Abstract—To maintain affordable access for the rapidly increasing mobile traffic, base station deployment has to be tailored to hot-spot areas and primarily indoors where facility owners, e.g., shopping malls or hotels, mostly provide wireless service. Since such local access providers (LAPs) do not have access to exclusive spectrum, one proposed option is sharing spectrum with other nearby LAPs, e.g. unlicensed or secondary spectrum. Due to limited or no coordination between the LAPs, they selfishly access the spectrum, causing harmful interference to the neighboring networks. Especially by increasing transmission power, one operator may attempt to improve its own throughput at the expense of its neighbors. In this paper, we explore the impact of power asymmetry on competition between LAPs. We model the competition between two networks with different maximum power constraints as a network-wide power control game. By analyzing the pure Nash equilibria, we find that a lower power (LP) network becomes more aggressive to overcome the inter-network interference. Due to the aggressive behavior, sharing spectrum can out-perform fixed spectrum split even for the LP network, provided that the power asymmetry is below a certain limit. On the other hand, a higher power (HP) network is mainly affected by its own “self-interference” so that it has little incentive to employ complicated inter-operator interference management schemes. In addition, we demonstrate that the power asymmetry limit strongly depends on the inter-network propagation conditions, e.g., inter-building distance or building penetration loss.

I. INTRODUCTION

As mobile broadband access traffic rapidly grows, wireless access should be provisioned in indoor or hotspot areas where most of mobile traffic will be created. Unlike the conventional wireless service by traditional operators, the indoor access service is mainly provided by facility owners, e.g., shopping malls, hotels, or airports for better customer relations or hotspot business [1]. Since those local access providers (LAPs) cannot have access to exclusive spectrum due to its limited availability or expensive license fee, regulatory bodies and research communities have recently considered the various ways of spectrum sharing, e.g., unlicensed/secondary access [2], [3]. From this paradigm shift, various novel network operation models are envisaged [4]. An example is shown in Fig. 1 where small-sized indoor wireless networks managed by different LAPs each provide services at adjacent locations in shared spectrum. However, it creates a new interference environment in which each network has interference from not only its own base stations (BSs) but also other BSs in other networks. With limited (or no) coordination between them, LAPs may access spectrum in a selfish way by creating harmful interference to the neighboring networks.

In particular, each network may increase its transmission power for improving its throughput whereas giving damage to its competitors unless any regulatory guidelines or operator-wise agreements are imposed. In presence of such power asymmetry, spectrum utilization between networks can be unfair, i.e., one giving more interference damage than the others. Intuitively, a network with lower power is in disadvantage due to excessive interference from competitors with higher transmission power so that it may prefer the competition-free environment, e.g., spectrum split. In contrast, the network with higher power may benefit by easily defeating the network with lower transmission power. Thus, it is greatly appealing investigating the impact of power asymmetry in the shared spectrum on individual network performance.

Most of existing studies on multi-operator operation have considered financial price competition for user or spectrum acquisition without any interference between involved operators [5], [6]. Relatively few studies researched an interference problem between competing wireless operators in shared spectrum [7]–[11]. Authors of [7], [8] addressed a coverage competition problem for attracting freely roaming users. Access probability competition between WLAN networks has been analyzed in [9]. [12] studied the achievable capacity of two competing wireless links with asymmetric power constraint rather than one of competing networks where self-interference...
exists as well. In our previous work [10], [11], we studied competition between two LAPs on shared spectrum in terms of downlink power control. [10] investigated the incentive of cooperation between LAPs under a symmetric conditions. In [11], the operator competition with different quality of service (QoS) requirements was explored under the symmetric power constraint. To our best knowledge, a network-wide competition between LAPs with the asymmetric transmission power has not been studied yet.

In this paper, we study power control competition between two wireless networks with asymmetric transmission power constraints. We aim to answer the following research questions:

- Can the spectrum sharing be beneficial to both competing networks in presence of asymmetric transmission power?
- How differently does the asymmetric transmission power affect the competition between networks?

