Cooperation and Competition between Wireless Networks in Shared Spectrum

Du Ho Kang, Ki Won Sung, and Jens Zander
Wireless@KTH, Royal Institute of Technology (KTH)
Electrum 229, 164 40 Kista, Sweden
Email: {dhkang, sungkw, jenz}@kth.se

***Abstract*—As the regulation in wireless communications is moving toward a more flexible and efficient way of managing radio spectrum, it is envisaged that multiple small-sized cellular networks owned by different operators will operate in close vicinity on shared spectrum. This brings a new interference environment where a cell is interfered by not only base stations in own network but also those in other networks. These networks may compete for their own utilities in a selfish manner or cooperate in order to minimize the mutual interference. Since a cooperation between the networks requires a business-wise agreement or extra infrastructure cost, the operators have to identify how much they will benefit from the cooperation. In this paper, we compare the effects of competition and cooperation between the cellular networks. The competition and cooperation are modeled as a transmit power control in downlink. It is observed that the incentive of cooperation and competition is differentiated depending on each network's utility region. However, as the network size increases, the cooperation gain in an average sense diminishes significantly. Furthermore, only marginal separation of network deployments, e.g., indoor deployments in adjacent buildings, can notably shrink the cooperation incentive.**

I. Introduction

A migration toward flexible spectrum management becomes eminent to alleviate spectrum scarcity for a rapidly growing mobile broadband access. Accordingly, regulatory bodies recently consider various ways of spectrum management such as spectrum trading/borrowing or temporal/geographical sharing [1]. From this paradigm shift, various novel network operation models are envisaged. An example is shown in Fig. 1 where small-sized cellular networks share the spectrum and provide services in adjacent locations [2]. We assume that the networks are owned and managed by different operators each. This will create a business opportunity to new entrants by lowering the barrier of expensive spectrum cost. However, it induces a new interference environment that each network has interference from its own base stations (BSs) as well as from other BSs in other networks.

These networks may *compete* with others to maximize their own utilities in a selfish manner or *cooperate* together to achieve a common objective. The competition may lead to the increase mutual interference as the result of a power combat, i.e., each network increases transmit power to beat the interference from other networks. On the other hand, the cooperation requires a business accordance or additional cost to build up an extra infrastructure for a synchronized decision. Consequently, it is essential investigating that the cooperation incentive is sufficient to suppress operators' concerns of the business-wise dependency.

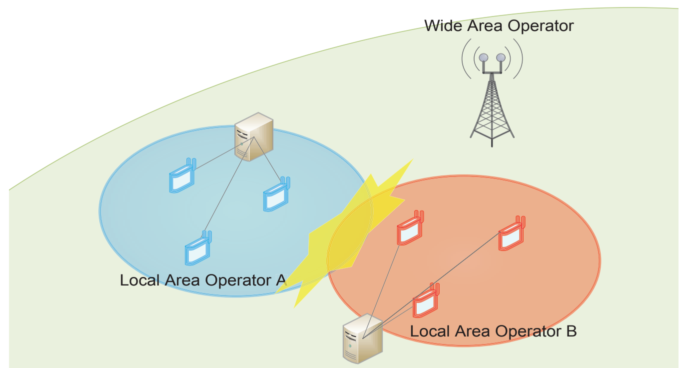

Fig. 1. An example of spectrum sharing scenarios where local area operators A and B serve hotspot data traffic on shared spectrum while a conventional macro-cellular operator still provides coverage-based services in exclusive spectrum.

Most of existing studies have intensively discussed the competitive and cooperative interference management [3]–[5]. For instance, authors in [3] analytically examined a competitive power control problem between two communication links. A beamforming vector selection problem has been studied in [4] with a game-theoretic approach when two wireless BSs have multiple antennas. [5] also addressed a power allocation problem to multiple frequency channels between two asymmetry competitive links. Even though there are some studies considering the cooperation not between wireless links but networks, most of them assumed infrastructure or user sharing in a non-shared spectrum situation where no interference issue between networks arises [6]–[8]. Relatively few studies researched competing wireless networks in shared spectrum [9]–[11]. A coverage competition problem has been addressed for attracting freely roaming users [9], [10]. Access probability competition between WLAN networks has been explored in [11]. To our best knowledge, competitive and cooperative interference mitigation between cellular networks has not been investigated yet.

