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Showcase Paper

Spectrum and Infrastructure Sharing in Wireless Networks: A Case Study with Relay-Assisted Communications

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Abstract: Physical resource sharing between wireless operators and service providers can be used to support efficient, competitive, and innovative wireless communication markets. By sharing resources, which are usually exclusively allocated such as spectrum or infrastructure, interference is created on the physical layer. Handling this new type of interference poses a significant and novel challenge to the design of suitable transmission techniques. In this paper, we investigate the example of two-way relaying with amplify and forward relays as a case study. Here, two operators physically share their spectrum and the relay (infrastructure). We demonstrate that both operators can serve their users by using multiple antennas at the relay via a naive scheme inspired by the block diagonalization method. Numerical results verify that already this simple approach results in significant gains in terms of the sum data rates as compared to an exclusive (orthogonal) assignment of the resources. This shows that cooperation leads to a more efficient use of the shared resources.

Keywords: Spectrum sharing, infrastructure sharing, relay-assisted communications, interference networks

1. Introduction

In current wireless communication systems, the radio spectrum and the infrastructure are typically used such that interference is avoided by exclusive allocation of frequency bands and employment of base stations. SAPHYRE[1] will demonstrate how equal-priority resource sharing in wireless networks improves the spectral efficiency, enhances coverage, increases user satisfaction, leads to increased revenue for operators, and decreases capital and operating expenditures.

The technical requirements for the air interface of IMT-Advanced include modern contention-based multiple access techniques, multi-antenna systems including space-division multiple-access (SDMA), adaptive modulation and coding schemes, and modern channel coding schemes, especially turbo and low-density parity-check (LDPC) codes [2]. Novel adaptive transmission techniques such as software defined radio (SDR), cognitive radio (CR), and co-operative communications are also explicitly included.

[1]The SAPHYRE (Sharing Physical Resources - Mechanisms and Implementations for Wireless Networks) project starts January 2010 and is a STREP funded by the European Union within framework program seven (FP7-ICT-248001), `http://saphyre.eu`.
[2]ITU: 'IMT advanced drafts', `http://www.ieee802.org/21/doctree/IMT-Advanced/`.

These developments and requirements lead to an indispensable paradigm change from exclusive resource allocation to ***cost-, spectrum-, and energy-efficient voluntary physical resource sharing*** which can be realized by innovative use of radio spectrum and network infrastructure under economic and regulatory constraints.

1.1 Physical resource sharing

The physical resources which are shared can be divided into two classes, namely spectrum and infrastructure. These are shared with respect to a set of 'players', consisting of operators and users. Each player has a set of private information, e.g., operators have their business models and their revenue strategies, users have their private interests and their partly private state information including traffic, mobility, channel parameters. These goals and parameters are usually not revealed to others.

The spectrum sharing is performed with respect to a set of constraints. These constraints are divided into two areas, namely regulatory and environmental constraints. They can partly overlap as in the case of spectrum masks and power constraints which are both regulatory and environmental. The main difference between these two areas is that regulatory constraints contain fairness and social welfare or legal issues whereas environmental constraints contain fundamental limitations imposed by physics.

The resource sharing problems are interdisciplinary and require regulatory and political bodies, business and market experts, and technical input from communication and network engineers. The ongoing discussion about spectrum commons is led mainly from a regulatory and market point of view. However, advances in communication systems (e.g., multi-antenna systems, multi-carrier transmission techniques, adaptive receivers, software defined radio, interference cancellation) are recognized already to have a very strong impact since they enable the efficient and concurrent use of spectrum [2].

1.2 Recent results in resource sharing

From a communications engineering point of view, different types of orthogonality in frequency, time, space of coding domain have been used for resource allocation depending on the type of interference: For users in one cell operated by one operator (intracell interference) TDMA combined with FDMA (used in GSM systems) or CDMA (combined with TDMA/FDMA in 3G systems) is applied to separate their signals at the receivers. For different sectors or cells, the intercell interference is controlled by applying different frequency reuse factors [3]. Fractional and adaptive frequency reuse is discussed in LTE and WiMAX [4]. Very recently, techniques for separating transmissions from different operators (inter-operator interference) without orthogonal resource allocation have been developed: First flexible resource sharing approaches have been developed and results indicate that the overall efficiency of the system can be improved by sharing different resources in the network between several operators [5, 6]. Sharing of spectrum or infrastructure ends up in creating interference on the physical layer. Therefore, interest in physical and MAC layer optimization for resource sharing has increased recently.

