Research Article

Technoeconomic Evaluation of Cooperative Relaying Transmission Techniques in OFDM Cellular Networks

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We evaluate the costs in the deployment of a 4G relay-assisted network in the 2.6 GHz band following a technoeconomic methodology that departs from cell dimensioning based on spectral efficiency and outage capacity requirements. Different decode-and-forward relaying protocols are considered in the analysis, assuming a certain traffic load evolution over a period of ten years, different geotypes, and a progressive deployment of base stations and relay stations. Results show significant benefits for operators as well as reduction in the total radiated power.

1. Introduction

1.1. Motivation. The research and development of the new fourth generation (4G) wireless systems face the challenge of provisioning high throughput in reasonably large areas to satisfy the user expectation of seamless access to broadband services. This challenge is specified in terms of requirements of higher average and cell-edge user throughput, minimum quality of services, and multiple scenario deployments that candidate systems to be defined as 4G, or IMT-Advanced as called by ITU, like 3GPP LTE-A or IEEE 802.16 m, should accomplish (see system requirements for IMT-Advanced in [1]).

Additionally, the commercial projection of flattering wireless communication revenues, resulting from the high penetration rate already achieved for the mobile communication services and the unlikely increase of the average revenues per user (ARPU), and exponentially rising wireless data traffic introduce a new fundamental requirement to these 4G wireless systems: the provision of substantially higher bit rate than in 2G-3G type of services, but at cost-per-bit that are substantially lower than in 2G-3G type of infrastructure. In fact, as suggested in [2], providing cost-effective, affordable wireless bandwidth everywhere is one of the key success factors for future wireless systems.

Almost a decade ago it was argued [3] that the infrastructure costs of a traditional cellular architecture could not provide affordable wide area coverage for high bit rates. More recently, [2, 4] defend the idea that a scaled-up version of traditional cellular concept is not by itself a viable solution to ubiquitous broadband wireless access and [2] proposes different alternatives to reduce the cost-per-bit from more advanced transmission techniques and multiple antenna technologies to the roll-out of shared networks. Among them, the integration of multihop or relaying capability into conventional wireless networks is one of the most promising architectural upgrade [4].

In this respect, many different relay transmission techniques have been developed over the last years. The simplest strategy (already deployed in commercial systems) is the analog repeater, which uses a combination of directional antennas and a power amplifier to repeat the transmit signal [5]. More advanced strategies assume some signal processing capabilities on the received signal. Amplify-and-forward
Relays are often assumed to be half-duplex (they can either send or receive but not at the same time) [12] or full-duplex (can send and receive simultaneously) terminals [14]. While implementation details of full-duplex relays are under investigation, relay-based enhancements in WiMAX [15] are considering half-duplex relay operation, which incur a rate penalty since they require two (or more timeslots) to relay a message from source to destination. These are conventionally called One-way Relay Channels (OWRCs). On its turn, the Two-way Relay Channels (TWRCs) overcome the half-duplex losses by using a form of superposition or network coding (combined with self-interference cancellation at the receiver) that allows two messages to be sent and received in two time-slots [16, 17]. Optimising the duration of the relay-receive and the relay-transmit phases (a feasible feature of WiMAX and LTE-A) is crucial to obtain high spectral efficiency both for OWRC and TWRC [12, 17, 18], even beyond the direct transmission thanks to the breaking up of the pathloss. Relaying has been combined with multiple antennas in the MIMO relay channel [10, 14] and the multiuser MIMO relay [19–22]. Prior work has not as extensively investigated the impact of interference as seen in cellular systems. One exception is [23], which utilizes resource allocation to avoid interference.

As a result of these efforts, relay-assisted or cooperative transmission has become a hot research topic nowadays and proponents of wireless cellular solutions are interested in incorporating such transmission technique for improving its performance and cost efficiency. Thus, a cellular-relaying architecture has been proposed as a more cost-effective alternative in amendment m of IEEE 802.16 [15].

In this framework, some studies show how, for a given base station infrastructure, the introduction of MIMO relay nodes provides simultaneous outage probability reduction and system capacity increase [5, 7]. Seen from an alternate point of view, the same system service level can be provided using a given base station (BS) density or through a lower BS density provided that RSs are also deployed. Consequently, the cost efficiency of the relay-enhanced architecture regarding a conventional cellular architecture depends on the relation between the relaying gain (defined as the reduction of deployed BS over the amount of RS used) and BS-to-RS cost ratio.

As a result, the same network performance can be obtained with various dimensioning solutions (in terms of BS and RS densities), frequently presented as iso-performance curves, or indifference plots [23]. The viability of the relaying solution must therefore be evaluated from an economic point of view [24]. Thus, most of previous works are focused on the assessment of the highest cost an RS may have so that cellular-relaying system provides the same service level at lower costs as purely cellular systems. Different values are found depending on the relay transmission technique, the architecture (macro-only or macro- and microwaves as in [25]) or the deployment scenario [24–28] considered. Moreover, most of these studies on the economic viability of relaying solutions assume that the entire network is deployed at once (with the exceptions of [29, 30] where incremental deployment strategies are studied), and thus, they do not consider realistic cases where the networks are incrementally enhanced to match the increase of the user traffic demand.

Conversely, in this paper, we provide an assessment of the economic gains, in terms of total network-related cost savings, provided by the integration of relaying capabilities into a conventional single-hop OFDM-based cellular network under a realistic scenario (the roll-out of a mobile broadband network in a western European country). This assessment is obtained by combining the dimensioning results of an OFDM-based 4G system model and a technoeconomic model whose unit costs assumptions (including the costs related to BS and RS) are based on industry data. Furthermore, as different relay transmission techniques (described in Appendix A) are evaluated under the same assumptions and models, a comparison of the performance and economic gains provided by each of them can be performed. An analysis of the economic feasibility of a relay-assisted OFDM network based on actual BS and RS costs assumptions has been previously presented in [26] but to a lesser extension.

1.2. Network Assumptions. The deployment of in-cell RS is the solution adopted to achieve high network spectral efficiency in a cellular network while simultaneously providing homogeneous quality of service levels. In this respect, we shall adopt some assumptions that influence not only the performance of the network but also its operational amenability to a system level simulator.

(1) The existence of a dedicated backhaul connecting the BSs, and over-the-air connection between BS and RS: RSs operate under a DF strategy, and different relaying protocols will be evaluated. Following the capabilities offered by the transmission frame specified in 802.16 m, the duration of relay-receive and relay-transmit phases is optimized on each mobile station (MS) connection (see Section 2.1).

(2) OFDM-TDMA transmission is adopted, and the channel state information (CSI) is restricted to the average channel gain, that is, the link pathloss. While its slowly varying nature helps keeping a low feedback rate, its sole knowledge precludes the BS processing workload to become unaffordable, as in the case where each per tone fading state is available [31].

(3) Time-division duplexing between UL and DL: the fraction of the WiMAX frame associated to the DL is fixed for all users in the cell and for all cells (except for the TWRC protocols, as will be mentioned in Appendix A).

(4) The density of users in the cell is uniform and all of them generate the same traffic. The UL traffic is assumed to be 1/5 of the traffic in the DL for each
The purpose of this paper is to develop a technoeconomic methodology allowing the evaluation of the economic gains provided by the integration of relaying technologies into an OFDM-based cellular network under a realistic scenario. To this end, an OFDM-based 4G system model and a technoeconomic model for wireless access networks have been combined, as described in the sequel, to dimension the whole access network (from macro-BS and RS up to the IP aggregation network) for both, purely macrocellular and relay-assisted systems, and to assess the total network-related costs that would be required in a specific operator environment, more specifically, the case of a new operator provisioning ubiquitous voice and broadband data services in the urban, suburban, and rural areas of a western European country.

Under this framework, a comparison of the performance and economic gains (in terms of total network-related cost savings) provided by different single-user cooperative transmission techniques is presented and compared to direct transmission. We have constrained our study to the halfduplex DF cases and have selected specific protocols for which achievable rates are known. Moreover, two different antenna configurations (one or two antennas in the user terminal devices) have been considered so as to evaluate the extra performance gains arising from MIMO transmissions. Results on cost efficiency of each of these relay protocols and antenna configurations are presented for the different scenario deployments in order to show the economic convenience of each one. Finally, the technoeconomic model developed is used to explore the economic feasibility of the roll-out of these access network solutions so as to identify possible exploitation strategies of these technologies over a 10-year period.

As a side outcome of the study, an evaluation of the transmitted power is obtained, showing that the radiated power density of half-duplex relay-based solutions may be reduced as compared to conventional nonrelay-assisted wireless networks.

### 1.4. Outline of the Paper
The rest of the paper is organized as follows. Section 2 introduces the system description and the methodology used to dimension the cell radius, the number of RS per sector, and the density of BS. An insight is also done for the evaluation of the transmitted power. In Section 3 the methodology used to dimension the 4G access network and to assess the network-related costs as well as the main assumptions in terms of business planning, network solution and unit costs assumed is presented. Section 4 presents the main results and the discussion about the economic gains provided by the different relay protocols as well as about the economic feasibility and possible exploitation strategies of these technologies. Section 5 eventually concludes the paper.