In this paper, we study the effects of competition and cooperation between networks owned by different cellular operators on shared spectrum. In particular, we consider the cooperation and the competition in terms of transmit power control in

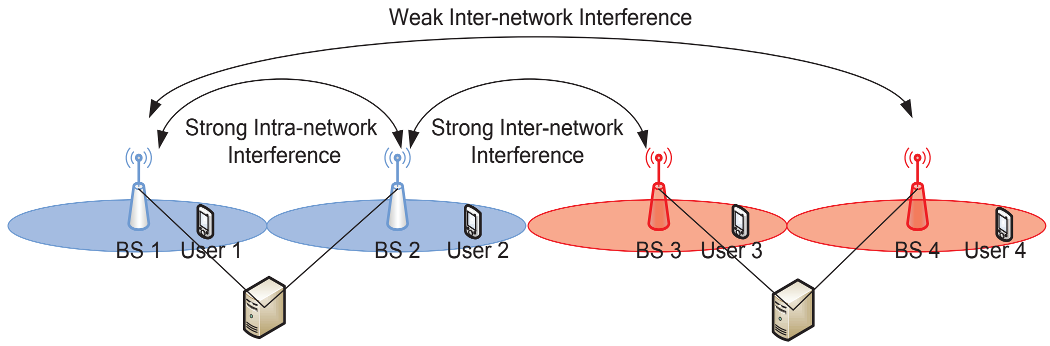

Fig. 2. Interference environment of two networks ($n_A = n_B = 2$).

downlink between two neighboring cellular networks. We aim to answer following research questions:

- How much is the utility gain of the cooperative power control between cellular networks in shared spectrum?
- When or where should the networks cooperate for the power control?

In order to obtain insights into the basic principles, we compare two power control schemes based on a simplified model. This is also analyzed with respect to individual network performance as well as overall performance of two networks which may be meaningful in shared network scenarios. We investigate how the cooperation incentive changes according to a network size and suggest a deployment guideline for the future small-sized mobile operators whether to compete or cooperate. The rest of paper is outlined as follows. Section II provides a system model. Section III and Section IV present a simulation model and evaluation results, respectively. Finally, Section IV concludes this study with future work.

II. System Model

A. Topology Model

Since the co-channel operation of networks is presumed, it is hard to imagine that the deployments of different networks are fully overlapped in the same geographical region as long as operators are rational to avoid excessive interference from other networks. Likewise, it is also a too pessimistic scenario that all BSs in each network are placed along with other BSs in other network. Instead, we consider that each network is deployed at the vicinity of other networks' service area. As one of practical settings, this can be interpreted as neighboring buildings with BSs installed by different building owners, e.g., hotels, shopping malls, or enterprizes. In addition, we assume that the number of BSs is same in each network for the analysis simplicity. Asymmetric environments with different number of BSs per network will be addressed as future work.

Under these assumptions, let us consider two independent networks, denoted by a set $\mathcal{M} = \{A, B\}$, which are individually managed by each operator. Network i has n_i BSs which belong to BS set $\mathcal{B}_i$. The all BSs in two networks are equally spaced along an one-dimensional geometry. This reflects that the closest BSs in two networks are separated at least with inter-BS distance in a given network. Also, BSs in one operator are connected via a network controller so that the transmit powers of BSs are internally coordinated. At a given time, one user per BS uniformly arrives along one-dimensional geometry within the its cell radius. This presumes a fully loaded system and equal time-sharing scheduling among users in a given BS. For the convenience of notations, we assume that user j belongs to BS j and is orderly indexed from the leftmost in a given one-dimensional topology. Note that we restrict ourselves to two operators and the linear topology in order to provide an insight into the basic principles of cooperation and competition in a multi-operator context.

