} \frac{|\mathcal{I}_0|}{|\mathcal{S}|} \tag{8}$$

where $\mathcal{K} \triangleq \{1, 2, \ldots, K\}$, $\mathcal{S} \subseteq \mathcal{K}$, $\mathcal{I}_0$ is the initial generator defined over $\mathcal{S}$, and $\mathcal{J}(\mathcal{S})$ is the set of all possible initial generators. Moreover, based on fractional selective graph coloring technique of [12], the achievable symmetric DoF per user is [12]

$$d_{SISO\_sym} = \frac{1}{s\chi f\left(\zeta_e^2, \mathbb{V}_e\right)} \tag{9}$$

where $\zeta_e = (\mathcal{V}, \mathcal{E})$ is the line graph, where the vertices in $\mathcal{V}$ correspond to the links of the network topology and there exists an edge between two vertices, if they have the same transmitter or receiver. Furthermore, $\mathbb{V}_e$ is the vertex partition of ζ_e, and $s\chi f$ is the so-called fractional selective chromatic number. For IA, the symmetric DoF per user [12]

$$d_{SISO\_sym} = \frac{2}{K} \tag{10}$$

is achievable, if there is a perfect matching in the alignment-feasible graph [12]. Moreover, the symmetric DoF per user of [12]

$$d_{SISO\_sym} = \frac{2}{K-q} \tag{11}$$

is achievable, if there exists a Hamiltonian cycle in the alignment-feasible graph, which is associated with an alignment non-conflict matrix $\boldsymbol{A}$ whose elements assume the value of 0 or 1, where $q \triangleq \min_{k} \sum_{j} \boldsymbol{A}_{kj}$.

For receiver-cooperation based TIM schemes, the DoF per user achieved by multiple-round message passing [13] is lower-bounded by [13]

$$d_{SISO\_sym} \geq \frac{1}{\chi_{A,f}(D)} \tag{12}$$

where we have

$$\begin{aligned} \chi_{A,f}(D) = \min & \sum_{A \in \mathcal{A}(D)} g(A) \\ s.t. & \sum_{A \in \mathcal{A}(D,v)} g(A) \geq 1, \\ & \forall v \in \mathcal{V}(D) \\ & g(A) \in [0, 1] \end{aligned} \tag{13}$$

with D denoting the conflict diagraph, and $\mathcal{A}(D)$ denoting the set of all possible acyclic sets in the conflict digraph D. Still referring to (13), $\mathcal{V}(D)$ denotes the set of all the vertices in the conflict diagraph D, $v \in \mathcal{V}(D)$, $\mathcal{A}(D, v)$ denotes the set of all possible acyclic sets, which involves vertex v, A is the acyclic set and $g(A)$ is the portion of the shared time of the acyclic set A. Remarkably, if $g(A)$ assumes only one of the two values of 0 or 1, the DoF achieved by single-round message passing is lower-bounded by [13] $\frac{1}{\chi_{A,f}(D)}$. Moreover, for the single-round message passing, the sufficient and necessary condition to achieve the optimal symmetric DoF per user of [13]

$$d_{SISO\_sym} = 1 \tag{14}$$

is that the conflict digraph is acyclic. Furthermore, if there exist either only directed odd cycles or only directed even cycles in the conflict digraph, the optimal symmetric DoF per user of [13]

$$d_{SISO\_sym} = 1/2 \tag{15}$$

is achievable through single-round message passing.

In [9], TIM schemes conceived for SIMO IC and MISO networks were discussed.

Explicitly, a specific 4-to-1 1×2 SIMO IC network was investigated, where four pairs of users are supported with each transmitter having one antenna and each receiver having two antennas. Furthermore, receiver 1 is interfered by the other three transmitters, while the other receivers only receive the desired signals. For receiver 1, the received signal space can be partitioned into three parts: the desired signal space, the appropriately aligned interference space and the remaining interference space, which cannot be aligned. In order to decode the desired signal, its signal space must be independent of both the aligned interference space and of the remaining interference space. Moreover, the sum of the three dimensions of the above three parts must not be higher than that of the received signal space. Under these constraints, the optimal symmetric DoF per user [9]

$$d_{SIMO\_sym} = 3/5 \tag{16}$$

can be achieved. For a $1 \times R$ SIMO IC network, where every receiver has N antennas and a receiver is interfered by K ($K > N$) transmitters, the symmetric DoF per user is upper-bounded by [9]

$$d_{SIMO\_sym} \leq \frac{K}{2K - N + 1} \tag{17}$$

For a MISO network, if the network topology is the same as that of the corresponding SISO network, the DoF of these two networks is identical [9].

Again, in [7], the symmetric MIMO network is defined as one specific system configuration where all the transmitters and receivers have the same number of antennas. The DoF results normalized by the number of antennas for the symmetric MIMO network are the same as those of the corresponding SISO network, provided that these two networks have identical topology.

Furthermore, transmitter cooperation based TIM schemes were proposed in [14] for K-user MIMO IC networks where the number of antennas of transmitter j is M_j and the number of antennas of receiver j is N_j. If there is a perfect matching in the alignment-feasible graph, under the conditions that K is even and $N_j \geq \tilde{M}_j$, the DoF for receiver j and receiver $j+1$ of [14]

$$d_j = d_{j+1} = \frac{2\tilde{M}_j}{K} \tag{18}$$

is achievable, where $j = 2m - 1, j \in \{1, 2, \cdots, K/2\}$, $\tilde{M}_j$ denotes the number of antennas of the transmitter which are chosen to transmit desired data symbols for receiver j.

