Selfish Distributed Compression Over Networks: Correlation Induces Anarchy

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***Abstract*—We consider the min-cost multicast problem (under network coding) with multiple correlated sources where each terminal wants to losslessly reconstruct all the sources. We study the inefficiency brought forth by the selfish behavior of the terminals in this scenario by modeling it as a noncooperative game among the terminals. The degradation in performance due to the lack of regulation is measured by the *Price of Anarchy* (POA), which is defined as the ratio between the cost of the worst possible *Wardrop equilibrium* and the socially optimum cost. Our main result is that in contrast with the case of independent sources, the presence of source correlations can significantly increase the price of anarchy. Toward establishing this result, we first characterize the socially optimal flow and rate allocation in terms of four intuitive conditions. Next, we show that the Wardrop equilibrium is a socially optimal solution for a different set of (related) cost functions. Using this, we construct explicit examples that demonstrate that the $\mathrm{POA} > 1$ and determine near-tight upper bounds on the POA as well. The main techniques in our analysis are Lagrangian duality theory and the usage of the supermodularity of conditional entropy.**

***Index Terms*—Distributed source coding, game theory, multicast, network coding, selfish behavior.**

I. Introduction

In large-scale networks such as the Internet, the agents involved in producing and transmitting information often exhibit selfish behavior, e.g., if a packet needs to traverse the network of various ISP's, each ISP will behave in a greedy manner and ensure that the packet spends the minimum time on its network. While this minimizes the ISP's cost, it may not be the best strategy from an overall network cost perspective. Selfish routing, that deals with the question of network performance under a lack of regulation has been studied extensively (see [1] and [2]) and has developed as an area of intense research activity. However, by and large, most of these studies have considered the network traffic injected into the network at various sources to be independent.

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From an information theoretic perspective, there is no need to consider the sources involved in the transmission to be independent. In this paper, we initiate the study of network optimization issues related to the transmission of correlated sources over a network when the agents involved are selfish. In particular, we concentrate on the problem of multicasting correlated sources over a network to different terminals, where each terminal is interested in losslessly reconstructing all the sources. We assume that the network is capable of network coding. Under this scenario, a generalization of the classical Slepian–Wolf theorem of distributed source coding [3] holds for arbitrary networks. In particular, when the network performs random linear network coding, each terminal can recover the sources under appropriate conditions on the Slepian–Wolf region and the capacity region of the terminals with respect to the sources, thereby allowing distributed source coding over networks (these conditions are discussed in detail later). The selfish agents in our setup are the terminals who pay for the resources. Each terminal aims to minimize her own cost while ensuring that she can satisfy her demands. It is important to note that this is a generalization of the problem of minimum cost selfish multicast of independent sources considered by Bhadra *et al.* [4].

A. Our Results

In this paper, we model the scenario as a noncooperative game amongst the selfish terminals who request rates from sources and flows over network paths such that their individual cost is minimized (i.e., with no regard for social welfare) while allowing for reconstruction of all the sources. We investigate properties of the socially optimal solution and define appropriate solution concepts (Nash equilibrium and Wardrop equilibrium) for this game and investigate properties of the flow-rates at equilibrium. We briefly describe our contributions in the following.

1) *Characterization of social-optimality conditions:* The problem of computing the socially optimal cost is a convex program. We present a precise characterization of the optimality conditions of this convex program in terms of four intuitive conditions, using Lagrangian duality theory and by judiciously exploiting the supermodularity of conditional entropy. This result is a key technical contribution of this paper and is of independent interest as well.
2) *Demonstrating the equivalence of flow-rates at equilibrium with social-optimal solutions for alternative instances:* We consider certain meaningful market models that split resource costs amongst the different terminals and show that the flows and rates under the game-theoretic equilibriums

are, in fact, socially optimal solutions for a different set of cost functions. This characterization allows us to quantify the degradation caused by the lack of regulation. The measure of performance degradation due to such loss in regulation that we adopt is the Price of Anarchy (POA), which is defined as the ratio between the cost of the worst possible equilibrium and the socially optimum cost [2], [5]–[7].

3) *Showing that source correlation induces anarchy:* The main result of this paper is that the presence of source correlations can significantly increase the POA under reasonable cost-splitting mechanisms. This is in stark contrast to the case of multicast with independent sources, where for a large class of cost functions, cost-splitting mechanisms can be designed that ensure that the price of anarchy is one. We construct explicit examples where the POA is greater than one and also obtain an upper bound on the POA which is near tight, i.e., we demonstrate an example of a network topology and a source distribution, where the POA is quite close to the derived upper bound.

Finally, we expect that the techniques developed in the this paper may be applicable to a large class of network information flow problems with correlated sources where the Slepian–Wolf polytope is replaced by polymatroid-like objects. These include multiterminal source coding with high resolution [8] and the CEO problem [9].

B. Background and Related Work

Distributed source coding (or distributed compression) (see [10, Ch.14] for an overview) considers the problem of compressing multiple discrete memoryless sources that are observing correlated random variables [8]. The landmark result of Slepian and Wolf [11] characterizes the feasible rate region for the recovery of the sources. However, the problem of Slepian and Wolf considers a direct link between the sources and the terminal. More generally, one would expect that the sources communicate with the terminal over a network. Different aspects of the Slepian–Wolf problem over networks have been considered in [12]–[17]; for a tutorial overview, see [18]. Network coding (first introduced in the seminal work of Ahlswede *et al.* [19]) for correlated sources was studied by Ho *et al.* [14]. They considered a network with a set of sources and a set of terminals and showed that as long as the minimum cuts between all nonempty subsets of sources and a particular terminal were sufficiently large (essentially as long as the Slepian–Wolf region of the sources has an intersection with the capacity region of a given terminal), random linear network coding over the network followed by appropriate decoding at the terminals achieves the Slepian–Wolf bounds.

The problem of minimum cost multicast under network coding has been addressed in [20] and [21]. The multicast problem has also been examined by considering selfish agents [4], [22], [23]. Our work is closest in spirit to the analysis of Bhadra *et al.* [4] that considers selfish terminals. In this scenario, for a large class of edge cost functions, they develop a pricing mechanism for allocating the edge costs among the different terminals and show that it leads to a globally optimal solution to the original optimization problem, i.e., the price of anarchy is one. Their POA analysis is similar to that in the case of selfish routing [2], [7]. Our model is more general and our results do not generalize from theirs in a straightforward manner. In particular, we need to judiciously exploit several nontrivial properties of the Slepian–Wolf polytope in our analysis.

Furthermore, motivated by the need to deal with selfish users, particularly in network setting, there has been a large body of recent work at the intersection of networking, game theory, economics, and theoretical computer science [1], [24], [25]. This paper adds another interesting dimension to this interdisciplinary area.

II. Model

Consider a directed graph $G = (S \cup T \cup V, E)$. There is a set of source nodes S that may be correlated and a set of sinks T that are the terminals (i.e., receivers). Each source node observes a discrete memoryless source X_i. The Slepian–Wolf region [11] of the sources is assumed to be known and is denoted $\mathcal{R}_{\mathcal{SW}}$. For notational simplicity, let $N_S = |S|, N_T = |T|$, $S = \{1, 2, \ldots, N_S\}$, and $T = \{t_1, t_2, \ldots, t_{N_T}\}$. For the case of N_S sources, $\mathcal{R}_{\mathcal{SW}}$ has the following form:

$$\mathcal{R}_{\mathcal{SW}} = \{(R_1, R_2, \ldots, R_{N_S}) : \sum_{i \in A} R_i \geq H(X_A | X_{A^c}) \text{ for all } A \subseteq \{1, \ldots, N_S\}, A \neq \phi\}$$

where $H(X_A|X_{A^c})$ denotes the conditional entropy of the sources indexed by set A given the remaining sources.

The set of paths from source s to terminal t is denoted by $\mathcal{P}_{s,t}$. Furthermore, define $\mathcal{P}_t = \cup_{s \in S} \mathcal{P}_{s,t}$, i.e., the set of all possible paths going to terminal t, and $\mathcal{P} = \cup_{t \in T} \mathcal{P}_t$, the set of all possible paths. A *flow* is an assignment of nonnegative reals to each path $P \in \mathcal{P}$. The flow on P is denoted f_P. A *rate* is a function $R : S \times T \longrightarrow \mathcal{R}^+$, i.e., the rate requested by the terminal t from the source s is $R_{s,t}$. We will refer to a flow and rate pair (f, R) as *flow-rate*. Also, let us denote the rate vector for terminal t by $\boldsymbol{R}_t$ and the vector of requested rates at source s by ρ_s, i.e., $\boldsymbol{R}_t = (R_{1,t}, R_{2,t}, \ldots, R_{N_S,t})$ and $\rho_s = (R_{s,t_1}, R_{s,t_2}, \ldots, R_{s,t_{N_T}})$.

Associated with each edge $e \in E$ is a cost c_e, which takes as argument a scalar variable z_e that depends on the flows to various terminals passing through e. Similarly, let d_s be the cost function corresponding to the source s, which takes as argument a scalar variable y_s that depends on the rates that various terminals request from s. These functions c_e's and d_s's are assumed to be *convex, positive, differentiable*, *and monotonically increasing*. Furthermore, the functions $\int \frac{c_e(x)}{x}\, dx$ are also assumed to be convex, positive, differentiable, and monotonically increasing. In particular, these conditions are satisfied by functions like $x^a, a > 1$, and $xe^{bx}, b > 0$ among others.

The network connection we are interested in supporting is one where each terminal can reconstruct all the sources, i.e., we need to jointly allocate rates and flows for each terminal so that it can reconstruct the sources. We now present a formal description of the optimization problem under consideration.

A. Min-Cost Multicast With Multiple Sources

Let us call the quadruple $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ an *instance*. The problem of minimizing the total cost for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ can be formulated as

$$\begin{aligned} \text{minimize} \quad & C(f,R) = \sum_{e\in E} c_e(z_e) + \sum_{s\in S} d_s(y_s) \\ \text{subject to} \quad & f_P \geq 0 \ \forall P \in \mathcal{P} \\ & \sum_{P\in\mathcal{P}_{s,t}} f_P \geq R_{s,t} \ \forall s \in S, \forall t \in T \\ & \boldsymbol{R}_t \in \mathcal{R}_{\mathcal{SW}} \ \ \forall t \in T \end{aligned} \tag{1}$$

where $z_e, \forall e \in E$ is a function of $x_{e,t_1}, x_{e,t_2}, \ldots, x_{e,t_{N_T}}$, that we denote $z_e(x_{e,t_1}, x_{e,t_2}, \ldots, x_{e,t_{N_T}})$ with $x_{e,t} = \sum_{P\in\mathcal{P}_t:e\in P} f_P \ \ \forall e \in E, \ \ \forall t \in T$, and $y_s, \forall s \in S$ is a function of ρ_s that we will denote $y_s(\rho_s)$. Henceforth, we will refer to this optimization problem as Network Information Flow—Convex Program (NIF-CP).

The aforementioned formulation is similar to the one presented in [4]. However, since we consider source correlations as well, their formulation is a specific case of our formulation. Since network coding allows the sharing of edges, the penalty at an edge is only the maximum and not the sum, i.e., z_e is the maximum flow (among the different terminals) across the edge e. Similarly, the penalty at the sources for higher resolution quantization is also driven by the maximum level requested by each terminal, i.e., y_s is also maximum. In this paper, for differentiability requirements, the maximum function will be approximated as L_p norm with a large p. Nevertheless, most of our analysis is done where z_e and y_s are nondecreasing functions partially differentiable with respect to their arguments, such that $c_e(z_e)$ and $d_s(y_s)$ are convex, positive, differentiable, and monotonically increasing. Note that in the aforementioned formulation, the objective function is convex and all constraints are linear which implies that this is a convex optimization problem.

The aforementioned constraint (1) models the fact that the total flow from the source s to a terminal t needs to be at least $R_{s,t}$. The next constraint enforces the rate point of each terminal $\boldsymbol{R}_t$ to be within the Slepian–Wolf polytope. A flow-rate (f, R) satisfying all the conditions in the aforementioned optimization problem (i.e., *(NIF-CP)*) will be called a *feasible* flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ and the cost $C(f, R)$ will be referred to as the *social cost* corresponding to this flow-rate. Also, we will call a solution (f^*, R^*) of the aforementioned problem as an *OPT* flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$.

Consider a feasible flow-rate (f, R) for the aforementioned optimization problem. It can be seen that the value of the flow from $A \subseteq S$ to a terminal $t \in T$ is $\sum_{P\in\cup_{s\in A}\mathcal{P}_{s,t}} f_P \geq \sum_{s\in A} R_{s,t}$. Since $\mathbf{R}_t \in \mathcal{R}_{\mathcal{SW}}$, the result of [14] (see also [15], [26]) shows that random linear network coding followed by appropriate decoding at the terminals can recover the sources with high probability. Conversely, the result in [12] and [27] shows the necessity of the existence of such a flow.

B. Terminals' Incentives and the Distributed Compression Game (DCG)

The aforementioned formulation for social cost minimization for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ disregards the fact that the agents who pay for the costs incurred at the edges and the sources may not be cooperative and may have incentives for strategic manipulation. In this paper, we consider the scenario where the terminals pay for the network resources they are being provided. The terminals are noncooperative and will behave selfishly trying to minimize their own respective costs without regard to the social cost, while ensuring that they can reconstruct all the sources. We have the following assumptions.

