High Capacity Indoor & Hotspot Wireless System in Shared Spectrum - A Techno-Economic Analysis

Du Ho Kang, Ki Won Sung, and Jens Zander
KTH Royal Institute of Technology, Wireless@KTH
Stockholm, Sweden

***Abstract*— Predictions for wireless and mobile Internet access suggest an exponential traffic increase, in particular in in-building environments. Non-traditional actors such as facility owners have a growing interest in deploying and operating their own indoor networks to fulfill the capacity demand. Such local operators will need spectrum sharing with neighboring networks because they are not likely to have their own dedicated spectrum. Management of inter-network interference then becomes a key issue for high capacity provision. Tight operator-wise cooperation provides superior performance, but at the expense of high infrastructure cost and business-related impairments. Limited coordination on the other hand causes harmful interference between operators, which in turn will require even denser networks. In this article, we propose a techno-economic analysis framework for investigating and comparing indoor-operator strategies. We refine a traditional network cost model by introducing new inter-operator cost factors. Then, we present a numerical example to demonstrate how the proposed framework can help us to compare different operator strategies. Finally, we suggest areas for future research.**

***Index Terms*—Operator strategy, Techno-economic analysis framework, Shared spectrum, Local operator, Indoor and hotspot deployment**

I. INTRODUCTION

A. *Emerging Local Operators in Shared Spectrum*

Over the last few years, mobile and nomadic broadband access has achieved tremendous success. Innovation in mobile handsets, e.g., smartphones and tablets, has caused a virtual "data tsunami" leading to severe capacity problems for many operators. The dramatic surge in traffic is expected to continue in upcoming years. Since the majority of the traffic is likely to be generated inside buildings, significant investment in indoor network deployment is foreseen.

Some of the investment will be made by incumbent mobile network operators (MNOs) for deploying heterogeneous networks. Another type of investment, which is the focus of this article, will be provided by new market actors, e.g., facility managers, real estate owners, and private companies [1]. The main driver for them is to deploy and operate dedicated networks for wireless internet access inside their buildings to increase their attractiveness to tenants or customers (e.g. hotels or office space providers). The private networks may also serve those MNO customers that happen to be in the buildings (i.e. provide offloading). This is a business model similar to the one seen in current fixed network access; public operators provide connection to buildings, whereas inbuilding networks are deployed and managed by the facility owners. An additional problem compared to fixed network access, is that such local operators[1] do not have their own dedicated spectrum. One possible solution is using *shared spectrum*, where the sharing take place between neighboring indoor operators.

B. Regulatory Trends in Shared Spectrum

There are regulatory initiatives worldwide aiming to promote shared access to new spectrum for fostering more competition and innovation in a wireless access market. The national regulators of Sweden and Netherlands recently announced that a portion of the spectrum around 1800 MHz was opened for cellular technologies with indoor usage in an unlicensed or a preregistration manner [2]-[3]. In the UK, 1781.7-1785 MHz paired with 1876.7-1880 MHz band was allocated to twelve operators with shared licenses in 2006 for low-power indoor networks [4]. The light licensing of nationwide 3650-3700 MHz was also adopted by the USA in 2007 [4]. An overview of regulatory initiatives can be found in [5]-[6].

C. Contribution of This Article

Local wireless access operation in shared spectrum presents new research challenges from a techno-economic perspective. In this article, we provide an analysis framework that effectively navigates and compares potential deployment strategies of the operators.

[1] For the remainder of the paper, an operator refers to any business entity that owns and operates its own network. In this context, the facility owners can be considered operators.

We define a strategy space that integrates technology and business aspects. Then, a legacy cost model for a single operator is reformulated by introducing new inter-operator cost factors. The validity of our framework is demonstrated by numerical comparisons of selected strategies in a two-operator example. Finally, we outline important research areas to be addressed for future studies.

II. Deployment Challenges For High Capacity

A. Wi-Fi may not be enough in upcoming years

The local operators certainly need a low-cost system to provide high capacity services in the new shared spectrum. Wi-Fi naturally seems the first candidate because substantial amount of indoor traffic is already offloaded to Wi-Fi in an ISM band. However, it has been reported that Wi-Fi may not cope with very large traffic loads due to the “performance wall” caused by the underlying CSMA/CA mechanism [7]. In these situations, we would need to consider cellular-type systems with interference coordination capabilities.

B. Tradeoff in Interference Management Options

In shared spectrum, interference management between adjacent operators is one of the key issues. The easiest option would be not to cooperate with neighbors. However, this may inflict mutual interference which may in turn lead to poor performance. Alternatively, a cellular technology developed in a single operator context can be applied. The simplest form would be traditional interference avoidance techniques with static resource partitioning (e.g. frequency planning), which, however comes at a significant performance loss. More advanced techniques, e.g., interference cancellation, joint multi-cell processing, or coordinated scheduling, can be further exploited for enhancing system capacity.

Improvement in technical performance is obviously expected from tighter interference coordination. However, additional cost and various business constraints are the hidden barriers which should not be overlooked. The coordination may require better infrastructure and extra network resources for reliable information exchange, which incurs a higher cost. Furthermore, a strategic cooperation agreement in a business domain needs to be made for the inter-operator coordination. An operator may be limited in his business strategies due to forming an alliance with its neighbor because he may lose competitive advantages by limitations in network operation and

Table 1. Changing business landscape and paradigm shift on system design in shared spectrum

		Traditional wide-area single operator system	**Local-area system in shared spectrum**
Business landscape	Who & Why?	MNOs: revenue generation from service provisioning	• MNOs: data offloading • Facility owners: complements to facility services • Hotspot operators: new revenue generation in niche markets
	Where?	Large-scale public outdoors	Mainly private/public indoors controlled by facility owners
	Inter-operator relation	Service/price competition in markets	• Service/price competition in markets • Cooperation/competition for inter-network interference coordination
	Major network-related cost	• Network cost • Spectrum cost	• Network cost • Inter-operator cost
System design	Design problem	Minimizing network cost at a given traffic demand	Minimizing network cost+inter-operator cost at a given traffic demand
	Decision domain	Mainly technology	Both technology and business
	Main decision maker	MNO	Both operators and a regulator
	Coordination target	Nodes (e.g., BSs)	Networks

network upgrades.[8]-[9].