Moreover, if there exists a Hamiltonian cycle in the alignment-feasible graph, the DoF for receiver j of [14]

$$d_j = \frac{\tilde{M}_j + \tilde{M}_{j-1}}{K - q} \tag{19}$$

is achievable when $N_j \geq \max\left\{\tilde{M}_j, \tilde{M}_{j-1}\right\}$, where N_j denotes the number of antennas of receiver j, $\tilde{M}_j$ and $\tilde{M}_{j-1}$ denote the number of antennas of the transmitter which are chosen to transmit desired data symbols for receiver j

Based on Table 2, some symmetric DoF results are presented for IC networks in Fig.1. As shown in Fig.1, depending on the specific topologies, the DoF results achieved by the TIM schemes may become rather different. Furthermore, for some topologies, the symmetric DoF remains constant upon increasing the number of users, i.e. it is independent of the number of users. By contrast, for other topologies, the symmetric DoF decreases with the number of users. Moreover,

TABLE 2. The DoF results of TIM with fixed topology for IC networks, where d_{SISO_sym} denotes the symmetric DoF for the SISO network, d_L denotes the symmetric DoF in the face of infinite different channel uses for the SISO network using reconfigurable antennas, $d_{MIMO\_sym\_nom}$ denotes the symmetric DoF normalized by the number of antennas for the symmetric MIMO network, d_{SIMO_sym} denotes the symmetric DoF for the SIMO network. d_j denotes the DoF of receiver j for the MIMO network, and in (M_i, N_j), M_i denotes the number of antennas for the transmitter i, N_j denotes the number of antennas for the transmitter i, $\tilde{M}_j$ denotes the number of antennas of the transmitter which are chosen to transmit desired data symbols for receiver j.

System Configuration	Constraints		DoF Results
SISO	[7]	No internal conflict	$d_{SISO\_sym} = \frac{1}{2}$
		The demand graph is acyclic	$d_{SISO\_sym} = \frac{1}{K}$
		Cycles and forks do not appear at the same time in each alignment set	$d_{SISO\_sym} = \min\left(\frac{\Delta}{2\Delta+1}, \frac{1}{\Psi}\right)$
		Cycles and forks do not appear at the same time in each alignment set of the dual of IC network	$d_{SISO\_sym} = \min\left(\frac{\Delta}{2\Delta+1}, \frac{1}{\Psi}\right)$
	[8]	A matrix $\boldsymbol{B}$ is defined	$d_{SISO\_sym} = \frac{1}{\mathrm{rank}(\boldsymbol{B})}$
	[11]	1.Each receiver has only one reconfigurable antenna 2.Each reconfigurable antenna has at least two modes 3.There exists at most one incoming internal conflict at each vertex in the conflict digraph	$d_L = \frac{1}{2}$
		1.Each receiver has only one reconfigurable antenna 2.There exist vertices which have two or more incoming internal conflicts in the conflict digraph	$d_L \leq \frac{\Delta_{\min}+1}{2\Delta_{\min}+3}$
		1.Each receiver has only one reconfigurable antenna 2.The maximum number of the co-interferes is less than three	$d_{L,opt} = \frac{\Delta_{\min}+1}{2\Delta_{\min}+3}$
	[12]	1.Transmitter cooperation 2.K users 3.Interference avoidance 4.Through generator sequence	$d_{SISO\_sym} \leq \min\limits_{\mathcal{S}\subseteq\mathcal{K}} \min\limits_{\mathcal{I}_0\subseteq\mathcal{J}(\mathcal{S})} \frac{\lvert\mathcal{I}_0\rvert}{\lvert\mathcal{S}\rvert}$
		1.Transmitter cooperation 2.K users 3.Interference avoidance 4.Through fractional selective graph coloring	$d_{SISO\_sym} = \frac{1}{sxf(\varsigma_e^2, v_e)}$
		1.Transmitter cooperation 2.K users 3.Interference alignment 4.There exists a perfect matching in the alignment-feasible graph	$d_{SISO\_sym} = \frac{2}{K}$
		1.Transmitter cooperation 2.K users 3.Interference alignment 4.There exists a Hamiltonian cycle in the alignment-feasible graph	$d_{SISO\_sym} = \frac{2}{(K-q)}$
	[13]	1.Receiver cooperation 2.Multiple-round message passing	$d_{SISO\_sym} \geq \frac{1}{\chi_{A,f}(D)}$
		1.Receiver cooperation 2.Single-round message passing 3.The conflict digraph is acyclic	$d_{SISO\_sym} = 1$
		1.Receiver cooperation 2.Single-round message passing 3.There exist either only directed odd cycles or only directed even cycles in the conflict digraph	$d_{SISO\_sym} = \frac{1}{2}$

TABLE 2. (*Continued.*) The DoF results of TIM with fixed topology for IC networks, where d_{SISO_sym} denotes the symmetric DoF for the SISO network, d_L denotes the symmetric DoF in the face of infinite different channel uses for the SISO network using reconfigurable antennas, $d_{MIMO\_sym\_nom}$ denotes the symmetric DoF normalized by the number of antennas for the symmetric MIMO network, d_{SIMO_sym} denotes the symmetric DoF for the SIMO network. d_j denotes the DoF of receiver j for the MIMO network, and in (M_i, N_i), M_i denotes the number of antennas for the transmitter i, N_i denotes the number of antennas for the transmitter i, $\tilde{M}_j$ denotes the number of antennas of the transmitter which are chosen to transmit desired data symbols for receiver j.

