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Resource sharing in LTE-Advanced relay networks: uplink system performance analysis

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ABSTRACT

Relay-enhanced networks are expected to fulfil the demanding coverage and capacity requirements in a cost-efficient way. Type 1 inband relaying has been standardised as an integral part of the Third Generation Partnership Project (3GPP) Long-Term Evolution Release 10 and beyond (LTE-Advanced). This type of relay nodes (RNs) supports a relaying mode where the RN to donor evolved node B (donor eNB, DeNB) link (relay link, a.k.a. backhaul link) transmission is time-division multiplexed with the RN-served user equipments (RUEs) to RN link (access link) transmission, whereas macrocell-served user equipments (MUEs) share the same resources with the RNs at DeNB. Hence, system performance depends strongly on the resource sharing strategy among and within the links. Further, the set of subframes assigned for the relay link transmission is semi-statically configured and thus a dynamic reconfiguration to adapt to fast-changing system conditions (e.g. RN cell load) is not viable. Besides, in order to fully exploit the benefits of relaying, the inter-cell interference, which is increased because of the presence of RNs, should be limited via a proper power control (PC) scheme on each link. Therefore, an optimisation of both the resource sharing and PC strategy is required to enhance the overall performance of relay networks. In order to tackle these issues, we employ a statistic-based over-provisioned backhaul subframe allocation to be utilised for flexible co-scheduling of RNs and MUEs at DeNB. In addition, we propose a combination of RN scheduling based on the number of RUEs and user throughput throttling achieving max–min fairness. Performance analysis of various resource sharing techniques along with PC optimisation is then carried out within the LTE-Advanced uplink framework in urban and suburban scenarios. Comprehensive results show that the proposed schemes achieve significant throughput gains and high system fairness with substantially increased flexibility in resource allocation. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS

LTE-Advanced; relay deployments; power control; resource sharing; co-scheduling; uplink

1. INTRODUCTION

The set of stringent requirements for future radio access networks has triggered the embodiment of relay nodes (RNs) as part of the next-generation network infrastructure. Relaying is considered an integral part of Third Generation Partnership Project (3GPP) Long-Term Evolution Release 10 and beyond (LTE-Advanced), which is recently accorded the official designation of International Mobile Telecommunications Advanced specified by the International Telecommunication Union-Radiocommunication sector for Fourth-Generation networks.

The motive behind choosing relaying as an enhancement technology to current radio access networks has been well elaborated in the literature. Namely, RNs promise to increase the network capacity [1] and to better...
distribute resources in the cell, or alternatively, extend the cell coverage area [1–3]. Relaying is regarded a cost-efficient technology as well [4].

A self-backhauling Type 1 RN is a layer 3 decode-and-forward RN, which controls its own cell; that is, it has its own physical cell ID and includes functionalities such as radio resource management, scheduling and hybrid automatic repeat request retransmission control. As illustrated in Figure 1, the connection between RN and the core network is carried out through the donor evolved node B (donor eNB, DeNB) via a wireless backhaul link, which is referred to, herein, as the relay link. Moreover, the link between user equipment (UE) and its serving RN is referred to as the access link and that between UE and its serving eNB, or DeNB, as the direct link. The RN utilises the same frequency band on both the access and relay links (inband operation), and the links are time-division multiplexed to prevent interference between the two links (half-duplex operation). However, the transmissions on the direct and access links can coexist; that is, the RNs and macrocells utilise full frequency reuse.

The set of backhaul subframes, which are referred to, herein, Un subframes, (Figure 1) is configured semi-statically by the DeNB. During the Un subframes, the DeNB may or may not schedule its macrocell-served UEs (MUEs). One common assumption in the performance evaluation of relay deployments is that Un subframes are exclusively assigned for the RN transmissions. However, such a hard resource split reduces the resource utilisation efficiency at the DeNB, as load conditions in RN cells may change rapidly. That is, because of the semi-static nature of the Un subframe configuration, the number of Un subframes cannot be changed dynamically, and thus, a fast enough adaptation to the load conditions may not be attained. Accordingly, it is important to investigate resource sharing schemes among and within the various links.