### 2. OFDM-Based 4G System Model

#### 2.1. System Description
We consider the half-duplex scenario shown in Figure 1 where the BS transmits the data to the MS either directly or via the RS in two orthogonal hops, depending on the strategy achieving largest transmission rate. All terminals may be equipped with a single or multiple antennas. The RSs are distributed uniformly in angle over the sector, all at the same distance $r_{BR}$ of the BS. The transmission

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**Table 1: System level key parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular layout</td>
<td>120° sectorial antennas</td>
</tr>
<tr>
<td>Frequency reuse</td>
<td>1/3</td>
</tr>
<tr>
<td>Propagation models</td>
<td>Winner propagation models</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2.6 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>5, 10, 15, 20 MHz</td>
</tr>
<tr>
<td>BS power</td>
<td>40 dBm</td>
</tr>
<tr>
<td>RS power</td>
<td>30 dBm</td>
</tr>
<tr>
<td>MS power</td>
<td>23 dBm</td>
</tr>
<tr>
<td>BS antenna gain plus cable loss</td>
<td>10.6 dBi</td>
</tr>
<tr>
<td>Sectorec antenna pattern at BS</td>
<td>Parabolic model</td>
</tr>
<tr>
<td>RS antenna gains plus cable loss</td>
<td>5 dBi</td>
</tr>
<tr>
<td>User antenna gain</td>
<td>-1 dBi</td>
</tr>
<tr>
<td>Noise spectral density</td>
<td>-174 dBm/Hz</td>
</tr>
<tr>
<td>Noise figure at MS and RS</td>
<td>7 dB</td>
</tr>
<tr>
<td>Body loss</td>
<td>5 dB</td>
</tr>
<tr>
<td>Antennas at (BS × RS × MS)</td>
<td>$2 \times 2 \times 1, 2 \times 2 \times 2$</td>
</tr>
<tr>
<td>DL to UL frame balance</td>
<td>Adapted for a variable over-time ratio of UL/DL</td>
</tr>
<tr>
<td>MAC overhead</td>
<td>39.7% direct transmission</td>
</tr>
<tr>
<td>Scheduling fairness $\gamma$</td>
<td>-1</td>
</tr>
</tbody>
</table>

user. This value is used to determine the relative duration of the UL and DL frames for each user.

1. All cells are sectorized to 120° and reuse 1/3 is adopted. It is assumed that all cells transmit synchronously: the RS-receive phase and RS-transmit phase in the DL are time-aligned for all cells. The same happens for the UL. This has significant consequences on the model adopted for the interference: interference power is constant over all transmission.

2. It has been observed that relaying transmission offers higher rates than direct transmission if sources are far from destinations [17]. Therefore, each MS is able to decide if it prefers receiving directly from the BS or through the RS.

In order to analyze the network performance, two fundamental measures are adopted: cellular spectral efficiency ($S_c$), as the average achievable rate over the cell area, and outage achievable rate ($R_{out}$), as the peak achievable rate of the $\epsilon$-percentile worst users in the cell. Both capture most of the benefits offered by relay-based transmission. These are measures that largely depend on the optimum number and position of RS; so these need to be optimized depending on the relaying protocol used as well as for other system level parameters (see Table 1).

1.3. Contribution. The purpose of this paper is to develop a technoeconomic methodology allowing the evaluation of the economic gains provided by the integration of relaying technologies into an OFDM-based cellular network under a realistic scenario. To this end, an OFDM-based 4G system model and a technoeconomic model for wireless access networks have been combined, as described in the sequel, to dimension the whole access network (from macro-BS and RS up to the IP aggregation network) for both, purely macrocellular and relay-assisted systems, and to assess the total network-related costs that would be required in a specific operator environment, more specifically, the case of a new operator provisioning ubiquitous voice and broadband data services in the urban, suburban, and rural areas of a western European country.

Under this framework, a comparison of the performance and economic gains (in terms of total network-related cost savings) provided by different single-user cooperative transmission techniques is presented and compared to direct transmission. We have constrained our study to the half-duplex DF cases and have selected specific protocols for which achievable rates are known. Moreover, two different antenna configurations (one or two antennas in the user terminal devices) have been considered so as to evaluate the extra performance gains arising from MIMO transmissions. Results on cost efficiency of each of these relay protocols and antenna configurations are presented for the different scenario deployments in order to show the economic convenience of each one. Finally, the technoeconomic model developed is used to explore the economic feasibility of the roll-out of these access network solutions so as to identify possible exploitation strategies of these technologies over a 10-year period.

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2.1. System Description. We consider the half-duplex scenario shown in Figure 1 where the BS transmits the data to the MS either directly or via the RS in two orthogonal hops, depending on the strategy achieving largest transmission rate. All terminals may be equipped with a single or multiple antennas. The RSs are distributed uniformly in angle over the sector, all at the same distance $r_{BR}$ of the BS. The transmission
is carried out in frames of length $T_f$ and bandwidth $W$, as in 802.16 m [15].

As shown in Appendix A, the capacity of cooperative relay protocols can be derived from the capacity of the different links involved. The duration of the relay-receive and relay-transmit phases is $\alpha T_f$ and $(1 - \alpha)T_f$, respectively. An optimal selection of $\alpha$ allows enhanced transmission performance when the BS-RS and RS-MS links present different capacity [18]. Assuming OFDM transmissions, where each carrier suffers independent fading and coding is done across carriers, it is reasonable to assume capacity expressions on each BS-RS, BS-MS, or RS-MS link given by the ergodic capacity:

$$C = E_H \left\{ \log_2 \left( 1 + \frac{P/n}{I W N_o + I H H^H} \right) \right\} \text{ bps/Hz}, \quad (1)$$

where $P$ is the transmitted power, $n$ is the number of antennas at the transmitter, $W$ is the bandwidth, $N_o$ is the noise power spectral density, $I$ is the interference power, and $H$ is the MIMO channel linking transmitter and receiver. It is assumed in the sequel that interference is white both in space (sustained by space-time coding) and among carriers (sustained by the presence of multiple interferers). The evaluation of the interference differs from one relaying protocol to the other; further details are given in Section 2.2.

To account for imperfect channel coding, an SNR penalty term $\Gamma$ is introduced and taken as 4 dB. Under these premises, exact expressions for the general correlated Rayleigh MIMO ergodic capacity are given in [31]. Note that if RSs are placed in above roof tops positions so that LOS propagation between BS and RS is found, channel is nearly static and close to nonfrequency selective, and the capacity of the Gaussian MIMO channel is more appropriate. The channel models adopted in the sequel are outdoor-to-outdoor from the WINNER project recommendations [32].

The radio access network (RAN) is based on an all-IP system architecture as described in Section 3.3 which is compatible with 802.16 m specifications [15]. In order to simplify the evaluation, a number of system level assumptions have been adopted.

(i) The frequency bands reserved for unpaired operation of the 2.6 GHz band (2500–2690 MHz) are considered. The duration of frames $T_f$ is assumed 10 milliseconds.

(ii) Channel bandwidth of 5, 10, 15, or 20 MHz: a reuse factor of 3 is considered and hence 15, 30, 45, or 60 MHz of spectrum are required. These bandwidths (apart from 20 MHz) are compatible with the channeling configuration used in most of European countries on the 2.6 GHz band (two paired blocks of $2 \times 70$ MHz for operation in FDD mode plus one of 50 MHz for TDD operation).

(iii) As in conventional cellular networks, cells are further divided into 120° sectors and frequency planning 1/3 is assumed. A deployment of 19 cells is simulated, and all cells are assumed synchronized. The consideration of fractional reuse factor (FRF) strategies ([15, Section 20]), in combination with relay transmissions, is considered beyond the scope of the paper.

(iv) The number of antennas at each terminal is $n_{BS}$, $n_{RS}$, and $n_{MS}$ (in the sequel denoted by $n_{RS} \times n_{RS} \times n_{MS}$ MIMO relay system), and hence extra performance gains arising from MIMO transmissions [33, 34] are captured. The number of antennas is 2 at the BS, 2 at the RS, and 1 or 2 at the MS.

(v) PUSC/FUSC channelization with coding across carriers: therefore no CSIT-based MIMO linear precoding is assumed in transmission.

(vi) Continuous-valued adaptive-modulation and coding scheme is adopted. The actual transmission rate on each cooperative link is taken from (1), and upper limited to a practical value of $\min(n_T, n_R) \times 5$ bps/Hz. The lower bound is taken as $\min(n_T, n_R) \times 2/3$ bps/Hz. MAC overheads are taken from WiMAX specifications and account for cyclic prefix extensions, preambles, and pilot symbols.

(vii) MSs are associated to BS and RS according to the received average SNR.

Other system level key parameters used in the simulator are listed in Table 1.

2.2. Transmission Rates for Relay-Based Cellular Systems. Constraining our study to the half-duplex DF cases, one can identify a number of One-Way Relay Channel (OWRC) and Two-Way Relay Channel (TWRC) protocols, for which achievable rates are known (see derivations in Appendix A). The specific protocols considered in the sequel are selected according to its simplicity (Forwarding protocol (FW)), and its spectral efficiency (Protocol III (OWRC-III) and Two-Way Relay Channel (TWRC-I)).

The presence of intercell interference is crucial to compute system performance. In the presence of RS, terminals interfere each other in a different way, depending on the protocol adopted. On each RS-receiving or RS-transmitting phase, different terminals transmit and hence the interference pattern varies. In all cases, interference is considered incoherent and power sum up at the receiving terminals. Tables 2 to 4 provide details on how interference is evaluated in each case, where $K$ RSs are assumed deployed on each sector.
The use of relay transmission has been shown advantageous compared to direct transmission only for far users (the gain is more important if the duration of relaying phases is optimized [17]). These are not a negligible number of MS, as the area in the far zone is larger than the area in rings close to the BS.

Therefore, in our setup each MS may choose between direct or relayed transmission. Figure 2 illustrates the benefits of this choice displaying the downlink achievable transmission rate on each position of a 120° sector featuring three RSs at 70% of the cell radius. Both the spectral efficiency and the outage transmission rate (as defined latter in Section 2.3) are increased for the two relaying protocols displayed (Figures 2(b) and 2(c)), as compared to direct transmission (Figure 2(a)). It is worth observing that as the coverage area.