SIMO	[9]	1.$(1, 2)$ 2.4 users 3.Receiver 1 is interfered by the other three transmitters 4.The other receivers only receive the desired signals	$d_{SIMO\_sym} = \frac{3}{5}$
		1.$(1, N)$ 2.A receiver is interfered by K $(K > N)$ transmitters	$d_{SIMO\_sym} \leq \frac{K}{2K-N+1}$
MISO	[9]	1.$(M_i, 1)$ 2.The MISO network topology is the same as one corresponding SISO network	The DoF region is the same as that of the SISO network
MIMO	[7]	1.Symmetric MIMO 2.The MIMO network topology is the same as one corresponding SISO network	$d_{MIMO\_sym\_nom} = d_{SISO\_sym}$
	[14]	1.Transmitter cooperation 2.K users and K is even 3.There exists a perfect matching in the alignment-feasible graph 4.$N_j \geq \tilde{M}_j$	$d_j = \frac{2\tilde{M}_j}{K}$
		1.Transmitter cooperation 2.K users 3.There exists a Hamiltonian cycle in the alignment-feasible graph 4.$N_j \geq \max\left\{\tilde{M}_j, \tilde{M}_{j-1}\right\}$	$d_j = d_{j+1} = \frac{\tilde{M}_j+\tilde{M}_{j-1}}{K-q}$

according to Fig.1, the system can be appropriately configured for increasing the DoF attained.

3) INTERFERENCE BROADCAST CHANNEL NETWORKS

The DoF results of TIM conceived for fixed topology when the channel coefficient values are constant based cellular networks - which constitute IBC networks - are summarized in Table 3.

In [7], a specific scenario was investigated, which consists of three cells and each base station (BS) of each cell is equipped with two antennas. Furthermore, cell A supports the pair of users a_1 and a_2 equipped with two antennas. Moreover, user a_1 is interfered by the BS of cell B and user a_2 is interfered by the BS of cell C. Cell B and cell C support a single user having one antenna, respectively. Based on the interference diversity concept, cell A achieves a DoF of 4/3 per cell, while both cell B and C achieve a DoF of 1 per cell [7].

Moreover, a special class of SISO IBC networks was investigated by Jafar [7], where only a single user is located at each boundary of the cells and this user can only receive signals from the BSs of the specific serving cells, which are assigned for covering this boundary. An so-called aligned frequency reuse method was proposed in [7]. For the simple scenario, where the cells are placed along a straight line, a DoF per cell [7]

$$d_c = 2/3 \tag{20}$$

can be achieved. For the somewhat more realistic scenario where the cells are assumed to form a square grid, as in the classic Manhatten-model, a DoF per cell [7]

$$d_c = 4/5 \tag{21}$$

can be achieved. For the popular hexagonal cellular array, where the cells are placed in a hexagonal grid, a DoF per cell [7]

$$d_c = 6/7 \tag{22}$$

can be achieved. The aligned frequency reuse method of [7] outperforms the conventional frequency reuse method.

Furthermore, a specific multi-layer downlink hexagonal cellular network supporting a single user is located at each cell-boundary was investigated in [10]. By introducing the concept of interference distance, if the distance between the

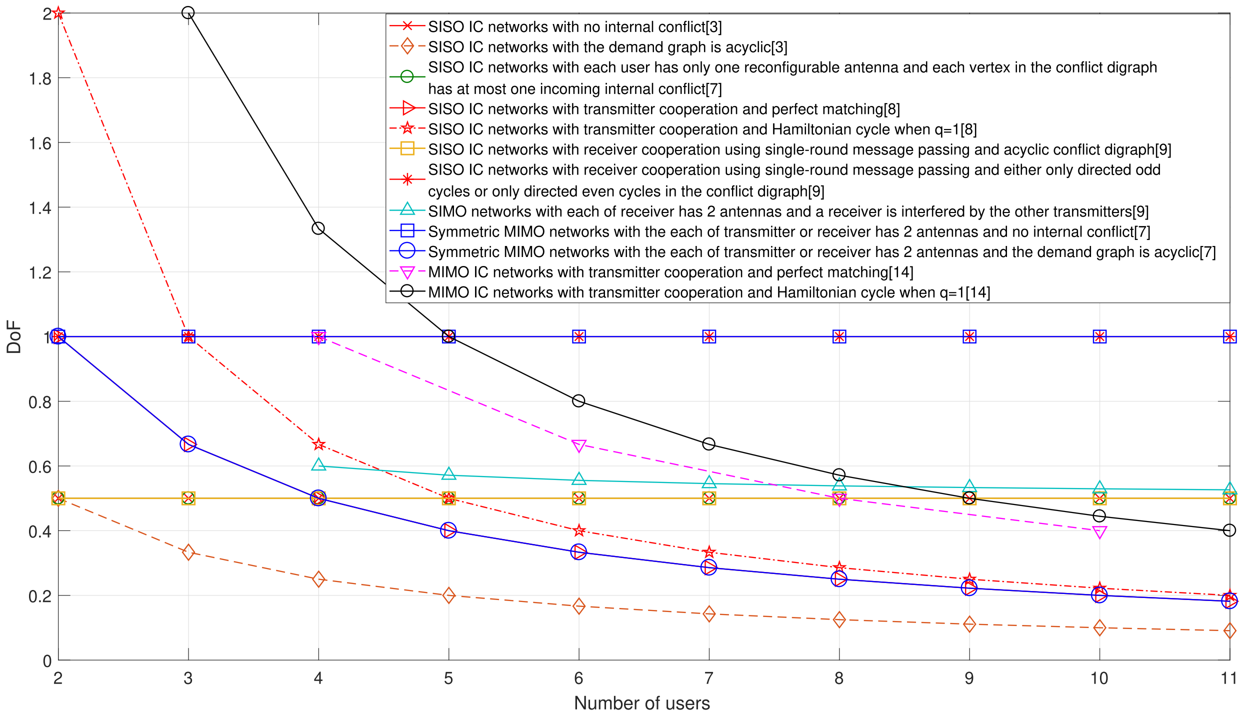

FIGURE 1. **Symmetric DoF results for some IC networks when channel coefficient values are constant.**

user and a BS is less than the interference distance, the user and the BS are considered to be connected, otherwise, the user and the BS are considered to be disconnected. Hence the topology of the cellular network is determined [10]. For the hexagonal cellular network topology having L layers of interference, the DoF per cell is upper-bounded by [10]

$$d_c(L) \leq \begin{cases} \dfrac{12}{9L^2+12L+1} & \text{when } L \text{ is odd} \\ \dfrac{12}{9L^2+12L+2} & \text{when } L \text{ is even} \end{cases} \tag{23}$$

Furthermore, when employing the aligned frequency reuse solution [7], the DoF per cell is lower-bounded by [10]

$$d_c(L) \geq \begin{cases} \dfrac{12}{9L^2+15L+6} & \text{when } L \text{ is odd and } L \geq 3 \\ \dfrac{12}{9L^2+12L+4} & \text{when } L \text{ is even} \end{cases} \tag{24}$$

Based on Table 3, the upper and lower bound of the DoF for the hexagonal cellular network topology having L layers of interference based on the specific TIM schemes of [10] are presented in Fig. 2. As shown in Fig 2, the upper and lower bound nearly coincide upon increasing the number of interference layers.

