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Spectral, energy and economic efficiency of relay-aided cellular networks

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Abstract: The authors investigate the relay-aided multicell multiple-input–multiple-output (MIMO) cellular network by comparing both the signal forwarding and interference forwarding relaying paradigms, each employing the adaptive MIMO relay scheme. The spectral, energy and economic efficiency values are utilised as key performance metrics. Furthermore, both radio frequency and circuit power consumption are considered in the energy calculation. They demonstrate that there is a tradeoff between spectral and energy efficiency. Thus, economic profitability is used to find a balance in the tradeoff as profitability is important to the long term deployment of a scheme. They introduce the economic efficiency metric which considers the inherent tradeoff as a complementary performance measure to obtain maximum economic profitability while maintaining gains in both spectral and energy efficiency.

1 Introduction

First described by Meulen [1] four decades ago, relay-aided wireless transmission has gained considerable attention and is envisaged to be a promising technology towards realising future communication infrastructures. The two-hop relay-aided cooperative transmission has been of particular interest [2]. During the first hop (broadcast phase), the source transmits its signal to the relay and sometimes the destination if it is near. The relay can then perform decode-and-forward (DF) [3], compress-and-forward (CF) [4] or amplify-and-forward (AF) [5] on the signal before relaying it to the destination during the second hop (relay phase).

Inter-cell interference occurs when two or more sources at different cells simultaneously transmit, without cooperation, to their intended destinations via relays. This interference relay channel was first studied in [6] for a two-source one-relay two-destination configuration in a Gaussian channel where the achievable rate region was derived with rate splitting. In [7, 8], two relays were considered instead, turning the channel into a cascaded interference channel where the sources transmit to the relays via an interference channel in the first hop and the relays cooperatively transmit to the destinations via a subsequent interference channel in the second hop. In [9], relays were utilised to forward a copy of the interference so that it is strong enough for the destination to cancel it. In [10], both the training signal and the arrival time interval of the interference were utilised by the relay to assist in interference cancellation at the destination. The work thus far considered either the signal forwarding or the interference forwarding relaying paradigms, with direct transmission normally taken as the benchmark. Therefore there is insufficient study in comparing the two relaying paradigms. Sahin *et al.* [11] attempted to address this by evaluating the capacity of the signal forwarding and the interference forwarding elements of the interference relay channel by utilising a relay infrastructure which transmits in orthogonal channels to the underlying interference channel with all nodes having single antenna.

Recently, there has been increased interest in green communication techniques which aim to design energy efficient communication networks. The concept of green communications encompasses the whole of wireless communication life cycle, including design and manufacturing, deployment, operation and decommissioning of the network. Our work focuses on the protocol design and operation cost of green communications, specifically for relay transmission techniques. Relay-aided cooperative communication is an attractive technique towards realising the energy efficiency target. Huang *et al.* [12] considered energy efficiency while maximising the lifetime of a cooperative network through joint relay selection and power allocation strategies. The work was confined to AF relays without any source–destination direct link. In [13], the additional energy cost of implementing relay selection schemes was considered and minimised. In [14], dynamically allocated mobile relays were deployed to minimise energy consumption and extend the lifetime of a network of static nodes. Besides that, a scheme that minimised the energy consumption of a DF relay network based on bit error rate constraint was proposed in [15] whereas in [16], a cooperative broadcasting method was proposed which allowed destination nodes to accumulate signal energy from multiple source nodes to improve signal detection and reduce energy consumption. Hong *et al.* [17] proposed power allocation schemes which reduced the transmission power for several relay network configurations. In both [16, 17], the relays were constrained to perform either DF or AF on the signal.

The majority of works from the aforementioned authors utilised either spectral efficiency or energy efficiency as a performance metric. Although in [18–20] there was an attempt to jointly consider them in their work, the tradeoff between spectral efficiency and energy efficiency of relay networks is yet to be completely understood. Furthermore, circuit power consumption, a major power drain in multiple-input–multiple-output (MIMO) systems, was not considered in [12–17] when evaluating energy efficiency. Our paper intends to address some of the shortcomings of the previous work. Our contributions are summarised as follows:

1. We investigate the performance of the signal forwarding and interference forwarding relaying paradigms in a relay-aided cellular network. For each relaying paradigm, an adaptive MIMO relay scheme [21] is considered where the relays perform both the DF and AF relaying mechanisms. The conventional direct transmission cellular network is compared with the relay schemes. Our purpose is not to propose spectrally efficient relaying mechanisms (e.g. dynamic DF) but to investigate the signal forwarding and interference forwarding relaying paradigms incorporating the adaptive MIMO relay scheme.
2. We consider both the spectral and energy efficiency of the schemes. The energy efficiency includes both radio frequency (RF) and circuit power consumption. We demonstrate that there is a tradeoff between spectral efficiency and energy efficiency of the relay schemes.
3. Inspired by Akhtman and Hanzo [20], we propose the economic efficiency metric as a complementary performance measure to spectral and energy efficiency. The economic efficiency metric finds a point in the spectral-energy efficiency tradeoff (SEET) region which provides maximum economic profitability. We differentiate our metric from [22] which mainly utilised one-off insertion and fixed costs as terms in their cost efficiency metric. These costs do not reflect the crucial operational power consumption cost and thus, the metric has limitation in representing the tradeoff accurately.
4. Lastly, we also investigate the influence of the relay position on spectral efficiency, energy efficiency and economic efficiency of the relay scheme.

In this paper, bold uppercase letters, for example, $\boldsymbol{X}$, denote matrices while bold lowercase letters, for example, $\boldsymbol{x}$, denote vectors. A scalar value is denoted by italics, for example, X or x. The Hermitian transpose, inverse, pseudo-inverse and Frobenius norm of a matrix are represented by $\boldsymbol{X}^{\mathrm{H}}$, $\boldsymbol{X}^{-1}$, $\boldsymbol{X}^{\dagger}$ and $\|\boldsymbol{X}\|_{\mathrm{F}}^{2}$, respectively, whereas $\boldsymbol{I}_N$ is an $N \times N$ identity matrix. Besides that, the expectation, determinant and XOR operators are given by $\mathbb{E}\{\cdot\}$, $\det[\cdot]$ and $\oplus$, respectively.

The rest of the paper is organised as follows. Section 2 describes the network topology, channel assumptions, the signalling protocol and the power consumption model of the relay-aided cellular network. In Section 3, the interference sources of the network are identified. The relaying mechanisms are explained next in Section 4, whereas in Section 5, the economic efficiency metric is proposed. Following that, some numerical examples and discussions are presented in Section 6. Finally, concluding remarks are given in Section 7.

2 System model

2.1 Network topology

Let us consider a multicell cellular network consisting of a 7-cell wrap-around hexagonal structure as illustrated in Fig. 1 with the set $\mathcal{C} = \{1, \ldots, 7\}$ representing the hexagonal cells of the network structure. Each cell has a base station (BS) at its centre and is further divided into N_{Sec} sectors described by the set $\mathcal{S} = \{1, \ldots, N_{\mathrm{Sec}}\}$. We assume M relay stations (RSs) are located at each sector. These equally spaced RSs are located at d_{RS} from the cell centre and are denoted by set $\mathcal{M} = \{1, \ldots, M\}$. A total of K user equipments (UEs) per sector defined by the set $\mathcal{K} = \{1, \ldots, K\}$ are selected to participate in the transmission. Furthermore, the indices $b(i, j)$, $r(i, j, m)$ and