2. Relay-Assisted Resource Sharing

In this section, we present a relay-assisted communication scenario in which multiple communication partners (owned by different operators) use one relay terminal (possibly owned by another operator / virtual operator) to bidirectionally exchange information

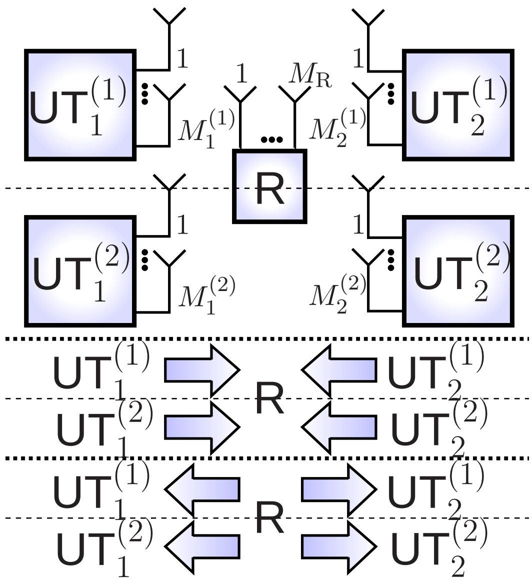


Figure 1: Multi-operator two-way relaying system model. The k-th terminal belonging to the ℓ-th operator has $M_k^{(\ell)}$ antennas and the relay station is equipped with M_R antennas.

using the same spectrum. All terminals as well as the relay have multiple antennas and operate in half-duplex mode. We have chosen this scenario because it contains *spectrum* as well as *infrastructure* (relay) *sharing*. This chapter contains an initial, simple proposal to accomplish this form of spectrum and infrastructure sharing by exploiting the multiple antennas at the relay via block diagonalization (BD). We compare this scheme to the traditional approach of using the resources exclusively in order to evaluate the potential gains from voluntary infrastructure (relay) and spectrum sharing.

2.1 System Model

The scenario under investigation is depicted in Figure 1. We assume that pairs of users belonging to the same operator would like to communicate with each other. Therefore, the relay station must take into account the fact that multiple operators are active and manage the interference they cause to each other according to their voluntary agreements. The relay is equipped with M_R antennas and uses amplify and forward two-way relaying. Moreover, the k-th terminal belonging to the ℓ-th operator has $M_k^{(\ell)}$ antennas.

The traditional solution to avoid inter-operator interference is to assign orthogonal resources to the two groups, e.g., different frequencies (FDMA) or different time slots (TDMA). Consequently, for each group, any single-operator two-way relaying techniques can be applied, e.g., the algebraic norm-maximizing transmit strategy (ANOMAX) [14]. This corresponds to the case of exclusive frequency bands and physically separated infrastructure. However, by using this scheme the individual sum data rate of each operator decreases by a factor of two since the time slots have to be shared. Therefore, in order to investigate the potential gain from voluntary infrastructure sharing, we propose an SDMA-based approach that allows both operators to serve their users via a physically shared relay by taking advantage of multiple antennas at the relay. This implies that the operators agree to voluntarily share their infrastructure and their spectrum in a coordinated manner. As we demonstrate, this form of cooperation not only reduces the operators' expenditure but additionally provides them with an improvement in the overall sum rate, since the resources are used more efficiently. These benefits provide the motivation for the operators to share their spectrum as well as their infrastructure. Our procedure consists of two steps. In the first step, the system is converted into two parallel independent sub-systems. Then, in the second step, arbitrary transmission techniques for single-operator two-way relaying can be applied. Note that this two-step approach is used here only for simplicity since it is in general suboptimal.