B. THE CHANNEL COEFFICIENT VALUES ARE TIME-VARYING

1) INTERFERENCE CHANNEL NETWORKS

The DoF results of IC networks attained in the face of time-variant channel coefficients are summarized in Table 4. When the channel coefficients are time-varing in K-user SISO IC networks relying on transmitter-cooperation based TIM schemes, the attainable symmetric DoF per user becomes [12]:

$$d_{SISO\_sym} = \frac{2}{K} \tag{25}$$

provided that there is a perfect matching in the alignment-feasible graph.

Furthermore, for K-user SISO IC networks, adopting the retransmission-based schemes, the necessary and sufficient condition to achieve the symmetric DoF per user given by [15]

$$d_{SISO\_sym} = 1/2 \tag{26}$$

over a finite symbol extension is that the reduced conflict graph is bipartite.

Based on Table 4, the symmetric DoF results of SISO IC networks relying on both transmitter cooperation and on TIM schemes [12] as well as the symmetric DoF results of SISO IC networks adopting the retransmission-based schemes of [15] are presented in Fig. 3. Briefly, observe in Fig. 3 that for SISO IC networks there is a critical number of users, beyond which the retransmission-based schemes of [15] outperform the schemes relying on transmitter cooperation, such as those in [12]. Otherwise, the schemes relying on transmitter cooperation [12] outperform the retransmission-based schemes of [15].

2) INTERFERENCE BROADCAST CHANNEL NETWORKS

The DoF results of IBC networks recorded for time-varying channel coefficients are summarized in Table 5. As for the

TABLE 3. IBC The DoF results of TIM with fixed topology for IBC networks, where in (M, N, u), M denotes the number of antennas for BS in each cell, N denotes the number of antennas for each user in each cell and u denotes the number of users in each cell. d_{cA}, d_{cB} d_{cC} denote the DoF per cell that can achieved by cell A, B, C respectively. d_c denotes the DoF per cell.

System Configuration		Constraints	DoF Results
IBC	[7]	1. Cell A:$(2,2,2)$ Cell B:$(2,1,1)$ Cell C:$(2,1,1)$ 2.User a_1 in cell A is interfered by the BS of cell B 3.User a_2 in cell A is interfered by the BS of cell C	$d_{cA} = \frac{4}{3}$ $d_{cB} = 1$ $d_{cC} = 1$
		1.$(1,1,2)$ 2.The linear cellular array 3.Only one user is located at each boundary of the cells 4.The user can only hear signals from the BSs of cells which cover this boundary 5.Using the aligned frequency reuse	$d_c = \frac{2}{3}$
		1.$(1,1,4)$ 2.The square cellular array 3.Only one user is located at each boundary of the cells 4.The user can only hear signals from the BSs of cells which cover this boundary 5.Using the aligned frequency reuse	$d_c = \frac{4}{5}$
		1.$(1,1,6)$ 2.The hexagonal cellular array 3.Only one user is located at each boundary of the cells 4.The user can only hear signals from the BSs of cells which cover this boundary 5.Using the aligned frequency reuse	$d_c = \frac{6}{7}$
	[10]	1.$(1,1,6)$ 2.The hexagonal cellular network topology with L layers of interference 3.Only one user is located at each boundary of the cells	$d_c(L) \leq \begin{cases} \frac{12}{9L^2+12L+1} & \text{when } L \text{ is odd} \\ \frac{12}{9L^2+12L+2} & \text{when } L \text{ is even} \end{cases}$
		1.$(1,1,6)$ 2.The hexagonal cellular network topology with L layers of interference 3.Only one user is located at each boundary of the cells 4.Using aligned frequency reuse	$d_c(L) \geq \begin{cases} \frac{12}{9L^2+15L+6} & \text{when } L \text{ is odd and } L \geq 3 \\ \frac{12}{9L^2+12L+4} & \text{when } L \text{ is even} \end{cases}$

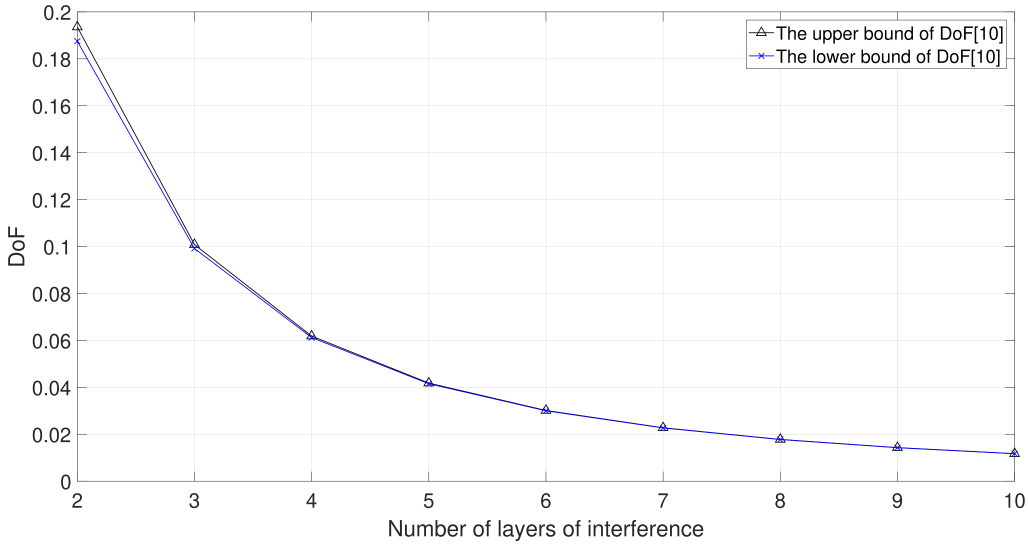

FIGURE 2. Symmetric DoF results for IBC networks when channel coefficient values are constant.