1) Let (f, R) denote a feasible flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$. The network operates via random linear network coding (or some practical linear network coding scheme) over the subgraph of G induced by the corresponding $\{z_e\}$ for $e \in E$. The terminals are capable of performing appropriate decoding to recover the sources.
2) Each terminal $t \in T$ can request for any specific set of flows on the paths $P \in \mathcal{P}_t$ and rates $\mathbf{R}_t$ as long as such a request allows reconstruction of the sources at t. There is a mechanism in the network by means of which this request is accommodated, i.e., the subgraph over which random linear network coding is performed is adjusted appropriately.

In this paper, we wish to characterize flow-rates that represent an equilibrium among selfish terminals who act strategically to minimize their own costs. Furthermore, we shall systematically study the loss that occurs due to the mismatch between the social goals and terminal's selfish goals.

Toward this end, we now formally model the game originating from the selfish behavior of the terminals. We model this game as a *normal form game* or *strategic game* [28], which we refer to as the DCG.

A normal form game, denoted $(\mathcal{N}, \{A_i\}_{i\in\mathcal{N}}, \{\succeq_i\}_{i\in\mathcal{N}})$, consists of the set of *players* $\mathcal{N}$, the tuple of *set of strategies* A_i for each player $i \in \mathcal{N}$, and the tuple of *preference relations* $\succeq_i$ for each player $i \in \mathcal{N}$ on the set $\mathcal{A} = \times_{i\in\mathcal{N}} A_i$. For $a, b \in \mathcal{A}$, $a \succeq_i b$ means that the player i prefers the tuple of strategies a to the tuple of strategies b. In the context of DCG, given an instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$, these parameters are defined as follows.

1) Distributed Compression Game (DCG):

- *Players*: $\mathcal{N} = T$, i.e., the terminals are the players. This is because, as aforementioned, the terminals are the users and they are the ones who pay for the network resources they are being provided.
- *Strategies*: The strategy set of a player $t \in T$ consists of tuples $(f_t, \boldsymbol{R}_t)$ where
  — f_t is the vector of flows on paths going to t, i.e., the vector of values f_P for all $P \in \mathcal{P}_t$, and recall that $\boldsymbol{R}_t$ denotes the rate vector for terminal t;
  — $f_P \geq 0 \ \forall P \in \mathcal{P}_t, \sum_{P\in\mathcal{P}_{s,t}} f_P \geq R_{s,t} \ \forall s \in S$ and $\boldsymbol{R}_t \in \mathcal{R}_{\mathcal{SW}}$.
  Therefore

$$A_t = \left\{ (f_t, \boldsymbol{R}_t) : \begin{array}{c} f_P \geq 0 \ \forall P \in \mathcal{P}_t \\ \sum_{P\in\mathcal{P}_{s,t}} f_P \geq R_{s,t} \ \forall s \in S \\ \boldsymbol{R}_t \in \mathcal{R}_{\mathcal{SW}} \end{array} \right\}. \tag{2}$$

  Note that a feasible flow-rate (f, R) for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ is an element of the set $\mathcal{A} = \times_{t\in T} A_t$ defined for the same instance.

- *Preference Relations*: To specify the preference relation of terminal $t \in T$, we need to know how much does she pay given a feasible flow-rate (f, R), i.e., what fractions of the costs at various edges and sources are being paid by t? To this end, we need market models, i.e., mechanisms for splitting the costs among various terminals.
  - *Edge Costs*: At a flow f, the cost of an edge $e \in E$ is $c_e(z_e)$. It is split among the terminals $t \in T$, each paying a fraction of this cost. Let us say that the fraction paid by the player t is $\Psi_{e,t}(\boldsymbol{x}_e)$, i.e., the player t pays $c_e(z_e)\Psi_{e,t}(\boldsymbol{x}_e)$ for the edge e where $\boldsymbol{x}_e$ denotes the vector $(x_{e,t_1}, x_{e,t_2}, \ldots, x_{e,t_{N_T}})$. Of course, $\sum_{t \in T} \Psi_{e,t}(\boldsymbol{x}_e) = 1$ to ensure that the total cost is borne by someone or the other. The total cost borne by t across all the edges is $\sum_{e \in E} c_e(z_e)\Psi_{e,t}(\boldsymbol{x}_e)$, denoted $C_E^{(t)}(f)$.
  - *Source Costs*: At a rate R, the cost for the source s is $d_s(y_s)$, which is split among the terminals $t \in T$, such that t pays a fraction $\Phi_{s,t}(\rho_s)$, i.e., the player t pays $d_s(y_s)\Phi_{s,t}(\rho_s)$ for the source s. Of course, $\sum_{t \in T} \Phi_{s,t}(\rho_s) = 1$. Therefore, the total cost borne by t for all sources, denoted $C_S^{(t)}(R)$, is $\sum_{s \in S} d_s(y_s)\Phi_{s,t}(\rho_s)$.

  Thus, with the *edge-cost-splitting mechanism* Ψ and the *source-cost-splitting mechanism* Φ, the total cost incurred by the player $t \in T$ at flow-rate (f, R) denoted $C^{(t)}(f, R)$ is

$$C^{(t)}(f, R) = C_E^{(t)}(f) + C_S^{(t)}(R) = \sum_{e \in E} c_e(z_e)\Psi_{e,t}(\boldsymbol{x}_e) + \sum_{s \in S} d_s(y_s)\Phi_{s,t}(\rho_s).$$

Now, each terminal t would like to minimize its own cost, i.e., the function $C^{(t)}(f, R)$, and therefore, the preference relations $\{\succeq_t\}$ are as follows. For two flow-rates $(f, R) \in \mathcal{A}$ and $(\tilde{f}, \tilde{R}) \in \mathcal{A}$, $(f, R) \succeq_t (\tilde{f}, \tilde{R})$ if and only if $C^{(t)}(f, R) \leq C^{(t)}(\tilde{f}, \tilde{R})$. Also, $(f, R) \succ_t (\tilde{f}, \tilde{R})$ iff $C^{(t)}(f, R) < C^{(t)}(\tilde{f}, \tilde{R})$.

Note that for specifying a DCG, in addition to the parameters G, c, d, and $\mathcal{R}_{\mathcal{SW}}$, we also need the cost-splitting mechanisms Ψ and Φ. We will call $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$ as an instance of the DCG.

2) Solution Concepts for the DCG: We now outline the possible solution concepts in our scenario. These are essentially dictated by the level of sophistication of the terminals. Sophistication refers to the amount of information and computational resources available to a terminal. In this paper, we shall work with two different solution concepts that we now discuss.

a) *Nash Equilibrium*. The solution concept of Nash equilibrium requires the complete information setting and requires each terminal to compute her best response to any given tuple of strategies of the other players. For notational simplicity, let f_{-t} be the vector of flows on paths not going to terminal t, i.e., the vector of values f_P for all $P \in \mathcal{P} - \mathcal{P}_t$; therefore, $f = (f_{-t}, f_t)$. Similarly, $\boldsymbol{R}_{-t}$ is the vector of rates corresponding to all players other than t; therefore, $R = (\boldsymbol{R}_{-t}, \boldsymbol{R}_t)$. In our setting, the best response problem of a terminal t is to minimize her cost function $C^{(t)}(f_{-t}, f_t, \boldsymbol{R}_{-t}, \boldsymbol{R}_t)$ over $(f_t, \boldsymbol{R}_t) \in A_t$ given any $(f_{-t}, \boldsymbol{R}_{-t})$. Therefore, a Nash flow-rate is defined as follows.

Definition 1 (**Nash Flow-Rate**)*:* A flow-rate (f, R) feasible for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ is at Nash equilibrium, or is a Nash flow-rate for instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$, if $\forall t \in T$

$$C^{(t)}(f, R) \leq C^{(t)}(f_{-t}, \tilde{f}_t, \boldsymbol{R}_{-t}, \tilde{\boldsymbol{R}}_t), \quad \forall (\tilde{f}_t, \tilde{\boldsymbol{R}}_t) \in A_t.$$

We note that computing the best response will, in general, require a given terminal to know flow assignments on all possible paths and rate vectors for all the terminals. Moreover, convexity of the objective function in NIF-CP (i.e., social cost $C(f, R)$) does not imply convexity of $C^{(t)}(f_{-t}, f_t, \boldsymbol{R}_{-t}, \boldsymbol{R}_t)$ in the variables $(f_t, \boldsymbol{R}_t) \in A_t$ in general. Therefore, the computational requirements at the terminals may be large. Consequently, Nash equilibrium does not seem to be an appropriate solution concept for the DCG when viewed through the algorithmic lens.

b) *Wardrop Equilibrium*. From a practical standpoint, a terminal may only have partial knowledge of the system and may be computationally constrained. A solution concept more appropriate under such situations is that of local Nash equilibrium or Wardrop equilibrium that is widely adopted in selfish routing and transportation literature [2], [29], [30]. We note that this solution concept has also been utilized in [4] and is further justified in [31]. We first present the precise definition of the Wardrop equilibrium in our case and then provide an intuitive justification. Toward this end, we need to define the marginal cost of a path.

Definition 2 (Marginal Cost of a Path): For a $P \in \mathcal{P}_t$ its marginal cost is

$$C_P(f) = \sum_{e \in P} \frac{c_e(z_e)\Psi_{e,t}(\boldsymbol{x}_e)}{x_{e,t}}.$$

Therefore, for the terminal t, the total cost for the edges, $C_E^{(t)}$, can be equivalently written as

$$C_E^{(t)}(f) = \sum_{P \in \mathcal{P}_t} C_P(f) f_P.$$

Definition 3 (Wardrop Flow-Rate): A flow-rate (f, R) feasible for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ is at local Nash equilibrium, or is a Wardrop flow-rate for instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$, if it satisfies the following conditions.

1) $\forall t \in T$, $\forall s \in S$, we have

$$\sum_{P \in \mathcal{P}_{s,t}} f_P = R_{s,t}.$$

2) $\forall t \in T$, we have

$$\sum_{s \in S} R_{s,t} = H(X_S).$$

3) $\forall t \in T$, $\forall s \in S, P, Q \in \mathcal{P}_{s,t}$ with $f_P > 0$

$$C_P(f) \leq C_Q(f).$$

4) For $t \in T$, consider $j \in S$ that participates in *all tight* rate inequalities involving $i \in S$ (i.e., if $A \subseteq S$, such that $i \in A$ and $\sum_{l \in A} R_{l,t} = H(X_A|X_{-A})$[1]; then, $j \in A$) and let $P \in \mathcal{P}_{i,t}, Q \in \mathcal{P}_{j,t}$ with $f_P > 0$; then, we have

$$C_P(f) + \frac{\partial C_S^{(t)}(R)}{\partial R_{i,t}} \leq C_Q(f) + \frac{\partial C_S^{(t)}(R)}{\partial R_{j,t}}.$$

Intuitively, conditions (1) and (2) require that each terminal requests as little rate and flow as possible. Condition (3) ensures that an infinitesimally small change in flow allocations from path P (where $f_P > 0$) to path Q where $P, Q \in \mathcal{P}_{s,t}$, will increase the sum cost along paths in $\mathcal{P}_t$. Now, consider an infinitesimally small change in flow allocation from $P \in \mathcal{P}_{i,t}$ (where $f_P > 0$) to $Q \in \mathcal{P}_{j,t}$. This also requires a corresponding change in the rates requested from sources i and j by terminal t. Under certain constraints on the source j, condition (4) ensures that the overall effect of this change will serve to increase terminal t's cost. The conditions on the source j are well motivated in light of the characterization of Nash flow-rate in Section V in the case when the best response problem of every terminal is convex.

We remark that a Nash flow-rate may not always be a Wardrop flow-rate and vice versa. When sources are independent, condition (2) implies that $R_{s,t} = H(X_s)$ for all $s \in S, t \in T$ and it is not required to check the condition (4). Also, we can recover condition (3) by setting $i = j$ in condition (4). They are stated separately for the sake of clarity.

As we discussed earlier, the solution concept based on Wardrop equilibrium seems more suitable to our scenario, and consequently, we define the price of anarchy [2], [5], [6] in terms of Wardrop flow-rate instead of Nash flow-rate.

Definition 4 Price of Anarchy (POA): Let $\mathcal{C}$ be a class of edge cost functions, $\mathcal{D}$ be a class of source cost functions, $\mathcal{G}$ be a class of networks/graphs, Ψ be an edge cost splitting mechanism, Φ be a source cost splitting mechanism, and $\mathcal{M}$ be a set of Slepian–Wolf polytopes. We will refer to $(\mathcal{G}, \mathcal{C}, \mathcal{D}, \Psi, \Phi, \mathcal{M})$ as a scenario. The price of anarchy for the scenario $(\mathcal{G}, \mathcal{C}, \mathcal{D}, \Psi, \Phi, \mathcal{M})$, denoted $\rho(\mathcal{G}, \mathcal{C}, \mathcal{D}, \Psi, \Phi, \mathcal{M})$, is defined as maximum over all instances $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ with $G \in \mathcal{G}, c \in \mathcal{C}, d \in \mathcal{D}, \mathcal{R}_{\mathcal{SW}} \in \mathcal{M}$, of the ratio between the cost of worst possible Wardrop flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$ and the cost of OPT flow-rate (i.e., the socially optimal cost) for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$. That is

$$\rho(\mathcal{G},\mathcal{C},\mathcal{D},\Psi,\Phi,\mathcal{M}) = \max_{G\in\mathcal{G}, c\in\mathcal{C}, d\in\mathcal{D}, \mathcal{R}_{\mathcal{SW}}\in\mathcal{M}} \left(\frac{1}{C_{OPT}(G,c,d,\mathcal{R}_{\mathcal{SW}})} \max_{(f,R) \text{ is a Wardrop flow-rate for } (G,c,d,\mathcal{R}_{\mathcal{SW}},\Psi,\Phi)} C(f,R) \right)$$

where $C_{OPT}(G, c, d, \mathcal{R}_{\mathcal{SW}})$ refers to the optimal cost of NIF-CP for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$.