C. Need for a Techno-Economic Analysis Framework

As summarized in Table 1, the system design in shared spectrum is inherently a multi-dimensional problem where technology, business, and regulatory issues are intertwined. The problem of choosing an operator strategy brings up several research challenges that have rarely been addressed in the literature. First, the analysis of operator-wise competition or cooperation is non-trivial due to the business complexity involved, although competition between individual users inside a network has been extensively studied [10]. Secondly, the operators need to be able to compare different levels of technical coordination in addition to their associated business complexity. There is a lack of systematic evaluation methodology for this. Thirdly, a proper cost model should be in place for a cost-performance tradeoff analysis. There are some attempts to model the network cost of a conventional single operator network [11]. However, the cost model in a multi-operator context has not been covered yet.

III. Defining The Solution Space – A Conceptual Framework

A fundamental network design problem that the operators face is minimizing their total network cost while satisfying their users' demands. In order to achieve this, the cost of different deployment options should be compared with respect to the performance (e.g., capacity) requirement. This comparison becomes more complicated in a shared spectrum environment because both cost and performance are heavily affected by neighboring operators.

Since cooperation intrinsically involves strategic decisions in the business domain, a means to assess the combined effects of a technology choice and business aspects is needed. In this section, we provide a conceptual framework to effectively categorize potential strategies. As shown in Fig. 1, various operator strategies are characterized on one hand by the strategic decision of the operators, i.e., cooperation and competition, and on the other hand by the technical solution expressed as the level of coordination.

A. Strategic Decision - Cooperation or Competition

The strategic decision in the business domain influences the way neighboring networks are coordinated. In this paper, we model cooperation and competition by using different technical objective functions that each operator aims to maximize. The two types of strategies are:

- Cooperation: the operators aim at maximizing a common objective function agreed between them.
- Competition: each operator aims at maximizing its own objective function in a selfish manner.

Cooperating operators who synchronize their technical behaviors form a *network alliance*. Reaching an agreement on a common objective function is in itself challenging, particularly when the partners have chosen different criteria for their quality of service (QoS), e.g., a guaranteed-rate video service versus a best-effort service. From a radio resource allocation perspective, the network alliance behaves as a

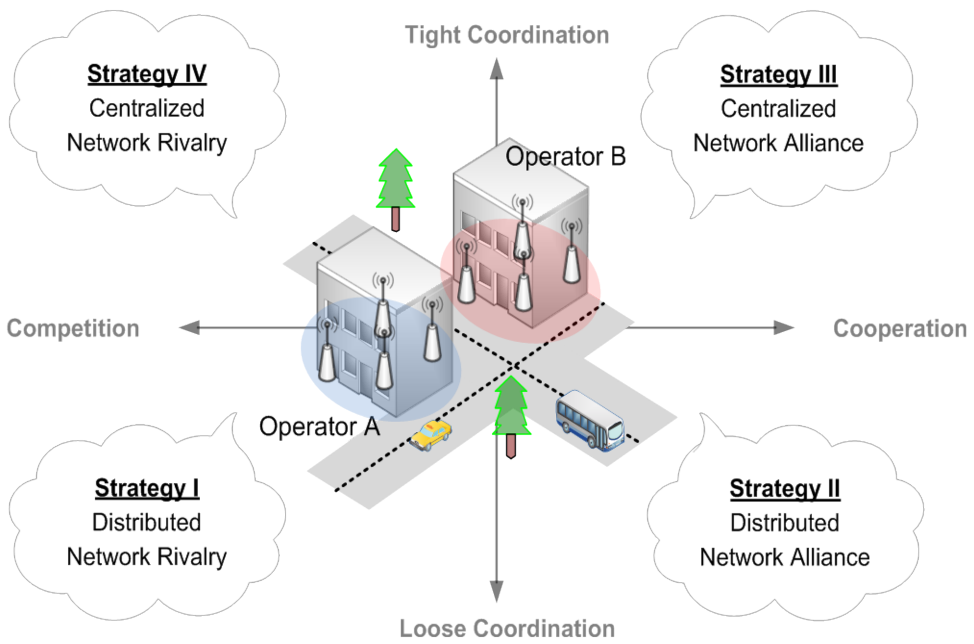

Fig. 1. A conceptual framework to define a strategy space and navigate the operator strategies.

conventional single operator network. The coordination issues turn into a problem of internal resource management for the combined network.

Competition between the operators requires a non-traditional system design. Regulators must provide guidelines for operator behavior by issuing co-existence rules ("etiquettes") which can coordinate the network rivalry to some extent. For the case of network-wise competition, inter-network interference is coupled with intra-network interference control, which creates new challenges.

B. Technical Solutions - Coordination between Networks

The technical solutions of the operators implementing their strategic decisions directly affect the network's performance. We define *coordination* in a technical domain as the process of sharing relevant information. The *level of coordination* is measured by the amount of information shared in the process. The information relevant to the interference coordination can be statistical or instantaneous traffic load or path gains between all the involved access points (APs) and user terminals, usually referred to as *channel state information* (CSI).

More accurate and frequent information exchange increases the global knowledge of the whole system. A system with complete information sharing can be interpreted as a centralized network (whether decisions are made centrally or not). Such a system is desirable from a performance perspective since it can provide real-time resource allocation, e.g., beamforming or coordinated scheduling [12]. On the other hand, only slow-varying information, e.g., average propagation conditions and the number of users per cell, might be shared. This requires considerably less sophisticated equipment, and the information may be exchanged using existing IP connections.