In order to obtain insights into basic principles, we investigate the power asymmetry effect based on a simplified model. Depending on the level of the asymmetry, individual network performance in the competition is compared with two cases: a fixed spectrum split and a random power control in shared spectrum. We also examine the effects of inter-network propagation conditions and the power asymmetry. The rest of the paper is outlined as follows. Section II provides a system model. Section III and Section IV state a simulation methodology and evaluation results, respectively. Finally, Section V concludes this study with future work.

II. SYSTEM MODEL

A. Radio Network Model

Let us consider two neighboring offices. In the inside of each office building, we assume that multiple interfering BSs in the same frequency channel are deployed by an office owner. Since the co-channel operation of networks is presumed, LAPs are rational to avoid excessive interference from other networks. Thus, it is a too pessimistic scenario that BSs in each network are placed along with other BSs in the neighbor network. Instead, each network is deployed at the one vicinity of the other network. In addition, we assume that the number of BSs is same in each network for the analysis simplicity. Environments with different number of BSs per network will be addressed as future work.

Under these assumptions, let us denote two independent networks as a set $\mathcal{M} = \{A, B\}$, which are individually managed by each LAP. Network $i$ has two BSs which belong to its BS set $\mathcal{B}_i$. Note that BS 1 and 2 belong to network $A$ while BS 3 and 4 are operated by network $B$. All BSs in both networks are equally spaced along an one-dimensional geometry as shown in Fig. 2. This can represent a linear deployment along the corridor in buildings. The closest BSs in two networks are separated at least with inter-Bs distance in a given network. Also, BSs in a given network are controlled via its network manager so that the transmit powers of BSs are internally coordinated. Here, each manager is presumed to know the complete channel state information between its BSs and users based on local measurement reports.

At a given time, one user per BS uniformly arrives within its cell radius $R$. This presumes a fully loaded system under equal time-sharing among users in a given BS. For the convenience of notations, we assume that user $j$ associates with BS $j$. Note that we restrict ourselves to two LAPs and the linear BS topology in order to provide an insight into the basic principles of the multi-operator competition. Let us consider a downlink transmission. Then, each user is exposed in two interference environments. For instance, User 2 served by BS 2 is affected not only by interference from BS 1 belonging to the same network, i.e., intra-network interference, but also in the range of interference from BS 3 and 4 in the other network, which is referred to as inter-network interference.

Let us denote a channel gain between BS $j$ and its user $j$ by $g_j$. $g_j$ consists of propagation loss and log-normal shadow fading with standard deviation $\sigma$. Propagation loss is described as $PL = 127 + 30 \log_{10}(d)$ (dB) where $d$ accounts for distance (km) from a transmitter [13]. Signal to interference and noise ratio (SINR) at user $j$, referred to as $\gamma_j$, can be obtained by

$$\gamma_j = \frac{g_j p_j}{I_{\text{intra}}^j + I_{\text{inter}}^j + N_\sigma},$$

where $p_j$ and $N_\sigma$ represent the transmit power of BS $j$ and noise power, respectively. Note that $I_{\text{intra}}^j$ and $I_{\text{inter}}^j$ are referred to as aggregate intra-network interference and inter-network interference received at user $j$, respectively. For a given $\gamma_j$, we simply compute the data rate $r_j$ from

$$r_j = \log_2(1 + \gamma_j) \text{ (bps/Hz)}.$$  

Each competitive network $i$ has its own objective function $U_i$. In real business case, each LAP may have differentiated target services or fairness objectives which possibly lead asymmetric objectives [11]. Since we are interested in the