Let us denote the set of Slepian–Wolf polytopes corresponding to the case where there are no source correlations (i.e., $H(X_A|X_{-A}) = H(X_A)$ for all $A \subseteq S$) by $\mathcal{M}_{ind}$ (subscript ind denotes— *independent*) and the set of Slepian–Wolf polytopes corresponding to the case where sources are correlated (i.e., there exists $A \subseteq S$ with $H(X_A|X_{-A}) < H(X_A)$) by $\mathcal{M}_c$. Also, we use $\mathcal{G}_{all}$ to denote the class of all graphs where every $t \in T$ is connected to every $s \in S$, and $\mathcal{G}_{dsw}$ (subscript dsw denotes—*direct Slepian–Wolf*) to denote the class of complete bipartite graphs between the set of sources and the set of terminals. Note that $\mathcal{G}_{dsw}$ corresponds to the case where every terminals is directly connected to every source by an edge and no network coding is required. A question we will be most concerned within this paper is whether $\rho(\mathcal{G}, \mathcal{C}, \mathcal{D}, \Psi, \Phi, \mathcal{M}_c) > \rho(\mathcal{G}, \mathcal{C}, \mathcal{D}, \Psi, \Phi, \mathcal{M}_{ind})$, and in particular whether $\rho(\mathcal{G}, \mathcal{C}, \mathcal{D}, \Psi, \Phi, \mathcal{M}_c) > 1$ but $\rho(\mathcal{G}, \mathcal{C}, \mathcal{D}, \Psi, \Phi, \mathcal{M}_{ind}) = 1$ for meaningful classes of cost functions $\mathcal{C}, \mathcal{D}$ and reasonable splitting mechanisms Ψ and Φ, i.e., does correlation induce anarchy?

[1]We use $H(X_A|X_{-A})$ and $H(X_A|X_{A^c})$ interchangeably in the text to denote the joint entropy of the sources in set A given the remaining sources.

III. Some Properties of Slepian–Wolf Polytope

In this section, we establish two properties of Slepian–Wolf polytope that will be useful in the later sections.

Lemma 5: Let $\boldsymbol{R}_t \in \mathcal{R}_{\mathcal{SW}}$, i.e., $\sum_{l \in A} R_{l,t} \geq H(X_A|X_{-A})$ for all $A \subseteq S$. If $S_1, S_2 \subseteq S$ satisfy

$$\sum_{l \in S_1} R_{l,t} = H(X_{S_1}|X_{-S_1})$$

and

$$\sum_{l \in S_2} R_{l,t} = H(X_{S_2}|X_{-S_2})$$

then we have

$$\sum_{l \in S_1 \cap S_2} R_{l,t} = H(X_{S_1 \cap S_2}|X_{-(S_1 \cap S_2)})$$

and

$$\sum_{l \in S_1 \cup S_2} R_{l,t} = H(X_{S_1 \cup S_2}|X_{-(S_1 \cup S_2)}).$$

Proof: We have

$$\begin{aligned} \sum_{l \in S_1 \cap S_2} R_{l,t} + \sum_{l \in S_1 \cup S_2} R_{l,t} &= \sum_{l \in S_1} R_{l,t} + \sum_{l \in S_2} R_{l,t} \\ &= H(X_{S_1}|X_{-S_1}) + H(X_{S_2}|X_{-S_2}) \\ &\leq H(X_{S_1 \cap S_2}|X_{-(S_1 \cap S_2)}) \\ &\quad + H(X_{S_1 \cup S_2}|X_{-(S_1 \cup S_2)}) \end{aligned}$$

where in the second step we have used the supermodularity property of conditional entropy. Now we are also given that

$$\sum_{l \in S_1 \cap S_2} R_{l,t} \geq H(X_{S_1 \cap S_2}|X_{-(S_1 \cap S_2)})$$

and

$$\sum_{l \in S_1 \cup S_2} R_{l,t} \geq H(X_{S_1 \cup S_2}|X_{-(S_1 \cup S_2)}).$$

Therefore, we can conclude that

$$\sum_{l \in S_1 \cup S_2} R_{l,t} = H(X_{S_1 \cup S_2} | X_{-(S_1 \cup S_2)})$$

and

$$\sum_{l \in S_1 \cap S_2} R_{l,t} = H(X_{S_1 \cap S_2} | X_{-(S_1 \cap S_2)}).$$

∎

Theorem 6: Consider a vector $(R_1, R_2, \ldots, R_n)$ such that

$$\sum_{i \in A} R_i \geq H(X_A | X_{A^c}), \text{ for all } A \subset \{1, 2, \ldots, n\}, \text{ and}$$
$$\sum_{i=1}^{n} R_i > H(X_1, X_2, \ldots, X_n).$$

Then, there exists another vector $(R'_1, R'_2, \ldots, R'_n)$ such that $R'_i \leq R_i$ for all $i = 1, 2, \ldots n$ and

$$\sum_{i \in A} R'_i \geq H(X_A | X_{A^c}), \text{ for all } A \subset \{1, 2, \ldots, n\}, \text{ and}$$
$$\sum_{i=1}^{n} R'_i = H(X_1, X_2, \ldots, X_n).$$

Proof: We claim that there exists a $R_{j^*} \in \{R_1, R_2, \ldots, R_n\}$ such that all inequalities in which R_{j^*} participates are loose. The proof of this claim follows.

Suppose that the aforementioned claim is not true. Then, for all R_i where $i \in \{1, 2, \ldots, n\}$, there exists at least one subset $S_i \subset \{1, 2, \ldots, n\}$ such that

$$\sum_{k \in S_i} R_k = H(X_{S_i} | X_{S_i^c})$$

i.e., each R_i participates in at least one inequality that is tight.

Now by applying Lemma 5 on the sets $S_1, S_2, \ldots, S_n$, since $S_1 \cup S_2 \ldots \cup S_n = \{1, 2, \ldots, n\}$, we get $\sum_{i=1}^{n} R_i = \sum_{i \in S_1 \cup S_2 \ldots \cup S_n} R_i = H(X_{S_1 \cup S_2 \ldots \cup S_n} | X_{-(S_1 \cup S_2 \ldots \cup S_n)}) = H(X_1, X_2, \ldots, X_n)$, which is a contradiction.

The aforementioned argument shows that there exists some j^* such that all inequalities in which R_{j^*} participates are loose. Therefore, we can reduce R_{j^*} to a new value $R_{j^*}^{red}$ until one of the inequalities in which it participates is tight. If the sum-rate constraint is met with equality, then we can set $R'_{j^*} = R_{j^*}^{red}$ otherwise we can recursively apply the aforementioned procedure to arrive at a new vector that is component-wise smaller that the original vector $(R_1, R_2, \ldots, R_n)$. ∎

IV. Characterizing the Optimal Flows and Rates

In this section, we investigate the properties of an OPT flow-rate via Lagrangian duality theory [32]. Since the optimization problem NIF-CP is convex and the constraints are such that the strong duality holds, the *Karush–Kuhn–Tucker(KKT)* conditions exactly characterize optimality [32]. Therefore, we start out by writing the Lagrangian dual of NIF-CP

$$L = \sum_{e \in E} c_e(z_e) + \sum_{s \in S} d_s(y_s) - \sum_{P \in \mathcal{P}} \mu_P f_P$$
$$+ \sum_{s \in S} \sum_{t \in T} \lambda_{s,t} (R_{s,t} - \sum_{P \in \mathcal{P}_{s,t}} f_P)$$
$$+ \sum_{t \in T} \left[\sum_{A \subseteq S} \nu_{A,t} \left(H(X_A | X_{A^c}) - \sum_{i \in A} R_{i,t} \right) \right]$$

where $\mu_P \geq 0, \lambda_{s,t} \geq 0$ and $\nu_{A,t} \geq 0$ are the dual variables (i.e., Lagrange multipliers). For notational simplicity, let us denote the partial derivative of z_e with respect to $x_{e,t}$, $\frac{\partial z_e}{\partial x_{e,t}}$ by $z'_{e,t}$. Note that the partial derivative of $x_{e,t}$ w.r.t. to f_P is 1 for a path $P \in \mathcal{P}_t$ such that $e \in P$. Similarly, we denote the partial derivative of y_s with respect to $R_{s,t}$, $\frac{\partial y_s}{\partial R_{s,t}}$ by $y'_{s,t}$. The KKT conditions are then given by the following equations that hold $\forall\ s \in S, t \in T$:

$$\frac{\partial L}{\partial f_P} = \sum_{e \in P} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e) - \mu_P - \lambda_{s,t} = 0, \ \forall P \in \mathcal{P}_{s,t}, \text{ and} \tag{3}$$

$$\frac{\partial L}{\partial R_{s,t}} = d'_s(y_s) y'_{s,t}(\rho_s) + \lambda_{s,t} - \sum_{A \subseteq S : s \in A} \nu_{A,t} = 0 \tag{4}$$

along with the feasibility of the flow-rate (f, R) and the complementary slackness conditions, $\mu_P f_P = 0$ for all $P \in \mathcal{P}$, $\lambda_{s,t}(R_{s,t} - \sum_{P \in \mathcal{P}_{s,t}} f_P) = 0$ for all $s \in S, t \in T$, and $\nu_{A,t} \left(H(X_A | X_{A^c}) - \sum_{i \in A} R_{i,t} \right) = 0$ for all $A \subseteq S, t \in T$.

Let us now interpret the KKT conditions at the *OPT flow-rate* (f^*, R^*). Suppose that $f_P^* > 0$ for $P \in \mathcal{P}_{s,t}$. Then due to complementary slackness, we have $\mu_P^* = 0$ and consequently from (3) we get $\sum_{e \in P} c'_e(z_e^*) z'_{e,t}(\boldsymbol{x}_e^*) = \lambda_{s,t}^*$, i.e., if there exists another path $Q \in \mathcal{P}_{s,t}$ such that $f_Q^* > 0$, then $\sum_{e \in P} c'_e(z_e^*) z'_{e,t}(\boldsymbol{x}_e^*) = \sum_{e \in Q} c'_e(z_e^*) z'_{e,t}(\boldsymbol{x}_e^*)$.

Now, if we interpret the quantity $\sum_{e \in P} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e)$ as the *differential cost* of the path P associated with the flow-rate (f, R), then this condition implies that the differential cost of all the paths going from the same source to the same terminal with positive flows at *OPT* is the same. It is quite intuitive for if it were not true the objective function could be further decreased by moving some flow from a higher differential cost path to a lower differential cost one without violating feasibility conditions, and, of course, this should not be possible at the optimum. Similarly, the differential cost along a path with zero flow at OPT must have higher differential cost and indeed this can be obtained as earlier by further noting that the dual variables μ_P's are nonnegative. We note this property of the OPT flow-rate in the following lemma.

Lemma 7: Let (f^*, R^*) be an OPT flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$. Then, $\forall t \in T$ *for all* $s \in S, P, Q \in \mathcal{P}_{s,t}$ with $f_P > 0$ we have

$$\sum_{e \in P} c'_e(z_e^*) z'_{e,t}(\boldsymbol{x}_e^*) \leq \sum_{e \in Q} c'_e(z_e^*) z'_{e,t}(\boldsymbol{x}_e^*).$$

The aforementioned lemma provides a simple and intuitive characterization of how the flow allocations on various paths of same type (that is originating at same source and ending at the same terminal) behave at the optimum solution. Although such a simple and intuitive characterization of the behavior of joint flow and rate allocations at optimum is not immediately clear, we can indeed obtain three other simple and intuitive conditions that together with Lemma 7, are equivalent to the KKT conditions. We establish this important characterization in the Theorem 11. First, we will show in the next three lemmas that these conditions are necessary for optimality.