IV. Shared Spectrum Cost model

Recall that the network design objective is to find the operator's strategy that enables them to offer the lowest total cost for the required capacity. The cost in a shared spectrum environment has an additional element with regard to technical inter-operator relations. In addition, there is "strategic cost" representing the business uncertainty caused by the decision to cooperate. In this section, we recap a traditional single operator cost model, and highlight new inter-operator cost items.

A. Traditional Single Operator Cost Model

For a legacy operator in a wide area, the cost of a wireless network mainly consists of two parts, i.e., infrastructure and spectrum, as described in [11]:

$$C_{tot} = C_{infra} + C_{spectrum} = NC_r + WC_w, \qquad (1)$$

where N and C_r are the number of deployed APs and the normalized cost per AP [€/AP], respectively. W represents the allocated spectrum [MHz] and C_w the cost per unit of spectrum [€/MHz]. Here, C_r includes all capital expenditure (CAPEX) and operational expenditure (OPEX) aspects. CAPEX is mostly related to all one-time investments, e.g., APs or core network equipment, site installation/build-out, and antenna systems. Cost during operation, e.g., backhaul transmission, site rental, operation and maintenance (O&M), and electricity, is categorized as OPEX. OPEX is typically discounted to present value assuming expected annual running cost and network life time.

Indoor and hotspot systems may have a simpler cost structure than the conventional macro networks due to the small physical size of equipment. For instance, cost related to site installation/build-out, site rental, antenna systems, and O&M may be free or ignorable, whereas expenses for the AP equipment and the new backhaul installation may be dominant. However, we can still employ a linear model as a function of the number of APs as in Eq. (1). By sharing spectrum, spectrum cost is also likely to become negligible.

B. Inter-operator Cost in Shared Spectrum

1) (Invisible) Strategic Cost

Operators have traditionally been reluctant to share networks or to cooperate across business boundaries mainly due to the limitations and uncertainties they perceive regarding their marketing strategies. Cooperation takes place only if large economic gains are foreseen, e.g., mobile broadband in rural areas where small customer base cannot support multiple parallel networks. In the business literature, such barriers against strategic alliance with competitors have been widely studied, e.g., see [13]. Similar issues have also been discussed in [9] in the context of outdoor network sharing. Some key network-related obstacles are:

- Management overhead: decision-making on network deployment/upgrade can be delayed because it requires an agreement with the cooperation partner.
- Limited network controllability: an operator may lose control over the deployment and operation of its own network, which can restrict individual network dimensioning and make its service not differentiable from the competitors.
- Risk of information leakage: the coordination may reveal customer statistics and know-how on network optimization to the other operator.
- Lack of trust: an operator may suspect that the partner delivers false information to take advantage of the coordination when there is no trustable intermediate coordination entity exists.

One way for decision makers to handle uncertainty or risk is to present a risk margin when calculating the expected profits of the operation. In this paper, we do this by introducing an additional fictitious cost, denoted by the *strategic cost* C_{stex}. Notice that C_{stex} may not be strictly measurable because it may be related not only to objectively computable risk but also to *perceived* uncertainty about the future. This is not a new concept in strategic decision making in the business domain where one often considers an uncertainty margin, e.g., using a fictitious "*required rate of return*" or

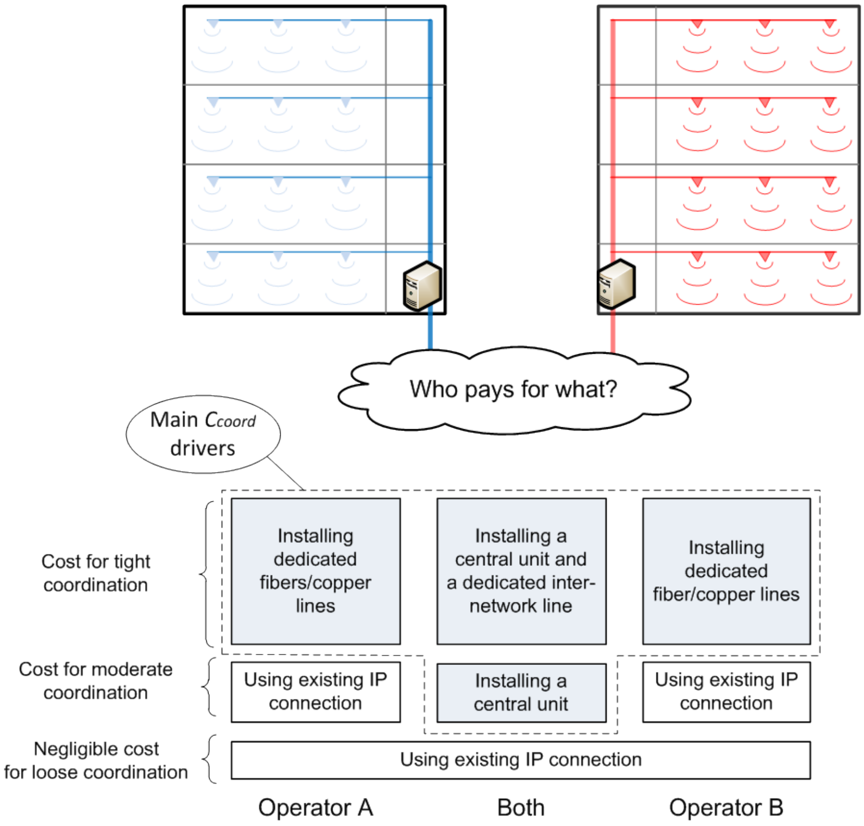

Fig. 2. Examples of C_{coord} according to the cooperation level.

"*hurdle rate*" when comparing investment options [14].