![Fig. 2. The example interference environment of two networks (User 2 perspective).](image-url)
network performance due to the transmit power asymmetry, we here assume that both networks have the same type of objectives. We consider each network aims to maximize the aggregate data rates, i.e.,

$$U_i = \sum_{j \in B_i} r_j.$$  

### B. Competitive Network Power Control

Without any inter-operator coordination, each network may compete for maximizing only its objective function regardless of how much interference it harms the other network. Let us define the feasible transmit power vector of a network $i$ as $p_i \in \Omega_i = \prod_{j \in B_i} \mathcal{P}_i$, where $\mathcal{P}_i = \{p_j \mid 0 \leq p_j \leq p_{i,\text{max}}\}$ and $\prod$ stands for Cartesian product. Note that the transmit power $p_j$ of BS $j$ belonging to a network $i$ is limited to the maximum transmission power $p_{i,\text{max}}$. In a practical system, network $i$ may adapt $p_i$ only depending on monitored inter-network interference when the other network employs a power vector $p_{-i}$. Then, the other network reconsiders its power vector since the network $i$ updates $p_i$. Here, note that the transmit powers of multiple BSs in a given network are assumed to be simultaneously coordinated, i.e., internal coordination. Such interactive power vector adaptation process will be continued until they reach a stable point or the monitoring phase ends. This can be analyzed by using a game model [14]. We formulate this as a strategic game denoted by $G$. The competitive power control game $G$ is described as follows:

- **Player:** $\mathcal{M}$
- **Action space:** $p_i \in \Omega_i$ for $i \in \mathcal{M}$
- **Payoff function:** $U_i(p_i, p_{-i})$ for $i \in \mathcal{M}$.

Note that $p_{-i}$ represents the transmit power vector of the other network aside from network $i$.

#### C. Transmission Power Asymmetry

Due to the independence between two LAPs, network $A$ and $B$ can have different $p_{i,\text{max}}$ since one LAP may be greedy to use higher transmission power capability by adopting different hardware specifications, e.g., power amplifier capability. Let us assume $p_{A,\text{max}} < p_{B,\text{max}}$ for the analysis convenience. Then, we call network $A$ and $B$ as a lower power (LP) network and a higher power (HP) network, respectively. Then, we define the power asymmetry as

$$\theta_{\text{asy}} := p_{B,\text{max}} - p_{A,\text{max}}.$$  

### III. Simulation Methodology

#### A. Numerical Evaluation of Competition

In the case of the competitive power control, we analyze pure strategy Nash equilibria (NEs) as a solution concept. By definition, it is the action profile that no players can yield a better payoff from unilateral deviation. The NEs can be found from the intersections of the best response curves of both players [14]. Also, the closed form solution for the best response function is generally unknown when the payoff function is non-convex for a given inter-network interference. However, [15] showed that binary power control is optimal in two links setting for maximizing the sum of data rates. Therefore, the best response can be easily obtained by examining all three possible power allocation combinations: $(0, p_{A,\text{max}})$, $(p_{B,\text{max}}, 0)$, and $(p_{A,\text{max}}, p_{B,\text{max}})$. Therefore, we can exhaustively search the nine feasible action profiles at a given user realization to obtain the NE. It is noteworthy that the pure NE may not exist for a given channel realization since the quasi-concavity in our payoff function does not always hold for any channel realizations. In this case, we randomly select one from the feasible profiles $p_i$ if no NE exists. There can be more than one NE depending on the payoff matrix. Then, we randomly choose one NE. The random outcome selection can reflect a practical system which employs a finite distributed decision process after random power initialization. By intensive experiments, we identify that our evaluation mainly yields the unique NE. Thus, the impact of randomly selected outcomes is negligible in the average network performance.

#### B. Simulation Parameters

We implement a Monte-Carlo simulation with 10000 channel realizations. The cell radius is set as 100 m. The noise power is set to -95 dBm, $\sigma$ is given as 6 dB. For the power asymmetry, we keep $p_{A,\text{max}}$ at the fixed value of 20 dBm, while the range of $\theta_{\text{asy}}$ varies.