Lemma 8: Let (f, R) be an OPT flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$. For $t \in T$, suppose that there exist $i, j \in S$ that satisfy the following property. If $A \subseteq S$, such that $i \in A$ and $\sum_{l \in A} R_{l,t} = H(X_A | X_{-A})$, then $j \in A$. For such i and j let $P \in \mathcal{P}_{i,t}, Q \in \mathcal{P}_{j,t}$ with $f_P > 0$. Then

$$\begin{aligned}\sum_{e \in P} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e) &+ d_i'(y_i) y_{i,t}'(\rho_i) \\ &\leq \sum_{e \in Q} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e) + d_j'(y_j) y_{j,t}'(\rho_j).\end{aligned}$$

Proof: Since (f, R) is an OPT flow-rate, it satisfies the KKT conditions for some suitable choice of dual variables $\lambda_{i,t} \geq 0$, $\mu_P \geq 0$, $\nu_{A,t} \geq 0$. Now, we are given that $j \in A$ for all $A \subseteq S$ such that $i \in A$ and $\sum_{l \in A} R_{l,t} = H(X_A | X_{-A})$, so if there is an $A \subseteq S$ such that $i \in A$ but $j \notin A$ then $\sum_{l \in A} R_{l,t} > H(X_A | X_{-A})$ and therefore by complementary slackness we get $\nu_{A,t} = 0$. Furthermore, from (4), we have

$$\begin{aligned}d_i'(y_i) y_{i,t}'(\rho_i) + \lambda_{i,t} &= \sum_{A \subseteq S : i \in A} \nu_{A,t} \\ &= \sum_{A \subseteq S : i \in A, j \in A} \nu_{A,t} \\ &\qquad \left(\text{since} \sum_{A \subseteq S : i \in A,\, j \notin A} \nu_{A,t} = 0\right)\end{aligned}$$

and

$$\begin{aligned}d_j'(y_j) y_{j,t}'(\rho_j) + \lambda_{j,t} &= \sum_{A \subseteq S : j \in A} \nu_{A,t} \\ &= \sum_{A \subseteq S : j \in A, i \in A} \nu_{A,t} \\ &\qquad + \sum_{A \subseteq S : j \in A, i \notin A} \nu_{A,t} \\ &\geq \sum_{A \subseteq S : j \in A, i \in A} \nu_{A,t} \\ &= d_i'(y_i) y_{i,t}'(\rho_i) + \lambda_{i,t}.\end{aligned}$$

Therefore, we get

$$d_i'(y_i) y_{i,t}'(\rho_i) + \lambda_{i,t} \leq d_j'(y_j) y_{j,t}'(\rho_j) + \lambda_{j,t}.$$

Furthermore, we are given that $f_P > 0$ which, using (3) and complementary slackness condition $f_P \mu_P = 0$, implies that $\lambda_{i,t} = \sum_{e \in P} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e)$ and since $\mu_Q \geq 0$ we have $\sum_{e \in Q} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e) \geq \lambda_{j,t}$. Therefore

$$\begin{aligned}d_i'(y_i) y_{i,t}'(\rho_i) &+ \sum_{e \in P} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e) \\ &\leq d_j'(y_j) y_{j,t}'(\rho_j) + \sum_{e \in Q} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e).\end{aligned}$$

This concludes the proof. ■

Lemma 9: Let (f, R) be an OPT flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ wherein the functions c_e's and d_s's are all strictly convex; then $\forall t \in T$, $\forall s \in S$, we have $\sum_{P \in \mathcal{P}_{s,t}} f_P = R_{s,t}$.

Proof: Let $\sum_{P \in \mathcal{P}_{s,t}} f_P > R_{s,t}$; then, there is a $P \in P_{s,t}$ with $f_P > 0$. Define a new feasible flow $\tilde{f}$ such that $\tilde{f}_Q = f_Q$ if $Q \neq P$ and $\tilde{f}_P = f_P - \delta$ for some $0 < \delta < \min\{f_P, \sum_{P \in \mathcal{P}_{s,t}} f_P - R_{s,t}\}$. Then

$$\begin{aligned}\sum_{e \in E} c_e(\tilde{z}_e) &= \sum_{e \in P} c_e(\tilde{z}_e) + \sum_{e \notin P} c_e(z_e) \\ &= \sum_{e \in E} c_e(z_e) + \sum_{e \in P} \left(c_e(\tilde{z}_e) - c_e(z_e)\right).\end{aligned}$$

Now, the function c_e is nondecreasing. In addition, z_e is nondecreasing in each coordinate. Together, this means that $c_e(\tilde{z}_e) - c_e(z_e) \leq 0$ for all $e \in P$. Therefore

$$\begin{aligned}\sum_{e \in E} c_e(\tilde{z}_e) &\leq \sum_{e \in E} c_e(z_e) \implies \\ C(\tilde{f}, R) &= \sum_{e \in E} c_e(\tilde{z}_e) + \sum_{s \in S} d_s(y_s) \\ &\leq \sum_{e \in E} c_e(z_e) + \sum_{s \in S} d_s(y_s) \\ &= C(f, R)\end{aligned}$$

which is a contradiction because (f, R), due to strict convexity of the function C, is the *unique* OPT flow-rate. ■

Lemma 10: Let (f, R) be an OPT flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ wherein the functions c_e's and d_s's are all strictly convex; then, $\forall t \in T$, we have $\sum_{s \in S} R_{s,t} = H(X_S)$.

Proof: As R is feasible, $\forall t \in T$, $\boldsymbol{R}_t \in \mathcal{R}_{\mathcal{SW}}$, and therefore, $\sum_{s \in S} R_{s,t} \geq H(X_S)$. Suppose $\sum_{s \in S} R_{s,t} > H(X_S)$ for some $t \in T$; then, from Theorem 6, there exist an $s \in S$, such that all (Slepian–Wolf) inequalities in which $R_{s,t}$ participates are loose. Therefore, we can decrease this rate $R_{s,t}$ by a positive amount r, i.e., to $\tilde{R}_{s,t} = R_{s,t} - r$, without violating feasibility. This means that we can define a feasible rate $\tilde{R}$ such that $\tilde{R}_{i,t} = R_{i,t}$ if $i \neq s$ and $\tilde{R}_{s,t} = R_{s,t} - r$ for some $r > 0$. Now

$$\sum_{i \in S} d_i(\tilde{y}_i) = \sum_{i \in S} d_i(y_i) + \left(d_s(\tilde{y}_s) - d_s(y_s)\right)$$

Now, d_s is nondecreasing; in addition, y_s is nondecreasing in each coordinate. Together, we conclude that $d_s(\tilde{y}_s) \leq d_s(y_s)$. Therefore

$$\begin{aligned}\sum_{i \in S} d_i(\tilde{y}_i) &\leq \sum_{i \in S} d_i(y_i) \implies \\ C(f, \tilde{R}) &= \sum_{e \in E} c_e(z_e) + \sum_{s \in S} d_s(\tilde{y}_s) \\ &\leq \sum_{e \in E} c_e(z_e) + \sum_{s \in S} d_s(y_s) \\ &= C(f, R)\end{aligned}$$

which is a contradiction because (f, R), due to strict convexity of the function C, is the *unique* OPT flow-rate. ■

Theorem 11: A feasible flow-rate (f, R) for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$, which satisfies the following four conditions is an OPT flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$. Also, there is always an OPT flow-rate that satisfies these four conditions. Furthermore, when the edge cost functions c_e for all $e \in E$ and the source cost functions d_s for all $s \in S$ are strictly convex, that is when the optimization problem NIF-CP is strictly convex, these conditions are also necessary for optimality.

1) $\forall t \in T,\ \forall s \in S$, we have

$$\sum_{P \in \mathcal{P}_{s,t}} f_P = R_{s,t}.$$

2) $\forall t \in T$, we have

$$\sum_{s \in S} R_{s,t} = H(X_S).$$

3) $\forall t \in T,\ \forall s \in S,\ P, Q \in \mathcal{P}_{s,t}$ with $f_P > 0$,

$$\sum_{e \in P} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e) \le \sum_{e \in Q} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e).$$

4) For $t \in T$, suppose that there exist $i, j \in S$ that satisfy the following property. If $A \subseteq S$, such that $i \in A$ and $\sum_{l \in A} R_{l,t} = H(X_A | X_{-A})$, then $j \in A$. For such i and j let $P \in \mathcal{P}_{i,t}, Q \in \mathcal{P}_{j,t}$ with $f_P > 0$. Then

$$\sum_{e \in P} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e) + d'_i(y_i) y'_{i,t}(\rho_i) \le \sum_{e \in Q} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e) + d'_j(y_j) y'_{j,t}(\rho_j).$$

Proof: We prove that the aforementioned four conditions imply optimality of (f, R). Our assumptions guarantee that the optimization problem NIF-CP for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ is convex and since all the feasibility constraints are linear, strong duality holds [32]. This implies that the KKT conditions are necessary and sufficient for optimality. We show that a feasible flow-rate (f, R) with the aforementioned four properties satisfies the KKT conditions for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ for a suitable choice of the dual variables given in the following.

Choosing $\lambda_{i,t}$'s:

$$\lambda_{i,t} := \min_{P \in \mathcal{P}_{i,t}} \sum_{e \in P} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e).$$

Note that, using *Condition 3*, for $i \in S$, if there exist a $P_i \in \mathcal{P}_{i,t}$ such that $f_{P_i} > 0$ then we have

$$\lambda_{i,t} = \sum_{e \in P_i} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e).$$

Choosing μ_P 's: For $P \in P_{i,t}$ take

$$\mu_P := \sum_{e \in P} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e) - \lambda_{i,t}.$$

Choosing $\nu_{A,t}$'s: Let

$$h_{i,t} := d'_i(y_i) y'_{i,t}(\rho_i) + \lambda_{i,t}.$$

Let π denote a permutation such that $0 \le h_{\pi(1),t} \le h_{\pi(2),t} \le \dots h_{\pi(N_S),t}$. Now take

$$\nu_{A,t} = \begin{cases} h_{\pi(1),t} & \text{if } A = \{\pi(1), \pi(2), \dots, \pi(N_S)\} \\ h_{\pi(i),t} - h_{\pi(i-1),t} & \text{if } A = \{\pi(i), \dots, \pi(N_S)\} \\ & \text{and } 2 \le i \le N_S \\ 0 & \text{otherwise.} \end{cases}$$

Now, with the aforementioned choice of dual variables, we will check all the KKT conditions one by one.

Dual Feasibility:

- $\lambda_{i,t} \ge 0$ as c_e and z_e are nondecreasing functions, i.e., $c'_e(z_e) \ge 0$ and $z'_{e,t}(\boldsymbol{x}_e) \ge 0$.
- $\mu_P \ge 0$ by the definition because $\lambda_{i,t} \le \sum_{e \in P} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e)\ \forall P \in P_{i,t}$.
- $\nu_{A,t} \ge 0$ by definition.

KKT Conditions as per (3):

$$\begin{aligned} \frac{\partial L}{\partial f_P} &= \sum_{e \in P} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e) - \lambda_{i,t} - \mu_P \\ &= \sum_{e \in P} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e) - \lambda_{i,t} - \left(\sum_{e \in P} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e) - \lambda_{i,t} \right) \\ &= 0. \end{aligned}$$

KKT Conditions as per (4):

$$\begin{aligned} \frac{\partial L}{\partial R_{\pi(i),t}} &= d'_{\pi(i)}(y_{\pi(i)}) y'_{\pi(i),t}(\rho_{\pi(i)}) + \lambda_{\pi(i),t} - \sum_{A \subseteq S: \pi(i) \in A} \nu_{A,t} \\ &= h_{\pi(i),t} - \sum_{A \subseteq S: \pi(i) \in A} \nu_{A,t} \\ &= h_{\pi(i),t} - \sum_{j \in \{1,2,\dots,i\}} \nu_{\{\pi(j), \pi(j+1), \dots, \pi(N_S)\},t} \\ &= h_{\pi(i),t} - \big[h_{\pi(1),t} + (h_{\pi(2),t} - h_{\pi(1),t}) \\ &\quad + (h_{\pi(3),t} - h_{\pi(2),t}) + \dots + (h_{\pi(i),t} - h_{\pi(i-1),t}) \big] \\ &= h_{\pi(i),t} - h_{\pi(i),t} = 0. \end{aligned}$$

Complementary Slackness Conditions:

- $\mu_P f_P = 0$ for all $P \in \mathcal{P}$.
  Let $P \in \mathcal{P}_{i,t}$ and $f_P > 0$; then, using *Condition 3* and definition of $\lambda_{i,t}$, we get

$$\sum_{e \in P} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e) = \lambda_{i,t}$$

  and therefore

$$\mu_P = \sum_{e \in P} c'_e(z_e) z'_{e,t}(\boldsymbol{x}_e) - \lambda_{i,t} = 0.$$

- $\lambda_{s,t}(R_{s,t} - \sum_{P \in \mathcal{P}_{s,t}} f_P) = 0$ for all $s \in S, t \in T$.
  This follows from the *Condition 1*.
- $\nu_{A,t} \left(H(X_A | X_{A^c}) - \sum_{i \in A} R_{i,t} \right) = 0$ for all $A \subseteq S, t \in T$.

Note that $\nu_{A,t} = 0$ except for $A = \{\pi(i), \pi(i+1), \dots, \pi(N_S)\}$, for $i = 1, 2, \dots, N_S$. Therefore, the only condition that needs to be checked is that if $\sum_{j=i}^{N_S} R_{\pi(j),t} > H(X_{\pi(i)}, X_{\pi(i+1)}, \dots, X_{\pi(N_S)} | X_{\pi(i-1)}, \dots, X_{\pi(1)})$, then $h_{\pi(i),t} - h_{\pi(i-1),t} = 0$.

Toward this end, let $j \in \{\pi(i), \pi(i+1), \ldots, \pi(N_S)\}$, and let A_j be the minimum cardinality set such that $j \in A_j$ and $\sum_{l\in A_j} R_{l,t} = H(X_{A_j}|X_{-A_j})$, i.e.

$$A_j = \arg\min_{A\subseteq S: j\in A, \sum_{l\in A} R_{l,t}=H(X_A|X_{-A})} |A|.$$

Such a set A_j always exists because from *Condition 2*, we have $\sum_{l=1}^{N_S} R_{l,t} = H(X_1, \ldots, X_{N_S})$, and therefore, the set $\left\{A \subseteq S : j \in A, \sum_{l\in A} R_{l,t} = H(X_A|X_{-A})\right\}$ is not empty.