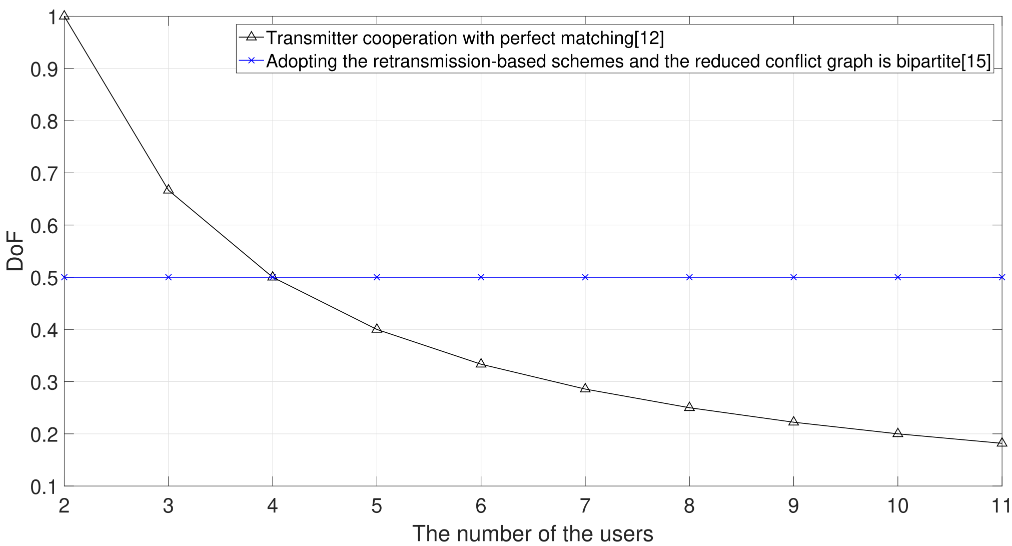

FIGURE 3. Symmetric DoF results for SISO IC networks when channel coefficient values are time-varing.

hexagonal cellular network topology having L layers of interference, the DoF per cell is upper-bounded by [10]

$$d_c(L) \leq \begin{cases} \dfrac{12}{9L^2+12L+1} & \text{when } L \text{ is odd} \\ \dfrac{12}{9L^2+12L+2} & \text{when } L \text{ is even} \end{cases} \tag{27}$$

Furthermore, when employing the aligned frequency reuse solution of [7], the DoF per cell is lower-bounded by [10]

$$d_c(L) \geq \begin{cases} \dfrac{12}{9L^2+15L+6} & \text{when } L \text{ is odd and } L \geq 3 \\ \dfrac{12}{9L^2+12L+4} & \text{when } L \text{ is even} \end{cases} \tag{28}$$

Interestingly, the results obtained for the IBC networks having time-varying channel coefficients is same as that associated with constant channel coefficients.

III. TIM FOR ALTERNATING CONNECTIVITY

In this section, the TIM schemes conceived for alternating connectivity are analyzed, where the network topology is time-varying. These schemes are mainly considered for IC, X channel, vector BC and IBC networks. The DoF results of TIM conceived for alternating connectivity are summarized in Table 6.

A. INTERFERENCE CHANNEL NETWORKS

The alternating connectivity based TIM scheme was considered in [16], commencing from a wired interference network

TABLE 4. **The DoF results of TIM with fixed topology when the channel coefficients are time-varying, where d_{SISO_sym} denotes the symmetric DoF for the SISO network.**

System Configuration	Constraints		DoF Results
SISO IC	[12]	1.Transmitter cooperation 2.K users 4.There exists a perfect matching in the alignment-feasible graph	$d_{SISO\_sym} = \frac{2}{K}$
SISO IC	[15]	1.K user 2.Adopting the retransmission-based schemes 3.The reduced conflict graph is bipartite	$d_{SISO\_sym} = \frac{1}{2}$

TABLE 5. **The DoF results of TIM with fixed topology when the channel coefficients are time-varying, where in (M, N, u), M denotes the number of antennas for BS in each cell, N denotes the number of antennas for each user in each cell and u denotes the number of users in each cell, d_c (L) denotes DoF per cell.**

System Configuration	Constraints		DoF Results
IBC	[10]	1.$(1, 1, 6)$ 2.The hexagonal cellular network topology with L layers of interference 3.Only one user is located at each boundary of the cells	$d_c(L) \leq \begin{cases} \frac{12}{9L^2+12L+1} & \text{when } L \text{ is odd} \\ \frac{12}{9L^2+12L+2} & \text{when } L \text{ is even} \end{cases}$
		1.$(1, 1, 6)$ 2.The hexagonal cellular network topology with L layers of interference 3.Only one user is located at each boundary of the cells 4.Using aligned frequency reuse	$d_c(L) \geq \begin{cases} \frac{12}{9L^2+15L+6} & \text{when } L \text{ is odd and } L \geq 3 \\ \frac{12}{9L^2+12L+4} & \text{when } L \text{ is even} \end{cases}$