### 2.3. Network Dimensioning for Relay-Based Cellular Systems

In order to assess the performance of RS deployment, we might fix the cell size and observe how much is gained in throughput or in satisfied users (in terms of quality of the services requested). Alternatively, one could set a desired cell performance and determine the cell radius required to achieve it, thus trading with the density in the deployment of base stations and relay stations. The latter is the approach taken here, based on two fundamental network performance measures. The first one is cell spectral efficiency ($S_e$), defined as the average achievable rate over the cell area. It is obtained easily if TDMA access is adopted as an average of the achievable rates on every position in the cell $A$ weighted by the relative transmission times. The transmission time associated to a user is a function of the achievable rate as $T_i \propto R_i^\gamma$:

$$S_e = \frac{\sum_{i \in A} R_i T_i}{\sum_{i \in A} T_i} = \frac{\sum_{i \in A} R_i^{\gamma+1}}{\sum_{i \in A} R_i^{\gamma}}$$

and thus it is a function of the scheduling strategy selected. When $\gamma = 0$, all users in the cell are given the same amount of time resources; so it turns to a round-robin strategy. When $\gamma > 0$, the resource allocation is balanced towards the users in best conditions, thus approaching greedy scheduling. On the other end, when $\gamma = -1$, the same rate is provided to all users in the coverage area. $S_e$ provides a hint on how efficient the system and how much traffic it can deliver, and therefore, it makes sense to set the cell radius as the value such that the spectral efficiency equates traffic offered to (or demanded by) users (see Figure 3(a)).

$S_e$ does not account for the disparity of achievable rates experienced by different users. Therefore, we are also interested in the outage cell-wide achievable rate ($R_{out}$), as the peak achievable rate obtained by a fraction $\epsilon$ of the worst users in the cell if all resources were given to those users.

$$\epsilon = Pr\{R_i \leq R_{out} \mid i \in A\}$$

When both $S_e$ and $R_{out}$ constraints are specified as a requirement to dimension the cell radius $r$, it is important to have in mind that both might not be achieved simultaneously. Therefore the system designer needs to decide select the cell radius as the minimum between $r_S$ and $r_o$. Let us analyse two possible cases depending on the traffic load (see Figure 3).

(i) $r_o < r_S$, as a result of a low-level traffic in the cell.

Cell dimensioning is coverage limited. As the $R_{out}$ is a decreasing function of the cell radius, if $r = r_o$ the cell spectral efficiency will be larger than the traffic generated by users, and hence the deployment of BS will be unnecessarily dense, resulting in uneconomical investment.
(ii) \( r_S < r_o \), as a result of a high level of traffic in the cell. Cell dimensioning is capacity limited. As the \( S_c \) is a decreasing function of the cell radius, if \( r = r_S \) the \( S_c \) will fit the requirements and the obtained \( R_{\text{out}} \) will exceed the requirements.

Hence it is necessary that both \( r_S \) and \( r_o \) be as large as possible and the condition \( r_S \leq r_o \) is met. Relay-based schemes are well suited to this situation as they are able to increase both the cell spectral efficiency and the outage rate.

2.3.1. Indifference Plots. As compared to conventional wireless networks, the inclusion of RS in the cell provides additional degrees of freedom in the system design (in the number of relays, its position, and protocol used) allowing to match the target values (\( S_c, o, R_{\text{out}, o} \)) by simultaneously varying the cell size and the number of relay terminals, that is, the density of BS and the density of RS. As cell performance improves with the number of RS, a decrease in the density of BS can be compensated by deploying additional RS. This implies that given a traffic scenario (in terms of density of users and per-user traffic requirements) we can draw iso-performance plots as a function of the density of BS and the density of RS. This approach was proposed in the EC-funded WINNER project [23].

Let \( x \) represent the density of BSs and \( y \) the density of RSs, such that the function \( y(x) \) describes an indifference curve, on which each point represents a different BS-RS density of deployment having identical cell performance.

**Figure 2**: Maximum transmission rate for each position in the cell for direct transmission (a) and for relaying transmission: FW protocol with reuse of RS transmission (b) and TWRC-I protocol (c).

**Figure 3**: Cell radius selection for low and high offered traffic in terms of spectral efficiency (a). As the density of users is homogeneous, the traffic grows quadratically with the cell radius (cell radius selection for a given \( \epsilon \)-outage rate).
Then, parallel technoeconomic studies are developed for plots approach for a range of discrete values of \( m \) number of relay stations is evaluated using the indifference plot showing the tradeoff between the density of BS and the density of RS required for a given cell performance. A value of \( m = 12.5 \) is displayed, so the optimum density of trisector BS is around 2.5 km\(^{-2}\), and the optimum density of RS is around 23 km\(^{-2}\) BS.

(see Figure 4 where the piece-linear plot indicates that 0, 1, 2, 3, 4, and 5 RS per sector have been tested). Let the cost of a BS, \( A \) (in terms of CAPEX and OPEX), be \( m \) times the cost of an RS, A linear model for the cost assumes that

\[
\psi(x, y) = Ax + \frac{A}{m} y(x). \tag{4}
\]

The minimum cost system configuration may be obtained by minimizing this expression, leading to the condition \( y'(x) = -m \). Hence, the optimum density of BS and RS is given by the point where a line of slope \(-m\) is tangent to the indifference function \( y(x) \), under the assumption of convexity of \( y(x) \). An example of indifference plot is shown in Figure 4. Note that the conventional nonrelay-assisted cellular system is represented by the point \( x_0 \) where the curve \( y(x) \) meets the \( x \)-axis. The tangent line represents equal-cost deployments; so the optimum total cost of the network is given by \( Ax_0 \), where \( x_0 \) is the point where the line intersects the \( x \)-axis. Additionally, let us define \( x_1 \) as \( y(x_1) = 0 \). Then \( A(x_1 - x_0) \) indicates the savings in cost due to the deployment of relay-based systems.

In conclusion, the value of \( m \) will determine the optimal number of RS per sector. The reader should notice that \( m \) is largely unknown in principle, as it depends on many factors that are going to be considered latter on in Section 3. Having in mind that some of the costs do not scale with the number of BSs or RSs, the actual number of RSs on each sector influences the value of \( m \). This chicken-and-egg problem is solved in a kind of fixed-point solution: the optimum number of relay stations is evaluated using the indifference plots approach for a range of discrete values of \( m \) (5 to 8). Then, parallel technoeconomic studies are developed for each value of \( m \), and as a result, a ratio of cost \( m' \) is obtained. We finally retain the technoeconomic study for which \( m \) and \( m' \) have the closest values.

\[\text{Figure 4: Example of an indifference plot showing the tradeoff between the density of BS and the density of RS required for a given cell performance. A value of } m = 12.5 \text{ is displayed, so the optimum density of trisector BS is around } 2.5 \text{ km}\(^{-2}\), and the optimum density of RS is around } 23 \text{ km}\(^{-2}\) BS.\]

### 2.3.2. Cell Dimensioning with UL and DL Traffic Constraints.

The methodology defined above can be used to define cell radii with simultaneous constraints on the traffic for the UL and the DL. While no further elaboration is needed for the TWRC, since the resources are allocated user by user to fit the UL/DL constraints (see parameter \( \kappa \) in (A.12)), for OWRC the resources allocated to the UL and the DL need to be balanced. This is done assuming also dynamic duplexing time allocation: the fraction of time devoted to UL/DL transmissions is adjusted for every position in the cell so that the ratio of UL-to-DL transmission rate is a given value. In this way, it is possible to adjust the \( S_c \) in DL and UL so that the required cell radii for UL and for DL meet.

### 2.3.3. Radiated Power.

It has been mentioned that RSs are assumed inexpensive terminals as compared to BS. One of the reasons is their lower transmitted power, which is usually considered to be in the order of magnitude of the transmitted power by MS. Considering that half-duplex condition implies that BS and RS only transmit a fraction of the frame, the total radiated power per cell can in fact be lower than the radiated power in a nonrelay-assisted network. In this respect, Appendix A includes the expressions of the radiated power for each of the protocols considered here. Moreover, as the cell radius is increased with the deployment of RS, the overall radiated power in the network can be reduced significantly, thus alleviating social concerns, reducing the overall energy consumption for the operator, and increasing the battery lifetime for handsets.

### 3. Technoeconomic Model

#### 3.1. Approach and Methodology.

Technoeconomic modeling is a simulation-based approach for developing and optimizing system solutions in different operator and business environments. It can be extended from basic cost modeling to business models to produce an extensive set of financial and technical results.

It gives an opportunity to analyze network cost structure and the effect of service penetrations and revenues on overall business feasibility. This methodology has been deeply analyzed and applied to wireless access networks through a series of large research programs organized by the European Union (see, e.g., [35, 36] and reference therein). Moreover, it is frequently used by the national regulatory authorities (NRA) for the evaluation of policy options or in price setting of regulated markets (see, e.g., [37, 38]).

In this paper, technoeconomic modeling is used, firstly, to stand for the benefits of introducing relay-based techniques into a 4G wireless access network, and secondly, to evaluate the economic feasibility of the proposed network solutions in order to explore possible exploitation strategies. The business planning and network solution information make up the contents of the technoeconomic model (Figure 5). They can be roughly divided into two parts.

Firstly, the model has to include information about the factors that determine the revenues (and also the traffic...
demand during busy hour (BH) used for network dimensioning). This information consists of estimated service penetrations, service demand, charged tariffs, and similar factors. The model may also include geographical characteristics of the coverage areas (all the assumptions considered in this paper are presented in Section 3.2). The demand side of a technoeconomic model is often recognized as the critical factor that requires assumptions as reliable as possible. As a consequence, the selection of a realistic scenario is very important in the applicability of the analysis. In this paper, Spain has been considered as our reference country and lessons learnt can also be applied to other “big” western European countries such as France, Italy, UK, or Germany. Particularly, the business planning is based on the provision of ubiquitous voice and broadband data services through smartphones and dongles using the harmonized spectrum in the 2.6 GHz band.

Secondly, the model must include all the relevant cost elements. Typical inputs include the network architecture, network dimensioning principles, cost information for the various network equipments, and the administrative costs of the network. The price evolutions over time have also to be included in order to take into account economies of scales.