We claim that there exists a $j^* \in \{\pi(i), \pi(i+1), \ldots, \pi(N_S)\}$ such that $A_{j^*} \cap \{\pi(1), \pi(2), \ldots, \pi(i-1)\}$ is not empty. If this is not true, then clearly we have $\cup_{j=\pi(i)}^{\pi(N_S)} A_j = \{\pi(i), \pi(i+1), \ldots, \pi(N_S)\}$ and using the supermodularity property of conditional entropy (ref. *Lemma 5*), we obtain

$$\sum_{j=i}^{N_S} R_{\pi(j),t} = H(X_{\pi(i)}, X_{\pi(i+1)}, \ldots, X_{\pi(N_S)}|X_{\pi(i-1)}, \ldots, X_{\pi(1)})$$

which is a contradiction; therefore, we must have such a $j^* \in \{\pi(i), \pi(i+1), \ldots, \pi(N_S)\}$ such that $A_{j^*} \cap \{\pi(1), \pi(2), \ldots, \pi(i-1)\}$ is not empty.

Next, we show that there exists a source $k \in \{\pi(1), \pi(2), \ldots, \pi(i-1)\}$ such that if $j^* \in A$ and $\sum_{l\in A} R_{l,t} = H(X_A|X_{-A})$, then $k \in A$. Toward this end, suppose that there exist subsets S_1 and S_2 of S such that $j^* \in S_1 \cap S_2$ and $\sum_{l\in S_1} R_{l,t} = H(X_{S_1}|X_{-S_1})$ and $\sum_{l\in S_2} R_{l,t} = H(X_{S_2}|X_{-S_2})$; then, using the supermodularity property of conditional entropy, we can show that rate inequality involving $S_1 \cap S_2$ is also tight (*Lemma 5*), i.e., $\sum_{l\in S_1\cap S_2} R_{l,t} = H(X_{S_1\cap S_2}|X_{-(S_1\cap S_2)})$. This implies that A_{j^*}, being of minimum cardinality, is the intersection of all sets that have j^* as a member on which the rate inequality is tight, i.e.

$$A_{j^*} = \bigcap_{A\subseteq S} \left\{A : j^* \in A, \sum_{l\in A} R_{l,t} = H(X_A|X_{-A})\right\}.$$

Moreover note that A_{j^*} is not a singleton set since $A_{j^*} \cap \{\pi(1), \pi(2), \ldots, \pi(i-1)\} \neq \phi$. Therefore, there exists a $k \in A_{j^*}$ such that $k \neq j^*$. By our aforementioned arguments, this implies that if $A \subseteq S$ is such that $j^* \in A$ and $\sum_{l\in A} R_{l,t} = H(X_A|X_{-A})$, then $k \in A$.

Clearly, $R_{j^*,t} > H(X_{j^*}|X_{-j^*})$ as k does not participate in this rate inequality. Therefore, $R_{j^*,t} > 0$ which implies that there exists a $P \in \mathcal{P}_{j^*,t}$ with $f_P > 0$; therefore, using *Condition 3* and the definition of $\lambda_{j^*,t}$, we have $\sum_{e\in P} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e) = \lambda_{j^*,t}$. Also, by the definition of $\lambda_{k,t}$ there is a $Q \in \mathcal{P}_{k,t}$ such that $\sum_{e\in Q} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e) = \lambda_{k,t}$.

Now using *Condition 4*, we get

$$\sum_{e\in P} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e) + d_{j^*}'(y_{j^*}) y_{j^*,t}'(\rho_{j^*}) \leq \sum_{e\in Q} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e) + d_k'(y_k) y_{k,t}'(\rho_k)\ \forall Q \in \mathcal{P}_{k,t}$$

which implies that

$$\lambda_{j^*,t} + d_{j^*}'(y_{j^*}) y_{j^*,t}'(\rho_{j^*}) \leq \lambda_{k,t} + d_k'(y_k) y_{k,t}'(\rho_k)$$

and therefore we get $h_{j^*,t} \leq h_{k,t}$. Now note that $k \in \{\pi(1), \pi(2), \ldots, \pi(i-1)\}$ while $j^* \in \{\pi(i), \ldots, \pi(N_S)\}$. This implies in turn that $h_{\pi(i),t} \leq h_{j^*,t} \leq h_{k,t}$. But, we know that $h_{k,t} \leq h_{\pi(i-1),t}$, i.e., $h_{\pi(i),t} - h_{\pi(i-1),t} \leq 0$ but we already have $h_{\pi(i),t} - h_{\pi(i-1),t} \geq 0$ and hence $h_{\pi(i),t} - h_{\pi(i-1),t} = 0$.

This establishes that the four conditions are sufficient for optimality. Furthermore, as per Lemmas 7, 8, 9, 10, under strict convexity conditions, these conditions are necessary too. ■

Corollary 12: If the sources are independent (i.e., $\mathcal{R}_{\mathcal{SW}} \in \mathcal{M}_{ind}$), there is a feasible flow-rate for instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ that is an OPT flow-rate for both the instances $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ and $(G, \tilde{c}, \tilde{d}, \mathcal{R}_{\mathcal{SW}})$, where $\tilde{c}_e(x) = \alpha c_e(x)$ for constant $\alpha > 0$, and $\tilde{d}_s$ is *any* convex, differentiable, positive, and nondecreasing function. Furthermore, this OPT flow-rate satisfies the four conditions in Theorem 11 for both the instances $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ and $(G, \tilde{c}, \tilde{d}, \mathcal{R}_{\mathcal{SW}})$.

Proof: The idea is that when the sources are independent, Condition (2) in Theorem 11 implies that $R_{s,t} = H(X_s)$ for all $s \in S, t \in T$, and therefore, there is no pair (i, j) such that j participates in all tight rate inequalities involving i, and consequently, it is not required to check Condition (4). For the sake of completeness, the proof follows.

Let (f, R) be an OPT flow-rate for $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ satisfying the four conditions in Theorem 11. Note that such an OPT flow-rate always exists as per Theorem 11. Since the sources are independent, the rate inequalities constraints becomes

$$\sum_{i\in A} R_{i,t} \geq H(X_A) \text{ for all } A\ \subseteq S,\ t\ \in T.$$

Therefore, using Condition (2) in Theorem 11, we obtain

$$R_{s,t} = H(X_s) \text{ for all } s\ \in S,\ t\ \in T.$$

Now, we will show that (f, R) is also an OPT flow-rate for the instance $(G, \tilde{c}, \tilde{d}, \mathcal{R}_{\mathcal{SW}})$ by showing that it satisfies the four conditions in Theorem 11 for instance $(G, \tilde{c}, \tilde{d}, \mathcal{R}_{\mathcal{SW}})$. Note that Conditions (1) and (2) are easily satisfied by (f, R) as they do not depend on particular cost functions. Furthermore

$$\sum_{e\in P} \tilde{c}_e'(z_e) z_{e,t}'(\boldsymbol{x}_e) = \alpha \sum_{e\in P} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e)$$

therefore condition

$$\sum_{e\in P} \tilde{c}_e'(z_e) z_{e,t}'(\boldsymbol{x}_e) \leq \sum_{e\in Q} \tilde{c}_e'(z_e) z_{e,t}'(\boldsymbol{x}_e)$$

is equivalent to

$$\sum_{e\in P} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e) \leq \sum_{e\in Q} c_e'(z_e) z_{e,t}'(\boldsymbol{x}_e)$$

therefore condition (3) is also satisfied. For the condition (4), let us first note that as discussed earlier $R_{s,t} = H(X_s)$ for all $s \in S, t \in T$. This implies that there is no pair $(i, j) \in S \times S$ satisfying the promise in condition (4), i.e., there is no pair (i, j) such that j participates in all tight rate inequalities involving i (simply because j does not participate in the tight rate inequality $R_{i,t} = H(X_i)$). Thus, (f, R) satisfies all the four conditions in Theorem 11 for the instance $(G, \tilde{c}, \tilde{d}, \mathcal{R}_{\mathcal{SW}})$ and, hence, is an OPT flow-rate for $(G, \tilde{c}, \tilde{d}, \mathcal{R}_{\mathcal{SW}})$. ■

V. Flows and Rates at Nash Equilibrium

In this section, we study the properties of a Nash flow-rate whenever the individual optimization problem (i.e., the best response problem) of each terminal is convex, that is whenever Nash equilibrium can be considered as an appropriate solution concept for the DCG when viewed through the algorithmic lens. Therefore, throughout this section, we assume that the edge cost splitting mechanism Ψ, as well as, the source cost splitting mechanism Φ are such that the functions $C^{(t)}$, for all $t \in T$, are convex. By considering the best response problem of each terminal, and an approach essentially the same as in the Section IV for characterizing OPT flow-rate, we can obtain the following Theorem 13 for characterizing Nash flow-rate.

Theorem 13: Consider an instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$ where $C^{(t)}$ is convex for all $t \in T$. A feasible flow-rate (f, R) for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$, which satisfies the following four conditions is a Nash flow-rate for $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$. Furthermore, when $C^{(t)}$ is strictly convex for all $t \in T$, these conditions are also necessary.

1) $\forall t \in T,\ \forall s \in S$, we have
$$\sum_{P \in \mathcal{P}_{s,t}} f_P = R_{s,t}.$$
2) $\forall t \in T$, we have
$$\sum_{s \in S} R_{s,t} = H(X_S).$$
3) $\forall t \in T,\ \forall s \in S,\ P, Q \in \mathcal{P}_{s,t}$ with $f_P > 0$
$$\frac{\partial C_E^{(t)}(f)}{\partial f_P} \le \frac{\partial C_E^{(t)}(f)}{\partial f_Q}.$$
4) For $t \in T$, let $j \in S$ participates in *all tight* rate inequalities involving $i \in S$ (i.e., if $A \subseteq S$, such that $i \in A$ and $\sum_{l \in A} R_{l,t} = H(X_A|X_{-A})$, then $j \in A$) and let $P \in \mathcal{P}_{i,t}, Q \in \mathcal{P}_{j,t}$ with $f_P > 0$ then we have
$$\frac{\partial C_E^{(t)}(f)}{\partial f_P} + \frac{\partial C_S^{(t)}(R)}{\partial R_{i,t}} \le \frac{\partial C_E^{(t)}(f)}{\partial f_Q} + \frac{\partial C_S^{(t)}(R)}{\partial R_{j,t}}.$$

Furthermore, under similar convexity conditions, we can also show that a Nash flow-rate always exists for the DCG This is done via first compactifying the strategy sets A_t's to obtain a restricted game where existence of a Nash equilibrium follows from the standard fixed point theorems [28]. Then, by utilizing the monotonically nondecreasing properties of various cost functions, it is argued that a Nash equilibrium of the restricted game is also a Nash flow-rate for our DCG thereby proving the existence of a Nash flow-rate for DCG.

The result stated in the following (Theorem 14) is a standard result on the existence of Nash equilibrium and can be found, for instance in the book by Osborne and Rubinstein [28].

Theorem 14: The strategic game $\langle \mathcal{N}, (A_i), (\succeq_i) \rangle$ has a Nash equilibrium if for all $i \in \mathcal{N}$, the following conditions hold.

1) The set A_i of actions of player i is a nonempty compact convex subset of a Euclidean space.
2) The preference relation $\succeq_i$ is continuous and quasi-concave on A_i. A preference relation $\succeq_i$ on $\mathcal{A}$ is said to be quasi-concave on A_i if for every $a \in \mathcal{A}$, the set $\{\tilde{a}_i \in A_i : (a_{-i}, \tilde{a}_i) \succeq_i a\}$ is convex. A preference relation $\succeq_i$ on $\mathcal{A}$ is said to be continuous if $a \succeq_i b$ whenever there are sequences $\{a^k\}$ and $\{b^k\}$ with $a^k, b^k \in \mathcal{A}$ and $a^k \succeq_i b^k$ for all k such that $\{a^k\}$ and $\{b^k\}$ converge to a and b, respectively.

Now, let us consider an instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$ of the DCG, where $C^{(t)}$ is convex for all $t \in T$.

The action set of the terminal $t \in T$ is
$$A_t = \left\{ (f_t, \boldsymbol{R}_t) : \begin{array}{l} f_P \ge 0\ \forall P \in \mathcal{P}_t \\ \sum_{P \in \mathcal{P}_{s,t}} f_P \ge R_{s,t}\ \forall s \in S \\ \boldsymbol{R}_t \in \mathcal{R}_{\mathcal{SW}} \end{array} \right\}. \quad (5)$$

Clearly, this is a nonempty convex subset of an Euclidean Space, but it is not compact.