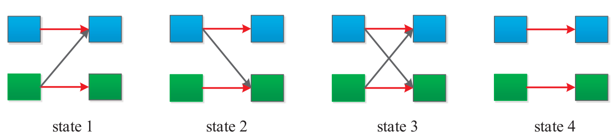

FIGURE 4. **2-user SISO IC networks with 4 connectivity states.**

scenario. The capacity results of the wired networks can be transformed into the DoF results of the corresponding wireless networks with the aid of a normalization by the capacity (DoF) of a wired (wireless) link [7]. For 2-user SISO IC networks, there are four possible connectivity states of the associated 4 possible links as shown in Fig.4 [16]. The parameter λ_i is defined as the fraction of time spent in State i, which satisfies $\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 = 1$. For 2-user SISO IC networks, upon invoking joint encoding, the optimal sum DoF is [16]

$$d_{sum} = 1 + \lambda_4 + \min(\lambda_1, \lambda_2, \lambda_3) \tag{29}$$

Moreover, 3-user SISO IC networks were investigated in [16] and [17]. In [16], two examples were provided, each of which consists of two connectivity states and the probability of each state is assumed to be equal. By using joint encoding, the optimal sum DoF of 3/2 can be achieved [16], which is higher than the sum DoF of 1 attained without joint encoding. In [17], a further example was provided which had seven specific possible connectivity states as shown in Fig.5 [17] and the probability of each state was not necessarily identical. Under these constraints, by the combination of joint encoding and state splitting, the sum DoF is [17]

$$d_{sum} = 2 + \delta \tag{30}$$

where $\delta = \min\left\{\frac{\lambda_1}{2}, \frac{\lambda_2}{2}, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7\right\}$.

B. X CHANNEL NETWORKS

In the 2-user SISO X channel network of [16], for TIM schemes, the connectivity states are the same as those for the 2-user SISO IC network. For the case of $\lambda_1 = \lambda_2$, the optimal

TABLE 6. The DoF results for TIM with alternating connectivity, where d_{sum} denotes the sum DoF.

System Configuration	Constraints		DoF Results
SISO IC	[16]	1.2 users 2.Four connectivity states 3.The possibility of each connectivity states could be non-equal	$d_{sum} = 1 + \lambda_4 + \min(\lambda_1, \lambda_2, \lambda_3)$
	[16]	1.3 users 2.Two connectivity states shown in [16] 3.The possibility of each connectivity states is equal	$d_{sum} = \frac{3}{2}$
	[17]	1.3 users 2.Seven connectivity states shown in [17] 3.The possibility of each connectivity states could be non-equal	$d_{sum} = 2 + \delta$ $\delta = \min\left\{\frac{\lambda_1}{2}, \frac{\lambda_2}{2}, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7\right\}$
SISO X channel	[16]	1.2 users 2.Four connectivity states 3.$\lambda_1 = \lambda_2$	$1 + \lambda_4 + \min(\lambda_1, \lambda_3)$
Vector BC	[16]	1.2 users 2.Four connectivity states 3.$\lambda_1 = \lambda_2$	$1 + \lambda_1 + \lambda_4$
SISO IBC	[18]	1.2-cell 2-user-per-cell 2.16 connectivity states 3.The possibility of each connectivity states could be non-equal 4.The mixed CSIT is available to each BS	$d_{sum} \leq 2 - \Theta$ $\Theta = \max\{\lambda_3 + \lambda_6, \lambda_3 + \lambda_6 + \lambda_{13} + \lambda_{14}, \lambda_1 + \lambda_3 + \lambda_{15} + \lambda_{16}\}$
MIMO/MISO IBC	[18]	1.2-cell 2-user-per-cell 2.16 connectivity states 3.The possibility of each connectivity states could be non-equal 4.The mixed CSIT is available to each BS	$d_{sum} \leq 2 + 2\lambda_2 + \lambda_4 + \lambda_5 + \lambda_7 + \lambda_8 + \Phi$ $\Phi = \max\{2\lambda_1, (2\lambda_3 + \lambda_4 + \lambda_5 + \lambda_9 + ... + \lambda_{12} + \lambda_{15} + \lambda_{16}), 2\lambda_6 + \lambda_7 + ... + \lambda_{14}\}$

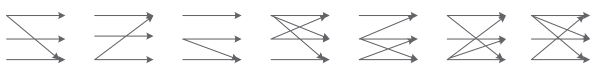

FIGURE 5. 3-user SISO IC networks with seven specific possible connectivity states.

sum DoF is [16]

$$d_{sum} = 1 + \lambda_4 + \min(\lambda_1, \lambda_3) \tag{31}$$

C. VECTOR BROADCAST CHANNEL NETWORKS

The 2-user vector BC network of [16] consists of one transmitter having two antennas plus two users having a single antenna, respectively. For TIM schemes, the four connectivity states are defined according to the links among antennas. For the case of $\lambda_1 = \lambda_2$, the optimal sum DoF is [16]

$$d_{sum} = 1 + \lambda_1 + \lambda_4 \tag{32}$$

D. INTERFERENCE BROADCAST CHANNEL NETWORKS

For IBC networks, a mixed CSIT based TIM scheme having alternating connectivity was investigated in [18], where the global topological information about the inter-cell topological information and the perfect local CSIT within its own cell is available to each BS. Furthermore, the alternating connectivity among cells was considered for SISO IBC, MISO IBC and MIMO IBC networks, respectively.