Furthermore, relay deployments will require a more detailed dimensioning and planning than conventional single-hop networks. RNs can create severe inter-cell interference in particular when a large number of RNs are deployed in a cell. In addition, because of various link characteristics such as antenna gain and propagation loss, the transmit power levels of UEs and RNs can be significantly different. This can also result in different interference characteristics during regular subframes, which are referred to, herein, Uu subframes, and Un subframes (Figure 1). Then, power control (PC) becomes an important means in the uplink (UL) transmission not only to compensate for channel variations, but also to mitigate the interference and to limit the receiver dynamic range especially at DeNB. A high receiver dynamic range increases the susceptibility of Single Carrier-Frequency Division Multiple Access (SC-FDMA) to the loss of orthogonality, which can cause severe intra-cell interference [5]. The PC optimisation methodology presented in our previous studies [6, 7] is taken as a basis in this work. Herein, we first present two resource sharing schemes for the resource split at DeNB between RNs and MUEs, namely, hard resource split, where RNs are exclusively allocated all resources during Un subframes, and flexible resource split, where Un subframes are over-provisioned and the MUEs and RNs are co-scheduled during these subframes. In the latter approach, the goal of achieving dynamic and efficient resource sharing is moved to the scheduler, which can instantaneously adapt to changes in system conditions, rather than relying on semi-static Un subframe allocation [8]. Besides, the number of Un subframes is chosen considering the statistical distribution of the fraction of RN-served UEs (RUEs) in the macrocell (i.e. the total load of RN cells). Moreover, in both schemes the impact of the number of Un subframes on the access link capacity is taken into account considering the half-duplex operation.

Second, we focus on resource sharing schemes on individual links. In [9], time-division and frequency-division multiplexing of relay and access link transmissions were investigated on the downlink (DL) excluding the resource sharing within the links. In [10], resource sharing on the relay link according to the buffer state at the RNs was investigated for urban scenarios without applying a PC optimisation, and the results including the suburban scenarios are provided in [11]. In this work, we adopt the model presented in [10, 11] and propose a combination of relay link scheduling based on the number of RUEs and a throughput (TP) throttling technique achieving max–min

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**Figure 1.** Exemplified 4-relay-node (RN) deployment with depicted links. RUEs, RN-served user equipment; DeNB, donor evolved node B.
fairness (MMF) in the end-to-end two-hop communication. The scheme is referred to as hop-optimisation model. The optimisations are carried out in conjunction with a PC strategy to guarantee a proper system performance. Thorough system-level simulations within the LTE-Advanced context show that the proposed optimisation strategies achieve significant TP gains and high system fairness along with substantially increased flexibility in resource allocation.

We note that herein optimisation refers to a parameter tuning within the allowed ranges in the LTE-Advanced standard and an adjustment of resource management strategies such that an appropriate trade-off between target performance metrics can be achieved. For instance, a PC optimisation strategy targeting cell capacity tunes the parameters in a way that the cell capacity is maximised without degrading the cell coverage below a given level.

The remainder of the paper is organised as follows. Section 2 provides the background material including PC and the key features of the general framework. In Section 3, different resource sharing techniques are presented. The system model and simulation assumptions are given in Section 4. In Section 5, detailed performance evaluation and analysis are carried out. Finally, Section 6 concludes the paper.

2. BACKGROUND AND DEFINITIONS

In this section, we first recall the framework of LTE UL technology. Then, fractional PC (FPC) scheme of LTE Release 8 is outlined. The key features of the work and the definitions are presented next.

2.1. LTE uplink technology

LTE UL has adopted SC-FDMA [12] because of its low peak-to-average power ratio allowing low power consumption and high efficiency at the UE [13]. This property is particularly important for UE battery lifetime and power amplifier design. The total bandwidth available for the UL transmission is defined by the multiplexing scheme used. In our work, we assume frequency-division duplex (FDD) mode, where the UL and DL are each allocated exclusive 10-MHz transmission bandwidth. In the frequency domain, the whole UL bandwidth is divided into subbands, which are called physical resource blocks (PRBs). The PRB defines the resource allocation granularity in LTE. As the system is operating on 10-MHz bandwidth, there are $M_{\text{total}} = 48$ PRBs available for data transmission on the physical uplink-shared channel (PUSCH), and two PRBs are reserved to the physical uplink control channel. The main difference of SC-FDMA compared with OFDMA is the single-carrier constraint, where only a set of adjacent PRBs can be allocated to a user. Further, the users can be assigned a subset of $M_{\text{total}}$ PRBs in each transmission time interval (TTI, a.k.a. subframe).

An LTE frame spans in total 10 ms and comprises 10 subframes. Given that LTE-Advanced networks are operated with full frequency reuse, MUEs and RUEs are served simultaneously on the same frequency band and time slots by DeNBs and RNs, respectively. Yet, considering the resource allocation strategy defined for inband Type 1 RNs in [14], relay and access link transmissions are time-division multiplexed. During the Un subframes, RUEs are not scheduled on the UL, thus experiencing transmission gaps. An example frame structure is given in Figure 2, where two subframes are reserved for the relay link. Moreover, a maximum of six Un subframes can be semi-statically allocated for the relay link [14]. In addition, MUEs can be optionally scheduled with RNs in Un subframes. That is, Un subframes are either assigned exclusively to RNs or MUEs and RNs are co-scheduled during Un subframes.