Operator costs for the network are often expressed as CAPital E XPenditure (CAPEX) and OPerating E XPenditure (OPEX). CAPEX is costs related to investment in equipment and the costs for the design and implementation of the network infrastructure, site acquisition, civil works, and so forth. The OPEX is made up of two different kinds of costs: network driven, costs associated with the operation and maintenance of the network, transmission, site rentals, and other expenses, and customer and revenue driven, also called business-driven, such as customer acquisition costs, user terminal subsidies, dealer commissions, administrative and personal costs, and interconnection. Finally, the economic viability could be assessed based on different financial parameters that compare revenues and costs such as Net Profit (NP), discounted cash flow (DCF), Net Present Value (NPV), or the Internal Rate of Return (IRR).

The dimensioning of the number of BS and RS is based on the OFDM-based 4G system model described in Section 2. The rest of network elements are dimensioned based on the carried traffic and on the configurations of the network elements considered as presented in Section 3.3.

Regarding network-related cost assessment, per-unit cost assumptions based on industry data is used in our model as described in Section 3.4. As a consequence, our technoeconomic model provides an estimation of actual CAPEX and OPEX costs associated with the roll-out of the different network elements letting us determine the actual

Figure 5: Flow diagram used in the technoeconomic model (assumptions and input values are shown in blue, intermediate calculations in orange, and final results in red).
BS-to-RS cost ratio (say \( m' \)). As it was mentioned earlier in Section 2.3.1, the radio planning model provides different dimensioning solutions corresponding to several values of \( m \). Each one of these solutions are used in the technoeconomic model in order to compare \( m \) and \( m' \) and to retain as final solution the one for what \( m \equiv m' \).

Finally, it is important to clarify that we are going to focus on network-related CAPEX and OPEX since a complete quantification of overall costs, especially in the case of business-driven OPEX, is difficult to perform. The estimations of the network-related costs allow us to provide an evaluation of the economic benefits that the integration of different relaying transmission techniques could provide (as presented in Section 4.1). However, the assessment of the economic feasibility of the roll-out recommends more viable exploitation strategies and requires the estimation of the overall costs. To this end, a typical value of 45% of total expenses corresponding to network-related OPEX and the rest (55%) corresponding to business-driven expenses have been assumed (as previously used in [2] or [39]).

### 3.2. Market Assumptions

Two target markets have been considered: the mobile communication market, where customers use voice and data services via mobile handsets, and the mobile broadband market, where a broadband Internet access service is provided using modem devices (such as USB dongles, PMClA cards, or modems integrated in different kinds of computers). The former market is characterized by having already reached very high penetration levels (higher than 100% of population in Western European countries) while the latter one is still an emerging market.

As a consequence, a slightly increasing service penetration has been assumed for the mobile communication market, from the 113% of the 1st year (Y1) to the 128% of the 10th year (Y10). In the case of the mobile broadband service, a penetration increasing from 6% in Y1 to 37% in Y10 has been assumed based on the current average penetration in Western Europe (6%) and the projection of the forecasted data provided by Analysys Mason in [40] (20% of penetration in Western Europe in 2015). In both cases, an increasing market share reaching 20% in Y10 is considered to simulate a new operator starting its operations. A logistic curve has been used for modeling the service penetration and market share increases. Finally, three scenario deployments (urban, suburban, and rural), characterized by typical population densities as shown in Table 5, are analyzed.

Service traffic is calculated considering the assumptions about service demand presented in Table 6. These assumptions are based on current commercial offering. Voice traffic during busy hour is calculated as 0.6% of monthly voice traffic volume, a standard assumptions provided by [41]. In the case of data services, 15% of the daily traffic being transmitted during the busy hour is assumed as proposed by [42].

### 3.3. Network Architecture and Dimensioning

Network dimensioning aims at calculating the optimal number of network elements (including nodes and links) that fulfill the capacity, coverage, and quality of service demanded in the service area at minimal total costs. The network architecture considered in this paper consists of a radio access network (RAN) based on a conventional single-hop or relay-assisted OFDM-based cellular network with an IP-based aggregation network (see Figure 6). The number of base stations and, in the case of using relaying transmission techniques, relay nodes required to attend service traffic is calculated using the OFDM-based 4G system model described in Section 2.

The costs associated with the IP aggregation network depend on physical distances among network locations (see per-unit expenses for backhaul links based on leased lines in Table 8). Therefore, the approach to modeling these network costs revolves around calculating realistic distance-dependent costs.

A typical approach is based on the definition of a geometric model where the coverage area, assumed square-shaped, is recursively divided in square-shaped subareas for the different aggregation levels that make up the aggregation network. This approach has been applied in the EC-funded BREAD project [43] and is used in this paper. Although the positioning and distances among the network elements provided by these models do not have to correspond to the architecture deployed in a real scenario (that could only be determined with detailed geographic information), these reference architectures give a first insight on the required infrastructure and facilitate the comparability of different scenarios (i.e., urban, suburban, and rural).

Our model assumes four hierarchical levels representing the different aggregation nodes (\( AN_n \)) presented in Figure 6, from base stations (\( AN_1 \)) to core routers (\( AN_4 \)). Each \( AN_n \) aggregates a configurable number of \( AN_{n-1} \) to which it is linked by an aggregation link (\( AL_{n-1} \)) following a bus, ring, or star topology. Having considered square-shaped areas, the length of each aggregation link for the different topologies could be easily determined based on a set of known formulas presented in [43, pages 12–15]. Additionally, a nonlinear factor (equal to 1.13), which increases length calculations, is considered in order to simulate the difficulties of connecting nodes with straight lines in a real deployment.

Here the procedure followed by the geometric model in dimensioning the IP aggregation network is briefly described. The users are uniformly distributed over a square, whose surface is equal to the coverage area, and the \( AN_1 \) (core router) is located in the middle of the square. This square is considered the reference square in the first step. The model connects \( m \) \( AN_3 \) (access routers) to the \( AN_4 \) each of the \( m \) \( AN_3 \) is distributed uniformly in the center of \( m \) squares.

#### Table 5: Population densities of the different scenario deployments.

<table>
<thead>
<tr>
<th>Scenario deployment</th>
<th>Population density per km²</th>
<th>Mobile communication subscribers per km² (Year 10)</th>
<th>Mobile broadband subscribers per km² (Year 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>10.000</td>
<td>2616</td>
<td>693</td>
</tr>
<tr>
<td>Suburban</td>
<td>1.000</td>
<td>262</td>
<td>69</td>
</tr>
<tr>
<td>Rural</td>
<td>50</td>
<td>13</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 6: Service demand assumptions used for traffic calculation and network dimensioning.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mobile communications user</th>
<th>Mobile broadband user</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data access service</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum downlink data rate (guaranteed in 70% of cell area)</td>
<td>1 Mbps</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>Minimum uplink data rate (guaranteed in 70% of cell area)</td>
<td>330 kbps</td>
<td>330 kbps</td>
</tr>
<tr>
<td>Monthly data volume cap (for download)</td>
<td>300 MB/month</td>
<td>3 GB/month</td>
</tr>
<tr>
<td>Yearly growth rate of data volume cap</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Uplink to downlink busy-hour (BH) data traffic ratio</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Voice services (Voice over IP)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average voice traffic per subscriber (busy hour)</td>
<td>13 mE</td>
<td>—</td>
</tr>
<tr>
<td>Yearly growth rate of voice service demand</td>
<td>10%</td>
<td>—</td>
</tr>
<tr>
<td>Voice call data rate</td>
<td>24 kbps</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 6: Radio access network architecture considered in our technoeconomic model.

with an area equal to the mth of the reference square’s area. This procedure is recursively repeated with each of the aggregation levels, AN3 (access routers) and AN2 (Ethernet switches). When the service traffic to attend requires the rollout of several core routers, the model performs an initial step where the coverage area is divided by the number of core routers before applying the geometric model to each of these squares.

In our model, eight AN3 per AN4, eight AN2 per AN3, and four AN1 (base stations) per AN2 have been assumed in order to achieve a good trade-off between reliability and costs. Regarding the technologies considered in each aggregation link, our model assumes Ethernet-leased lines in AL2 and AL3 and Synchronous Digital Hierarchy- (SDH-) leased lines in the transport network (AL4) based on typical leased lines commercial offering of incumbent operators in most countries and its geographic availability. Although the choice of using leased lines could be more expensive than the rollout of an own fiber network, it results in a lower risky option due to its lower initial investment required. In the case of rural areas, backhaul links (AL2) based on packet microwave point-to-point backhaul are considered for representing a cost-effective solution to typically unavailable leased lines.

3.4. Investment and Operating Cost Assessments. In general, obtaining an exact prediction of the deployment costs of a wireless cellular network is difficult as a consequence of the many different aspects that affect the results. To deal with this complexity, the per-unit investments and operating costs assumed in this paper are based on the costs of other well-known technologies, such as WiMAX or UMTS and on prices provided by operators, manufacturers, and national regulatory authorities (see Table 8 for all per-unit cost assumptions and information sources used). Notice, though, that the costs of an OFDM-based relay-assisted cellular network are hypothetical since the system is not yet available on the market. However, it should be a reasonable assumption (also used in [44]) that the cost of physical infrastructure, such as sites and transmission lines, be similar to those of previous technologies. Moreover, although price levels of electronics are constantly falling, new generation of radio access technologies with increased performance tends to have the same price level (per unit) as those in the previous systems.