For the 2-cell 2-user-per-cell IBC network, there are 16 inter-cell connectivity states [18]. For the SISO IBC network, the sum DoF is upper-bounded by [18]

$$d_{sum} \le 2 - \Theta \tag{33}$$

where $\Theta = \max\{\lambda_3 + \lambda_6, \lambda_3 + \lambda_6 + \lambda_{13} + \lambda_{14}, \lambda_1 + \lambda_3 + \lambda_{15} + \lambda_{16}\}$. For the 2-cell 2-user-per-cell $M \times 1 (M \ge 2)$ MISO IBC network and $M \times N (M \ge 2, N \ge 2)$ MIMO IBC network, the same sum DoF outer bound can be obtained as [18]

$$d_{sum} \le 2 + 2\lambda_2 + \lambda_4 + \lambda_5 + \lambda_7 + \lambda_8 + \Phi \tag{34}$$

under the condition that the intra-cell interference is eliminated by spatial multiplexing, where we have $\Phi = \max\{2\lambda_1, (2\lambda_3 + \lambda_4 + \lambda_5 + \lambda_9 + \ldots + \lambda_{12} + \lambda_{15} + \lambda_{16}), 2\lambda_6 + \lambda_7 + \ldots + \lambda_{14}\}$.

IV. OPEN RESEARCH DIRECTIONS

As discussed, TIM schemes have been intensely investigated, but there are still open research directions for TIM schemes.

Complex Networks: The networks we discussed in this paper were limited to some simple idealized topologies, such as IC networks and IBC networks supporting a low number of users. However, the topologies of realistic networks, for example such as ultra dense networks and multi-hop networks are more complex. TIM schemes conceived for complex networks will become the main research direction in the near future.

Joint TIM and caching: Caching has become a salient technique of improving the attainable throughput. The combination of caching and IA has been investigated in [20] with the objective of mitigating the interference. However the previous contributions are based on the idealized simplifying assumption of having perfect CSIT. Hence joint design of TIM and caching constitutes an open problem, which may be capable of achieving a good performance with no CSIT.

Joint TIM and resource allocation: In some scenarios, only using the IA technique in isolation may not be capable of achieving optimal performance. Joint IA and resource allocation schemes have been investigated with the objective of improving the system performance [21]. However, joint TIM and resource allocation requires further investigations for exploring the attainable performance in the absence of CSIT.

V. CONCLUSIONS

TIM schemes have been considered under the condition that only topology-related information, but no CSI knowledge is available at the transmitters. Naturally, dispensing with CSI knowledge eliminates the CSI-feedback overhead that would be imposed on the network. Some TIM schemes are capable of achieving the same DoF results as those attained under perfect CSIT. For example, an optimal symmetric DoF of 1/2 per message is achieved if and only if there exists no internal conflict for the SISO K-groupcast settings. This DoF result is the same as that attained under perfect CSIT knowledge [7]. In this paper, the existing fixed topology and alternating connectivity based schemes have been discussed for different network topology configurations, for example, IC networks, X networks, IBC networks.

APPENDIX

Alignment graph [7]: The vertices correspond to messages, where the messages W_i and W_j are connected by an edge if both these messages are heard by a destination that desires message $W_k \notin \{W_i, W_j\}$.

Alignment set [7]: Each connected component of an alignment graph is referred to as an alignment set.

Conflict graph [7]: The vertices correspond to messages, where each message W_i is connected by an edge to all other messages, which are heard by a destination that desires message W_i.

The reduced conflict graph [15]: The reduced conflict graph of a K-user interference network is a directed graph $G = (V, A)$ with $V = \{1, 2, \cdots, K\}$. As for the edges, vertex i is connected to vertex j (i.e., $(i, j) \in A$) if and only if $i \neq j$ and the following two conditions hold:

1) Transmitter i is connected to receiver j.

2) $\exists s, k \in \{1, 2, \ldots, K\} \setminus \{i\}, s \neq k$ such that both transmitter i and transmitter s are connected to receiver k.

Internal conflict [7]: If two messages that belong to the same alignment set have a conflict edge between them, this is termed as an internal conflict.

Conflict distance [7]: For two nodes that have an internal conflict between them, the conflict distance is defined as the minimum number of alignment graph edges that have to be traversed through in order to proceed from one node to the other node.

Demand graph [7]: For a K-groupcast topological interference management problem, the demand graph is defined as the following directed bi-partite graph associated with the destination nodes on one side and message nodes on the other. There is a directed edge from message node W_j to a destination node D_i, if the message W_j is desired by destination D_i. There is a directed edge from a destination node D_i to a message W_j, if the destination D_i cannot hear the source of the message W_j.

Acyclic subset of messages [7]: A subset of messages $\mathcal{W}_o \in \mathcal{W}$ is said to be acyclic, if the symmetric capacity (DoF) of this subset of messages is $\frac{1}{|\mathcal{W}_o|}$ per message, where $\mathcal{W}$ denotes the set of all messages.

Reconfigurable antenna [11]: The term reconfigurable antenna refers to the antenna, which has multiple preset modes that can be optionally selected for transmission or reception.

Generator sequence [12]: Given $\mathcal{S} \subseteq \mathcal{K}$, $\mathcal{K} \triangleq \{1, 2, \ldots, K\}$, a sequence $\{\mathcal{I}_0, \mathcal{I}_1, \ldots, \mathcal{I}_S\}$ is called a generator sequence, if it is a partition of $\mathcal{S}$ (i.e., $\bigcup_{s=0}^{S} \mathcal{I}_s = \mathcal{S}$ and $\mathcal{I}_i \bigcap \mathcal{I}_j = \emptyset, \forall i \neq j$), such that $\boldsymbol{B}_{\mathcal{I}_s} \subseteq^{\pm} \text{rowspan}\left\{\boldsymbol{B}_{\mathcal{I}_0}, \mathbf{I}_{\mathcal{A}_s}\right\}, \forall s = 1, \ldots, S$, where $\boldsymbol{B}_{\mathcal{I}}$ is the submatrix of $\boldsymbol{B}$ with rows of indices in $\mathcal{I}$ selected, $\mathcal{A}_s \triangleq \left\{i|\left[\boldsymbol{B}^T\right]_i \cdot \mathbf{f}_{idx}\left(\bigcup_{r=0}^{s-1}\mathcal{I}_r\right) = |\mathcal{R}_i\backslash\mathcal{S}^c|\right\}$ with $\left[\boldsymbol{B}^T\right]_i$ being the i-th row of $\boldsymbol{B}^T$ and $\mathbf{f}_{idx}$ being an index function which is defined as $\mathbf{f}_{idx} : \mathcal{B} \mapsto \{0, 1\}^K$ in order to map the position indicated by $\mathcal{B} \in \mathcal{K}$ to a $K \times 1$ binary vector with the corresponding position being 1, and 0 otherwise, as well as $\mathbf{I}_{\mathcal{A}_s}$ denotes a submatrix of $\mathbf{I}_K$ with the rows in $\mathcal{A}_s$ selected. $\boldsymbol{A}_1 \subseteq^{\pm} \text{rowspan}\{\boldsymbol{A}_2\}$ indicates that two matrices $\boldsymbol{A}_1 \in \mathbb{C}^{m_1\times n}$ and $\boldsymbol{A}_2 \in \mathbb{C}^{m_2\times n}$ satisfy $\boldsymbol{A}_1 = \boldsymbol{C}\boldsymbol{A}_2\mathbf{I}^{\pm}$, where $\boldsymbol{C} \in \mathbb{C}^{m_1\times m_2}$ can be any full-rank matrix, $\mathbf{I}^{\pm}$ is as the same as the identity matrix up to the sign of elements.