Fig. 2 illustrates the considered model when $n_A = n_B = 2$. In this figure, BS 1 and 2 belong to network A while BS 3 and 4 are the part of network B. Let us consider a downlink transmission. Then, each user is exposed in different interference environments. User 1 and user 4 are mostly affected by interference from the BSs belonging to the same network, i.e., *intra-network interference*, whereas they receive weak interference from the other network. On the other hand, user 2 and user 3 are not only coupled with intra-network interference but also in the range of strong interference from the other network, which is referred to as *inter-network interference*.

B. Network Utility Function

Let us denote a channel gain between BS j and its user j by g_j. Signal to interference and noise ratio (SINR) at user j, referred to as γ_j, can be obtained by

$$\gamma_j = \frac{g_j p_j}{I_j^{intra} + I_j^{inter} + N_o}, \quad (1)$$

where p_j and N_o represent the transmit power of BS j and constant noise power, respectively. Note that I_j^{intra} and I_j^{inter} are aggregate intra-network interference and inter-network interference received at user j, respectively. For a given γ_j, we simply compute an achievable rate r_j from Shannon capacity given by

$$r_j = \log_2(1 + \gamma_j) \ (bps/Hz). \quad (2)$$

In the case of competitive networks, each network i has its own utility function referred as U_i. Also, U_A and U_B can be a different type due to differentiated target services or the fairness objective of each operator. Since we are interested in the performance gain depending on the cooperation, we assume that two networks have the same form of U_i. In particular, we in this paper consider each network aims to maximize the sum of rates, i.e.,

$$U_i = \sum_{j \in \mathcal{B}_i} r_j.$$

As two networks fundamentally have a conflict situation due to the interference coupling environment, it is challenging to find a proper common utility function U which can maximize both U_A and U_B. Thus, while leaving it out of the scope in this study, we consider U for the cooperation as a linear sum of U_A and U_B, i.e., $U = U_A + U_B$.

C. Network Power Control Model

As an inter-network interference mitigation scheme, we consider the power control of BSs. Since BSs for a given network i are coordinated via a network i's controller, we differentiate two power control schemes depending on inter-network operation. Here, each controller is presumed to know the complete information of channel gains between its BSs and users based on local measurement reports.

1) Cooperative Network Power Control: In order to maximize U, two networks may adjust transmit powers in a decentralized manner due to architectural simplicity or considerable extra cost for an additional inter-network coordinator. In this case, they follow pre-agreed protocols or behave based on a statistical information of the other network. On the other hand, they cooperate in a centralized manner via the explicit inter-network coordinator. As the upper bound performance of the cooperation, we consider the centralized case since the local information given in the distributed approaches is more limited than the information available to a central controller. Then, this can be seen as a conventional centralized wireless system owned by single operator with respect to implementation and network behavior. A difference from the single operator case is that each operator may still be interested in its individual performance, i.e., U_A or U_B, even though the unified network behaves to maximize U.

For practicability, we assume that a transmit power p of a BS is limited to the maximum allowed power p_{max}. Let us define the feasible power set $\mathcal{P} = \{p \mid 0 \leq p \leq p_{max}\}$ that is used all BSs in the considered system. Then, transmit power vector $\mathbf{p}$ in all BSs can be defined in a feasible power vector space $\Omega = \prod_{j \in \mathcal{B}_A \cup \mathcal{B}_B} \mathcal{P}$. Note that Π stands for Cartesian product. For a given channel realization, we formulate the corresponding cooperative power control problem as follows:

$$\begin{aligned} \text{maximize} \quad & U(\mathbf{p}), \\ \text{subject to} \quad & \mathbf{p} \in \Omega. \end{aligned}$$