In order to calculate total network-related costs, operating expenses and annualized investments are obtained from the per-unit cost assumptions and the network dimensioning
solutions according to (5) and (7), respectively. Annual price trends have been considered for the different per-unit costs meaning a reduction of equipment-related costs as a result of economies of scale or an increase in the case of assets involving labor activities or real estate rentals. Capital expenses (i.e., investments) are turned into yearly cost items by depreciating the required investment on each asset over its lifetime, the annualized CAPEX already mentioned, and calculated according to (6):

\[
\text{OPEX}^{(i)} = \sum_j N_j^{(i)} c_j^{\text{opex}} (1 + p_j^{\text{opex}})^{-i-1}, \tag{5}
\]

\[
\text{CAPEX}^{(i)} = \sum_j M_j^{(i)} c_j^{\text{capex}} (1 + p_j^{\text{capex}})^{-i-1}, \tag{6}
\]

\[
\text{Annualized CAPEX}^{(i)} = \sum_j \sum_{k = \max(i - LF_j + 1, 1)} \frac{\text{CAPEX}^{(i)}}{LF_j}, \tag{7}
\]

where \( j \in (\text{spectrum license acquisition, MBS equipment, etc.}) \) (i.e., each asset considered in Table 8), \( N_j^{(i)} \) is the number of items of type \( j \) operated during year \( i \), \( M_j^{(i)} \) is the number of items of type \( j \) purchased in year \( i \) (i.e., \( M_j^{(i)} = \max(N_j^{(i)} - N_j^{(i-1)}; 0}) \), \( c_j^{\text{capex}} \) and \( c_j^{\text{opex}} \) are the per-unit investment and operating cost, respectively, for each asset \( j \) in the 1st year, and \( p_j^{\text{opex}} \) and \( p_j^{\text{capex}} \) its yearly price trends. Finally, \( \text{CAPEX}^{(i)} \) is the investment in asset type \( j \) in year \( i \) as \( \text{CAPEX}^{(i)} = M_j^{(i)} \cdot c_j^{\text{capex}} \cdot (1 + p_j^{\text{capex}})^{i-1} \).

The different assets are classified in seven groups (spectrum, base stations, sites, backhaul, backhaul equipment, transport network, and core network), as presented in Table 8, for the presentation of the cost results in Section 4.1. The investment for the acquisition of spectrum license in the 2.6 GHz band is based on prices of the recently finished German auction (Table 7).

As shown in Table 7, prices for the unpaired frequencies of the 2.6 GHz band are very different in the countries that have already auctioned those bands. Many reasons justify those differences like, to mention a few, the market situation in term of competition and players, the availability of other frequency bands, or the technical and regulatory restrictions for the use of this band. Nevertheless, this uncertainty about spectrum acquisition prices does not really affect our results as a consequence of its invariability when comparing relay-assisted and conventional single-hop and of its minor importance regarding total network-related costs (representing lower than 1% for all network solutions considered).

Yearly costs, in terms of annualized CAPEX and OPEX, are then discounted by a cost of capital (a Weighted Average Cost of Capital, WACC) for the whole ten-year study period according to (8), in order to take into account the “time value of money”:

\[
\text{PV OPEX} = \frac{\sum_{i=1}^{n} \text{OPEX}^{(i)}}{(1 + \text{WACC})^i},
\]

\[
\text{PV Annualized CAPEX} = \frac{\sum_{i=1}^{n} \text{Annualized CAPEX}^{(i)}}{(1 + \text{WACC})^i}.
\]

A cost of capital equal to 15%, higher than the European mobile industry’s average, is assumed in this paper to reflect the risk premium associated with the entrance on a highly competitive market. These discounted values let us draw conclusions of the economic benefits of integrating relay transmission techniques by comparing total costs of both relay-assisted and conventional single-hop wireless networks as presented in Section 4.1.

Finally, the evaluation of economic feasibility is based on the Net Present Value (NPV), defined as the sum of the present value of the annual cash flow produced by a certain investment and calculated according to (9):

\[
\text{NPV} = \frac{\sum_{i=1}^{n} \text{Revenues}^{(i)} - \text{OPEX}^{(i)} - \text{CAPEX}^{(i)}}{(1 + \text{WACC})^i}.
\]

The annual cash flow is, in essence, the sum of the incoming (revenues) and outgoing (total costs, network-related and business-driven expenses considering the ratio 45%–55% already indicated in Section 3.1) money in the specific year, or in other words, the annual net benefit. Thus, the NPV is an indicator of how much value an investment adds to the firm with a positive value meaning a profitable investment.

### 4. Main Results and Discussion

The OFDM-based 4G system model and the technoeconomic model described in the previous sections have been combined to dimension the network elements and to calculate its corresponding network-related costs in the three scenario deployments. Simulations considering relay-assisted and conventional single-hop architectures have been performed for the system level parameters in Table 1. Based on the simulation results, a comparison of the performance and economic gains provided by each of the relay protocols regarding is presented in Section 4.1 in terms of reduction in the density of base station, relaying gain, and total network-related cost savings. Moreover, an economic feasibility
analysis and possible exploitation models and a discussion about the effects of relay transmission on the radiated power densities are also presented.

4.1. Performance and Economic Gains Comparison. Figure 6 shows the reduction in the base station density for urban (on the left) and rural scenarios (on the right) allowed by the use of the different relay protocols compared to the conventional single-hop architecture. Results considering one and two antennas in the user terminal devices are illustrated separately on the top (2 × 2 × 1 case) and on the bottom (2 × 2 × 2 case) of the figure, although the reductions shown are related, for both 2 × 2 × 1 and 2 × 2 × 2 cases, to the nonrelay-assisted 2 × 1 network solution in order to explore the complementarity of MIMO and relaying technologies. All simulations correspond to a network using 15 MHz per sector at the 2.6 GHz frequency band and the traffic demand assumptions described in Section 3.2 are used.

This reduction in the base station density is consequence of the enhanced spectral efficiency and the more homogeneous coverage provided by relayed transmissions. As the use of relay nodes introduces additional equipment and site costs, the cost efficiency of the relay-enhanced architecture regarding a conventional cellular architecture depends on the relation between the relaying gain, that is, the relation between the reduction of base station and the number of relay nodes, and the BS-to-RS cost ratio. Using the per-unit cost assumptions used in this paper and presented in Section 3.4, the BS-to-RS cost ratio turns out to be around 7-8 depending on the deployment scenario. The relaying gains, according to the following definition:

\[
\text{Relaying Gain}_{T_r} = \frac{\text{NumBS}_{\text{NoRelay}}(2 \times 1) - \text{NumBS}_{T_r}}{\text{NumRelayNodes}_{T_r}}, \quad (10)
\]

for each of the relay protocols and antenna configurations are also presented in Figure 6, where \( T_r \) represents a combination of a relay protocol (FW with or without reuse of RS transmit phase, OWRC-Prot-III or TWRC-Prot-I) and antenna configuration (2 × 2 × 1 or 2 × 2 × 2).

Although not shown, the results for suburban areas display slightly lower relaying gains than the ones obtained for urban areas for all relay protocols and antenna configurations. In addition to the gains provided by relaying transmission techniques, the benefits of using MIMO 2 × 2 are also shown (see the reduction in the BS density in the case of the nonrelay-assisted and 2 × 2 antenna configuration versus the 2 × 1 case on the bottom-left). As expected, the improvements provided by MIMO transmission are higher for more capacity-constrained networks (urban areas).

Regarding the relaying gain, some conclusions could be drawn. Firstly, comparing the different deployment scenarios, relaying gains are considerably higher in rural areas than those in urban and suburban ones for the four relaying protocols presented. Average relaying gains in the range from 38% to 96% (depending on the specific relay protocols and antenna configuration considered) are achieved in rural areas for the ten-year study period, showing even higher values in the first years, compared to mean values from 17% to 32% for urban and from 14% to 28% for suburban areas. This result shows the efficiency of relaying transmission techniques, especially in coverage limited environments.

Secondly, the results presented in Figure 6 show the complementarity of MIMO and relaying technology as higher relaying gains are obtained for all relay protocols when a higher number of antennas are used in the user terminal devices. As expected, this complementarity is higher for urban and suburban areas, as the system becomes capacity limited, and relays take advantage of the multiplexing gain offered by MIMO transmissions. Comparatively among the four protocols analyzed, OWRC-Prot-III takes higher advantage of MIMO technology than the other ones.

Finally, OWRC-Prot III and TWRC-Prot I show better performance than FW with and without reuse of RS tx in all deployment scenarios. More specifically, TWRC Prot I provides the higher relaying gain when using one antenna in the mobile terminal (2 × 2 × 1) and OWRC-III when using two antennas as a consequence of its higher ability to exploit the MIMO technology. In rural areas, where the advantages provided by MIMO technology are lower, TWRC-I becomes the best option for both antenna configurations.

Regarding economic benefits, Figure 8 shows the network-related costs savings provided by the integration of the different relay protocols compared to the conventional single-hop architecture for the three deployment scenarios. These network-related costs correspond to total OPEX and annualized CAPEX discounted over the ten-year study period according to (8). Once again, these cost savings are related to the total costs of the conventional nonrelay-assisted 2 × 1 architecture.

The substantial reductions on network-related costs provided by all the relay protocols analyzed (with the only exception of protocol FW with and without reuse of RS tx and 2 × 2 × 1 antenna configuration in suburban areas) explain the interest of incorporating cooperative relaying-assisted transmission in all 4G candidate systems. Moreover, these cost savings are higher in rural areas where the low population density increases the importance of achieving cost-efficient network solutions to facilitate the business cases as discussed in the following section. In the urban and suburban areas, the higher cost savings achieved in the case of using two antennas per user terminal evidence the complementarity, already mentioned, of the relaying and MIMO technologies. Comparatively among the different protocols studied, higher cost savings are achieved for the protocols with higher relaying gains. Therefore, TWRC-Prot I results in the more cost-efficient solution in the case of using one antenna per user terminal and in rural areas, and OWRC-Prot-III when using 2 × 2 × 2 in urban and suburban areas.