Fractional selective graph coloring [12]: Consider an undirected graph $\zeta = (\mathcal{V}, \mathcal{E})$ with a vertex partition $\mathbb{V} = \{\mathcal{V}_1, \mathcal{V}_1, \ldots, \mathcal{V}_p\}$ where $\bigcup_{i=1}^{p}\mathcal{V}_i = \mathcal{V}$ and $\mathcal{V}_i \bigcap \mathcal{V}_j = \emptyset, \forall i \neq j$. The portion $\mathcal{V}_i(i \in [p] \triangleq \{1, 2, \ldots, p\})$ is termed as a cluster. A graph with the partition $\mathbb{V}$ is said to be selectively $n : m$-colorable, if:

• each cluster $\mathcal{V}_i(\forall i)$ is assigned a set of m colors drawn from a palette of n colors, regardless of which vertex in the cluster is receiving;

• no two adjacent vertices have colors in common.

Fractional selective chromatic number [12]: Denoted by $s\chi f(\zeta, \mathbb{V})$ the fractional selective chromatic number of the above selective coloring over the graph ζ with the partition $\mathbb{V}$, which is defined as $s\chi f(\zeta, \mathbb{V}) = \lim_{m\to\infty}\frac{s\chi m(\zeta,\mathbb{V})}{m} = \inf_{m}\frac{s\chi m(\zeta,\mathbb{V})}{m}$, where $s\chi m(\zeta, \mathbb{V})$ is the minimum n for the selective $n : m$-coloring associated with the partition $\mathbb{V}$.

Alignment-feasible graph [12]: The terminology of an alignment-feasible graph refers to a graph with the vertices representing the messages and with edges between any two messages indicating whether they are alignment-feasible. A pair of messages W_i and W_j are said to be alignment-feasible, denoted by $i \leftrightarrow j$, if $\mathcal{T}_i \nsubseteq \mathcal{T}_j$ and $\mathcal{T}_j \nsubseteq \mathcal{T}_i$, where $\mathcal{T}_i$ represents indices of the transmitters connected to receiver i.

Alignment non-conflict matrix $\boldsymbol{A}$ [12]: Regarding a cycle $i_1 \leftrightarrow i_2 \leftrightarrow \cdots i_K \leftrightarrow i_1$ in an alignment-feasible graph, we construct a $K \times K$ binary matrix $\boldsymbol{A}$, referred to as alignment non-conflict matrix, with elements $\boldsymbol{A}_{kj} = 1(i, j \in \mathcal{K})$, if $\mathcal{T}_{i_j} \bigcap \mathcal{T}^c_{i_{j+1}} \nsubseteq \mathcal{T}_{i_k}$, and $\mathcal{T}_{i_{j+1}} \bigcap \mathcal{T}^c_{i_j} \nsubseteq \mathcal{T}_{i_k}$, and with $\boldsymbol{A}_{kj} = 0$ otherwise. Furthermore, we reset $\boldsymbol{A}_{kj} = 0(\forall k)$, if $\mathcal{T}_{i_j} \bigcap \mathcal{T}^c_{i_{j+1}} \bigcap_{k:\boldsymbol{A}_{kj}=1} \mathcal{T}^c_{i_k} = \emptyset$, or $\mathcal{T}_{i_{j+1}} \bigcap \mathcal{T}^c_{i_j} \bigcap_{k:\boldsymbol{A}_{kj}=1} \mathcal{T}^c_{i_k} = \emptyset$.

Conventional frequency reuse [7]: The terminology of conventional frequency reuse refers to the scenario, where the total spectral band is partitioned into several orthogonal sub-bands and these sub-bands are allocated to active cells alternating, as in classic FDMA.

Interference distance [10]: Given a frequency reuse pattern, the interference distance D is defined as that between a user and the nearest active co-channel cell's BS (base station).

The multi-layer hexagonal cellular network topology [10]: In a multi-layer hexagonal cellular network, the Lth layer topology is defined by the corresponding interference distance D_L which is determined by the frequency reuse cluster size r. The relationship between the layer L and the frequency reuse cluster size r is $\frac{3(L+1)^2}{4}$, when L is odd, otherwise r by $\frac{3(L+1)^2+1}{4}$, where $L \in \mathbb{N}$, and the cluster size r is simply the reciprocal of the corresponding frequency reuse factor.

State splitting [17]: State splitting indicates that all the connectivity states considered are divided into several groups. Each group may have more than one state, where none of them has any overlapping.

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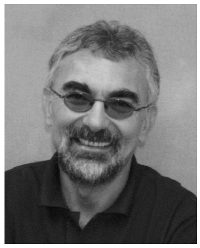

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