As in the basic two-way relaying scenario, where two users exchange data with the help of one relay, all belonging to a single operator [14], the transmission takes place in two phases. In the first phase, each terminal transmits to the relay using the same resources, so that their transmissions interfere. Assuming frequency-flat fading and denoting the channel between the k-th user of the ℓ-th operator and the relay by $\boldsymbol{H}_k^{(\ell)} \in \mathbb{C}^{M_{\mathrm{R}} \times M_k^{(\ell)}}$, where $k, \ell \in \{1, 2\}$, the signal received by the relay can be expressed as

$$\boldsymbol{r} = \boldsymbol{H}^{(1)} \cdot \boldsymbol{x}^{(1)} + \boldsymbol{H}^{(2)} \cdot \boldsymbol{x}^{(2)} + \boldsymbol{n}_{\mathrm{R}} \in \mathbb{C}^{M_{\mathrm{R}} \times 1}, \tag{1}$$

where $\boldsymbol{H}^{(\ell)} = \left[\boldsymbol{H}_1^{(\ell)}, \boldsymbol{H}_2^{(\ell)}\right]$ represents the concatenated MIMO channel of the ℓ-th operator, $\boldsymbol{x}^{(\ell)} = \left[\boldsymbol{x}_1^{(l)^{\mathrm{T}}}, \boldsymbol{x}_2^{(l)^{\mathrm{T}}}\right]^{\mathrm{T}}$ is the aggregate transmitted signal from each operator, and the vector $\boldsymbol{n}_{\mathrm{R}}$ is the noise component at the relay. Moreover, to simplify the notation, we assume that reciprocity is valid so that the backward channel between the relay and the k-th user of the ℓ-th operator is given by $\boldsymbol{H}_k^{(\ell)^{\mathrm{T}}}$. This assumption is fulfilled in a TDD system if identical RF chains are applied.

In the second transmission phase, the relay transmits to all terminals simultaneously. Since we assume an amplify and forward relay, the signal transmitted by the relay can be expressed as

$$\bar{\boldsymbol{r}} = \gamma \cdot \boldsymbol{G} \cdot \boldsymbol{r} \quad \text{for} \quad \boldsymbol{G} = \gamma_0 \cdot \boldsymbol{G}_{\mathrm{T}} \cdot \boldsymbol{G}_{\mathrm{S}} \cdot \boldsymbol{G}_{\mathrm{R}}. \tag{2}$$

Here, the parameter $\gamma_0 \in \mathbb{R}^+$ is chosen such that the relay amplification matrix $\boldsymbol{G} \in \mathbb{C}^{M_{\mathrm{R}} \times M_{\mathrm{R}}}$ is normalized to unit Frobenius norm. Moreover, $\gamma \in \mathbb{R}^+$ is the scaling factor used for adjusting the signal so that the transmit power constraint is fulfilled. The matrices $\boldsymbol{G}_{\mathrm{T}} \in \mathbb{C}^{M_{\mathrm{R}} \times 2M_{\mathrm{R}}}$ and $\boldsymbol{G}_{\mathrm{R}} \in \mathbb{C}^{2M_{\mathrm{R}} \times M_{\mathrm{R}}}$ represent the relay's receive filter and transmit filter, respectively. Their task is to mitigate the inter-operator interference for each sub-system. The matrix $\boldsymbol{G}_{\mathrm{S}} \in \mathbb{C}^{2M_{\mathrm{R}} \times 2M_{\mathrm{R}}}$ is constructed via

$$\boldsymbol{G}_{\mathrm{S}} = \begin{bmatrix} \boldsymbol{G}_{\mathrm{S}}^{(1)} & \boldsymbol{0}_{M_{\mathrm{R}} \times M_{\mathrm{R}}} \\ \boldsymbol{0}_{M_{\mathrm{R}} \times M_{\mathrm{R}}} & \boldsymbol{G}_{\mathrm{S}}^{(2)} \end{bmatrix}, \tag{3}$$

where $\boldsymbol{G}_{\mathrm{S}}^{(1)}, \boldsymbol{G}_{\mathrm{S}}^{(2)} \in \mathbb{C}^{M_{\mathrm{R}} \times M_{\mathrm{R}}}$ are the relay amplification matrices for each sub-system. Note that $\boldsymbol{G}_{\mathrm{S}}$ is block diagonal since it represents the processing performed in the individual subsystems.