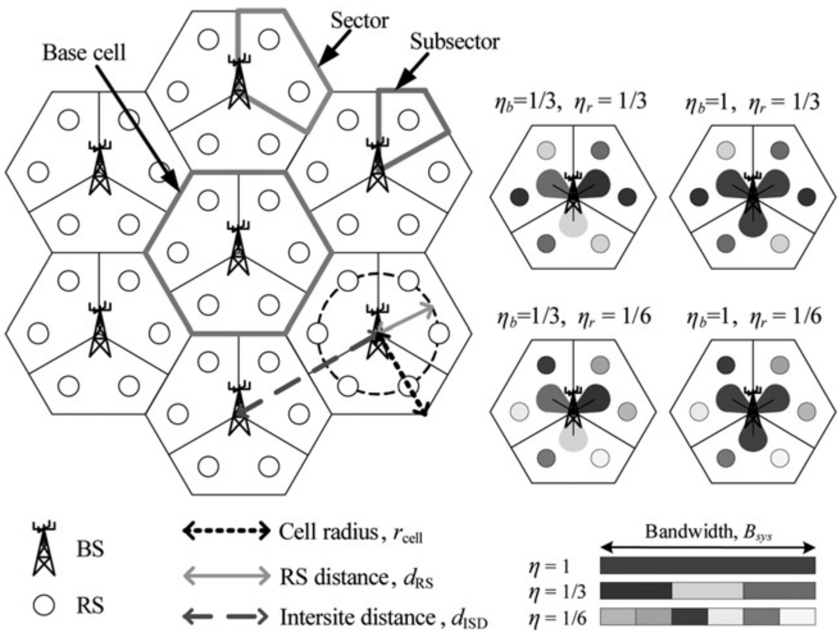

Fig. 1 *Relay-aided MIMO cellular network with different frequency planning modes for both the broadcast and relay phases (M = 2)*

$u(i, j, k)$ describe the BS from the ith sector of the jth cell, the mth RS from the ith sector of the jth cell and the kth user from ith sector of the jth cell, respectively. The performance of the base (centre) cell is of primary focus in this work. Each BS has N_b antennas per sector, whereas the number of antennas of the RSs and UEs are N_r and N_u, respectively. The system bandwidth is B_{sys}.

2.2 Propagation channel model

Consider two nodes X and Y whereby X is transmitting data to Y. Let $\boldsymbol{H}_{X,Y} \in \mathbb{C}^{A\times B}$ be the channel matrix of size $A \times B$ between X and Y. The elements of $\boldsymbol{H}_{X,Y}$ are $h_{a,b}$ where $1 \le a \le A$ and $1 \le b \le B$. These elements are modelled as

$$h_{a,b} = G_X\ G_Y\left(L_{X,Y}\right)^{-1}\ 10^{(\xi_{X,Y}/10)}\ \mu_{X,Y} \tag{1}$$

where G_X and G_Y are the transmit antenna gain of X and the receive antenna gain of Y, respectively. The path loss between X and Y is defined as $L_{X,\ Y}$. The following term represents log-normal shadowing with $\xi_{X,\ Y}$ being a Gaussian random variable having zero mean and standard deviation, σ_s dB. The values for these terms depend on whether X and Y are BS, RS or UE nodes. These are shown in Table 1 with parameters selected from [23]. Lastly, $\mu_{X,\ Y}$ denotes the complex Rayleigh fast fading coefficient with unit variance.

2.3 Transmission protocols

Let us consider the downlink transmission of a cellular mobile network. The transmission protocol is described for the relay-aided cellular network over a single transmission frame having time interval T. In the relay-aided cellular network, both the BSs and RSs participate in data transmission. For practical reasons, a half-duplex transmission mode is assumed for the RSs. We assume a single user scheduler to clearly demonstrate the benefit of relaying alone without any multiuser diversity gains typically obtained from a multiuser scheduler. In this case, one UE per subsector is selected to participate in the transmission while the corresponding RS at that subsector is assigned to serve the selected UE, giving $K = M$. A full traffic load is assumed so that there is at least one UE per subsector waiting to be served at any given instant. In addition, the broadcast and relay channels are known to the RSs and UEs, respectively.

The downlink transmission at each sector uses time division multiple access whereby each of the K UEs is allocated equal fraction of the transmission frame timeslot denoted by $\tau_d T$, where $\tau_d = (1/K)$. Within $\tau_d T$, either a direct transmission or relay transmission will be performed, depending on which returns a higher throughput. Although direct transmission utilises the whole $\tau_d T$, relay transmission further subdivides it into a broadcast phase and a relay phase having transmission duration $\tau_{bc}\tau_d T$ and $\tau_r\tau_d T$, respectively, given that $\tau_{bc} = 1 - \tau_r$ and $0 \le \tau_{bc} \le 1$. The mechanisms for relay transmission will be described in Section 4.

We also implement frequency reuse planning for transmission of both BSs and RSs where the frequency reuse patterns are as illustrated in Fig. 1. For the BS transmission, a frequency reuse factor of η_b indicates a frequency reuse at every $1/\eta_b$ consecutive sectors in a cell whereas for the RS transmission, a frequency reuse factor of η_r suggests a frequency reuse after every $1/\eta_r$ consecutive RSs in a cell.

Table 1 Simulation parameters

Path loss model, $L_{X,Y}$ (d in km)	BS–RS BS–UE RS–UE	$125.2 + 36.3\log_{10}(d)$ dB $131.1 + 42.8\log_{10}(d)$ dB $145.4 + 37.5\log_{10}(d)$ dB
Shadowing standard deviation, σ_s	BS–RS BS–UE RS–UE	6 dB 10 dB 10 dB
Antenna pattern ($\theta_{3\,dB} = 70°$, $A_m = 2$ dB)	BS	$\rho(\theta) = -\min\left(12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right)$ dB
	RS–BS	$\rho(\theta) = -\min\left(12\left(\frac{\theta}{\theta_{3dB}}\right)^2, A_m\right)$ dB
	RS–UE UE	Omni Omni
Antenna gain (boresight)	BS RS–BS RS–UE UE	14 dBi (including cable losses) 7 dBi (including cable losses) 5 dBi (including cable losses) 0 dBi
Noise power spectral density, N_0		−174 dBm
Base service data rate (voice), r_{base}		10 kbps
Revenue per bit, κ_r		1.54×10^{-6} pence/bit [24]
Energy cost per Ws, κ_c		2.8×10^{-6} pence/Ws [25]

2.4 Power consumption model

In modelling the circuit power consumption, we adopt a methodology similar to [26]. The circuit power consumption of BSs and RSs is proportional to their allocated RF transmit power P_b and P_r, respectively. Thus, there is no circuit power consumption when no transmission is occurring. This is to emulate how future green BSs are expected to operate [27] when the BS hardware efficiency is improved. Let $P_{c,\mathrm{ref}}$ be the circuit power consumption at a given RF transmit power P_{ref}. Therefore circuit power consumption of the BS is given as

$$P_{c,b} = \frac{P_b P_{c,\mathrm{ref}}}{P_{\mathrm{ref}}} \tag{2}$$

while the circuit power consumption of the RS is written as

$$P_{c,r} = \frac{P_r P_{c,\mathrm{ref}}}{P_{\mathrm{ref}}} \tag{3}$$

The operational power of the system includes both the RF transmit power and circuit power consumption. Considering the aggregate effects of the duplexer/feeder losses and the efficiencies of the antenna/amplifier modules, let the effective operational efficiencies of the BS and RS be represented by α_b and α_r, respectively. Therefore the operational power utilised for transmission to the kth UE in a relay-aided cellular network is written as

$$P_{\mathrm{op}}^{(k)} = \begin{cases} (1-\tau_r)\tau_d\alpha_b P_b + \tau_r\tau_d\alpha_r P_r + P_{c,b}/K + P_{c,r} & \text{if relay} \\ \tau_d\alpha_b P_b + P_{c,b}/K + P_{c,r} & \text{if direct} \end{cases} \tag{4}$$

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The circuit power consumed by the RS is included in the second line of (4) even though direct transmission is selected. This is because in a relay-aided cellular network, the RS circuitry must be functioning at all times for fast response. We do not consider advanced methods like sleep modes, for example [28], where algorithms are designed mostly for green BSs to switch off non-essential circuit components while being idle. As for the conventional direct transmission cellular network which operates without employing RSs, the operational power is solely because of the BSs and is given by $\tau_d\alpha_b P_b + P_{c,b}/K$.