2) Competitive Network Power Control: Unlike the cooperative power control, two networks compete for maximizing U_A and U_B regardless of how much their interference harms other network. In a practical system, network i may adapt its transmit power vector $\mathbf{p}_i$ only according to monitored interference from other network's transmit power vector $\mathbf{p}_{-i}$. Then, the other network reconsiders its power vector since the network i changes $\mathbf{p}_i$. Such interactive adaptation process between two networks will be continued until they reach into the equilibrium or the monitoring phase ends. This interaction can be analyzed by using a game model. Thus, we formulate this as a strategic game denoted by $\mathcal{G}$. Let us define a feasible set of $\mathbf{p}_i$ as $\Omega_i = \prod_{j \in \mathcal{B}_i} \mathcal{P}$. Since $\mathcal{G}$ is composed of triplets, the competitive power control game of two networks is described as follows:

- Player: $\mathcal{M}$
- Action space: $\mathbf{p}_i \in \Omega_i$ for $i \in \mathcal{M}$
- Payoff function: $U_i(\mathbf{p}_i, \mathbf{p}_{-i})$ for $i \in \mathcal{M}$.

D. Performance Metric

Depending on the business strategy between two operators, the performance metric can be different. Clearly, each operator is interested in its own network performance, i.e., $E[U_i]$. However, they may be interested in overall system performance, i.e., $E[U]$, in the case of business collaboration where two operators may fully share two networks as single operator. Thus, the cooperation gain with respect to both $E[U_i]$ and $E[U]$ is considered as performance metric. Note that $E[\cdot]$ represents an expectation operator.

III. Simulation Model

A. Numerical Approximation

Solving the cooperative network power control problem is inherently challenging due to the lack of convexity in the utility function. Thus, our approach is approximating the optimal power allocation by solving a discrete optimization problem after quantizing p into discrete levels[1]. Then, we find the optimal solution of cooperative networks by an exhaustive search. In the case of the competitive network game, we analyze Nash equilibrium (NE). By definition, it is the action profile that no player can yield a better utility from unilateral deviation. The NEs can be determined by finding the intersections of the best response curves of two players. However, the best response function also is non-convex for a given inter-network interference. Thus, instead of analytically solving the game solution, we again adopt the computational approximation based on quantized power levels. It is noteworthy that the NE does not necessarily exist and there might be more than one NE for a general game problem. Accordingly, we search all existing NEs on the discrete action space for a given user realization and then randomly select one NE if multiple NEs are identified[2].

[1] It has been identified that the discrete power control gives the sub-optimal solution for the sum rate maximization when the number of all wireless links, $n_A + n_B$, is small [12]. Particularly, [12] also showed that binary power control is optimal in two links setting.

[2] By experiments over different realizations, we identify the proposed game model mainly yields the unique NE, and thus the impact of multiple NEs is negligible.

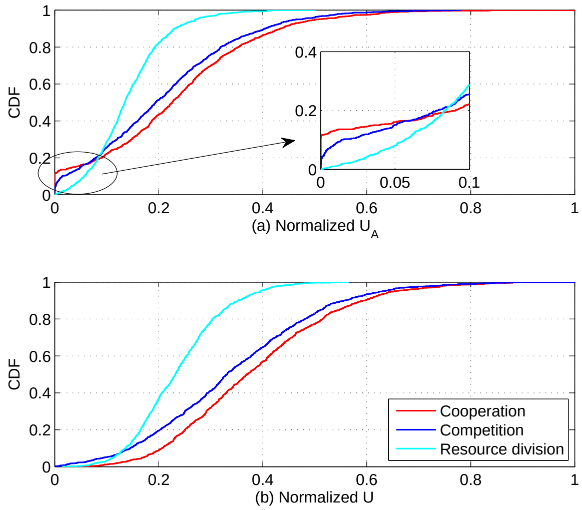

Fig. 3. The statistical behavior comparison of power control cooperation and competition ($n_A = n_B = 2$ and $\alpha = 3$).