The transmit and receive filter matrices $\boldsymbol{G}_{\mathrm{T}}$ and $\boldsymbol{G}_{\mathrm{R}}$ can also be partitioned as

$$\boldsymbol{G}_{\mathrm{T}} = \left[\boldsymbol{G}_{\mathrm{T}}^{(1)}, \quad \boldsymbol{G}_{\mathrm{T}}^{(2)}\right] \text{ and } \boldsymbol{G}_{\mathrm{R}} = \left[\boldsymbol{G}_{\mathrm{R}}^{(1)^{\mathrm{T}}}, \quad \boldsymbol{G}_{\mathrm{R}}^{(2)^{\mathrm{T}}}\right]^{\mathrm{T}}, \tag{4}$$

where $\boldsymbol{G}_{\mathrm{T}}^{(\ell)} \in \mathbb{C}^{M_{\mathrm{R}} \times M_{\mathrm{R}}}$ and $\boldsymbol{G}_{\mathrm{R}}^{(\ell)} \in \mathbb{C}^{M_{\mathrm{R}} \times M_{\mathrm{R}}}$ for $\ell \in \{1, 2\}$.

After establishing the system model, in the next section, we focus on the question how to find the matrices $\boldsymbol{G}_{\mathrm{T}}$, $\boldsymbol{G}_{\mathrm{S}}$, and $\boldsymbol{G}_{\mathrm{R}}$.

2.2 Two-step algorithm

The separation of the the two sub-systems requires the suppression of the inter-operator interference. The scheme we propose here is inspired by the precoding technique block diagonalization (BD) that was first proposed in [13]. Via BD we force all the inter-operator interference to zero by choosing one operator's relay receive filter matrix $\boldsymbol{G}_{\mathrm{R}}^{(\ell_1)}$ such that it projects the signal into the null space of the other operator's channel matrices $\boldsymbol{H}^{(\ell_2)}$ for $\ell_1 \neq \ell_2$ and $\ell_1, \ell_2 \in \{1, 2\}$. Thereby, the received signal at the relay is decomposed into two parallel independent sub-systems. The projection matrix can for example be calculated from the SVD of $\boldsymbol{H}^{(\ell_2)}$, as in BD [13]. To ensure that the system seen by the users of each operator in the second transmission phase is also isolated from the inter-operator interference, the transmit filter matrix $\boldsymbol{G}_{\mathrm{T}}$ for the second ("downlink") phase needs to be applied. Due to the reciprocity of the channel, we can simply choose $\boldsymbol{G}_{\mathrm{T}} = \boldsymbol{G}_{\mathrm{R}}^{\mathrm{T}}$. However, we should be aware that the BD algorithm has a dimensionality constraint stating that the number of antennas at the relay M_{R} must satisfy $M_{\mathrm{R}} > \max\{M_1^{(1)} + M_2^{(1)}, M_1^{(2)} + M_2^{(2)}\}$.

After canceling the interference between the operators, the overall received signal in the downlink can be expressed as

$$\begin{aligned}
\begin{bmatrix} \boldsymbol{y}^{(1)} \\ \boldsymbol{y}^{(2)} \end{bmatrix} &= \gamma \cdot \gamma_0 \cdot \begin{bmatrix} \boldsymbol{H}^{(1)^{\mathrm{T}}} \\ \boldsymbol{H}^{(2)^{\mathrm{T}}} \end{bmatrix} \cdot \boldsymbol{G}_{\mathrm{T}} \cdot \boldsymbol{G}_{\mathrm{S}} \cdot \boldsymbol{G}_{\mathrm{R}} \cdot \left[\boldsymbol{H}^{(1)} \boldsymbol{H}^{(2)}\right] \cdot \begin{bmatrix} \boldsymbol{x}^{(1)} \\ \boldsymbol{x}^{(2)} \end{bmatrix} + \begin{bmatrix} \tilde{\boldsymbol{n}}^{(1)} \\ \tilde{\boldsymbol{n}}^{(2)} \end{bmatrix} \\
&= \gamma \cdot \gamma_0 \cdot \begin{bmatrix} \boldsymbol{H}^{(1)^{\mathrm{T}}} \cdot \boldsymbol{G}_{\mathrm{R}}^{(1)^{\mathrm{T}}} \cdot \boldsymbol{G}_{\mathrm{S}}^{(1)} \cdot \boldsymbol{G}_{\mathrm{R}}^{(1)} \cdot \boldsymbol{H}^{(1)} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{H}^{(2)^{\mathrm{T}}} \cdot \boldsymbol{G}_{\mathrm{R}}^{(2)^{\mathrm{T}}} \cdot \boldsymbol{G}_{\mathrm{S}}^{(2)} \cdot \boldsymbol{G}_{\mathrm{R}}^{(2)} \cdot \boldsymbol{H}^{(2)} \end{bmatrix} \\
&\cdot \begin{bmatrix} \boldsymbol{x}^{(1)} \\ \boldsymbol{x}^{(2)} \end{bmatrix} + \begin{bmatrix} \tilde{\boldsymbol{n}}^{(1)} \\ \tilde{\boldsymbol{n}}^{(2)} \end{bmatrix},
\end{aligned} \tag{5}$$