Similar to [26], the energy consumption ratio (ECR) is used to measure the energy efficiency of the system. It is proportional to the ratio of the average operational power to the average capacity of the system under consideration. The ECR per sector of the system under consideration is, thus, given as

$$\text{ECR}_{\text{sys}} = \frac{\mathbb{E}\left\{P_{\text{op,sys}}\right\}}{B_{\text{sys}}\,\mathbb{E}\left\{C_{\text{sys}}\right\}} \tag{5}$$

where C_{sys} is the spectral efficiency per sector of the system under consideration in bits/s/Hz while the total operational power per sector of the system under consideration is denoted as $P_{\text{op,sys}} = \sum_{k\in\mathcal{K}} P_{\text{op}}^{(k)}$, assuming that there are K UEs per sector as represented by set $\mathcal{K}$. Therefore the ECR has units of Joules per bit (J/bit).

3 Interference analysis

We will now briefly describe the interference sources of the relay-aided cellular network. Let $s \in \mathcal{S}$ be the current sector under consideration in the base cell. Also, let $f_{b(1,s)}$ be the BS transmitting frequency to the RSs and UEs at sector s of the base cell. The set of interference sources experienced by the RSs during the broadcast phase of the relay transmission and by the UEs during direct transmission at sector s are from the other BSs transmitting to other sectors at frequency $f_{b(i,j)}$ equals to $f_{b(1,s)}$, that is

$$\mathcal{X} = \left\{(i,j)\middle|(i,j) \in \mathcal{C}\times\mathcal{S}, f_{b(i,j)} = f_{b(1,s)}\right\} \tag{6}$$

Thus, assuming the interference sources are independent, the interference covariance matrix at the mth RS at sector s of the base cell is given as

$$\boldsymbol{R}_{BC}^{r(1,s,m)} = \sum_{(i,j)\in\mathcal{X}} \frac{P_b}{N_b}\left(\boldsymbol{H}_{b(i,j),r(1,s,m)}\boldsymbol{H}_{b(i,j),r(1,s,m)}^{\text{H}}\right) \tag{7}$$

while for the kth UE at sector s of the base cell, the interference covariance matrix is given as

$$\boldsymbol{HR}_D^{u(1,s,k)} = \sum_{(i,j)\in\mathcal{X}} \frac{P_b}{N_b}\left(\boldsymbol{H}_{b(i,j),u(1,s,k)}\boldsymbol{H}_{b(i,j),u(1,s,k)}^{\text{H}}\right) \tag{8}$$

From (6), the strongest interfering BS to the kth UE at sector s of the base cell is identified as $b(i_0, j_0)$ where

$$\left(i_0, j_0\right) = \underset{(i,j)\in\mathcal{X}}{\arg\max}\left\|\boldsymbol{H}_{b(i,j),u(1,s,k)}\right\|_F^2 \tag{9}$$

Subsequently, the interference covariance matrix for the kth UE at sector s of the base cell without the strongest interfering BS is defined as

$$\bar{\boldsymbol{R}}_D^{u(1,s,k)} = \sum_{(i,j)\in\mathcal{X}\oplus(i_0,j_0)} \frac{P_b}{N_b}\left(\boldsymbol{H}_{b(i,j),u(1,s,k)}\boldsymbol{H}_{b(i,j),u(1,s,k)}^{\text{H}}\right) \tag{10}$$

Furthermore, let index $r(i_0, j_0, m_0)$ represent the RS that is designated to relay the interference of $b(i_0, j_0)$. Thus, the interference covariance matrix for $r(i_0, j_0, m_0)$ during the broadcast phase is written as

$$\boldsymbol{R}_{BC}^{r(i_0,j_0,m_0)} = \sum_{\substack{(i,j)\in\mathcal{C}\times\mathcal{X}\\(i,j)\neq(i_0,j_0)}} \frac{P_b}{N_b}\left(\boldsymbol{H}_{b(i,j),r(i_0,j_0,m_0)}\boldsymbol{H}_{b(i,j),r(i_0,j_0,m_0)}^{\text{H}}\right) \tag{11}$$

When all the RSs are actively transmitting during the relay phase, the RSs interfering in the kth UE with receiving frequency $f_{u(1,s,k)}$ at sector s of the base cell are the surrounding RSs from other sectors that are relaying at frequency $f_{r(i,j,m)} = f_{u(1,s,k)}$. The set of RSs interfering in the kth UE at sector s of the base cell is thus

$$\mathcal{P}^{u(1,s,k)} = \left\{(i,j,m)\middle|(i,j,m) \in \mathcal{X}\times\mathcal{M}, f_{r(i,j,m)} = f_{u(1,s,k)}\right\} \tag{12}$$

Consequently, its interference covariance matrix is given by

$$\boldsymbol{R}_R^{u(1,s,k)} = \sum_{(i,j,m)\in\mathcal{P}^{u(1,s,k)}} \frac{P_r}{N_r}\left(\boldsymbol{H}_{r(i,j,m),u(1,s,k)}\boldsymbol{H}_{r(i,j,m),u(1,s,k)}^{\text{H}}\right) \tag{13}$$

whereas its interference covariance matrix in the absence of $r(i_0, j_0, m_0)$ is given by

$$\bar{\boldsymbol{R}}_R^{u(1,s,k)} = \boldsymbol{R}_R^{u(1,s,k)} - \frac{P_r}{N_r}\left(\boldsymbol{H}_{r(i_0,j_0,m_0),u(1,s,k)}\boldsymbol{H}_{r(i_0,j_0,m_0),u(1,s,k)}^{\text{H}}\right) \tag{14}$$

The expressions presented here are utilised when describing the signal forwarding and interference forwarding relaying paradigms in Section 4.

4 Overview of the relaying schemes

In this section, we describe the relaying mechanisms for the signal forwarding relaying (SFR) and interference forwarding relaying (IFR) paradigms, focusing on the kth UE and its assigned mth RS at sector s of the base cell. For conciseness, indices $b(1, s)$, $r(1, s, m)$ and $u(1, s, k)$ are abbreviated to $\bar{b}, \bar{r}$ and $\bar{u}$, respectively, in subsequent channel matrix notations. Furthermore, the index for the strongest interfering BS, $b(i_0, j_0)$, is abbreviated to b_0 while the index $r(i_0, j_0, m_0)$, representing the RS that is designated to relay the interference caused by b_0, is abbreviated to r_0. Also, the noise power is represented by $\sigma^2 = N_0 B_{\text{sys}}$.

4.1 *Signal forwarding relaying*

The main idea of the SFR scheme is to increase the reliability of the desired signal at the destination by relaying a copy of it to the corresponding UE. The DF and AF relaying mechanisms are considered whereby the designated signal forwarding RS $\bar{r}$ will select either one of the two relaying mechanisms depending on the channel condition between $\bar{b}$ and $\bar{r}$. The received signal vector of $\bar{r}$ is

$$\boldsymbol{y}_{\bar{r}} = \sqrt{\frac{P_b}{N_b}}\boldsymbol{H}_{\bar{b},\bar{r}}\boldsymbol{s}_{\bar{b}} + \sum_{(i,j)\in\mathcal{X}}\sqrt{\frac{P_b}{N_b}}\boldsymbol{H}_{b(i,j),\bar{r}}\boldsymbol{s}_{b(i,j)} + \boldsymbol{n}_{\bar{r}} \tag{15}$$

where the first term is the desired signal component, whereas the second and third terms are the inter-cell interference and noise present at $\bar{r}$, respectively. Assuming that $\mathbb{E}\{\boldsymbol{s}_i\boldsymbol{s}_i^{\mathrm{H}}\} = \boldsymbol{I}_{N_b}$, the maximum supported transmission rate is, therefore given by

$$R_{\bar{b},\bar{r}} = \log_2\det\left[\boldsymbol{I}_{N_r} + \frac{P_b}{N_b}\boldsymbol{H}_{\bar{b},\bar{r}}\boldsymbol{H}_{\bar{b},\bar{r}}^{\mathrm{H}}\left(\boldsymbol{R}_{BC}^{\bar{r}} + \eta_b\sigma^2\boldsymbol{I}_{N_r}\right)^{-1}\right] \tag{16}$$