2) Coordination Cost

From a technical point of view, information sharing between networks requires additional complexity and infrastructure cost. The coordination cost C_{coord} is spent for acquiring relevant information for resource allocation. Depending on the amount of information to be shared, C_{coord} can be negligible or significant. As exemplified in Fig. 2, the extra cost mainly emanates from installing dedicated backhaul and/or intermediate entity to coordinate the interference between networks. For instance, real-time interference coordination may necessitate expensive dedicated backhaul in both inside and between buildings to allow for reliable low-latency information sharing. In addition, an inter-network coordinator should be put in place for fast and synchronized resource allocation. While inbuilding backhaul would be paid by an individual operator, the common cost, i.e., inter-building backhaul or the intermediate equipment, can be shared. In a moderate coordination scenario, each network may use its existing inbuilding IP connection to control its own APs. Even in this case, intermediate coordination equipment may need to be introduced by a third party due to a regulatory constraint, e.g., spectrum-broker, or due to the trust reason in a business domain. The cost for extra coordination equipment can also be saved by directly exchanging information between neighboring operators, resulting in a distributed network architecture. In general, lower level of coordination requires more APs to satisfy required traffic demand [7]. Thus, finding a proper level of coordination to give the lowest total cost is an important issue.

By including the two inter-operator cost factors, the total cost model of an operator in shared spectrum is extended to:

$$C_{tot} = C_{infra} + C_{spectrum} + C_{coord} + C_{stex}. \tag{2}$$

In the following section, we demonstrate how to use our proposed techno-economic modeling approach in a typical scenario.

V. Comparison of Operator Strategies

A. Two-Buildings Scenario

Let us consider a scenario with two nearby buildings as illustrated in Fig 1. Two indoor operators without exclusive spectrum want to deploy networks in their respective buildings. We assume that the regulator has arranged a shared frequency band in order to foster such local deployments under light licensing regime. This band only requires cost-free preregistration to avoid uncertain interference from end-users. Both operators run their networks in this frequency band. In this scenario, two operators want to find the most economic deployment strategy.

B. Candidate Operator Strategies

Multitude of solutions for the operators can be envisaged that combine technology and business aspects. However, we choose three candidate strategies as follows for illustrative purposes:

- **Strategy I (No cooperation):** Neither operator wants to cooperate due to the potential limitations of strategic alliance. Instead, they choose to deploy a *CSMA/CA* network which is imposed by a regulator as a coexistence mechanism unless cooperation between operators is implemented.

- **Strategy II (Loose cooperation):** The operators decide upon joint deployment of cellular technology based on a mutual contract. Although this improves network performance compared to Strategy I, it increases dependency on the neighbor operator. They choose a traditional picocell system across the two buildings employing conventional *frequency planning* that can be implemented without further investment in infrastructure.
- **Strategy III (Tight cooperation):** The operators jointly deploy a cellular network. This time, they want to use a system with an advanced multi-cell joint processing technique, i.e., *Zero-forcing (ZF) coordinated beamforming*, in order to have higher system capacity with fewer APs. In this strategy, they essentially need to invest in intra/inter-building optical fiber infrastructure.

C. Cost Comparison of Strategies

1) Evaluation Assumptions

For analysis simplicity, we assume that each local propagation condition and average traffic demand λ (GB/month/user) are symmetric. Two neighboring single-story buildings with the size of 50 m by 100 m accommodate 500 employees each. Wall loss of L_w dB exists both inside of a building and between. The CSMA/CA network assumes channel bonding (aggregation) to fully exploit available frequency range. Perfect carrier sensing without redundant idle APs is assumed to have an optimistic CSMA/CA performance. The loose cooperation uses the best static frequency reuse subject to a given outage constraint. The tight cooperation assumes ideal ZF without any CSI at the transmitter (CSIT) error and feedback delay in an uncorrelated channel. Some of important simulation parameters used are summarized as follows:

- Pathloss exponent and transmission power: 3 and 20 dBm
- The maximum link spectral efficiency: 6.67 bps/Hz
- System bandwidth and SINR outage threshold: 60 MHz and 3 dB
- Carrier sensing threshold for the CSMA/CA network: -72 dBm

More detailed system modeling and simulation parameters can be found in [7]. Hereafter, the three strategies, i.e., no cooperation, loose cooperation, and tight

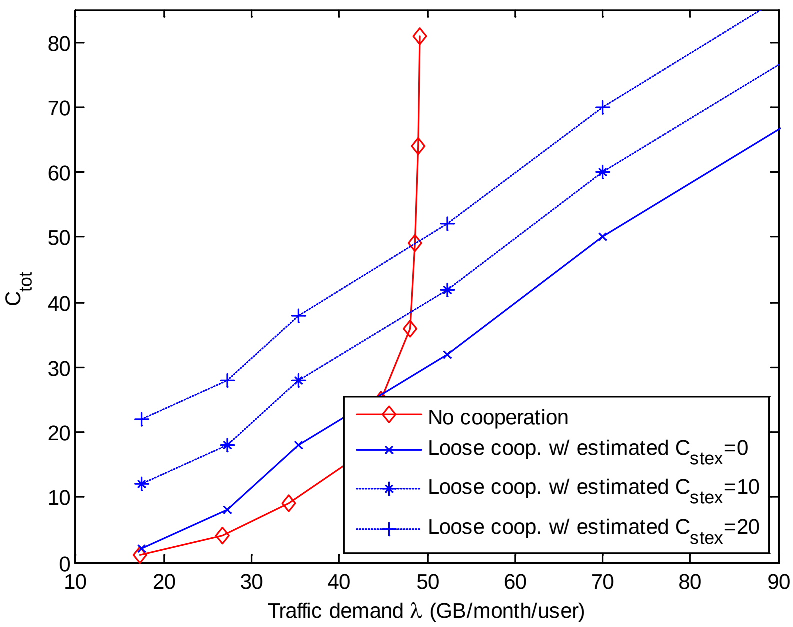

Fig. 3. Comparison of the total cost between no cooperation and loose cooperation; the economic strategy differs depending on traffic demand level ($C_r^n = 1, C_r^l = 2$, $L_w = 0$ dB, 95% coverage requirement).

cooperation will be denoted by superscripts *n*, *l*, and *t*, respectively.