Let us consider a game with a restricted set of strategies denoted $\tilde{A}_t$'s as follows and let us call this new game as the *restricted game* for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$
$$\tilde{A}_t = \left\{ (f_t, \boldsymbol{R}_t) : \begin{array}{l} f_P \ge 0\ \forall P \in \mathcal{P}_t \\ \sum_{P \in \mathcal{P}_{s,t}} f_P \ge R_{s,t}\ \forall s \in S \\ \boldsymbol{R}_t \in \mathcal{R}_{\mathcal{SW}} \\ f_P \le H(X_S)\ \forall P \in \mathcal{P}_t \\ R_{s,t} \le H(X_S)\ \forall s \in S \end{array} \right\}. \quad (6)$$

Now, the set $\tilde{A}_t$ becomes compact as it is a closed and bounded subset of an Euclidean space, and therefore, $\tilde{A}_t$ satisfies the requirement (a) of the Theorem 14.

Since players' cost functions $C^{(t)}$ are convex and continuous for all $t \in T$, the condition (b) in the Theorem 14 is also satisfied and we obtain the following result.

Lemma 15: The restricted game for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$, where $C^{(t)}$ is convex for all $t \in T$, admits a Nash equilibrium.

Now, we claim that every Nash equilibrium of the restricted game is also a Nash equilibrium for the original game and that will imply the existence of a Nash flow-rate for the original game.

Lemma 16: Every Nash equilibrium of the restricted game for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$, where $C^{(t)}$ is convex for all $t \in T$, is also a Nash flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$.

Proof: Let (f, R) be a Nash equilibrium of the restricted game for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$. Then, for all t, we have
$$C^{(t)}(f, R) \le C^{(t)}(f_{-t}, \boldsymbol{R}_{-t}, \tilde{f}_t, \tilde{\boldsymbol{R}}_t)$$
for all $\tilde{f}_t, \tilde{\boldsymbol{R}}_t$ feasible for the restricted game, i.e., coming from the restricted strategy set $\tilde{A}_t$.

Now, let $(\tilde{f}_t, \tilde{\boldsymbol{R}}_t) \in A_t \setminus \tilde{A}_t$, i.e., $\tilde{f}_t, \tilde{\boldsymbol{R}}_t$ is feasible for the original game but not feasible for the restricted game. For ease of notation, let us define the following quantities:
$$\begin{aligned} S_{1,t} &= \left\{ s \in S : \tilde{R}_{s,t} > H(X_S) \right\},\ S_{2,t} = S \setminus S_{1,t} \\ \boldsymbol{R}'_t &= \left\{ R'_{s,t} \mid R'_{s,t} = H(X_S) \text{ for } s \in S_{1,t} \right\} \\ \mathcal{P}_t^1 &= \left\{ P \in \mathcal{P}_t : \tilde{f}_P > H(X_S) \right\},\ \mathcal{P}_t^2 = \mathcal{P}_t \setminus \mathcal{P}_t^1 \\ f'_t &= \left\{ f'_P \mid f'_P = H(X_S) \text{ for } P \in \mathcal{P}_t^1 \right\}. \end{aligned}$$

Note that in defining $\boldsymbol{R}'_t$ and f'_t, we have projected all the flows and rates violating the feasibility for the restricted game to their boundary values and, therefore, the strategy $(f'_t, \{\tilde{f}_P : P \in \mathcal{P}^2_t\}, \boldsymbol{R}'_t, \{\tilde{R}_{s,t} : s \in S_{2,t}\}) \in \tilde{A}_t$, i.e., it is feasible for the restricted game.

Now

$$\begin{aligned}&C^{(t)}(f_{-t}, \boldsymbol{R}_{-t}, \tilde{f}_t, \tilde{\boldsymbol{R}}_t)\\ &\geq C^{(t)}(f_{-t}, \boldsymbol{R}_{-t}, \tilde{f}_t, \boldsymbol{R}'_t, \{\tilde{R}_{s,t} : s \in S_{2,t}\})\\ &\geq C^{(t)}(f_{-t}, \boldsymbol{R}_{-t}, f'_t, \{\tilde{f}_P : P \in \mathcal{P}^2_t\}, \boldsymbol{R}'_t, \{\tilde{R}_{s,t} : s \in S_{2,t}\})\end{aligned}$$

and since (f, R) is a Nash equilibrium for the restricted game and $(f'_t, \{\tilde{f}_P : P \in \mathcal{P}^2_t\}, \boldsymbol{R}'_t, \{\tilde{R}_{s,t} : s \in S_{2,t}\})$ is feasible for the restricted game, we have

$$\begin{aligned}&C^{(t)}(f, R)\\ &\leq C^{(t)}(f_{-t}, \boldsymbol{R}_{-t}, f'_t, \{\tilde{f}_P : P \in \mathcal{P}^2_t\}, \boldsymbol{R}'_t, \{\tilde{R}_{s,t} : s \in S_{2,t}\})\\ &\leq C^{(t)}(f_{-t}, \boldsymbol{R}_{-t}, \tilde{f}_t, \tilde{\boldsymbol{R}}_t)\end{aligned}$$

and therefore $C^{(t)}(f, R) \leq C^{(t)}(f_{-t}, \boldsymbol{R}_{-t}, \tilde{f}_t, \tilde{\boldsymbol{R}}_t)$ for all $(\tilde{f}_t, \tilde{\boldsymbol{R}}_t) \in A_t$ implying that (f, R) is a Nash equilibrium of the original game meaning (f, R) is a Nash flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$. ■

Combining the Lemmas 15 and 16, we obtain the following theorem.

Theorem 17: An instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$, where $C^{(t)}$ is convex for all $t \in T$, admits a Nash flow-rate.

VI. Wardrop Flow-Rate and the Price of Anarchy

In this section, we investigate the inefficiency brought forth by the selfish behavior of terminals. First, we will show that the Wardrop equilibrium is a socially optimal solution for a different set of (related) cost functions. Using this, we will construct explicit examples that demonstrate that the POA > 1 and determine near-tight upper bounds on the POA as well. We start out with the characterization of Wardrop flow-rate.

Theorem 18: Let $z_e(\boldsymbol{x}_e) = \left(\sum_{t \in T} x^n_{e,t}\right)^{\frac{1}{n}}, \Psi_{e,t}(\boldsymbol{x}_e) = \frac{x^n_{e,t}}{\left(\sum_{j \in T} x^n_{e,j}\right)}$ and $\Phi_{s,t}(\rho_s) = \frac{1}{N_T}$. A Wardrop flow-rate for $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$ is an OPT flow-rate for $(G, \tilde{c}, d, \mathcal{R}_{\mathcal{SW}})$, where $\tilde{c}_e(x) = N_T \int \frac{c_e(x)}{x} dx$. Furthermore, when the edge cost functions c_e for all $e \in E$ and the source cost functions d_s for all $s \in S$ are strictly convex, an OPT flow-rate for $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ is also a Wardrop flow-rate for $(G, \hat{c}, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$, where $\hat{c}_e(x) = \frac{1}{N_T} x c'_e(x)$.

Proof: We will show that the definition of a Wardrop flow-rate for instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$ exactly corresponds to the four conditions for the instance $(G, \tilde{c}, d, \mathcal{R}_{\mathcal{SW}})$ in Theorem 11.

We have

$$z'_{e,t}(\boldsymbol{x}_e) = \frac{1}{n}\left(\sum_{j \in T} x^n_{e,j}\right)^{\frac{1}{n}-1} n x^{n-1}_{e,t} = \frac{z_e}{x_{e,t}} \frac{x^n_{e,t}}{\sum_{j \in T} x^n_{e,j}}.$$

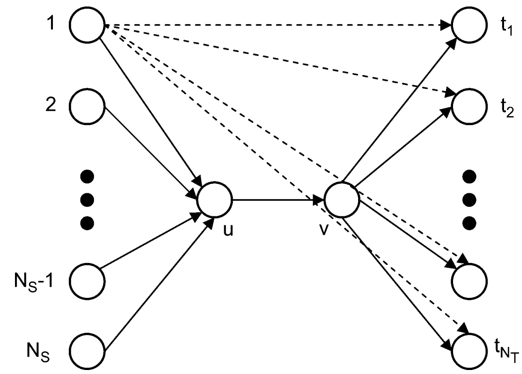

Fig. 1. Example of a network where POA is linear in N_T.

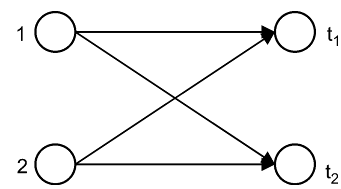

Fig. 2. Classical Slepian–Wolf network with appropriate costs also has POA > 1.

Therefore

$$\begin{aligned}C_P(f) &= \sum_{e \in P} c_e(z_e) \frac{x^{n-1}_{e,t}}{\left(\sum_{j \in T} x^n_{e,j}\right)}\\ &= \sum_{e \in P} c_e(z_e) \frac{z'_{e,t}(x_e)}{z_e}\\ &= \frac{1}{N_T} \sum_{e \in P} \tilde{c}'_e(z_e) z'_{e,t}(x_e)\end{aligned}$$

where the last equality follows from the fact that

$$\tilde{c}_e(x) = N_T \int \frac{c_e(x)}{x} dx \implies \tilde{c}'_e(x) = N_T \frac{c_e(x)}{x}.$$

Also

$$\begin{aligned}C^{(t)}_S(R) &= \frac{1}{N_T} \sum_{i \in S} d_i(y_i) \implies\\ \frac{\partial C^{(t)}_S(R)}{\partial R_{i,t}} &= \frac{1}{N_T} d'_i(y_i) y'_{i,t}(\rho_i).\end{aligned}$$

Therefore

$$C_P(f) + \frac{\partial C^{(t)}_S(R)}{\partial R_{i,t}} = \frac{1}{N_T}\left[\sum_{e \in P} \tilde{c}'_e(z_e) z'_{e,t}(\boldsymbol{x}_e) + d'_i(y_i) y'_{i,t}(\rho_i)\right].$$

The result follows from the equivalence of conditions coming from Definition 3 and Theorem 11. ■

In contrast with the result of [4] that holds for a single source with the edge cost splitting mechanism used earlier, from Theorem 18, we can note that for most reasonable cost splitting mechanisms, the POA will not equal one for all monomial edge cost functions. We construct explicit examples for POA > 1 in Figs. 1 and 2. The example in Fig. 1 is near tight as will be evident from an upper bound on POA derived in Theorem 20.

It is interesting to note that in the case when sources are independent, in the Wardrop or OPT solutions, the rates requested at various sources will equal their respective lower bounds (i.e., their entropies). Therefore, the cost term corresponding to the sources will be fixed, and one only needs to find flows that minimize the edge costs. In this situation, it is not hard to see that the POA will again equal one for *all* monomial edge cost functions. This means that *it is the correlation among the sources that is responsible for bringing more anarchy*. We formalize this as follows.

Let $\mathcal{C}_k = \{c : c_e(x) = a_e x^k,\ a_e > 0, \forall e \in E\}$ be the set of edge cost functions where all edge cost functions are monomial of the same degree k possibly with different coefficients, and $\mathcal{C}_{mon} = \cup_{k \geq 1} \mathcal{C}_k$. Similarly, $\mathcal{D}_k = \{d : d_i(y) = b_i y^k,\ b_i > 0, \forall s \in S\}$. Also, let $D_{convex} = \{d : d_i \text{ is convex}, \forall i \in S\}$.

Corollary 19 Correlation Induces Anarchy: Let $z_e(\boldsymbol{x}_e) = \left(\sum_{t\in T} x_{e,t}^n\right)^{\frac{1}{n}}$, $\Psi_{e,t}(\boldsymbol{x}_e) = \frac{x_{e,t}^n}{\left(\sum_{j\in T} x_{e,j}^n\right)}$, $y_s(\rho_s) = \left(\sum_{t\in T} R_{s,t}^m\right)^{\frac{1}{m}}$, and $\Phi_{s,t}(\rho_s) = \frac{1}{N_T}$; then, we have

1) $\rho(\mathcal{G}_{all}, \mathcal{C}_{mon}, \mathcal{D}_{convex}, \Psi, \Phi, \mathcal{M}_{ind}) = 1$.
2) $\rho(\mathcal{G}_{all}, \mathcal{C}_{N_T}, \mathcal{D}_{convex}, \Psi, \Phi, \mathcal{M}_c) = 1$.
3) $\rho(\mathcal{G}_{all}, \mathcal{C}_{mon}, \mathcal{D}_{convex}, \Psi, \Phi, \mathcal{M}_c) > 1$ for large values of m and n. In fact, $\rho(\mathcal{G}_{all}, \mathcal{C}_1, \mathcal{D}_2, \Psi, \Phi, \mathcal{M}_c) > \frac{1+N_T}{5}$.
4) $\rho(\mathcal{G}_{dsw}, \mathcal{C}_{mon}, \mathcal{D}_{convex}, \Psi, \Phi, \mathcal{M}_c) > 1$ for large values of m and n.

Proof: Let $c \in \mathcal{C}_{mon}$, i.e., $c_e(x) = a_e x^k$ for $a_e > 0$ for all $e \in E$; therefore, $\int \frac{c_e(x)}{x} dx = \int a_e x^{k-1}\ dx = a_e \frac{1}{k} x^k = \frac{1}{k} c_e(x)$. Also, $d \in \mathcal{D}_{convex}$. Now, since the sources are independent (i.e., $\mathcal{R}_{\mathcal{SW}} \in \mathcal{M}_{ind}$), from Theorem 18 and Corollary 12, it follows that a Wardrop flow-rate for instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$ is also an OPT flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ which implies that $\rho(\mathcal{G}_{all}, \mathcal{C}_{mon}, \mathcal{D}_{convex}, \Psi, \Phi, \mathcal{M}_{ind}) = 1$.