Given that the BS transmission rate is $R_{\bar{b}}$, the DF relaying mechanism is selected if $R_{\bar{b}} \le R_{\bar{b},\bar{r}}$ in order for the signal to be decodable at the RS. At the destination, the UE achieves diversity gain by utilising both the direct and relay link signals. These signals are stacked before commencement of the decoding process. The transmission rate achieved by the UE is thus

$$R_{\bar{u},\mathrm{DF}} = \log_2\det\left[\boldsymbol{I}_{2N_u} + \boldsymbol{Q}_{\mathrm{SFR,DF}}\boldsymbol{W}_{\mathrm{SFR,DF}}^{-1}\right] \tag{17}$$

Assuming that the signal and interference sources are mutually independent, the covariance matrices $\boldsymbol{Q}_{\mathrm{SFR,DF}}$ and $\boldsymbol{W}_{\mathrm{SFR,DF}}$ in (17) can be defined as

$$\boldsymbol{Q}_{\mathrm{SFR,DF}} = \begin{bmatrix} \frac{P_b}{N_b}\boldsymbol{H}_{\bar{b},\bar{u}}\mathbf{H}_{\bar{b},\bar{u}}^{\mathrm{H}} & \boldsymbol{0} \\ \boldsymbol{0} & \frac{P_r}{N_r}\boldsymbol{H}_{\bar{r},\bar{u}}\boldsymbol{H}_{\bar{r},\bar{u}}^{\mathrm{H}} \end{bmatrix} \tag{18}$$

and

$$\boldsymbol{W}_{\mathrm{SFR,DF}} = \begin{bmatrix} \boldsymbol{R}_D^{\bar{u}} + \eta_b\sigma^2\boldsymbol{I}_{N_u} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{R}_R^{\bar{u}} + \eta_r\sigma^2\boldsymbol{I}_{N_u} \end{bmatrix} \tag{19}$$

If $R_{\bar{b}} > R_{\bar{b},\bar{r}}$, the RS is unable to decode the incoming signal. Hence, the AF relaying mechanism is selected whereby the RS will just amplify the signal before relaying it to the UE. The amplification factor is given as

$$g_{\bar{r}} = \frac{P_r}{\left\|\left(P_b/N_b\right)\boldsymbol{H}_{\bar{b},\bar{r}}\boldsymbol{H}_{\bar{b},\bar{r}}^{\mathrm{H}}\right\|_{\mathrm{F}}^2 + \eta_b\sigma^2N_r} \tag{20}$$

whereas the transmission rate achieved by the UE is hence

$$R_{\bar{u},\mathrm{AF}} = \log_2\det\left[\boldsymbol{I}_{2N_u} + \boldsymbol{Q}_{\mathrm{SFR,AF}}\boldsymbol{W}_{\mathrm{SFR,AF}}^{-1}\right] \tag{21}$$

where the covariance matrices $\boldsymbol{Q}_{\mathrm{SFR,AF}}$ and $\boldsymbol{W}_{\mathrm{SFR,AF}}$ are defined as

$$\boldsymbol{Q}_{\mathrm{SFR,AF}} = \begin{bmatrix} \frac{P_b}{N_b}\boldsymbol{H}_{\bar{b},\bar{u}}\boldsymbol{H}_{\bar{b},\bar{u}}^{\mathrm{H}} & \boldsymbol{0} \\ \boldsymbol{0} & g_r\frac{P_b}{N_b}\boldsymbol{H}_{\bar{r},\bar{u}}\boldsymbol{H}_{\bar{b},\bar{r}}\boldsymbol{H}_{\bar{b},\bar{r}}^{\mathrm{H}}\boldsymbol{H}_{\bar{r},\bar{u}}^{\mathrm{H}} \end{bmatrix} \tag{22}$$

and

$$\boldsymbol{W}_{\mathrm{SFR,AF}} = \begin{bmatrix} \boldsymbol{R}_D^{\bar{u}} + \eta_b\sigma^2\boldsymbol{I}_{N_u} & \boldsymbol{0} \\ \boldsymbol{0} & g_r\boldsymbol{H}_{\bar{r},\bar{u}}\left(\boldsymbol{R}_{\mathrm{BC}}^{\bar{r}} + \eta_b\sigma^2\right)\boldsymbol{H}_{\bar{r},\bar{u}}^{\mathrm{H}} + \boldsymbol{R}_R^{\bar{u}} + \eta_r\sigma^2\boldsymbol{I}_{N_u} \end{bmatrix} \tag{23}$$

with the spectral efficiency of the kth UE for the SFR scheme given as

$$C_{\mathrm{SFR}}^{(k)} = \begin{cases} \tau_d\min\{\eta_b\tau_{bc}R_{\bar{b},\bar{r}},\ \eta_r\tau_rR_{\bar{u},\mathrm{DF}}\} & \text{if } R_{\bar{b}} \le R_{\bar{b},\bar{r}} \\ \eta_r\tau_r\tau_dR_{\bar{u},\mathrm{AF}} & \text{otherwise} \end{cases} \tag{24}$$

If the quality of the BS-UE direct link is high, for example, when the UE is near the BS, it is desirable to perform direct transmission throughout the τ_dT transmission time duration which is allocated to the kth UE. The direct transmission spectral efficiency for the kth UE is given as

$$C_{\mathrm{Direct}}^{(k)} = \eta_b\tau_d\log_2\det\left[\boldsymbol{I}_{N_u} + \frac{P_b}{N_b}\boldsymbol{H}_{\bar{b},\bar{u}}\boldsymbol{H}_{\bar{b},\bar{u}}^{\mathrm{H}}\left(\boldsymbol{R}_D^{\bar{u}} + \eta_b\sigma^2\boldsymbol{I}_{N_u}\right)^{-1}\right] \tag{25}$$

Therefore the SFR scheme adapts its transmission mode between direct and relay transmission according to the current channel conditions. Assuming there are K UEs per sector as represented by set $\mathcal{K}$, the system spectral efficiency per sector of the SFR scheme is, thus, given by

$$C_{\mathrm{sys,SFR}} = \sum_{k\in\mathcal{K}}\max\left\{C_{\mathrm{SFR}}^{(k)},\ C_{\mathrm{Direct}}^{(k)}\right\} \tag{26}$$

We observe that the SFR scheme offers improvement to the signal-to-interference ratio (SIR) by enhancing the strength of the desired signal. This increases the success rate of reliably detecting the desired signal in the presence of interference.

4.2 Interference forwarding relaying

The tenet behind the IFR scheme is to increase the power of the strongest interfering signal to the UE so that it can be reliably detected and cancelled before the UE decodes the desired signal. This helps in improving the overall quality of the desired signal in the absence of the strongest interfering signal. Similarly, the designated interference forwarding RS, r_0 will select either the DF or AF relaying mechanism when forwarding a copy of the interfering signal to the UE. The received signal vector of r_0 is

$$\boldsymbol{y}_{r_0} = \sqrt{\frac{P_b}{N_b}}\mathbf{H}_{b_0,r_0}\boldsymbol{s}_{b_0} + \sum_{\substack{(i,j)\in\mathcal{C}\times\mathcal{X} \\ (i,j)\neq(i_0,j_0)}}\sqrt{\frac{P_b}{N_b}}\boldsymbol{H}_{b(i,j),r_0}\boldsymbol{s}_{b(i,j)} + \boldsymbol{n}_{r_0} \tag{27}$$

where the first term is the desired interfering signal to be forwarded by r_0, whereas the second and third terms are the undesired inter-cell interference and noise present at r_0, respectively. Therefore the maximum supported transmission

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rate between b_0 and r_0 is given as

$$R_{b_0,r_0} = \log_2 \det\left[\mathbf{I}_{N_r} + \frac{P_b}{N_b}\boldsymbol{H}_{b_0,r_0}\boldsymbol{H}^{\mathrm{H}}_{b_0,r_0}\left(\boldsymbol{R}^{R_0}_{\mathrm{BC}} + \eta_b\sigma^2\boldsymbol{I}_{N_r}\right)^{-1}\right] \quad (28)$$

although the transmission rate of b_0 itself will be given as R_{b_0}. The RS will select the DF relaying mechanism if $R_{b_0} \le R_{b_0,r_0}$ else the AF relaying mechanism will be selected instead.