B. Simulation Parameters

We perform Monte-Carlo simulation with 1000 randomly generated user locations and channel realizations. All relevant simulation parameters are followed. The cell radius and distance between the closet BSs in two networks are set as 100 m. Path loss can be described with a general log-distance path loss model, i.e., $PL = 10\alpha \log_{10}(d) + L$ where α, d, and L account for pathloss exponent, distance (meter) from a transmitter, and a constant due to system losses, respectively. We in this simulation assume L equal to 30 dB while α varies for evaluating different propagation environments. Additionally, log-normal shadow fading with standard deviation $\sigma = 6$ dB is included. Also, $\mathcal{P}$ is quantized into a finite set $\{-\infty, -3, 8.5, 20\}$ dBm. The noise power N_o is assumed to be -95 dBm.

IV. Numerical Results

Fig. 3 provides the cumulative distribution function (CDF) of U and U_A when users are uniformly distributed with log-normal shadowing. For individual network performance, we illustrate only U_A since the statistics of U_B is equivalent to U_A due to the symmetry of the network geometry and traffic statistics. Also note that resource division represents that two networks equally divide the spectrum so that the rate of each user is simply reduced by half. This case sketches a conventional static spectrum allocation between networks or spectrum sharing between an orthogonal spectrum usage agreement between networks [1]. While the cooperation is always better than the competition in terms of U from Fig. 3-(b), we can identify that the cooperation can result in both positive and negative effects on U_A as shown in Fig. 3-(a). Since our cooperation objective aims to maximize overall sum rates, either one of networks will be sacrificed in order to reduce inter-network interference when it has low signal quality users.

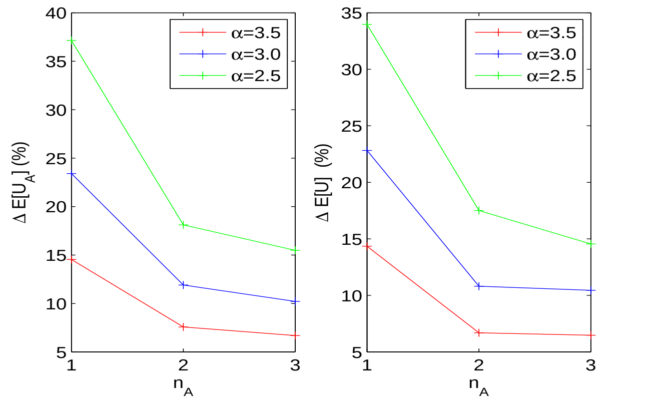

Fig. 4. Average cooperation gain according to the network size ($n_A = n_B$).

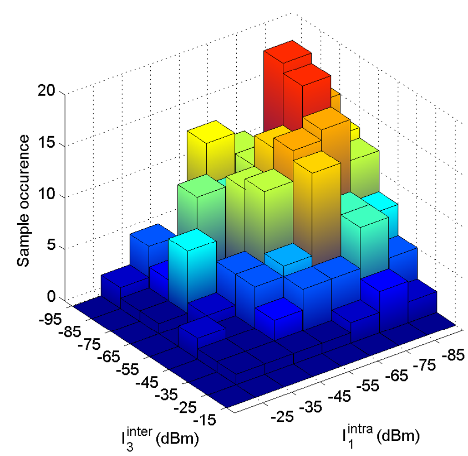

Fig. 5. Illustration of relation between intra-network and inter-network interference in competition ($\alpha = 3$ and $n_A = n_B = 2$).

Conversely, it will have much more utility due to reduced inter-network interference when the network has good signal quality users. In other words, each network has a cooperation incentive at high utility region while the temptation to be selfish exists in the low utility region. Nevertheless, Fig. 3-(a) shows that the 80% cases of cooperation result in better performance in terms of individual performance while the other 20% have worse utility. This reflects that each network still have in an average sense larger incentive for cooperation than being selfish.