Even if the sources are correlated, when we have $k = N_T$, we have $N_T \int \frac{c_e(x)}{x} dx = c_e(x)$ and using Theorem 18, a Wardrop flow-rate for instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$ is also an OPT flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$ which implies that

$$\rho(\mathcal{G}_{all}, \mathcal{C}_{N_T}, \mathcal{D}_{convex}, \Psi, \Phi, \mathcal{M}_c) = 1.$$

We prove $\rho(\mathcal{G}_{all}, \mathcal{C}_1, \mathcal{D}_2, \Psi, \Phi, \mathcal{M}_c) > \frac{1+N_T}{5}$ and consequently

$$\rho(\mathcal{G}_{all}, \mathcal{C}_{mon}, \mathcal{D}_{convex}, \Psi, \Phi, \mathcal{M}_c) > 1$$

by explicitly constructing an example as provided in Fig. 1. All sources are identical with entropy h; therefore, $\mathcal{R}_{\mathcal{SW}} \in \mathcal{M}_c$. Let $d_s(y) = C_1 y^2$ for all $s \in S$; therefore, $d \in \mathcal{D}_2$, and the edge cost functions, $c_e(x) = x$ except for the edge (u, v) for which $c_e(x) = C_2\ x$. Therefore, $c \in \mathcal{C}_1$. Let us consider the following flow-rate (f, R)

$$\begin{aligned} R_{1,t} &= h\ \forall t \in T \\ R_{s,t} &= 0\ \forall s \in S - \{1\}, t \in T \\ f_{(1,t)} &= h\ \forall t \in T \text{ over dotted edges in Fig. 1} \\ f_P &= 0\ \forall P \in \mathcal{P}_t - \{(1,t)\}, t \in T. \end{aligned}$$

Clearly, (f, R) is feasible for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$. We claim that (f, R) is a Wardrop flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$ when $\frac{2C_1 h}{N_T} \leq 1 + C_2$. To see this, first note that (f, R) satisfies the conditions (1) and (2) in the definition of Wardrop flow-rate (Definition 3) for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$. We will now check the conditions (3) and (4) in Definition 3. Note that $\Psi_{e,t}(\boldsymbol{x}_e) = \frac{1}{N_T}$ whenever $x_{e,t} = x$ for all $t \in T$ for some $x > 0$ and by continuity this is true even if $x = 0$. Therefore

$$\begin{aligned} C_{(1,t)}(f) &= \sum_{e\in\{(1,t)\}} \frac{c_e(z_e)\Psi_{e,t}(\boldsymbol{x}_e)}{x_{e,t}} = \frac{h \cdot 1}{h} = 1 \\ C_{(1,u,v,t)}(f) &= \sum_{e\in\{(1,u),(u,v),(v,t)\}} \frac{c_e(z_e)\Psi_{e,t}(\boldsymbol{x}_e)}{x_{e,t}} \\ &= \lim_{x\longrightarrow 0} \left[\frac{x\cdot\left(\frac{1}{N_T}\right)}{x} + \frac{C_2 x\cdot\left(\frac{1}{N_T}\right)}{x} + \frac{x\cdot 1}{x}\right] \\ &= 1 + \frac{1+C_2}{N_T}, \text{ and similarly} \\ C_{(s,u,v,t)}(f) &= 1 + \frac{1+C_2}{N_T},\ s \in S - \{1\}. \end{aligned}$$

Clearly, the condition (3) is satisfied as $C_{(1,t)}(f) < C_{(1,u,v,t)}(f)$. Also

$$\begin{aligned} \frac{\partial C_S^{(t)}(R)}{\partial R_{i,t}} &= \frac{1}{N_T} d_i'(y_i) y_{i,t}'(\rho_i) \\ &= \frac{1}{N_T} 2C_1 y_i y_{i,t}'(\rho_i) \\ &= \frac{2C_1}{N_T} y_i^2 \frac{R_{i,t}^{m-1}}{\sum_{j\in T} R_{i,j}^m} \\ &= \frac{2C_1}{N_T} \left(\sum_{j\in T} R_{i,j}^m\right)^{\frac{2}{m}} \frac{R_{i,t}^{m-1}}{\sum_{j\in T} R_{i,j}^m}. \\ \therefore\ \frac{\partial C_S^{(t)}(R)}{\partial R_{1,t}} &= \frac{2C_1}{N_T} (N_T h^m)^{\frac{2}{m}} \frac{h^{m-1}}{N_T h^m} \\ &= \frac{2C_1 h}{N_T^2} \text{ as } m \longrightarrow \infty \text{ and} \\ \frac{\partial C_S^{(t)}(R)}{\partial R_{s,t}} &\geq 0, \forall s \in S - \{1\}. \end{aligned}$$

Therefore, when $\frac{2C_1 h}{N_T} \leq 1 + C_2$, we get

$$\begin{aligned} C_{(1,t)}(f) + \frac{\partial C_S^{(t)}(R)}{\partial R_{1,t}} &\leq C_{(s,u,v,t)}(f) \\ &\quad + \frac{\partial C_S^{(t)}(R)}{\partial R_{s,t}}\ \forall s \in S - \{1\} \end{aligned}$$

which implies that the condition (4) is also satisfied. Thus, (f, R) is indeed a Wardrop flow-rate for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}}, \Psi, \Phi)$. Furthermore

$$\begin{aligned} C(f, R) &= \sum_{e\in\cup_{t\in T}\{(1,t)\}} c_e(z_e) + \sum_{e\in\cup_{s\in S}\{(s,u)\}} c_e(z_e) \\ &\quad + c_{(u,v)}(z_{(u,v)}) + \sum_{e\in\cup_{t\in T}\{(v,t)\}} c_e(z_e) + \sum_{s\in S} d_s(y_s) \\ &= N_T h + 0 + 0 + 0 + C_1 (N_T h^m)^{\frac{2}{m}} \text{ as } n \longrightarrow \infty \\ &= N_T h + C_1 h^2 \text{as } m \longrightarrow \infty. \end{aligned}$$

Now, let us consider another flow-rate (f^*, R^*)

$$R^*_{s,t} = \frac{h}{N_S} \ \forall s \in S, t \in T$$
$$f^*_{(1,t)} = 0 \ \forall t \in T, \text{and}$$
$$f^*_{(s,u,v,t)} = \frac{h}{N_S} \ \forall s \in S, t \in T.$$

Clearly, (f^*, R^*) is feasible for the instance $(G, c, d, \mathcal{R}_{\mathcal{SW}})$. Furthermore

$$\begin{aligned} C(f^*, R^*) = & \sum_{e \in \cup_{t\in T}\{(1,t)\}} c_e(z^*_e) \\ & + \sum_{e \in \cup_{s\in S}\{(s,u)\}} c_e(z^*_e) + c_{(u,v)}(z^*_{(u,v)}) \\ & + \sum_{e \in \cup_{t\in T}\{(v,t)\}} c_e(z^*_e) + \sum_{s\in S} d_s(y^*_s) \\ & = 0 + N_S\left(N_T(\frac{h}{N_S})^n\right)^{\frac{1}{n}} + C_2(N_T h^n)^{\frac{1}{n}} \\ & + N_T h + N_S C_1 \left(N_T(\frac{h}{N_S})^m\right)^{\frac{2}{m}} \\ & = h(1 + C_2 + N_T) + \frac{C_1 h^2}{N_S} \\ & \text{as } m \longrightarrow \infty,\ n \longrightarrow \infty \end{aligned}$$

we get $C(f^*, R^*) = h(1 + C_2 + N_T) + \frac{C_1 h^2}{N_S}$ as $m \to \infty, n \to \infty$.

Thus, when $\frac{1+C_2}{C_1} < h\ (1 - \frac{1}{N_S})$, we have $C(f^*, R^*) < C(f, R)$. As $\mathrm{OPT}(G, c, d, \mathcal{R}_{\mathcal{SW}}) \le C(f^*, R^*)$, this implies that the POA is greater than one.

In particular

$$\rho\left(\mathcal{G}_{all}, \mathcal{C}_1, \mathcal{D}_2, \Psi, \Phi, \mathcal{M}_c\right) > \frac{C_1 + \frac{N_T}{h}}{\frac{1+C_2+N_T}{h} + \frac{C_1}{N_S}}.$$

Now, take $h = 1, N_S = N_T > 4, 1 + C_2 = 3N_T, C_1 = N_T^2$, and note that

$$\frac{2C_1 h}{N_T} = 2N_T < 3N_T = 1 + C_2$$

as well as

$$\frac{1 + C_2}{C_1} = \frac{3}{N_T} < (1 - \frac{1}{N_T}) = (1 - \frac{1}{N_S}) \text{ as } N_T > 4.$$

Therefore, we get

$$\rho(\mathcal{G}_{all}, \mathcal{C}_1, \mathcal{D}_2, \Psi, \Phi, \mathcal{M}_c) > \frac{1 + N_T}{5}.$$

This is near tight as will be evident from Theorem 20.

To establish (4), we will prove a stronger result, $\rho(\mathcal{G}_{dsw}, \mathcal{C}_3, \mathcal{D}_3, \Psi, \Phi, \mathcal{M}_c) > 1$, by constructing an example as described in the following. As shown in Fig. 2, there are two sources and two terminals which are directly connected to each source. Both sources are identical with entropy 1, $d_1(y) = C_1 y^3, d_2(y) = C_2 y^3$ with $C_1, C_2 > 0, C_1 \neq C_2$ and $c_e(x) = x^3$ for all edges. We now outline the argument that shows that the POA > 1.

First, observe that the instance is symmetric with respect to terminals and all cost functions are strictly convex. Therefore, the OPT flow-rate for the instance, denoted (f^*, R^*) is such that $R^*_{s,t_1} = R^*_{s,t_2}$ for $s = 1, 2$. Next, by the characterization as per Theorem 18, the Wardrop flow-rate, denoted (f, R) is an OPT flow-rate for $\tilde{c}_e(x) = \frac{2}{3}x^3$ with the source cost functions remaining the same. This new instance with $\tilde{c}_e(x) = \frac{2}{3}x^3$ is also symmetric with respect to the terminals and the cost functions remain strictly convex. Therefore, we conclude that for the Wardrop flow-rate as well $R_{s,t_1} = R_{s,t_2}$ for $s = 1, 2$. Let $R_{1,t_1} = R_{1,t_2} = h$ and $R^*_{1,t_1} = R^*_{1,t_2} = h^*$. Using the properties of Wardrop flow-rate and OPT flow-rate as per condition (2) in Theorem 11, we have $R_{2,t_1} = R_{2,t_2} = 1 - h$ and $R^*_{2,t_1} = R^*_{1,t_2} = 1 - h^*$. We argue in the following that $h \neq h^*$. Consequently, by uniqueness of the OPT flow-rate (due to strict convexity of the objective function), we will have $C(f, R) > C(f^*, R^*)$ implying $\rho(\mathcal{G}_{dsw}, \mathcal{C}_3, \mathcal{D}_3, \Psi, \Phi, \mathcal{M}_c) > 1$. We have for $t = t_1, t_2$

$$\begin{aligned} \frac{\partial C^{(t)}_S(R)}{\partial R_{1,t}} &= \frac{1}{N_T} d'_1(y_1) y'_{1,t}(\rho_1) \\ &= \frac{3}{2} C_1 y_1^2 y_1 \frac{R^{m-1}_{1,t}}{\sum_{j=1}^2 R^m_{1,j}} \\ &= \frac{3}{4} C_1 h^2 \text{ as } m \ \to \infty. \end{aligned}$$

Similarly

$$\frac{\partial C^{(t)}_S(R)}{\partial R_{2,t}} = \frac{3}{4} C_2 (1 - h)^2.$$

By the definition of Wardrop flow-rate, we have

$$f_{(1,t)} = h,\ f_{(2,t)} = (1 - h).$$

Thus

$$C_{(1,t)}(f) = h^2,\ C_{(2,t)}(f) = (1 - h)^2.$$

Furthermore

$$\frac{\partial C^{(t)}_S(R)}{\partial R_{1,t}} + C_{(1,t)}(f) = \frac{\partial C^{(t)}_S(R)}{\partial R_{2,t}} + C_{(2,t)}(f)$$

implies that

$$\frac{3}{4} C_1 h^2 + h^2 = \frac{3}{4} C_2 (1 - h)^2 + (1 - h)^2.$$

Therefore

$$\frac{h}{1 - h} = \sqrt{\frac{\frac{3}{4} C_2 + 1}{\frac{3}{4} C_1 + 1}}.$$

Now, from Theorem 18, (f^*, R^*) is a Wardrop flow-rate for the instance where everything remains the same except for the edge cost functions which are now $\frac{3}{2}x^3$ instead of x^3 and performing the similar calculations as earlier for (f, R), we obtain

$$\frac{h^*}{1 - h^*} = \sqrt{\frac{\frac{3}{4} C_2 + \frac{3}{2}}{\frac{3}{4} C_1 + \frac{3}{2}}}.$$

Clearly, since $C_1 \neq C_2$, we get $h \neq h^*$. In particular, take $C_1 = 4, C_2 = 8$; then, $h = 0.5695$ and $h^* = 0.5635$. Thus, $C(f,R) = 1.9061, C(f^*,R^*) = 1.9052$ implying that $POA \geq 1.004 > 1$, in this example. ■

Note that while constructing the aforementioned examples, the source cost splitting function we have used is $\Phi_{s,t}(\rho_s) = 1/N_T$. Furthermore, for the same mechanism, Corollary 19 (2) provides an example of edge cost functions that gives a POA of one, and possibly this is the only choice giving POA one. Before considering another reasonable splitting mechanism, we first establish an upper bound which is nearly attainable by instance given in Fig. 1.