Figure 9 illustrates the distribution of the total costs among the different groups considered in Table 8 for the different access network solutions in both urban and rural deployment scenarios. Additionally, the cost savings provided by the different relay transmission techniques in each of these asset groups as compared to the costs of the conventional single-hop architecture are also shown.
<table>
<thead>
<tr>
<th>Group</th>
<th>Network element/Asset</th>
<th>Configuration quoted</th>
<th>Per-unit investment (€)—Year 1</th>
<th>Asset lifetime</th>
<th>Per-unit yearly expense (€)—Year 1</th>
<th>Yearly price trend</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum</td>
<td>Spectrum license acquisition at 2600 MHz frequency band</td>
<td>0.02 × MHz × Pop</td>
<td>20</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Table 7</td>
</tr>
<tr>
<td></td>
<td>Base stations Tri-sec ted Multi-hop capable Base Station (MBS)</td>
<td>48.000€</td>
<td>10</td>
<td>17.5% of CAPEX</td>
<td>−5%</td>
<td>[45]</td>
<td></td>
</tr>
<tr>
<td>Base stations Multi-hop relay station (MRS)</td>
<td>8.000€</td>
<td>10</td>
<td>15% of CAPEX</td>
<td>−5%</td>
<td>[45]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MBS</td>
<td>Site acquisition and construction</td>
<td>75.000€</td>
<td>20</td>
<td>—</td>
<td>2.5%</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td>Site lease</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2%</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td>MRS</td>
<td>Site acquisition and construction</td>
<td>5.000€</td>
<td>20</td>
<td>—</td>
<td>2.5%</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td>Site lease</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>2%</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td>MBS backhauling based on packet microwave link (AL2 in rural areas)—100 Mbps</td>
<td>16.242€</td>
<td>8</td>
<td>22% of CAPEX</td>
<td>−5%</td>
<td>[46]</td>
<td></td>
</tr>
<tr>
<td>Backhaul</td>
<td>Backhaul link based on Ethernet leased line (AL2 in urban and suburban areas and AL3)</td>
<td>Ethernet leased line—valid up to 12 km</td>
<td>—</td>
<td>—</td>
<td>7.729€</td>
<td>−5%</td>
<td>[47]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ethernet leased line—from 12 km to 35 km</td>
<td>—</td>
<td>—</td>
<td>11.613€</td>
<td>−5%</td>
<td>[47]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fast Ethernet leased line (100 Mbps)—valid up to 12 km</td>
<td>—</td>
<td>—</td>
<td>9.014€</td>
<td>−5%</td>
<td>[47]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fast Ethernet leased line—from 12 km to 35 km</td>
<td>—</td>
<td>—</td>
<td>13.278€</td>
<td>−5%</td>
<td>[47]</td>
</tr>
<tr>
<td>Transport network</td>
<td>Leased line used for the transport network (AL4)</td>
<td>STM-4 (622 Mbps)</td>
<td>—</td>
<td>—</td>
<td>72.336€</td>
<td>(3.220€ per additional km)</td>
<td>[48]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>STM-16 (2.5 Gbps)</td>
<td>—</td>
<td>—</td>
<td>87.533€</td>
<td>(3.901€ per additional km)</td>
<td>[48]</td>
</tr>
<tr>
<td>Group</td>
<td>Network element/Asset</td>
<td>Configuration quoted</td>
<td>Per-unit investment (€)—Year 1</td>
<td>Asset lifetime</td>
<td>Per-unit yearly expense (€)—Year 1</td>
<td>Yearly price trend</td>
<td>Source</td>
</tr>
<tr>
<td>-----------------------</td>
<td>---------------------------------------------------------------------------------------</td>
<td>----------------------</td>
<td>--------------------------------</td>
<td>----------------</td>
<td>-----------------------------------</td>
<td>-------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Backhaul equipment</td>
<td>Ethernet switch (up to 11 Gigabit Ethernet network interface cards)</td>
<td></td>
<td>30,000 €</td>
<td>10</td>
<td>9% of CAPEX</td>
<td>−4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Access router (up to 10 network interface cards based on Gigabit Ethernet or SDH hierarchy)</td>
<td></td>
<td>35,000 €</td>
<td>10</td>
<td>9% of CAPEX</td>
<td>−4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gigabit Ethernet network interface card (for Ethernet switches or access routers)</td>
<td></td>
<td>65,000 €</td>
<td>10</td>
<td>9% of CAPEX</td>
<td>−4%</td>
<td>Internal data provided by an operator</td>
</tr>
<tr>
<td></td>
<td>SDH network interface card (for Ethernet switches or access routers)</td>
<td></td>
<td>50,000 € (STM-4)</td>
<td>10</td>
<td>9% of CAPEX</td>
<td>−4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>200,000 € (STM-16)</td>
<td></td>
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<tr>
<td></td>
<td>Add-Drop Multiplexer (ADM)</td>
<td></td>
<td>16,632 € (STM-16)</td>
<td>10</td>
<td>9% of CAPEX</td>
<td>−4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aggregation point tower lease (per each AN₂ and AN₃)</td>
<td></td>
<td>—</td>
<td>—</td>
<td>30,000 €</td>
<td>2%</td>
<td>[45]</td>
</tr>
<tr>
<td>Core network</td>
<td>Core router (up to 10 network interface cards based on SDH hierarchy)</td>
<td></td>
<td>80,000 €</td>
<td>10</td>
<td>9% of CAPEX</td>
<td>−4%</td>
<td>Internal data provided by an operator</td>
</tr>
<tr>
<td></td>
<td>SDH network interface card (for core routers)</td>
<td></td>
<td>50,000 € (STM-4)</td>
<td>10</td>
<td>9% of CAPEX</td>
<td>−4%</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>200,000 € (STM-16)</td>
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<tr>
<td></td>
<td>ADM</td>
<td></td>
<td>16,632 € (STM-16)</td>
<td>10</td>
<td>9% of CAPEX</td>
<td>−4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NGN Platform per VoIP</td>
<td></td>
<td>6 €/subscriber</td>
<td></td>
<td></td>
<td>−4%</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td>Firewall (for each 500 MBS)</td>
<td></td>
<td>120,000 €</td>
<td>8</td>
<td>6% of CAPEX</td>
<td>−4%</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td>Internet traffic at Point of Presence (PoP)</td>
<td></td>
<td>—</td>
<td>—</td>
<td>25 €/Mbps</td>
<td>−10%</td>
<td>[45]</td>
</tr>
<tr>
<td></td>
<td>Site rental and utilities per PoP</td>
<td></td>
<td>—</td>
<td>—</td>
<td>48,000 €</td>
<td>2%</td>
<td>[45]</td>
</tr>
</tbody>
</table>
As expected, the higher cost savings provided by relaying technologies are obtained on the IP aggregation network (backhaul and aggregation network). The costs associated with these network elements consist of fixed costs, dependent on the number of equipments and transmission lines required, and variable costs, dependent on the service traffic. The introduction of relay nodes affects these two kinds of costs in opposite directions. Regarding fixed costs, the reduction on the number of aggregation nodes of the first layer of the hierarchical architecture (i.e., base stations), provided by the introduction of relay nodes, also decreases the number of aggregation nodes on the higher layer. Thus, a lower number of Ethernet switches, access routers, and its transmission lines are required what reduces the fixed costs in proportion to the reduction of base stations. However, the lower number of aggregation nodes and links increases the service traffic attended by each aggregation node and link and, thus, tends to increase variable costs.

Regarding sites and base stations costs, which include those related with both macrobase stations and relay nodes, the effect of the introduction of relay nodes depends on the relation between the relaying gain and the BS-to-RS cost ratio, as previously mentioned. Thus, an increase of those costs is achieved in those cases where a low relaying gain is obtained, that is, as the cases of the two FW and the OWRC-III protocols with \(2 \times 2 \times 1\) antenna configuration in urban areas, while additional cost savings are achieved in the rest of cases. However, the additional cost introduced by the presence of relay nodes makes the saving achieved in these asset groups lower than the ones obtained in the aggregation network.

Finally, the integration of relay transmission techniques changes the distribution of the total costs among the different asset groups of the OFDM cellular network as a consequence of these different cost savings. Thus, the typical cost distribution of a conventional single-hop cellular network...
scenario deployments. Thus, Figure 10 presents the feasibility of the roll-out of these access network solutions in the mobile communication market. Finally, our models are used to explore the economic aspect of the roll-out of these mobile networks, two can be mentioned: cable operators or alternative operators that provide broadband services based on the access to incumbent operators networks.

This roll-out could let them give respond to the fixed-mobile convergence trend and increase the competition with incumbent operators by offering differentiated services using its own wireless access networks in the urban and suburban areas. In fact, some examples of this trend can be mentioned as the consortium made up of bigger cable operators in the USA to acquire wireless spectrum licenses for the Advanced Wireless Services (AWSs) frequency band [49] or the acquisition of spectrum in the 2.6 GHz frequency band by two cable operators in Denmark [50].

Finally, the results obtained for rural areas confirms the general idea that the provision of mobile broadband services in these areas should be based on lower-frequency bands, such as the 800 MHz frequency band, resulting from the switchover from analog to digital television and usually known as digital dividend, or the 900 MHz band once its liberalization has been concluded in Europe and new technologies, in addition to GSM, are allowed. The better signal propagation in these frequency bands increases the range of the base stations and leads to significant CAPEX and OPEX cost savings (as presented, e.g., in [51] for the case of HSDPA networks operating at 900 MHz band).

Regarding the relaying technologies, the high cost savings provided by the integration of relaying capabilities into a single-hop OFDM-based cellular network in coverage-limited environments and the easily deployment of sites in these areas (easier than in urban and suburban areas) seem to justify that RS be part of the architecture of the future wireless access networks deployed in rural areas.

4.2. Economic Feasibility and Possible Exploitation Strategies. Finally, our models are used to explore the economic feasibility of the roll-out of these access network solutions in the operator environment considered (a new operator in the mobile communication market). Thus, Figure 10 presents the minimum ARPU required to achieve a profitable business case (i.e., a NPV equal to zero) depending on the technical solution used in the access wireless network deployed. The ARPU values shown in the figure correspond to users of the mobile communications market. In the case of users of the mobile broadband market, an ARPU 76% higher has been considered following pricing practices frequently used in these markets. A reference level of 30 € per month is marked as an estimation of what a typical user of the mobile communication market is willing to spend on these services.