2.2. Uplink frame structure in frequency-division duplex LTE-Advanced networks

Thanks to the orthogonality of SC-FDMA, intra-cell interference is not of main concern in LTE. The aim of PC mechanisms is then to maximise the received power of wanted signals through compensating the long-term channel variations, while limiting the amount of the inter-cell interference generated. Nevertheless, the receiver dynamic range of eNBs, DeNBs and RNs should also be

3This constraint, which is defined in LTE Release 8, is considered herein for the sake of backward compatibility.
adjusted via PC to avoid intra-cell interference, where a high dynamic range can cause the loss of orthogonality [5]. To fulfil these objectives in LTE, FPC [15] is used for the PUSCH (see Section 2.1 for further details on this channel) to determine the UE transmit power. In this work, FPC is also employed for the relay-specific PUSCH (R-PUSCH) which is the physical channel for the UL relay data transmission. Accordingly, the transmit power of a node $\eta$ (UE or RN) that employs open-loop PC is given in dBm as

$$P_\eta = \min\{P_{\text{max}}, P_0 + 10 \cdot \log_{10} M_\eta + \alpha \cdot L\} \quad (1)$$

In this equation,

- $P_{\text{max}}$ is the maximum allowed transmit power, which has an upper limit of 23 dBm for UE power class 3 [16] and 30 dBm for RN transmissions (optionally 37 dBm for suburban scenarios) [14].
- $P_0$ is the power offset comprising cell-specific and node-specific components, and it is used for controlling the received signal-to-noise-power ratio target that can be set from $-126$ dBm to $P_{\text{max}}$ with a step size of 1 dB.
- $M_\eta$ is the number of PRBs allocated to node $\eta$.
- $\alpha$ is a cell-specific path loss compensation factor that can be set to 0.0 and from 0.4 to 1.0 with a step size of 0.1 via 3-bit signalling.
- $L$ is the DL path loss estimate calculated by the node.

Open-loop PC compensates slow channel variations (i.e. path loss changes including shadowing). If $\alpha$ is set to one in Equation (1), the path loss is fully compensated and the resulting scheme is called full compensation PC (FCPC). For a given $P_0$ value, FCPC improves the cell-edge user performance at the cost of increased inter-cell interference as a result of higher transmit power levels. Yet, the inter-cell interference can be reduced by setting $\alpha$ smaller than one, which increases the cell-centre performance, however, at the cost of penalising the cell-edge performance [17–19]. One of the important determinants of the motivation of studying the applicability of the existing FPC for the relay networks is the desired backward compatibility between LTE Release 8 and LTE-Advanced users, that is, the legacy LTE Release 8 users, which cannot be updated with a new PC scheme should also support relay operations.

As mentioned before, RNs have their own independent cells, for example, from legacy LTE Release 8 UE perspective, RNs are identical to eNBs [14]. Therefore, PC parameters for RUeNs in RN cells, that is, $c_{\text{RUe}}$ and $P_{\text{RUe}}^0$, are configured by RNs, and their transmit power levels are determined taking into account the path loss on the access link between the serving RN and RUeNs, and the number of allocated PRBs according to Equation (1). Similarly, during Uu subframes, the PC parameters for MUEs in macrocells, that is, $c_{\text{MUE}}$ and $P_{\text{MUE}}^0$ (Uu), are set independently by the serving eNB or DeNB. Furthermore, for the co-scheduled MUE and RNs, the DeNB can configure different $P_0$ values, namely, $P_{\text{MUE}}^0$ (Un) and $P_{\text{RN}}^0$.

### 2.4. Physical downlink control channel limitation

In practice, the maximum number of the UEs that can be scheduled in each TTI is limited by the possible number of scheduling grants which are carried by the physical DL control channel (PDCCH). A scheduling grant includes dedicated user information which is necessary to decode the data channel, e.g. data bandwidth allocation, and modulation and coding scheme (MCS). Typically 8–10 UEs can be scheduled per TTI because of PDCCH limitation (or PDCCH blocking) [20]. In this work, this number is set to 8. That is, if there are more than eight UEs accessing to an eNB, a DeNB or an RN, a subset consisting of eight UEs will be scheduled in each TTI. The unscheduled UEs in a given TTI will be scheduled in other TTIs in a way that resource fairness is achieved in the time domain. Note that in reality, PDCCH limitation changes from TTI to TTI depending on the used control channel elements by the served UEs. A cell-centre user with better channel conditions requires a smaller number of control channel elements, whereas this number increases as the channel conditions worsen towards the cell edge [21]. We further note that we assume that, in the considered relay scenario, there is no limitation because of relay-specific PDCCH (R-PDCCH), that is, all RNs can be scheduled in a TTI, as the relay link experiences good channel conditions and a small number of RNs are deployed, namely, 4-RN and 10-RN deployments are considered herein.