Theorem 20: Let $z_e(\boldsymbol{x}_e) = \left(\sum_{t\in T} x_{e,t}^n\right)^{\frac{1}{n}}, \Psi_{e,t}(\boldsymbol{x}_e) = \frac{x_{e,t}^n}{\left(\sum_{j\in T} x_{e,j}^n\right)}$ and $\Phi_{s,t}(\rho_s) = \frac{1}{N_T}$. Then

$$\rho(\mathcal{G}_{all}, \mathcal{C}_k, \mathcal{D}_{convex}, \Psi, \Phi, \mathcal{M}_c) \leq \max\{\frac{N_T}{k}, \frac{k}{N_T}\}.$$

Proof: As in the proof of Theorem 18, we have $C_P(f) = \frac{1}{N_T}\sum_{e\in P} \tilde{c}_e'(z_e) z_{e,t}'(x_e)$ and $C_{P_i}(f) + \frac{\partial C_S^{(t)}(R)}{\partial R_{i,t}} = \frac{1}{N_T}\left[\sum_{e\in P_i} \tilde{c}_e'(z_e) z_{e,t}'(\boldsymbol{x}_e) + d_i'(y_i) y_{i,t}'(\rho_i)\right]$.

Let (f,R) be a Wardrop flow-rate and (f^*,R^*) be OPT for $(G,c,d,\mathcal{R}_{\mathcal{SW}})$, respectively. Furthermore, let $\tilde{c}_e(x) = N_T \int \frac{c_e(x)}{x} dx = N_T \int a_e x^{k-1} dx = \frac{N_T}{k} a_e x^k$. Now

$$\begin{aligned} C(f,R) &= \sum_{e\in E} c_e(z_e) + \sum_{s\in S} d_s(y_s) \\ &= \sum_{e\in E} a_e z_e^k + \sum_{s\in S} d_s(y_s) \end{aligned}$$

and

$$\begin{aligned} C(f^*,R^*) &= \sum_{e\in E} c_e(z_e^*) + \sum_{s\in S} d_s(y_s^*) \\ &= \sum_{e\in E} a_e (z_e^*)^k + \sum_{s\in S} d_s(y_s^*). \end{aligned}$$

Let us first consider the case where $N_T \geq k$, i.e., $1 \leq \frac{N_T}{k}$

$$\begin{aligned} C(f,R) &= \sum_{e\in E} a_e z_e^k + \sum_{s\in S} d_s(y_s) \\ &\leq \sum_{e\in E} \frac{N_T}{k} a_e z_e^k + \sum_{s\in S} d_s(y_s) \\ &= \sum_{e\in E} \tilde{c}_e(z_e) + \sum_{s\in S} d_s(y_s). \end{aligned}$$

Now, from Theorem 18, (f,R) is OPT for $(G,\tilde{c},d,\mathcal{R}_{\mathcal{SW}})$ and because (f^*,R^*) is feasible for $(G,\tilde{c},d,\mathcal{R}_{\mathcal{SW}})$, we get

$$\begin{aligned} \sum_{e\in E} \tilde{c}_e(z_e) + \sum_{s\in S} d_s(y_s) &\leq \sum_{e\in E} \tilde{c}_e(z_e^*) + \sum_{s\in S} d_s(y_s^*) \\ &= \sum_{e\in E} \frac{N_T}{k} a_e (z_e^*)^k + \sum_{s\in S} d_s(y_s^*) \\ &\leq \frac{N_T}{k}\left[\sum_{e\in E} a_e (z_e^*)^k + \sum_{s\in S} d_s(y_s^*)\right] \\ &= \frac{N_T}{k} C(f^*,R^*). \end{aligned}$$

Therefore

$$\frac{C(f,R)}{C(f^*,R^*)} \leq \frac{N_T}{k}.$$

Similarly, for the case when $N_T \leq k$, i.e., $1 \geq \frac{N_T}{k}$

$$\begin{aligned} C(f,R) &= \sum_{e\in E} a_e z_e^k + \sum_{s\in S} d_s(y_s) \\ &= \frac{k}{N_T}\left[\sum_{e\in E} \frac{N_T}{k} a_e z_e^k + \sum_{s\in S} \frac{N_T}{k} d_s(y_s)\right] \\ &\leq \frac{k}{N_T}\left[\sum_{e\in E} \frac{N_T}{k} a_e z_e^k + \sum_{s\in S} d_s(y_s)\right] \\ &= \frac{k}{N_T}\left[\sum_{e\in E} \tilde{c}_e(z_e) + \sum_{s\in S} d_s(y_s)\right]. \end{aligned}$$

Now, from Theorem 18, (f,R) is OPT for $(G,\tilde{c},d,\mathcal{R}_{\mathcal{SW}})$ and because (f^*,R^*) is feasible for $(G,\tilde{c},d,\mathcal{R}_{\mathcal{SW}})$ we get

$$\begin{aligned} \sum_{e\in E} \tilde{c}_e(z_e) + \sum_{s\in S} d_s(y_s) &\leq \sum_{e\in E} \tilde{c}_e(z_e^*) + \sum_{s\in S} d_s(y_s^*) \\ &= \sum_{e\in E} \frac{N_T}{k} a_e (z_e^*)^k + \sum_{s\in S} d_s(y_s^*) \\ &\leq \sum_{e\in E} a_e (z_e^*)^k + \sum_{s\in S} d_s(y_s^*) \\ &= C(f^*,R^*). \end{aligned}$$

Therefore

$$\frac{C(f,R)}{C(f^*,R^*)} \leq \frac{k}{N_T}.$$

■

Now, we consider another splitting mechanism Φ that looks more like the edge cost splitting mechanism Ψ. Specifically, take $y_s(\rho_s) = \left(\sum_{t\in T}(R_{s,t})^m\right)^{\frac{1}{m}}$ and $\Phi_{i,t}(\rho_i) = \frac{(R_{i,t})^m}{\sum_{j\in T}(R_{i,j})^m}$. Let us first note the generalization of Corollary 19(1) for any source cost splitting mechanism Φ. Proof is essentially the same as earlier. The condition (2) in the definition of Wardrop flow-rate as well as OPT flow-rate renders all the rates to be equal to their corresponding entropies, and consequently, the condition (4) need not be checked.

Lemma 21: Let $z_e(\boldsymbol{x}_e) = \left(\sum_{t\in T} x_{e,t}^n\right)^{\frac{1}{n}}, \Psi_{e,t}(\boldsymbol{x}_e) = \frac{x_{e,t}^n}{\left(\sum_{j\in T} x_{e,j}^n\right)}$, and $\Phi_{s,t}(\rho_s)$ be any source cost splitting function; then, we have

$$\rho\left(\mathcal{G}_{all}, \mathcal{C}_{mon}, \mathcal{D}_{convex}, \Psi, \Phi, \mathcal{M}_{ind}\right) = 1.$$

Now, we will argue that with $y_s(\rho_s) = \left(\sum_{t\in T}(R_{s,t})^m\right)^{\frac{1}{m}}$ and $\Phi_{i,t}(\rho_i) = \frac{(R_{i,t})^m}{\sum_{j\in T}(R_{i,j})^m}$, we have $\rho(\mathcal{G}_{dsw}, \mathcal{C}_{mon}, \mathcal{D}_{convex}, \Psi, \Phi, \mathcal{M}_c) > 1$ for large values of m and n. Let us consider the same example as in Fig. 2 but with the new source cost splitting mechanism. First, note that OPT flow-rate is independent of the choice of cost splitting functions and the previously calculated OPT flow-rate for this instance (f^*, R^*) is given by

$$R^*_{1,t} = f^*_{(1,t)} = h^*, \quad \text{and}$$
$$R^*_{2,t} = f^*_{(2,t)} = 1 - h^*.$$

We will argue that this is not a Wardrop flow-rate and since the OPT flow-rate is unique (by strict convexity), we will obtain $POA > 1$. After some simple calculations, we get

$$\frac{\partial C_S^{(t)}(R)}{\partial R_{i,t}} = d_i'(y_i)\frac{y_i}{R_{i,t}}\Phi^2_{i,t}(\rho_i) + m\frac{d_i(y_i)}{R_{i,t}}\Phi_{i,t}(\rho_i)\left(1 - \Phi_{i,t}(\rho_i)\right).$$

Therefore

$$\frac{\partial C_S^{(t)}(R^*)}{\partial R_{1,t}} = (m+3)(N_T)^{\frac{3}{m}}\frac{C_1}{4}(h^*)^2 \quad \text{and}$$
$$\frac{\partial C_S^{(t)}(R^*)}{\partial R_{2,t}} = (m+3)(N_T)^{\frac{3}{m}}\frac{C_2}{4}(1-h^*)^2.$$

Also, $C_{(1,t)}(f^*) = (h^*)^2$ and $C_{(2,t)}(f^*) = (1-h^*)^2$. Note that $N_T = 2$ in this example. Now, with $C_1 = 4, C_2 = 8$, we have $h^* = 0.5635$ and therefore

$$\begin{aligned}
&\frac{C_{(1,t)}(f^*) + \frac{\partial C_S^{(t)}(R^*)}{\partial R_{1,t}}}{C_{(2,t)}(f^*) + \frac{\partial C_S^{(t)}(R^*)}{\partial R_{2,t}}} \\
&= \frac{(h^*)^2 + (m+3)(N_T)^{\frac{3}{m}}\frac{C_1}{4}(h^*)^2}{(1-h^*)^2 + (m+3)(N_T)^{\frac{3}{m}}\frac{C_2}{4}(1-h^*)^2} \\
&= \frac{(m+3)(N_T)^{\frac{3}{m}} + 1}{2(m+3)(N_T)^{\frac{3}{m}} + 1}\,\frac{0.5635^2}{(1-0.5635)^2} \\
&= \frac{1}{2}\frac{0.5635^2}{(1-0.5635)^2} \\
&= 0.8333 \neq 1 \text{ as } m \to \infty.
\end{aligned}$$

Theorem 22: Let $z_e(\boldsymbol{x}_e) = \left(\sum_{t\in T} x^n_{e,t}\right)^{\frac{1}{n}}$, $y_s(\rho_s) = \left(\sum_{t\in T}(R_{s,t})^m\right)^{\frac{1}{m}}$, $\Psi_{e,t}(\boldsymbol{x}_e) = \frac{x^n_{e,t}}{\left(\sum_{j\in T} x^n_{e,j}\right)}$, and $\Phi_{i,t}(\rho_i) = \frac{(R_{i,t})^m}{\sum_{j\in T}(R_{i,j})^m}$ for large values of m and n; then, we have

$$\rho\left(\mathcal{G}_{dsw}, \mathcal{C}_{mon}, \mathcal{D}_{convex}, \Psi, \Phi, \mathcal{M}_c\right) > 1.$$

VII. Future Directions

In this paper, we have initiated a study of the inefficiency brought forth by the lack of regulation in the multicast of *multiple correlated sources*. We have established the foundations of the framework by providing the first set of technical results that characterize the equilibrium among terminals, when they act selfishly trying to minimize their individual costs without any regard to social welfare, and its relation to the socially optimal solution. Our paper leaves out several open problems that we discuss as follows.

Network Information Flow Games: From Slepian–Wolf to Polymatroids: The results presented in this paper are expected to naturally extend to a large class of network information flow problems where the entropy is replaced by any rank function [33] and equivalently conditional entropy is replaced by any supermodular function. This is because the only special property of conditional entropy used in our analysis is its supermodularity. Polytopes described by such rank functions are called *contra-polymatroids* and the SW polytope is an example. Therefore, by abstracting the network coding scenario to this more general setting, we can obtain a nice class of multiplayer games with compact representations.

Dynamics of Wardrop Flow-Rate: Can we design a noncooperative decentralized algorithm that steers flows and rates in way that converges to a Wardrop flow-rate? What about such an algorithm which runs in polynomial time? A first approach could be to consider an algorithm where each terminal greedily allocates rates and flows by calculating marginal costs at each step.

Better Bounds on POA: Although we have provided explicit examples where correlation brings more anarchy, as well as, an upper bound on POA which is nearly achievable, we believe that more detailed analysis is necessary. An important approach in this direction would be to characterize exactly how the POA depends on structure of SW region, i.e., to analyze the finer details on how correlation among the sources changes the POA, even in the case of two sources. Furthermore, other interesting splitting mechanisms can also be studied.

Capacity Constraints and Approximate Wardrop Flow-Rates: Another direction of investigation could be to consider the scenario where there is a capacity constraint on each edge, i.e., the maximum amount of flow that can be sent through that edge. It may also be useful to investigate the sensitivity of the implicit assumption in our analysis that terminals can evaluate various quantities, and in particular the marginal costs, with arbitrary precision. This can be approached by formulating a notion of approximate Wardrop flow-rate, where terminals can distinguish quantities only when they differ significantly.

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