The results are shown for the three deployment scenarios considering conventional single-hop and relay-enhanced (only protocols showing best performance in Section 4.1 have been selected) wireless networks using the 2.6 GHz frequency bands and different channel bandwidths per sector. As shown in the figure, the profitability of the networks using the 2.6 GHz frequency band is especially high for the urban deployment scenario and, to a lesser extent, for the suburban ones. In this latter case, 15 MHz or 20 MHz per sector, which corresponds to a total of 45 MHz or 60 MHz in the 2.6 GHz frequency band, respectively, are required to achieve a profitable business case. As a consequence, an OFDM-based macrocellular network enhanced by different relaying transmission techniques as the ones presented in this paper and operating in the recently available 2.6 GHz frequency band could be used by a new operator to enter the mobile communications market. Among the operator candidates to be interested in the roll-out of these mobile networks, two can be mentioned: cable operators or alternative operators that provide broadband services based on the access to incumbent operators networks.

Figure 8: Network-related costs savings over the ten-year study period provided by the different relaying techniques in the three scenario deployments.

![Network-related costs savings](image_url)

(45% corresponding to base station and site costs, slightly lower in urban areas and higher in rural areas as a consequence of the higher or lower weight of the core network costs, resp., 50% corresponding to backhaul and aggregation network and among 5% and 2% for core network costs in urban and rural areas, resp.) changes and the site and base station costs gain a higher weight regarding the costs associated to the aggregation network (in the margin 10%–15%).

4.3. Radiation Density of Relay Transmissions and Human Exposure. The ongoing concern about the radiation levels and electromagnetic pollution of wireless communications systems might affect the acceptance ratio of relay-based deployments: on one side, the size of cells is larger and hence the number of large BS will decrease, but on the other side, an increased number of RS (although smaller) could generate social concerns. It is however the case that RS can transmit at a lower power since they are in line-of-sight of BS and the pathloss to the assisted MS is smaller (see Table 1). Additionally, to the half-duplex operation of RS, they are not transmitting all the time; so the average radiated power is smaller than their maximum nominal power.
In this respect, Figure 11 shows the radiated power density (in dBm/Km²) for different protocols over the ten-year study period, for DL (including BS-to-RS/MS and RS-to-MS transmissions) in the urban scenario (similar conclusions can be derived for the UL and the suburban and rural scenarios). In all cases, the radiated power density for relay-based deployments exhibits a much gentler uptake than for the nonrelay network, and for the highest demand considered (latest years), the radiated power may have been reduced by 1/3 compared with the relay-based deployment. Notice also that different relay protocols are also emitting slightly different power levels, and that the use of multiple antennas at the MS also reduces the transmitted power density, around a 30% for both nonrelay-assisted and relay-assisted cases (with the exception of TWRC-I protocol for what a lower reduction, 10%, is achieved).
Although not specifically proved in this work due to the lack of data about BS and RS power consumptions, these results suggest that relay technologies are also serious candidates for greener wireless network practices.

5. Conclusions and Future Work

A technoeconomic methodology has been proposed as a means to assess the economic gains provided by the integration of different relaying techniques into an OFDM-based cellular network. To this end, an OFDM-based 4G system model and a technoeconomic model for wireless access networks have been used and combined with the dimensioning of the whole access network (from the macrobase and relay stations up to the IP aggregation network) to calculate total network-related costs. By recognizing that the selection of a realistic scenario is very significant in the applicability of the analysis made, a new operator provisioning ubiquitous voice and broadband data services in the urban, suburban, and rural areas of a western European country using the 2.6 GHz band has been considered.

Under this framework, the performance and economic gains provided by different half-duplex DF relay protocols regarding the nonrelay-based case are presented in terms of reduction in the density of base station, relay gain, and total network-related cost savings. Specifically, a simple forwarding relaying protocol and more complex protocols (One-Way Relay Channel Protocol III and Two-Way Relay Channel Protocol I) are selected so as to evaluate in economical terms the gains of deploying relay technologies based on noncooperative or cooperative protocols. Moreover, two different antenna configurations have been considered to evaluate the extra performance gains arising from MIMO transmissions.

Substantial reductions on network-related costs have been observed for the different relay protocols and scenario deployments that justify the interest of incorporating relaying-assisted transmission in all 4G candidate systems. These cost savings are especially high in rural areas (around 50%) where low population density increases the importance of achieving cost-efficient technical solutions to facilitate the business cases. This higher efficiency of relaying in coverage limited environments is in line with previously published works.

The results presented also show the complementarity of MIMO and relaying technology as higher relaying gain, and consequently, higher cost savings are obtained for (almost) all relay protocols when more than one antenna are used in the user terminal devices. As expected, this complementarity is higher for urban and suburban areas, as the system becomes capacity limited, and relays take advantage of the multiplexing gain offered by MIMO transmissions.

Comparing protocols, OWRC-III and TWRC-I show better performance than pure forwarding in all geographic areas (especially in rural). More specifically, TWRC-I results in the more cost-efficient solution in the case of $2 \times 2 \times 1$ antenna configuration and in rural areas, and OWRC-III in the case of using $2 \times 2 \times 2$ in urban and suburban areas as a consequence of its ability to take higher advantage of the MIMO transmission.

Finally, the results provided for an economic feasibility analysis demonstrate the viability of the exploitation strategies of these technologies. Conclusions have also been
derived about the radiated power of relay-based wireless communications systems.

Future works will focus on applying the technoeconomic methodology described here to analyzing other relaying transmission techniques and on considering mixed frequency planning issues where the network uses the spectrum resources available at different frequency bands to optimize the network deployment, for example, using the spectrum shadowing (channel component and matrix $H$) relay ($ff$) consumption that can be obtained from different frequency planning issues where the network uses the spectrum methodology described here to analyzing other relaying derived about the radiated power of relay-based wireless communications systems.

**Appendices**

**A. Analysis of Relaying Protocols**

We derive here the achievable rates and the overall power consumption that can be obtained from different relaying protocols based on half-duplex DF operation at the RS.

Both forward and Protocol III can be applied to the UL or DL; so let us define the signal model received at the generic destination ($D$) terminal, when sent by the relay ($R$), the source ($S$) terminal, or jointly by the source and relay ($SR$). Let us define $L$ the slow fading (path loss and shadowing) channel component and matrix $H$ the single-carrier MIMO spatial channel that accounts for multipath Rayleigh/Rice statistics in each link. The dimension of each $H$ matrix is the number of receive antennas times the number of transmit antennas. $x_s$ and $x_r$ are the transmitted signals from the source and relay, respectively, while $y_r$ and $y_d$ are the received signals at the relay and the destination terminals, respectively. The power input constraints are $E\{|x|^2\} = P_s$, and $E\{|x|^2\} = P_R$ at the BS and RS, respectively. Terms $z$ include the Gaussian noise plus interference.

**A.1. OWRC-Forwarding Protocol.** The received signal at the destination terminal on a single carrier is given by

$$y_d = \sqrt{L_{S,D}} H_{S,D} x_s + z_d \quad \text{(A.1)}$$

in the case where there is a direct transmission from the source and the destination. For relaying transmission, the signals at the relay and the destination are given by

$$y_r = \sqrt{L_{S,R}} H_{S,R} x_s + z_r, \quad y_d = \sqrt{L_{R,D}} H_{R,D} x_r + z_d.$$  \quad \text{(A.2)}$$

During phase I, the RS listens to the source destination transmission. Later on, the relay decodes the data and transmits to the destination. The optimum fraction of time $\alpha$ each terminal accesses the channel is computed according to the following optimisation problem:

$$R = \max_{\alpha \in [0,1]} \left( C_{S,D} \max_{\alpha \in [0,1]} \left( \min(\alpha C_{S,R}, (1 - \alpha) C_{R,D}) \right) \right), \quad \text{(A.3)}$$

where, following to the assumptions adopted in Section 3.1, $C_{S,D}, C_{S,R},$ and $C_{R,D}$ account for the ergodic capacity of the source-destination, source-relay, and relay-destination links. The optimum fraction of transmission time associated to the source-relay link $\alpha$ is obtained after equating the two arguments in the min$(\cdot)$ function in (A.3):

$$R^* = \max \left( C_{S,D}, \frac{C_{S,R} C_{R,D}}{C_{S,D} + C_{R,D}} \right),$$

$$\alpha^* = \begin{cases} 1 & \text{if } C_{S,D} > \frac{C_{S,R} C_{R,D}}{C_{S,D} + C_{R,D}}, \\ \frac{C_{R,D}}{C_{S,D} + C_{R,D}} & \text{otherwise}. \end{cases} \quad \text{(A.4)}$$

As for the average radiated power over the cell, and assuming uniform traffic distribution, it is simple to derive the expressions for the radiated power in the UL and the DL:

$$P_{DL} = (1 - \alpha_{UL-DL}) \sum_{i \in A} (P_{BS} \alpha_i + P_{RS} (1 - \alpha_i)) T_i = \frac{\sum_{i \in A} T_i}{\sum_{i \in A} T_i}, \quad \text{(A.5)}$$

$$P_{UL} = \alpha_{UL-DL} \sum_{i \in A} (P_{MS} \alpha_i + P_{RS} (1 - \alpha_i)) T_i,$$  \quad \text{(A.6)}$$

where $\alpha_{UL-DL}$ denotes the fraction of the frame devoted to the UL transmission. As mentioned in Section 2.3, the transmission time $T_i$ allocated to user $i$ is related to the rate of the relayed-transmission through $T_i \approx R_i^*$ and, hence, the overall transmitted power depends on the scheduling strategy adopted.

**A.2. OWRC-Forwarding Protocol with Reuse of RS Resources.** Due to its simplicity, the forwarding protocol allows an improved allocation of resources on the basis of the harsh propagating conditions in the RS-MS link: the same portion of the frame devoted to RS-MS transmissions (in the DL) or MS-RS transmissions (in the UL) could be allocated to transmissions from the multiple RS in the sector (in the DL) or MS (in the UL). If this is the case, increased interference is compensated by a more intensive use of the radio resources.