At the destination, the UE will attempt to decode the interfering signal with the assistance of the relayed copy. The interfering signals received by the UE from both the direct and relay links are stacked before the decoding process is attempted. For successful interference decoding, the transmission rate, R_{b_0} must further satisfy

$$R_{b_0} \le \log_2 \det\left[\boldsymbol{I}_{2N_d} + \boldsymbol{Q}_{\mathrm{IFR}}\boldsymbol{W}^{-1}_{\mathrm{IFR}}\right] \quad (29)$$

where $\boldsymbol{Q}_{\mathrm{IFR}}$ and $\boldsymbol{W}_{\mathrm{IFR}}$ are the covariance matrices of the stacked signals representing the desired interfering signal and other residual interference, respectively. The expressions for these covariance matrices will depend on the type of relaying mechanism which the RS employed when performing interference forwarding and are given as

$$\boldsymbol{Q}_{\mathrm{IFR}} = \begin{cases} \begin{bmatrix} \frac{P_b}{N_b}\boldsymbol{H}_{b_0,\bar{u}}\boldsymbol{H}^{\mathrm{H}}_{b_0,\bar{u}} & \mathbf{0} \\ \mathbf{0} & \frac{P_r}{N_r}\boldsymbol{H}_{r_0,\bar{u}}\boldsymbol{H}^{\mathrm{H}}_{r_0,\bar{u}} \end{bmatrix} & \text{if DF} \\ \begin{bmatrix} \frac{P_b}{N_b}\boldsymbol{H}_{b_0,\bar{u}}\boldsymbol{H}^{\mathrm{H}}_{b_0,\bar{u}} & \mathbf{0} \\ \mathbf{0} & g_{r_0}\frac{P_b}{N_b}\hat{\boldsymbol{H}}_{r_0}\hat{\boldsymbol{H}}^{\mathrm{H}}_{r_0} \end{bmatrix} & \text{otherwise} \end{cases} \quad (30)$$

where $\hat{\boldsymbol{H}}_{r_0} = \boldsymbol{H}_{r_0,\bar{u}}\boldsymbol{H}_{b_0,r_0}$ and (see (31))

where $\hat{\boldsymbol{R}}_{\mathrm{BC}} = \boldsymbol{R}^{r_0}_{\mathrm{BC}} + \eta_b\sigma^2\boldsymbol{I}_{N_u}$.

If the condition in (29) is not satisfied, the interference is not decodable. Instead, the UE will calculate a scaled version of the relayed interference signal. After detection by either decoding or scaling, the desired interfering signal will then be reconstructed to match the one originally received by the UE during the broadcast phase. Subsequently, the reconstructed interference is subtracted from that originally received signal.

We observe that there are four outcomes which can transpire, each contributing to a different spectral efficiency of the IFR scheme. The observed outcomes are

1. RS r_0, performs DF interference relaying while UE $\bar{u}$ successfully decodes it.
2. RS r_0 performs DF interference relaying while UE $\bar{u}$ is unsuccessful in decoding it.
3. RS r_0 performs AF interference relaying while UE $\bar{u}$ successfully decodes it.
4. RS r_0 performs AF interference relaying while UE $\bar{u}$ is unsuccessful in decoding it.

Specifically, these four outcomes determine the final amount of residual interference and therefore influence the interference covariance matrix embedded in the spectral efficiency expression of the IFR scheme. The general spectral efficiency expression of the kth UE for the IFR scheme which encompasses the four outcomes is, thus, given as

$$C^{(k)}_{\mathrm{IFR}} = \eta_b\tau_d\tau_{bc}\log_2\det\left[\boldsymbol{I}_{N_u} + \frac{P_b}{N_b}\boldsymbol{H}_{\bar{b},\bar{u}}\boldsymbol{H}^{\mathrm{H}}_{\bar{b},\bar{u}}\boldsymbol{W}^{-1}_0\right] \quad (32)$$

where $\boldsymbol{W}_0$ is the said interference covariance matrix. Its elements are shown in Table 2 for the four different outcomes. Similarly, the IFR scheme adapts its transmission mode between direct and relay transmissions according to the current channel conditions. Assuming we have K UEs per sector as given in set $\mathcal{K}$, the system spectral efficiency per sector of the IFR scheme is

$$C_{\mathrm{sys,IFR}} = \sum_{k\in\mathcal{K}} \max\left\{C^{(k)}_{\mathrm{IFR}}, C^{(k)}_{\mathrm{Direct}}\right\} \quad (33)$$

where $C^{(k)}_{\mathrm{Direct}}$ is the direct transmission spectral efficiency for the kth UE as defined in (25). Contrary to the SFR scheme, the IFR scheme does not offer SIR gains by increasing the desired signal strength but rather by removing the strongest interfering signal to improve the reliability of the received signal for successful detection.

The conventional direct transmission cellular network (DIRECT) employs only direct transmission throughout its operation. Its system spectral efficiency per sector is given as

$$C_{\mathrm{sys,DIRECT}} = \sum_{k\in\mathcal{K}} C^{(k)}_{\mathrm{Direct}} \quad (34)$$

4.3 Energy efficiency optimisation

In this section, we present the formulation to optimise the energy efficiency of a given relay scheme, $\wp$, with a targeted spectral efficiency identical to that achieved by the DIRECT scheme which is taken as the baseline. With the $\mathrm{ECR_{sys}}$ being defined in (5), the energy efficiency optimisation problem is formulated as

$$\begin{aligned} \underset{\{P_b,P_r\}}{\text{minimise}} \quad & \mathrm{ECR}_{\mathrm{sys},\wp} \\ \text{subject to} \quad & C_{\mathrm{sys},\wp} = C_{\mathrm{sys,DIRECT}} \\ & P_b + MP_r \le P_0 \\ & P_{b,\mathrm{DIRECT}} = P_0 \\ & P_b, P_r > 0 \end{aligned} \quad (35)$$

$$\boldsymbol{W}_{\mathrm{IFR}} = \begin{cases} \begin{bmatrix} \frac{P_b}{N_b}\boldsymbol{H}_{\bar{b},\bar{u}}\boldsymbol{H}^{\mathrm{H}}_{\bar{b},\bar{u}} + \bar{\boldsymbol{R}}^{\bar{u}}_D + \eta_b\sigma^2\boldsymbol{I}_{N_u} & \mathbf{0} \\ \mathbf{0} & \bar{\boldsymbol{R}}^{\bar{u}}_R + \eta_r\sigma^2\boldsymbol{I}_{N_u} \end{bmatrix} \\ \begin{bmatrix} \frac{P_b}{N_b}\boldsymbol{H}_{\bar{b},\bar{u}}\boldsymbol{H}^{\mathrm{H}}_{\bar{b},\bar{u}} + \bar{\boldsymbol{R}}^{\bar{u}}_D + \eta_b\sigma^2\boldsymbol{I}_{N_u} & \mathbf{0} \\ \mathbf{0} & g_{r_0}\boldsymbol{H}_{r_0,\bar{u}}\hat{\boldsymbol{R}}_{\mathrm{BC}}\boldsymbol{H}^{\mathrm{H}}_{r_0,\bar{u}} + \bar{\boldsymbol{R}}^{\bar{u}}_R + \eta_r\sigma^2\boldsymbol{I}_{N_u} \end{bmatrix} \end{cases} \quad (31)$$