A. Average Cooperation Gain in Shared Spectrum

When differentiating U_A of two power control schemes with superscript *comp* and *coop*, let us define the average cooperation gain in terms of U_A as

$$\Delta E[U_A] := \frac{E[U_A^{coop}] - E[U_A^{comp}]}{E[U_A^{comp}]} \times 100\ (\%).$$

Likewise, we also define the average cooperation gain in terms of U as $\Delta E[U]$. Then, Fig. 4 illustrates that $\Delta E[U_A]$ and $\Delta E[U]$ drastically drops as the network size increases regardless of α. This implies that cooperation between mutually

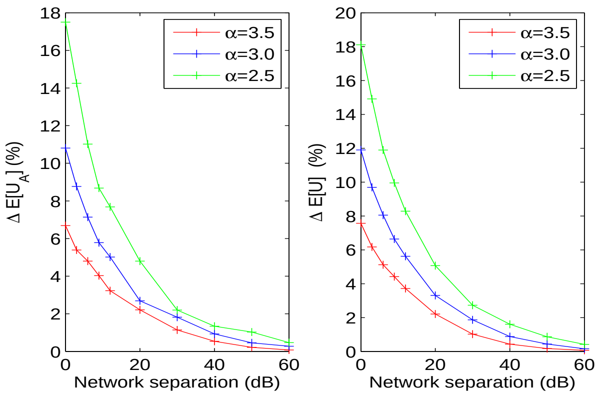

Fig. 6. Network separation effect ($n_A = n_B = 2$).

interfering networks may not be highly attractive as the network size increases. This effect can be explained in two ways. As the network size increases, the service area over which the inter-network interference affects is reduced so that more users in a given network relatively becomes decoupled from other BSs in other network. In addition, when each network owns multiple BSs, the intra-network interference mitigation benefits lowering inter-network interference. In other words, the selfish behavior to its own network can also reduce the harmful interference to other network. Fig. 5 illustrates an example statistics of NEs where reduced interference to itself, i.e., user 1, benefits other user, i.e., user 3 in the other network. This reflects that mutually beneficial decisions occur even during network-wide competition. Note that this phenomenon never happens in the case of $n_A = n_B = 1$ where each BS always gives full interference to the other BS if they are in competition.

B. Deployment Principle in Shared Spectrum

As discussed in Section II, one of realistic assumptions for multi-operator deployments is that each network somehow is separated, e.g., geographically or with high wall penetration. $\Delta E[U_A]$ and $\Delta E[U]$ are plotted in Fig. 6 according to additional constant path loss in channel gains across two networks, i.e., *network separation*. When typical outer building wall penetration loss is presumed as 20 dB [13], equivalently 40 dB network separation between two adjacent buildings, deploying a network at the neighboring building may not be critical without agreed cooperation. In the figure, the cooperation gain at 40 dB network separation turns very marginal, i.e., less than 2% in a highly interference coupled situation with $\alpha = 2.5$. In other words, the incentive for cooperation between networks may lose a value when an operator deploys a network in close buildings.

V. Conclusion

When small-sized cellular networks owned by different operators are deployed in interference range on shared spectrum, we addressed a cooperative and a competitive power control problem. From the evaluation results, we identified that there exist both cooperative and competitive incentives for each network sum rate maximization according to a utility region. By comparing Nash equilibria and the social optimal power allocation, we also found in an average sense that the cooperation improves not only an overall system performance but also an individual network performance. Nevertheless, the cooperation incentive is drastically reduced as the size of network increases since interference between two networks can be mitigated by self-motivated interference reduction inside of each network. From this, operators may not have enough motivation for cooperation to suppress strategic cost such as business-wise agreement. Additionally, by exploring the network separation effect, we identified that only marginal separation, e.g., deployments in adjacent buildings, makes the competition comparable to the cooperation due to sufficiently decoupled interference from adjacent networks. These results are under a network symmetry assumption so that asymmetric networks need to be studied as a future work.

Acknowledgment

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