Because we are using common resources for the relay transmission (or reception in the UL) period, the optimization of $\alpha$ will depend on the characteristics of all the users. Therefore, we have to maximize the sum-capacity ($C_{\text{reuse}}$) when $K$ terminals are transmitting on the same resource:

$$C_{\text{reuse}} = \max \left( \frac{1}{K} \sum_{i=1}^{K} C_{S,R}(i), \max_{0 < \alpha < 1} \sum_{i=1}^{K} C_{\text{ind}}(i) \right), \quad \text{(A.6)}$$

$$C_{\text{ind}}(i) = \min \left( \frac{\alpha}{K}, C_{S,R}(i), (1 - \alpha) C_{R,D}(i) \right).$$

In order to illustrate the benefits of reusing the relay-transmit period we will consider that all the users had the same capacities on every link (and no-interference in the relay-transmit period). In that case, the optimum value of $\alpha^*$ and the optimum capacity are given by

$$R_{\text{reuse}}^* = \begin{cases} \alpha^* C_{S,R} & \text{if } C_{S,D} < \frac{C_{S,R} C_{R,D} K}{C_{S,R} + C_{R,D} K}, \\ C_{S,D} & \text{otherwise}, \end{cases} \quad \text{(A.7)}$$

$$\alpha^* = \begin{cases} 1 & \text{if } C_{S,D} > \frac{C_{S,R} C_{R,D} K}{C_{S,R} + C_{R,D} K}, \\ \frac{C_{R,D} K}{C_{S,R} + C_{R,D} K} & \text{otherwise}. \end{cases} \quad \text{(A.7)}$$

$$\alpha^* = \begin{cases} 1 & \text{if } C_{S,D} > \frac{C_{S,R} C_{R,D} K}{C_{S,R} + C_{R,D} K}, \\ \frac{C_{R,D} K}{C_{S,R} + C_{R,D} K} & \text{otherwise}. \end{cases} \quad \text{(A.7)}$$
A.3. OWRC-Protocol III. This is the protocol described in [12] and provides the best spectral efficiency among all OWRC protocols so far published. However, it requires complex receiver at the destination. The reason is that in the first time slot, the source transmits a message \( w_s \) to the relay and destination using signal \( x_s(w_s) \). On the second time slot, the relay transmits an independent signal \( x_r(w_r) \) associated to the same message, while the source transmits a new message to the destination \( x_s(w_d) \). The total information transmitted is given by the messages delivered to the relay (in the first time slot) and the message delivered from the source (in the second time slot). The capacity of the TD relay channel is lower-bounded by

\[
R = \max_{0 \leq \alpha \leq 1} \min(R_1, R_2),
\]

(A.8)

with \( R_1 \) and \( R_2 \), being the information rate delivered in the first and second relay phases, respectively, and \( \alpha \) is the normalised duration of the slot. \( R_1 \) and \( R_2 \) will be defined in the following:

\[
R_1 = aR_{S,R} + (1 - \alpha)R_{S,D},
\]

\[
R_2 = aR_{S,D} + (1 - \alpha)R_{SR-D}.
\]

The maximization of the achievable rate (A.8) has to be done over \( \alpha \), taking into account the different possible values of the capacities, as depicted in Figure 12.

Therefore, the optimum \( \alpha \) is given by

\[
\alpha^* = \begin{cases} 
\frac{C_{SR-D} - C_{S-D}}{C_{S-R} - 2C_{S-D} + C_{SR-D}} & \text{if } C_{S-R} > C_{S-D}, \\
0, & \text{otherwise,}
\end{cases}
\]

(A.10)

and the maximum rate is given by

\[
R^* = \max(C_{S-D}, \alpha^* C_{S-R} + (1 - \alpha^*)C_{S-D})
\]

\[
= \begin{cases} 
\frac{C_{SR-D}C_{S-R} - (C_{S-D})^2}{C_{S-R} - 2C_{S-D} + C_{SR-D}} & \text{if } C_{S-R} > C_{S-D}, \\
C_{S-D}, & \text{otherwise.}
\end{cases}
\]

(A.11)

As for the average radiated power over the cell, and assuming uniform traffic distribution, it is straightforward to derive the following expressions:

\[
P_{DL} = (1 - \alpha_{DL}) \sum_{i \in A} (P_{BS}a_i + (P_{RS} + P_{BS})(1 - a_i))T_i.
\]

\[
P_{UL} = \alpha_{UL-DL} \sum_{i \in A} (P_{MS} + P_{RS})a_i + P_{BS}(1 - a_i))T_i.
\]

(A.12)

A.4. Two-Way Relay Channel. Two protocols are devised for the TWRC: forwarding and protocol I, both sketched in Figure 13. In the former (Figure 13(a)), the transmission consists of two orthogonal phases: in phase I, BS and MS transmit simultaneously to RS, while in phase II, RS transmits to BS and MS. However, if the direct link between BS and MS is exploited, the protocol must be redefined using three orthogonal phases (Figure 13(b)). In the first phase, BS transmits to MS and RS. Afterwards in the second phase, the MS transmits to BS and RS. Finally, the RS transmits to both terminals in phase III.

The RS can adopt different transmissions strategies in the last transmission phase of the TWRC protocols. For instance, [16] analyzes AF and DF protocols with superposition coding criteria. While in the first one, the RS just amplifies the received signal, in the second one it transmits two streams and distributes the power among them. However, the transmission strategy that gets the highest spectral efficiency is based on network coding relaying (NCR) [52, 53], where the RS generates a common signal intended to both, BS and MS, which is based on the messages received in previous phases.

We will again assume that the duration of the phases can be optimized. The achievable rate regions for protocols sketched in Figure 13 are shown in [17] to be

\[
B_{NCR}^F(\alpha_1, \alpha_2) = \begin{cases} 
R_{BS} \leq \alpha_1C_{BS-MS}(P_{BS}), \\
R_{BS} \leq \alpha_2C_{RS-MS}(P_{RS}), \\
R_{MS} \leq \alpha_1C_{MS-RS}(P_{MS}), \\
R_{MS} \leq \alpha_2C_{BS-RS}(P_{BS}), \\
R_{BS} + R_{MS} \leq \alpha_1C_{BS-MS-RS}(P_{BS}, P_{MS}), \\
\end{cases}
\]

\[
B_{NCR}(\alpha_1, \alpha_2, \alpha_3) = \begin{cases} 
R_{BS} \leq \alpha_1C_{BS-MS}(P_{BS}), \\
R_{BS} \leq \alpha_1C_{BS-MS}(P_{BS}) + \alpha_3C_{BS-MS}(P_{RS}), \\
R_{MS} \leq \alpha_2C_{BS-RS}(P_{MS}), \\
R_{MS} \leq \alpha_2C_{BS-RS}(P_{MS}) + \alpha_3C_{BS-BS}(P_{RS}), \\
\end{cases}
\]

(A.13)

where \( R_{BS} \) and \( R_{MS} \) denote the transmitted rate by BS and MS, respectively, \( \alpha_1, \alpha_2, \) and \( \alpha_3 \) account for the fraction of time allocated to each phase of the TWRC (see Figure 13), \( C_{X-Y} \) stands for the capacity of the X-Y link, and finally, \( C_{BS,MS-RS} \) is the capacity assuming that BS and MS transmit simultaneously to RS.

The optimal selection of phase duration, data rate, and power allocated by the relay terminal to each message
are found as the solution of the following constrained optimization problem:

\[
\begin{align*}
\max_{\alpha_1, \alpha_2, \alpha_3, R_{BS}, R_{MS}, P_{BS}, P_{MS}, P_{RS}} & \quad \mu_{BS} R_{BS} + \mu_{MS} R_{MS}, \\
\psi(P_{BS}, P_{MS}, P_{RS}) & \leq P, \\
R_{BS} - \kappa R_{MS} & \leq 0, \\
(R_{BS}, R_{MS}) & \in B_{NCR}^{TW}(\alpha_1, \alpha_2), \\
\alpha_1 + \alpha_2 & = 1, \quad \text{forwarding}, \\
(R_{BS}, R_{MS}) & \in B_{NCR}^{I}(\alpha_1, \alpha_2, \alpha_3), \\
\alpha_1 + \alpha_2 + \alpha_3 & = 1, \quad \text{protocol I},
\end{align*}
\]

(A.14)

where \(\mu_{BS}\) and \(\mu_{MS}\) denote the priorities of the streams transmitted by BS and MS and parameter \(\kappa\) accounts for the traffic asymmetry between DL and UL transmissions. Finally, function \(\psi\) considers the cases when there is a sum-average power constraint, or in contrast, all terminals transmit with maximum power. In this latter case, the transmitted power variables are not optimized and the constraint due to function \(\psi\) in (A.12) disappears. The problem defined in (A.12) is shown in [17] to be convex, and hence, to have a unique solution that can be obtained by simple algorithms based on interior point methods. It has been observed that TWRC Prot I achieves better spectral efficiency for a wide range of positions of the RS [17], and hence it is the TWRC protocol considered in this study.

Similarly, the average radiated power over the cell can be obtained from the following expressions, for the forwarding protocol:

\[
\begin{align*}
P_{DL} & = \frac{\sum_{i \in A} (P_{BS} \alpha_1 + (1 - \gamma) P_{RS} \alpha_2) T_i}{\sum_{i \in A} T_i}, \\
P_{UL} & = \frac{\sum_{i \in A} (P_{MS} \alpha_1 + \gamma P_{RS} \alpha_3) T_i}{\sum_{i \in A} T_i},
\end{align*}
\]

(A.15)

where \(\gamma\) is the fraction of power allocated at the RS for the message transmitted by the MS. For the protocol I case, similar expressions can be derived which now involve the duration of the three phases:

\[
\begin{align*}
P_{DL} & = \frac{\sum_{i \in A} (P_{BS} \alpha_1 + (1 - \gamma) P_{RS} \alpha_3) T_i}{\sum_{i \in A} T_i}, \\
P_{UL} & = \frac{\sum_{i \in A} (P_{MS} \alpha_2 + \gamma P_{RS} \alpha_3) T_i}{\sum_{i \in A} T_i}.
\end{align*}
\]

(A.16)

Acknowledgments

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