Table 2 Interference covariance matrix, $\boldsymbol{W}_0$, of the IFR scheme

Outcome		RS r_0 relaying mechanism	
		DF	AF
Is UE $\bar{u}$ able to decode?	yes	$\bar{\boldsymbol{R}}_D^{\bar{u}} + \eta_b\sigma^2\boldsymbol{I}_{N_u}$	$\bar{\boldsymbol{R}}_D^{\bar{u}} + \eta_b\sigma^2\boldsymbol{I}_{N_u}$
	no	$\frac{P_bN_r}{P_rN_b}\boldsymbol{V}\left(\bar{\boldsymbol{R}}_R^{\bar{u}} + \eta_r\sigma^2\boldsymbol{I}_{N_u}\right)\boldsymbol{V}^{\mathrm{H}} + \bar{\boldsymbol{R}}_D^{\bar{u}} + \eta_b\sigma^2\boldsymbol{I}_{N_u}$	$\boldsymbol{F}\left(\boldsymbol{R}_{\mathrm{BC}}^{r_0} + \eta_b\sigma^2\boldsymbol{I}_{N_u}\right)\boldsymbol{F}^{\mathrm{H}} + \frac{1}{g_{r_0}}\boldsymbol{G}\left(\bar{\boldsymbol{R}}_R^{\bar{u}} + \eta_r\sigma^2\boldsymbol{I}_{N_u}\right)\boldsymbol{G}^{\mathrm{H}} + \bar{\boldsymbol{R}}_D^{\bar{u}} + \eta_b\sigma^2\boldsymbol{I}_{N_u}$

Definitions: $\boldsymbol{V} = \boldsymbol{H}_{b_0,\bar{u}}\boldsymbol{H}^{\dagger}_{r_0,\bar{u}}$, $\boldsymbol{F} = \boldsymbol{H}_{b_0,\bar{u}}\boldsymbol{H}^{\dagger}_{b_0,r_0}$ and $\boldsymbol{G} = \boldsymbol{H}_{b_0,\bar{u}}\left(\boldsymbol{H}_{r_0,\bar{u}}\boldsymbol{H}_{b_0,r_0}\right)^{\dagger}$

where P_b and P_r are the transmit powers for BS and RS of the relay scheme, $\wp$, respectively, whereas $P_{b,\mathrm{DIRECT}}$ is the transmit power for the BS of the DIRECT scheme, given that the available transmit power is P_0. We perform an exhaustive search for the values of the $\{P_b, P_r\}$ pair which will minimise $\mathrm{ECR}_{\mathrm{sys},\wp}$ as our objective is not to implement the optimisation algorithm but rather to investigate the interplay between spectral efficiency and energy efficiency. We symbolise the minimised $\mathrm{ECR}_{\mathrm{sys},\wp}$ of the relay scheme, $\wp$, as $\Omega_{0,\wp}$.

5 Economic efficiency

Guo and O'Farrell [22] did not consider the potential revenue generated from the spectral efficiency provided by the investigated scheme as a viable source to mitigate costs. Furthermore, the capital expenditure (CAPEX) and operational expenditure (OPEX) costs in the proposed cost efficiency metric shown in (12) of [22] were mostly decoupled from the spectral and energy efficiency metrics. Although the CAPEX cost was a one-off insertion cost to initially set up the network, most of the utilised OPEX costs were fixed rental costs which have little to do with the cost incurred because of the operational power consumption. This decreases the effectiveness of the proposed cost efficiency metric to represent the tradeoff between spectral and energy efficiency.

As there is a tradeoff between spectral and energy efficiency, neither quantity may be optimised without constricting the other. A system which solely relies on one of them as a performance measure may not yield the best overall network performance. Motivated by the idea first introduced in [20], the economic efficiency metric is proposed as a possible complementary measure to the spectral efficiency and energy efficiency performance metrics.

The spectral efficiency and energy efficiency can be sufficiently characterised by both C_{sys} and $P_{\mathrm{op,sys}}$. By jointly considering both parameters, a suitable SEET point that will deliver the maximum economic profitability can be found. We define the economic efficiency metric as

$$U_{\mathrm{sys}} = \kappa_r r_{\mathrm{base}} \log_2\left(1 + \frac{B_{\mathrm{sys}}C_{\mathrm{sys}}}{r_{\mathrm{base}}}\right) - \kappa_c P_{op,\mathrm{sys}} \quad \mathrm{m.u./s} \quad (36)$$

where r_{base} is the base service data rate which refers to the essential service expected by every mobile user, whereas κ_r and κ_c are the revenue per bit and energy cost per Watt-second (Ws), respectively. Both revenue and cost are measured in the same monetary unit (m.u.), for example, in pence. We do not consider the CAPEX costs, for example, planning, equipment and installation costs, as they are usually one-off insertion costs in setting up the network. Also, we do not consider the OPEX costs which are related to the rental costs, for example, cell site and backhaul rentals as they are fixed costs. However, our cost is related to the electricity cost component of the OPEX as it is due to operational power consumption of the scheme under investigation. Therefore unlike the CAPEX costs and the fixed rental costs of the OPEX, the electricity cost in the OPEX is variable as it depends on the performance of the network and thus, provides the opportunity for further optimisation.

Taking a closer look at the economic efficiency metric, we see that the first term on the right-hand side (RHS) of (36) represents the revenue attainable with that scheme in the chosen m.u. per second (m.u./s). Based on the observation in [20], a user is only willing to pay a small additive premium on top of the basic service for a multiplicative increase in the attainable data rate. Thus, the attainable revenue grows incrementally with every new service enabled by the scheme rather than following the multiplicative growth in data rate attainable by such a scheme. This economic trend is known as the law of diminishing returns and this leads to a logarithmic relationship between the attainable revenue and attainable data rate. The second term on the RHS of (36) represents the operational cost, also in m.u./s, incurred by the scheme and unlike revenue growth, is linearly proportional to $P_{\mathrm{op,sys}}$. The values used for the economic efficiency parameters are shown in Table 1.

Although the proposed economic efficiency metric is illustrated for the relay-aided cellular network, its framework can also be employed as a practical engineering tool to optimise the economic profitability of any network architecture. Another advantage of the parameterised economic efficiency metric is that it is applicable to different mobile standards and economic conditions. The mobile operators only need to assign different parameter values in order to represent that particular change. For example, r_{base} may change from voice to multimedia in future standards as complete migration towards wireless internet access occurs [29]. Furthermore, κ_r and κ_c may also be adapted to reflect the change in future electric tariffs.

5.1 Economic efficiency optimisation

In this section, we present the formulation for optimisation of the economic efficiency metric which takes into account the SEET. This approach differs from the optimisation presented in (35) which attempts to maximise energy efficiency by minimising the ECR, given a targeted spectral efficiency value. In contrast, the spectral efficiency and ECR are now left as variables to be suitably chosen to maximise the economic profitability of the network. Therefore the economic efficiency metric can be utilised as a common reference point to compare the performance of schemes with different spectral and energy efficiency. The optimisation of the economic efficiency metric of (36) for a

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given relay scheme, $\wp$, can be written as

$$\begin{aligned} \underset{\{P_b, P_r\}}{\text{maximise}} \quad & U_{\text{sys},\wp} \\ \text{subject to} \quad & P_b + MP_r \le P_0 \\ & P_b, P_r > 0 \end{aligned} \tag{37}$$

As we are interested in investigating the interplay of these metrics rather than implement an actual optimisation algorithm in real time, we choose to solve (37) by performing an exhaustive search for the values of the $\{P_b, P_r\}$ pair to find one which maximises $U_{\text{sys},\wp}$. We symbolise the maximised $U_{\text{sys},\wp}$ of the relay scheme, $\wp$, as $\zeta_{0,\wp}$.

6 Simulation results and discussions

We now present some numerical results of the relaying schemes for downlink transmission. The link-level and system-level performance in terms of spectral efficiency, ECR and economic efficiency are evaluated for these schemes. We assume a cell radius of $r_{\text{cell}} = 2000$ m and inter-site distance of $d_{\text{ISD}} = \sqrt{3}r_{\text{cell}}$. Furthermore, we set $\tau_r = 1/2$, $B_{\text{sys}} = 10$ MHz, $\alpha_b = \alpha_r = 2.84$ and $P_{c,\text{ref}} = 577$ W at $P_{\text{ref}} = 40$ W. The rest of the simulation parameters are listed in Table 1.