where $\boldsymbol{y}^{(\ell)} \in \mathbb{C}^{(M_1^{(\ell)} + M_2^{(\ell)}) \times 1}$ and $\tilde{\boldsymbol{n}}^{(\ell)} \in \mathbb{C}^{(M^{l}_{(\ell)} + M_2^{(\ell)}) \times 1}$ are the signal and the effective noise term received by operator ℓ. Consequently, for each sub-system we obtain

$$\boldsymbol{y}^{(\ell)} = \gamma \cdot \gamma_0 \cdot \tilde{\boldsymbol{H}}^{(\ell)^{\mathrm{T}}} \cdot \boldsymbol{G}_{\mathrm{S}}^{(\ell)} \cdot \tilde{\boldsymbol{H}}^{(\ell)} \cdot \boldsymbol{x}^{(\ell)} + \tilde{\boldsymbol{n}}^{(\ell)}, \tag{6}$$

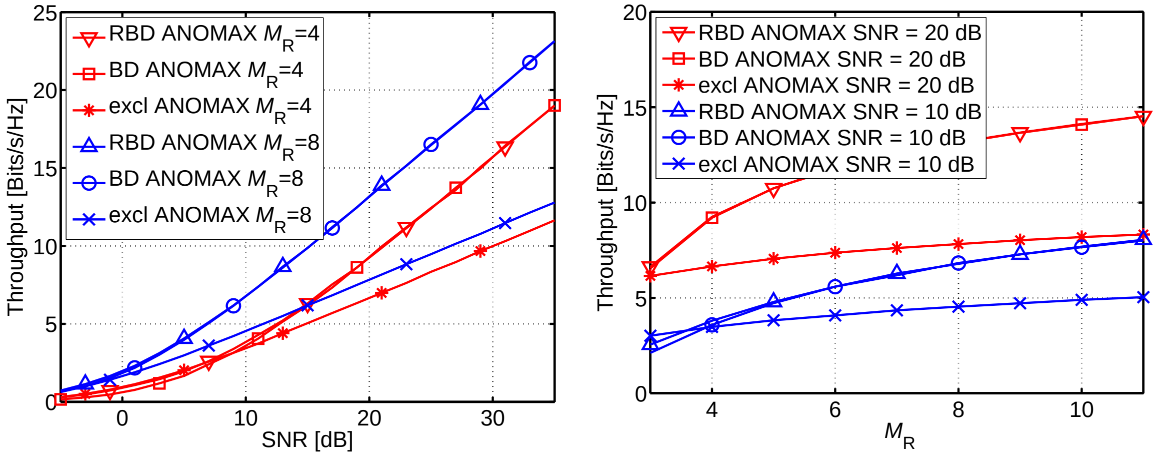
where the transformed channel matrices per operator are given by $\tilde{\boldsymbol{H}}^{(\ell)} = \boldsymbol{G}_{\mathrm{R}}^{(\ell)} \cdot \boldsymbol{H}^{(\ell)}$.

In order to find a suitable $\boldsymbol{G}_{\mathrm{S}}^{(\ell)}$ for each sub-system, any single-operator two-way relaying technique can be applied to the transformed channels $\tilde{\boldsymbol{H}}^{(\ell)}$, e.g., zero forcing (ZF) or minimum mean square error (MMSE) transceive filters [16]. However, in our simulations, we will use the ANOMAX strategy proposed in [14] due to its simplicity and its good performance compared to other single-operator two-way relaying transmit strategies.