2) No Cooperation vs. Loose Cooperation

We assume a unit price for an AP with the no cooperation (C_r^n=1) without loss of generality. Fig. 3 illustrates C_{tot}^n and C_{tot}^l depending on λ. The strategic cost C_{stex} can make a heavy influence on the lowest cost strategy. If two operators are very reluctant to cooperate, C_{stex} will be high, potentially significantly enough to prevent cooperation as depicted by the dotted lines in Fig. 3.

From an analysis perspective, we can quantify the condition for C_{stex} given that $N^l(\lambda)C_r^l + C_{stex} \le N^n(\lambda)C_r^n$. Then, let us define *maximum acceptable cooperation risk* (MACR) for a given demand λ:

$$\text{Max. acceptable cooperation risk (MACR)} := \max\left(N^n(\lambda)C_r^n - N^l(\lambda)C_r^l, 0\right). \quad (3)$$

This quantitatively provides us with the upper bound of risk that the operators are willing to take when choosing their cooperation strategy. MACR of zero means

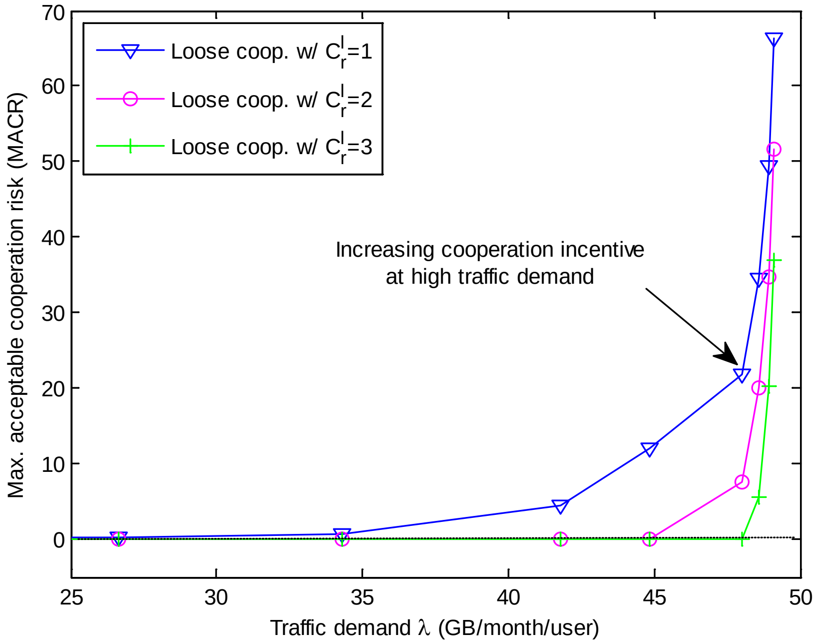

Fig. 4. The maximum acceptable cooperation risk depending on traffic demand ($C_r^n = 1, L_w = 0$ dB, 95% coverage requirement).

that the cooperation is worthless because C_r^l is already too high. On the contrary, high MACR represents that operators need to cooperate even if they perceive high risk of cooperation. As shown in Fig. 4, MACR can be explicitly plotted as a function of λ and C_r^l for a given unit cost $C_r^n = 1$ in order to aid operator's decision making. This only requires estimating $N^n(\lambda)$ and $N^l(\lambda)$ for varying λ. In this particular example, we can observe from Fig. 4 that MACR rapidly increases after a certain demand level because the CSMA/CA mechanism cannot satisfy such a high demand. This indicates that operators will have to rely on the cooperation in the end as the traffic demand continues to grow.

3) Loose Cooperation vs. Tight Cooperation

Tight cooperation additionally incurs the cost of fiber installation between all APs (or remote radio head) and a central baseband processor. Let C_{fiber} denote the fiber installation cost per AP. Then, unlike C_{stex}, C_{coord} is assumed to be approximately linear to the number of placed APs, i.e., $C_{coord} = N^t(\lambda)C_{fiber}$. We assume the costs for the central processor and inter-building fiber are relatively negligible and C_{stex} is same for

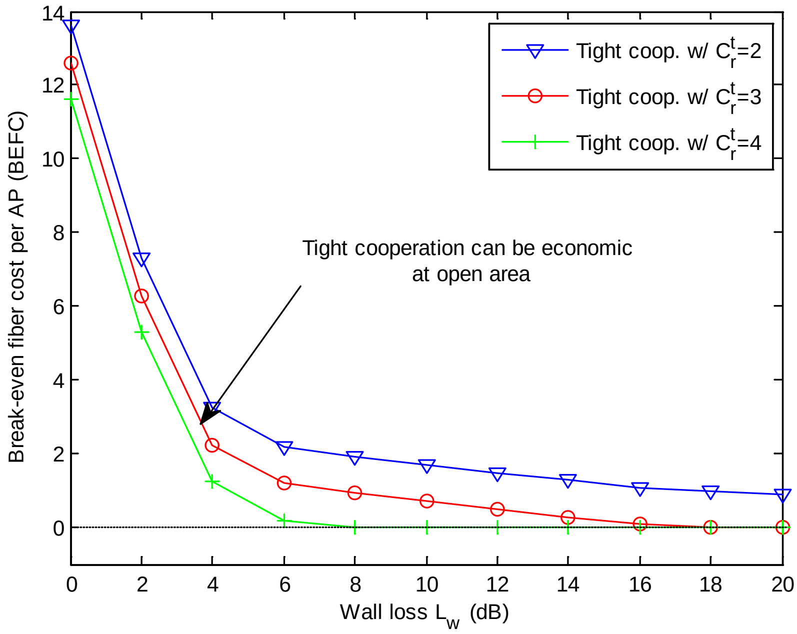

Fig. 5. The break-even fiber cost per AP for different indoor environments ($C_r^l = 2, \lambda = 200$ GB/month/user, 95% coverage requirement).