6.1 Link-level performance

We begin by evaluating the link-level performance of the relaying schemes. This is to initially demonstrate the advantage of one scheme over the other in a simple setting. The link-level depiction can also loosely represent the network topology of Fig. 1 with frequency planning having parameters of $\eta_b = \eta_r = 1/2$.

In Fig. 2, the maximum spectral efficiencies for the SFR and IFR schemes are illustrated at various normalised relay distances, d_{RS}, as compared with the DIRECT scheme. The maximum spectral efficiency refers to the highest possible spectral efficiency attainable by each scheme regardless of its energy consumption. The IFR scheme maintains a fairly constant maximum spectral efficiency at $0.1 \le d_{\text{RS}} \le 0.4$ when the chances of RS r_0 decoding the interference source are fairly high but it begins to drop at $d_{\text{RS}} > 0.4$ as the performance is now constrained by relay phase when the RS is positioned farther away from the UE. It is also observed that the spectral efficiency of the IFR scheme never exceeds that of the DIRECT scheme. SIR improvement of the IFR scheme over the DIRECT scheme, whenever the interference is successfully removed, is unfortunately not enough to compensate for the multiplexing loss because of the necessary two-hop relaying protocol. In contrast, SIR improvement of the SFR scheme outweighs the multiplexing loss and thus, it is able to deliver higher spectral efficiency than both the IFR and DIRECT schemes. This shows that SIR improvement through the desired signal enhancement is more effective than trying to remove interference from the received signal at the UE designated for relay transmission. The SFR scheme is able to obtain roughly a 67% spectral efficiency improvement over the DIRECT scheme at $d_{\text{RS}} = 0.5$.

Next, the relation between spectral efficiency and energy efficiency (represented by ECR) is shown in Fig. 3 for the SFR and IFR schemes at $d_{\text{RS}} = 0.5$. The SEET region is formed for both schemes when different combinations of $\{P_b, P_r\}$ pairs satisfying the constraints in (35) are considered. Each $\{P_b, P_r\}$ pair maps to a unique point in the region of a given relay scheme. For the DIRECT scheme, there is only one point in the figure since only one transmit power value, $P_{b,\text{DIRECT}} = P_0$, is considered. We observe that the IFR SEET region is confined to the left, covering a wide ECR range, whereas the SFR SEET region elongates narrowly to the right with its ECR having smaller range and values. This suggests that the SFR scheme is generally able to attain higher spectral efficiency at lower energy consumption than the IFR scheme which is unable to deliver spectral efficiency in excess of 3.3 bits/s/Hz. Furthermore, the DIRECT scheme point is outside the IFR SEET region, indicating that the IFR scheme also performs poorly in comparison to the DIRECT scheme.

Next, the relation between spectral efficiency and energy efficiency (represented by ECR) is shown in Fig. 3 for the SFR and IFR schemes at $d_{\text{RS}} = 0.5$. The SEET region is formed for both schemes when different combinations of $\{P_b, P_r\}$ pairs satisfying the constraints in (35) are considered. Each $\{P_b, P_r\}$ pair maps to a unique point in

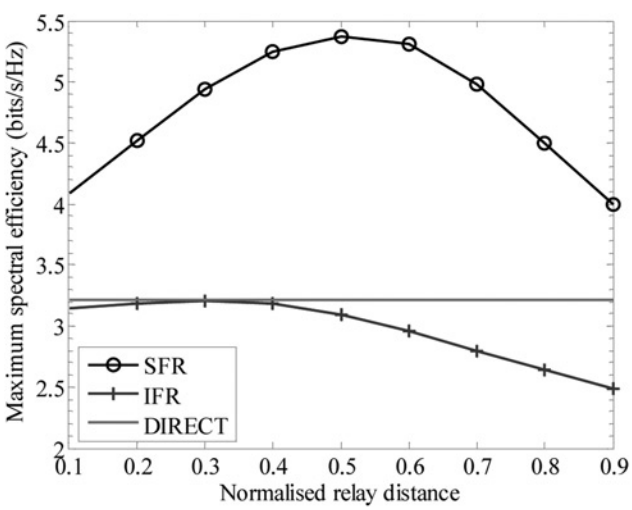

Fig. 2 *Maximum spectral efficiency of the SFR and IFR schemes against the normalised relay distance with the DIRECT scheme taken as the baseline*

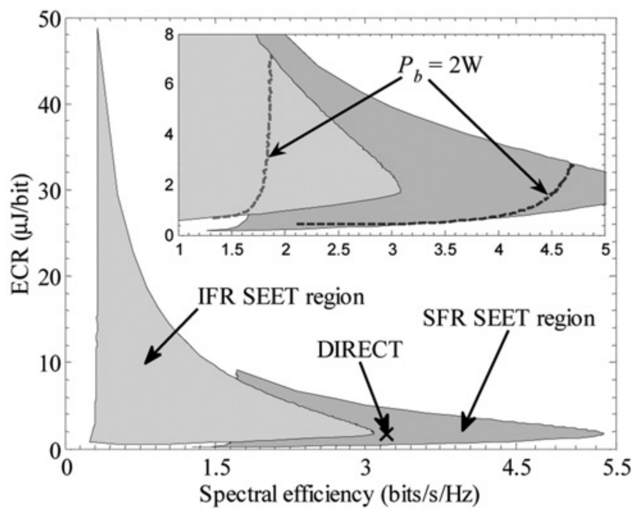

Fig. 3 *SEET region for the SFR and IFR schemes with the inset illustrating a specific tradeoff at $P_b = 2$ W. The DIRECT scheme is shown for comparison*

the region of a given relay scheme. For the DIRECT scheme, there is only one point in the figure since only one transmit power value, $P_{b,\text{DIRECT}} = P_0$, is considered. We observe that the IFR SEET region is confined to the left, covering a wide ECR range, whereas the SFR SEET region elongates narrowly to the right with its ECR having smaller range and values. This suggests that the SFR scheme is generally able to attain higher spectral efficiency at lower energy consumption than the IFR scheme which is unable to deliver spectral efficiency in excess of 3.3 bits/s/Hz. Furthermore, the DIRECT scheme point is outside the IFR SEET region, indicating that the IFR scheme also performs poorly in comparison to the DIRECT scheme.

A tradeoff between spectral efficiency and energy efficiency is illustrated with the SEET curves in the inset of Fig. 3 for both the SFR and IFR schemes at $P_b = 2$ W. It is observed that initially the ECR does not change much when spectral efficiency gains are registered. However, the ECR begins to increase with each marginal improvement in spectral efficiency. This quickly culminates into an accelerated growth in ECR beyond the knee of the curves which is at around 4.5 and 1.75 bits/s/Hz for the SFR and IFR schemes, respectively. Past this, very negligible spectral efficiency gains are observed for a large increase in ECR. Nevertheless, the SEET curve for the SFR scheme is still more favourable than the IFR scheme. As the SFR scheme is more superior than the IFR scheme, it is selected for further investigation in the results that follow.

The economic efficiency metric in (36) is employed to measure the economic profitability of the SFR scheme in Fig. 4. The same set of $\{P_b, P_r\}$ pairs used to generate Fig. 3 is used to produce the economic efficiency region of Fig. 4. For comparison, the economic profitability of the SFR scheme when operating at maximum energy efficiency of Ω_0 is also shown with its corresponding economic efficiency of 0.179 pence/s. Immediately, we see that operating at Ω_0 is not economically optimum. The maximum economic efficiency, ζ_0 is obtained at 0.188 pence/s with the corresponding ECR and spectral efficiency of about 1.55 μJ/bit and 5.35 bits/s/Hz, respectively. Moving from Ω_0 to ζ_0 in the SEET region as shown in the inset of Fig. 4 maximises the economic efficiency but, because of the tradeoff, incurs a 3.5 times increase in ECR, whereas the spectral efficiency improves by 1.7 times. Therefore by tolerating a decrease in energy efficiency, the SFR scheme stands to gain further in terms of economic efficiency and spectral efficiency.