### IV. Numerical Results

#### A. Network Behavior at Pure Nash Equilibrium

In Fig.3, we evaluate $E[U_i]$ according to $\theta_{\text{asy}}$. Here, *global* represents the average aggregate rates of both networks. As $\theta_{\text{asy}}$ increases, the performance of the LP network decreases while one of the HP network increases. However, the aggregate rates of both networks do not change much although the power asymmetry increases. As discussed earlier, there exist three possible best responses for a given $I_{\text{inter}}$. In any responses, each BS either transmits with the maximum power or not.
In order to obtain a better insight about the chosen action of each BS at NE, Fig.4 illustrates activity probability, i.e., the probability that each BS transmits with the maximum power. The left two sub-plots express the behavior of BSs in the LP network. As $\theta_{asy}$ increases, i.e., higher transmit power in the HP network, the activity probability of BSs in the LP network also increases in order to defeat $I_{inter}$ from the HP network since $I_{intra}$ is not so dominant as $I_{inter}$ in high power asymmetry. On the other hand, in the right two sub-plots, two BSs in the HP network are less likely to be turned on because they are dominated by $I_{intra}$ to make the HP network more likely turn off one of its BSs to remove dominant $I_{intra}$.

### B. Shared Spectrum vs. Spectrum Split

One simple way of fully eliminate $I_{inter}$ is permanently dividing whole spectrum at the expense of the reduced amount of spectrum availability in each LAP. We compare the average aggregate rates from the competition in shared spectrum with one from the spectrum split case. Fig. 5 plots average spectrum sharing gain over the spectrum split according to $\theta_{asy}$. Both networks have positive spectrum sharing gain up to a certain limit in the power asymmetry, i.e., break-even $\theta_{asy}$. After this limit, the gain of spectrum sharing in the LP network is negative due to too strong $I_{inter}$ from the HP network. Consequently, the LP network becomes favorable to use the spectrum split.

### C. Selfish Decision vs. Random Power Control

In order to mitigate or avoid $I_{inter}$, extra complexity is necessarily required in practical implementation, e.g., iterative process to converge the NE. Alternatively, a simple algorithm without such iteration overhead may be employed which may sacrifice a certain network performance. The random power control without any optimization efforts is one way of this where each network uniform-randomly chooses one of three power allocation combinations for a given channel realization regardless of interference [16]. Fig. 6 plots average aggregate rates gain from competition over the random power control. It demonstrates that the HP network has less motivation to implement a $I_{inter}$ scheme than the LP network as it has sufficiently high transmission power to defeat the competition without it. On the other hand, the LP network has more incentive of employing the sophisticated $I_{inter}$ management scheme than the HP network since the LP network can additionally weaken $I_{inter}$ by intentionally turning on both two BSs.

### D. Network Separation Effects

One of realistic assumptions for indoor network deployments is that each network somehow is separated, e.g., geographically or with high wall penetration. Fig.7 plots the break-even $\theta_{asy}$ according to network separation, i.e., additional constant path loss in channel links across both networks. From this figure, we can observe that the break-even $\theta_{asy}$ is strongly dependent on the network separation. It shows that spectrum sharing is beneficial to both LAPs if $\theta_{asy}$ and network separation is below the line, whereas it gives advantage to only the HP network above the line.

### V. CONCLUSION

We addressed the effects of asymmetric maximum transmission power on network-wide power control competition where interference is created both from the inside of a network and from an neighboring network. Two linearly deployed networks with lower power (LP) and higher power (HP) constraints were considered. We modeled the network-level competition as a strategic game and examined the average aggregate rates of individual network at Nash equilibrium according to the difference of the maximum power. We found that the LP network becomes more aggressive by activating more BSs to overcome inter-network interference from the HP network. Thanks to the aggressive behavior in competition, spectrum sharing can provide substantial benefit over a static spectrum...
split approach even to the LP network within the tolerable level of power asymmetry. In contrast, the HP network more likely deactivates some of its own BSs for lowering dominant intra-network interference. This weakens the incentive of employing a complex inter-interference management scheme. It is also observed that the break-even power asymmetry heavily depends on inter-network propagation conditions, e.g., inter-building distance or penetration loss. We obtained these results in the case of the symmetric number of BSs and their locations.

Thus, the effect of a more realistic asymmetric deployment needs to be further explored.

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