both strategies. Then, we can assess the condition for C_{fiber} from $N^t(\lambda)C_r^t + N^t(\lambda)C_{fiber} + C_{stex} \le N^l(\lambda)C_r^l + C_{stex}$. Similar to the MACR, let us define *break-even fiber cost per AP* (BEFC):

$$\text{Break-even fiber cost per AP (BEFC)} := \max\left(\eta(\lambda)C_r^l - C_r^t, 0\right) \qquad (4)$$

where $\eta(\lambda) := \dfrac{N^l(\lambda)}{N^t(\lambda)}$ represents *coordination efficiency* indicated by the relative difference in the required deployment density between two system solutions. The BEFC provides an upper bound on fiber cost per AP to make the tight cooperation more economic than the loose cooperation. When the actual fiber cost per AP is larger than the BEFC, the system with advanced coordination does not yield a cost benefit even with its superb performance. The zero value of BEFC suggests that the tight cooperation cannot be economic regardless of fiber cost due to too expensive equipment cost C_r^t. BEFC can be quantitatively shown in Fig. 5 according to wall loss at a given traffic demand. When wall loss is small, the tight cooperation provides more technical gain by cancelling significant amount of interference. Thus, $\eta(\lambda)$ becomes large so that the tight cooperation is preferred for given C_{fiber}. Nevertheless, closed environments with higher wall loss do not bring about total cost benefit by tight cooperation. In this situation, a more sophisticated system may not be desirable due to the marginal performance benefit compared to the fiber investment.

VI. FUTURE RESEARCH AREAS

Although substantial work has to be done to realize affordable high capacity provisioning, research on the design of local operator networks in shared spectrum is still in its early stage. In the following, we suggest high-level research areas to be addressed.

A. Tradeoff between Different Levels of Coordination

Various levels of intra-/inter-network coordination result in different system performances as well as coordination costs. Therefore, the quantitative comparison of different forms of coordination needs to be done to identify the most viable coordination strategy. The main tasks are categorizing relevant information to be shared and quantifying network performances in various local environments. Performance improvement by the coordination can be converted into cost saving in terms of the reduced number of APs. Then, operators can examine if this compensates for the associated coordination cost.

B. Impact of Network Separation

Indoor and hotspot networks will be located close to each other particularly in dense-urban districts, inflicting mutual interference. However, they are usually separated by walls and geographic distance. Their inter-network interference can be outweighed by intra-network interference if the separation between the networks is large enough. This means that the benefit of inter-network coordination relies on the network separation, which requires thorough investigation. We scratched the surface in [15].

C. Asymmetry between Operators in Demand and Deployment Environment

It is likely that nearby networks have the different user demands, QoS requirements, or inbuilding propagation conditions. Such asymmetry in demand and physical environments may lead to unequal incentives or even negative cooperation gain to one of the participants. Moreover, finding a proper common objective function for the cooperation is a challenging task especially when the partners aim at different QoS requirements specific to local services.

D. Multitude of Interfering Networks/Cooperation Partners

It is common that a multi-story building accommodates several networks. At the same time, the building is surrounded by multiple neighboring buildings. Thus, the number of networks generating interference can be substantial. As the number of potential cooperation partners increases, the performance gain would be higher since more interference could be controlled. However, it would come at the expense of inflating business complexity. Therefore, the relation between cooperation incentive and the number of involved partners needs to be further explored.

E. Impact on Existing MNOs

As more investments are made by the local operators, subscribers of existing MNOs can have more opportunities to enjoy high-speed access. Such investments indirectly relieve the soaring traffic burden in wide-area networks owned by MNOs. In addition, new local infrastructure can be shared by MNOs via roaming agreements. This can provide MNOs with competitive advantages over other competitors. While most of the literature focuses on the technical performance of a single operator's heterogeneous network, the impact of local operators on the existing MNOs has to be studied further both in the technical and business domains.

VII. CONCLUSION

We have proposed an analysis framework to explore the tradeoff between performance benefits of operator cooperation in shared spectrum and involved technical and strategic costs. The key application in mind has been indoor wireless access networks that could potentially offload wide-area cellular networks. In this framework, the implications of various operators' strategic decisions to cooperate or compete and the related costs of inter-network coordination level are explicitly modeled. We have also validated our framework by showing a quantitative analysis example, in which we compare the total cost of the candidate deployment strategies. Future research challenges involve assessing different operator strategies in various business situations and physical environments by using the framework, with the objective of finding the strategy that provides the lowest cost satisfying performance requirements.

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BIOGRAPHIES

DU HO KANG [S'10] (dhkang@kth.se) received his B.S. degree in electrical and electronics engineering from Pohang University of Technology and Science, Korea, in 2008. In 2010 he got his M.S. degree in electrical and electronics engineering from Seoul National University, Seoul, Korea. He is pursuing his Ph.D. degree at the Communication Systems Department, KTH Royal Institute of Technology, Sweden. He is currently participating in EU FP7 project METIS since 2012. His research interests include future low-cost ultra-high capacity wireless access network design and spectrum options.

KI WON SUNG [M'10] (sungkw@kth.se) is a Docent researcher in the Communication Systems Department at KTH Royal Institute of Technology, Stockholm, Sweden. He is also affiliated with KTH Center for Wireless Systems (Wireless@KTH). He received a B.S. degree in industrial management, and M.S. and Ph.D. degrees in industrial engineering from Korea Advanced Institute of Science and Technology (KAIST) in 1998, 2000, and 2005, respectively. From 2005 to 2007 he was a senior engineer in Samsung Electronics, Korea, where he participated in the development and commercialization of a mobile WiMAX system. In 2008 he was a visiting researcher at the Institute for Digital Communications, University of Edinburgh, United Kingdom. He joined KTH in 2009. He served as an assistant project coordinator of European FP7 project QUASAR. He also served as a track chair for CROWNCOM 2012 and as a TPC member for several international conferences. His research interests include dynamic spectrum access, energy-efficient wireless networks, cost-effective deployment and operation, and future wireless architecture.