6.2 System-level performance

We further study the performance of the SFR scheme under more realistic conditions of a relay-aided multicell cellular network. In Fig. 5, the spectral efficiency of the SFR scheme while employing frequency reuse planning modes η_b and η_r for BS and RS transmission, respectively, is illustrated at different BS transmit power, P_b. It is observed that the SFR scheme with full BS frequency reuse ($\eta_b = 1$) delivers higher spectral efficiency than partial BS frequency reuse ($\eta_b = 1/3$) as the system bandwidth is utilised more efficiently in the former. However, as the BS transmit power increases, the SFR scheme with $\eta_b = 1/3$ is able to obtain larger improvement in spectral efficiency as compared with $\eta_b = 1$ as the performance of full BS frequency reuse is interference limited. A similar observation is made while investigating the RS frequency planning modes, η_r for a given η_b. The more bandwidth efficient RS frequency reuse mode of $\eta_r = 1/3$ delivers higher system spectral efficiency than the $\eta_r = 1/6$ mode which is designed to avoid RS interference during the relay phase. However, further spectral efficiency improvement is determined by the type of BS frequency planning mode during the broadcast phase. In all cases, the DIRECT scheme underperforms the SFR scheme but even here, we see that the $\eta_b = 1$ mode provides better spectral efficiency then the $\eta_b = 1/3$ mode.

Next, we investigate the economic profitability of the SFR scheme against its energy efficiency as depicted in Fig. 6 while considering both the BS and RS frequency reuse planning modes. The energy efficiency corresponds to the spectral efficiency spanned in Fig. 5. From Fig. 6, the SFR scheme with $\eta_b = 1$ generally has higher economic efficiency than with $\eta_b = 1/3$ as more bandwidth is being translated to spectral efficiency for revenue generation. However, as $\eta_b = 1$ is interference limited during the broadcast phase, the spectral efficiency improves only

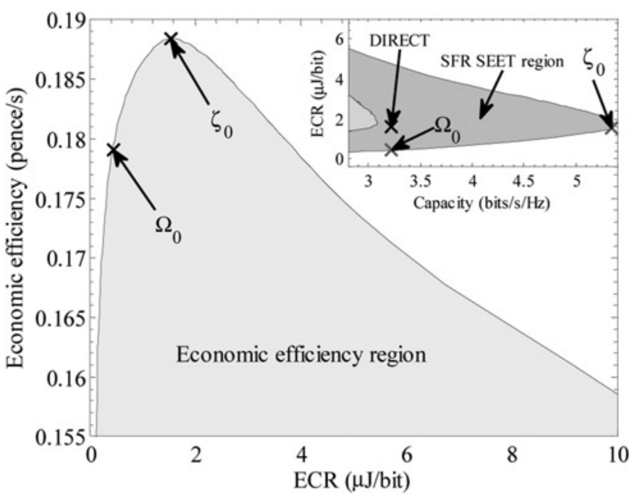

Fig. 4 *Economic efficiency against ECR of the SFR scheme at various $\{P_b, P_r\}$ pairs. The min. ECR Ω_0 and max. economic efficiency ζ_0 are shown with the inset indicating their corresponding locations in the SEET region*

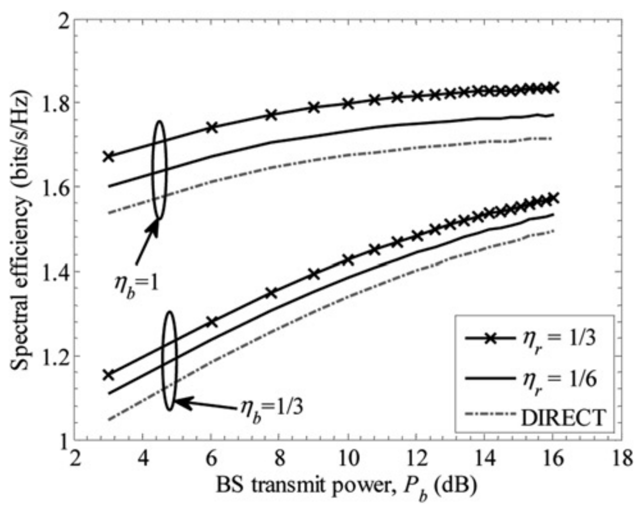

Fig. 5 *System spectral efficiency against BS transmit power of the SFR scheme at different frequency planning modes of both the broadcast and relay phases. The DIRECT scheme is taken as the baseline*

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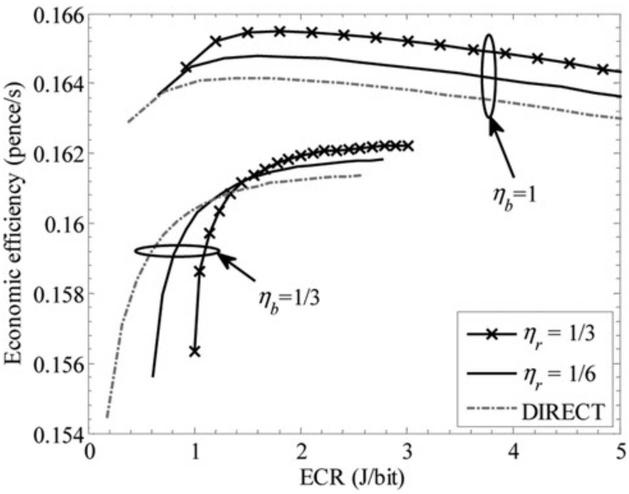

Fig. 6 *System economic efficiency against ECR of the SFR scheme at different frequency planning modes of both the broadcast and relay phases. The DIRECT scheme is taken as the baseline*

slightly even though more energy is expended per bit. As a result, the economic efficiency increases slightly until reaching ECR of around 1.5 and 1.6 μJ/bit for $\eta_r = 1/3$ and $\eta_r = 1/6$, respectively, before declining as the operational power consumption cost escalates further whereas revenue remains almost stagnant.

Conversely, regardless of the RS frequency planning mode, the economic efficiency increases sharply for the SFR scheme with $\eta_b = 1/3$, though at lower values, than that of $\eta_b = 1$ as the system has less interference during the broadcast phase. However, the marginal gains quickly decrease as the ECR continues to increase to a point where profitability is now limited by the operational power consumption cost. We now look at the influence of the RS frequency planning mode. Unlike operating at $\eta_b = 1$ during the broadcast phase where the relay phase having $\eta_r = 1/3$ performs consistently better than $\eta_r = 1/6$, it is observed that the economic efficiency is separated into two distinct ECR regimes for $\eta_r = 1/3$ and $\eta_r = 1/6$ when the SFR scheme adopts $\eta_b = 1/3$. At the lower ECR regime, the relay phase with $\eta_r = 1/6$ requires less energy per bit than the relay phase with $\eta_r = 1/3$ to achieve the same economic efficiency as the former has a lower RS interference level. When the SFR scheme migrates to the higher ECR regime where the operational power consumption cost becomes more significant, it is more essential for the SFR scheme to operate at higher bandwidth efficiency in order to deliver higher spectral efficiency to be generated as revenue to compensate for the increased cost. Thus, the more aggressive bandwidth use of $\eta_r = 1/3$ performs better than $\eta_r = 1/6$ in the higher ECR regime.

7 Conclusions

The signal forwarding and interference forwarding relaying paradigms of the relay-aided cellular network have been compared. The spectral, energy and economic efficiency values have been considered. Both the RF and circuit power consumption values have been included in energy efficiency. Simulation results have shown that the SFR scheme outperforms the IFR scheme. This indicates that enhancing the desired signal strength is more favourable than attempting to remove the interference from the received signal. Furthermore, the economic efficiency metric is proposed to select a balance point in the spectral-energy efficiency tradeoff in order to maximise economic profitability. Investigation into frequency reuse planning modes of the SFR scheme has shown that full bandwidth utilisation delivers higher performance than bandwidth allocation strategies which avoid interference with results demonstrating 41 and 16% spectral efficiency improvements at low and high BS transmit power, respectively.

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