2.3 Simulation results

In this section we compare the performance of an exclusive technique, e.g., FDMA or TDMA, corresponding to the traditional exclusive frequency bands and physically separated infrastructure, with the SDMA-based techniques corresponding to voluntary infrastructure and spectrum sharing. To this end, we consider uncorrelated Rayleigh fading channels and set $M_k^{(\ell)} = 1$ for $k, \ell \in \{1, 2\}$, a transmit power of one, and the same noise level σ_{N}^2 at each terminal and the relay. Therefore, the SNR is defined as

SNR $= 1/\sigma_{\mathrm{N}}^2$. Moreover, ANOMAX employed for both the exclusive and the SDMA-based approach uses equal weighting, i.e., $\beta = 0.5$ (cf. [14]). Note that due to the dimensionality constraint, the relay needs at least $M_{\mathrm{R}} = 3$ antennas in this scenario.



(a) Throughput vs. SNR

(b) Throughput vs. M_{R}

Figure 2: Multi-operator two-way relaying: exclusive approach vs. resource sharing approach using BD and Regularized BD (RBD). We compare the maximum mutual information in uncorrelated Rayleigh fading for $M_1^{(1)} = M_2^{(1)} = M_1^{(2)} = M_2^{(2)} = 1$. Left: varying SNR for $M_{\mathrm{R}} = 4$ and $M_{\mathrm{R}} = 8$. Right: Varying M_{R} for SNR = 20 dB and SNR = 10 dB.

In Figure 2(a) we show the comparison of the maximum mutual information by varying the SNR values for $M_{\mathrm{R}} = 4$ and $M_{\mathrm{R}} = 8$. Moreover, in Figure 2(b) we depict the comparison of the maximum mutual information by varying the number of antennas at the relay for SNR $= 20$ dB and SNR $= 10$ dB. We conclude from the two figures that the resource sharing approach via BD ("BD ANOMAX") outperforms the traditional exclusive approach ("excl ANOMAX") for large values of M_{R} as well as moderate and high SNR values. Note that the spatial multiplexing gain (i.e., the slope of the mutual information curve for high SNRs) for BD ANOMAX and RBD ANOMAX is twice the multiplexing gain of excl ANOMAX. We additionally include curves labeled "RBD ANOMAX". They represent the case where instead of the BD algorithm we use Regularized BD (RBD) introduced in [17]. Regularized BD allows a small amount of residual multi-user interference (in our case, inter-operator interference), balancing it with the noise enhancement. Therefore, RBD features a better sum rate performance at low SNRs and performs similarly to BD at high SNRs. As for BD, the gain from infrastructure and spectrum sharing is particularly pronounced for high SNRs. More detailed numerical results of the multi-operator two-way relaying system will be presented in [15].

Consequently, we see a large potential for infrastructure sharing in this scenario. Even the simple schemes based on BD and RBD have outperformed the traditional approach of exclusive resources for moderate and high SNRs. Moreover, the more antennas the shared relay station possesses, the more pronounced is the improvement. This simple technique already demonstrates the benefit gained from cooperation. Therefore, we conclude that spectrum and infrastructure sharing will help the operators not only to lower their expenditure but also provide a better service, since the available resources are used much more efficiently.

3. Conclusions

In this paper, we have discussed the novel approach of voluntary physical resource sharing between wireless operators via a case study. We have selected two-way relaying with amplify and forward relays, because it involves spectrum sharing as well as infrastructure (relay) sharing and therefore allows to demonstrate the available gains from these two forms of resource sharing.

We have introduced a simple scheme inspired by block diagonalization (BD) that allows both operators to serve their users simultaneously by taking advantage of multiple antennas at the relay station. This paper shows that BD decouples the multi-operator system into two independent subsystems in which the operators can perform any technique known from the traditional approach where the physical resources are used exclusively.

In simulations we have demonstrated that the approach using shared physical resources outperforms the exclusive approach for moderate to high SNRs and this gain increases with the number of antennas at the relay. By replacing the BD algorithm by Regularized BD (RBD), the performance for low SNRs and a small number of antennas at the relay can be improved even further.

We conclude that there is a large potential gain from spectrum and infrastructure sharing between wireless operators. As we have demonstrated in this paper, this form of voluntary cooperation uses the physical resources even more efficiently which improves the operators' individual sum data rates. Moreover, it reduces the operators' expenditure since the cost of deploying and maintaining the infrastructure as well as licensing the spectrum can be shared as well. There might be even potential for infrastructure owners to offer relaying services to multiple operators.

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