JENS ZANDER [S'82, M'85] (jenz@kth.se) is a full professor as well as co-founder and scientific director of KTH Center for Wireless Systems (Wireless@KTH).at KTH Royal Institute of Technology, Stockholm, Sweden.He was past project manager of the FP7 QUASAR project assessing the technical and commercial availability of spectrum

for secondary (cognitive radio) use. He is on the board of directors of the Swedish National Post and Telecom Agency (PTS) and a member of the Royal Academy of Engineering Sciences. He was the Chairman of the IEEE VT/COM Swedish Chapter (2001–2005) and TPC Chair of the IEEE Vehicular Technology Conference in 1994 and 2004 in Stockholm. He is an Associate Editor of ACM/Springer Wireless Networks Journal. His current research interests include architectures, resource and flexible spectrum management regimes, as well as economic models for future wireless infrastructures.

Table 1. Changing business landscape and paradigm shift on system design in shared spectrum

		Traditional wide-area single operator system	**Local-area system in shared spectrum**
Business landscape	Who & Why?	MNOs: revenue generation from service provisioning	• MNOs: data offloading • Facility owners: complements to facility services • Hotspot operators: new revenue generation in niche markets
	Where?	Large-scale public outdoors	Mainly private/public indoors controlled by facility owners
	Inter-operator relation	Service/price competition in markets	• Service/price competition in markets • Cooperation/competition for inter-network interference coordination
	Major network-related cost	• Network cost • Spectrum cost	• Network cost • Inter-operator cost
System design	Design problem	Minimizing network cost at a given traffic demand	Minimizing network cost+inter-operator cost at a given traffic demand
	Decision domain	Mainly technology	Both technology and business
	Main decision maker	MNO	Both operators and a regulator
	Coordination target	Nodes (e.g., BSs)	Networks

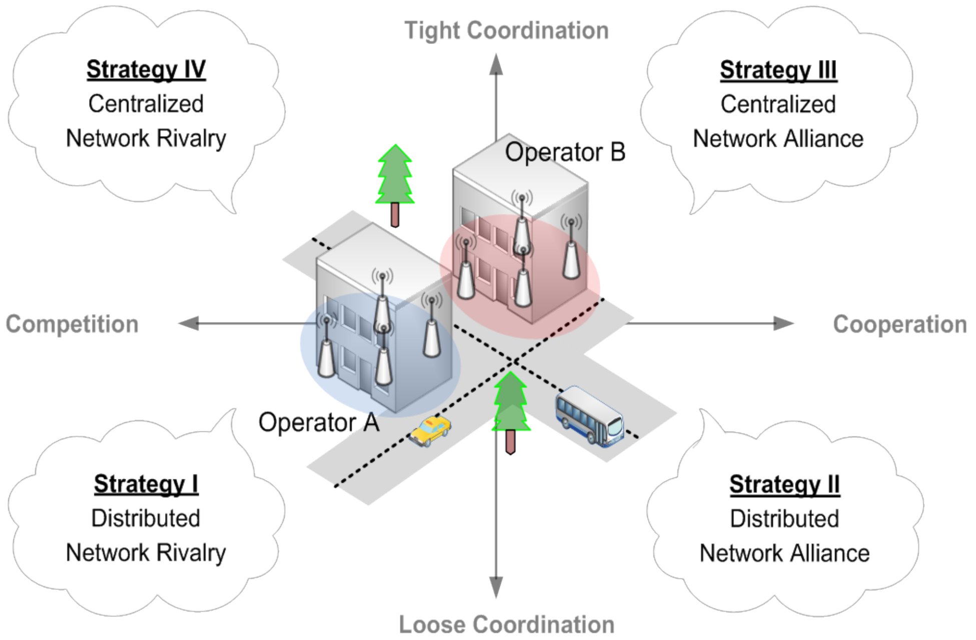

Fig. 1. A conceptual framework to define a strategy space and navigate the operator strategies.

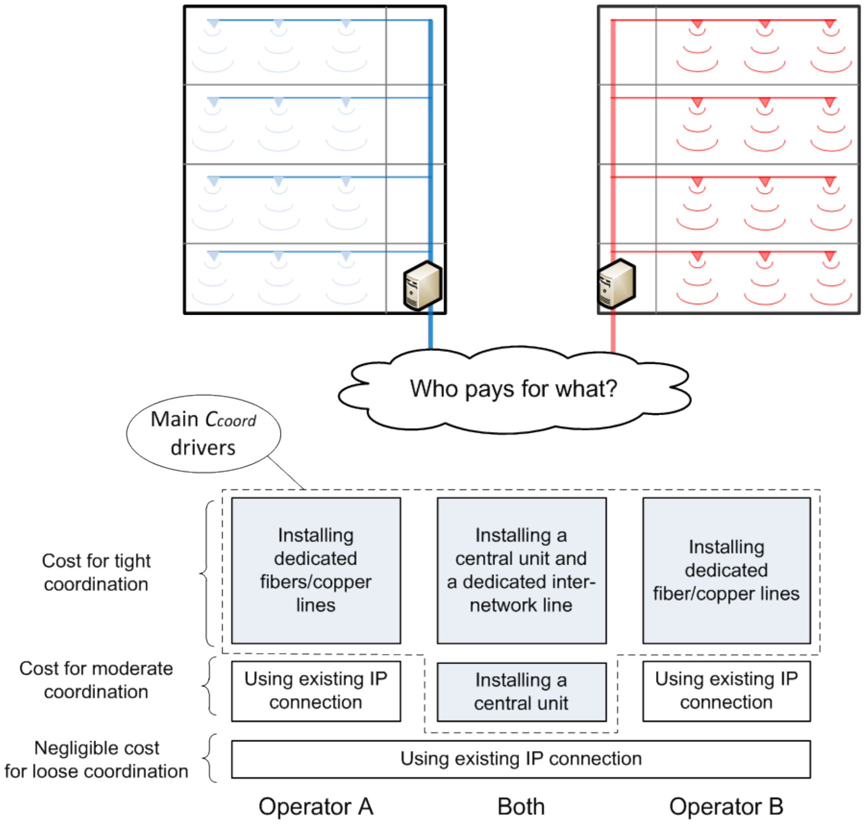

Fig. 2. Examples of C_{coord} according to the cooperation level.

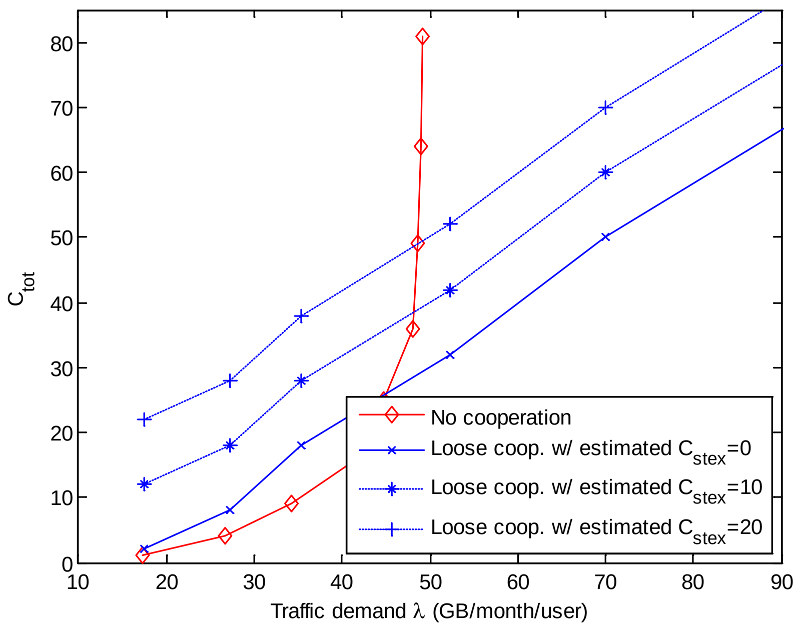

Fig. 3. Comparison of the total cost between no cooperation and loose cooperation; the economic strategy differs depending on traffic demand level ($C_r^n = 1, C_r^l = 2$, $L_w = 0$ dB, 95% coverage requirement).

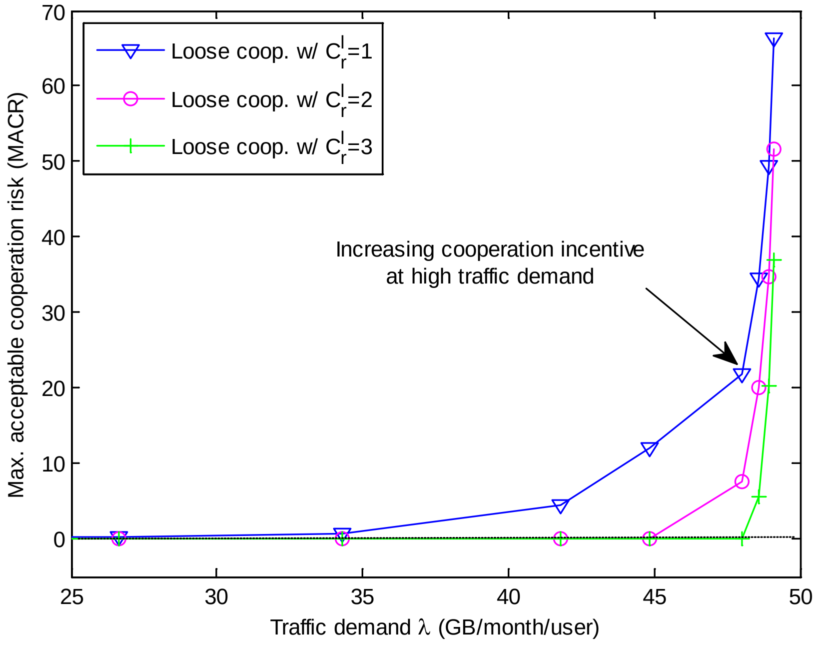

Fig. 4. The maximum acceptable cooperation risk depending on traffic demand ($C_r^n = 1, L_w = 0$ dB, 95% coverage requirement).

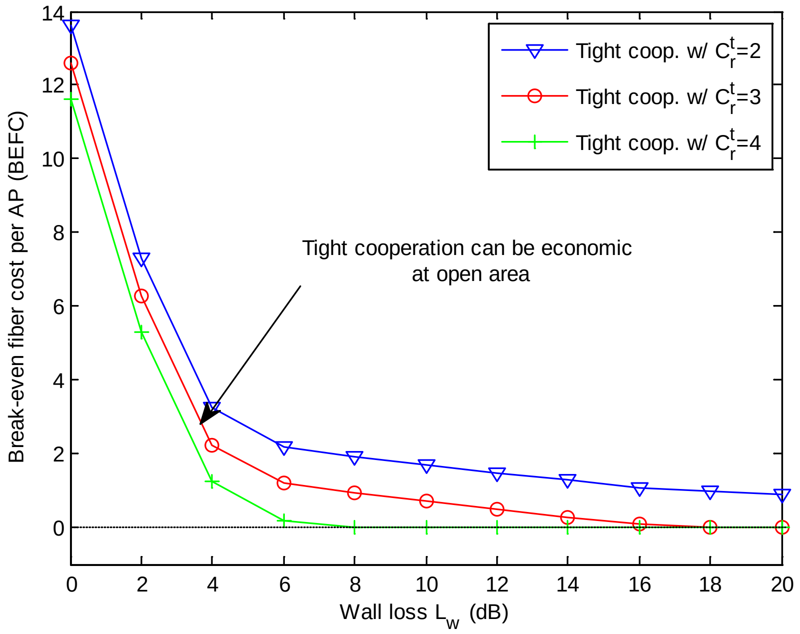

Fig. 5. The break-even fiber cost per AP for different indoor environments ($C_r^l = 2, \lambda = 200$ GB/month/user , 95% coverage requirement).