### 2.5. Power limitation and adaptive transmission bandwidth

The maximum number of PRBs—denoted by $M_{\text{max}}$—which can be assigned to a UEs depends on the difference between $P_{\text{max}}$ and the per-PRB power spectral density (PSD) of that UEs. The per-PRB PSD of a UEs can be obtained via the open-loop component of Equation (1) by setting $M_\eta = 1$ such that

$$\text{PSD}_{\text{UE}} = \min\{P_{\text{max}}, P_0 + \alpha \cdot L\} \quad (2)$$

The actual PSD is given by Equation (2) as long as the UEs is not driven into power limitation; otherwise, $P_{\text{max}}$ will be equivalently spread over the assigned PRBs resulting in decreased signal-to-interference-plus-noise ratio (SINR) per PRB. Such an assignment may result in outage, especially when the UEs is experiencing poor channel conditions. Consequently, linear $M_{\text{max}}$ is obtained from the difference $P_{\text{max}} - \text{PSD}_{\text{UE}}$ given in dB as

$$M_{\text{max}} = \text{round}\left(10^{0.1(P_{\text{max}} - \text{PSD}_{\text{UE}})}\right) \quad (3)$$

Hence, power-limited UEs will not be assigned more resources than those they can afford. The unallocated resources can then be better utilised by other UEs resulting in more efficient bandwidth usage. This functionality is called adaptive transmission bandwidth (ATB) [22]. It is
worth mentioning that in contrast to [22] where floor operator is used, we have adopted round operator. The aim is to decrease the quantisation errors caused by this operation and to further enhance the performance over the $P_0$ set of interest. It is as well empirically justified via our simulations. A detailed comparison of ATB with fixed transmission bandwidth (FTB) is given in [23]. Therein, it is shown that ATB is particularly advantageous for suburban scenarios having large inter-site distance (ISD). The reason is mainly twofold. First, because of large ISD, there are a considerable number of power-limited UEs experiencing poor channel conditions. Second, the resources that are not used by the power limited UEs are allocated to other UEs with better channel conditions. This in turn improves the mean UEs TP. Therefore, ATB is applied only for suburban scenarios in this work.

3. RESOURCE SHARING TECHNIQUES

The performance of relay networks depends significantly on the resource allocation strategy, that is, on the balance between different links that compete for resources or that may act as bottlenecks for other consecutive links. In this section, we first outline the schemes of resource split at DeNB, which mainly aim at determining the number of Un subframes. Next, we present the different investigated resource sharing techniques on the relay link along with the TP throttling schemes on the access link.

3.1. Resource split at donor evolved node B

The number of Un subframes needs to be tuned properly to find a balance in the resource share between relay and direct links. Moreover, its impact on the access link capacity should also be taken into account, as RUEs experience transmission gaps during Un subframes, which may render the access link a bottleneck in the two-hop communications. In this context, we investigate the following two schemes.

3.1.1. Hard resource split.

One common assumption in the literature is that Un subframes are exclusively assigned for the relay link transmissions, for example, [1, 2, 6, 10, 11]. An example of hard resource split is illustrated in Figure 3(a) where the resource allocation at DeNB is depicted on the time-frequency plane. In this scheme, MUEs also experience the same transmission gaps as RUEs. Crucially, such a split implies a reduction in the total amount of resources available to MUEs and, thus, a performance degradation in case the relay link resources are not fully utilised because of, for example, lower RN cell load. Consequently, given the semi-static nature of the Un subframe configuration, the hard resource split can reduce the resource utilisation efficiency. In this work, we take this approach as a benchmark. We note that the optimal number of Un subframes in such a case is chosen according to the long-term average demand of UEs, and hence, on a short-term basis, it is not optimal.

$$m_c = (1 - \zeta_{RN}) M_f, \quad 0 \leq m_c \leq M_f \tag{4}$$

where $\zeta_{RN}$ is the resource share of RNs per Un subframe and $M_f$ is the total number of relay link resources in a Un subframe. Further, $\zeta_{RN}$ is determined in terms of $\rho_{RN}$, the RUEs fraction in the cell, and $N_b$, the number of Un subframes out of 10 as

$$\zeta_{RN} = \min\{1, \frac{\rho_{RN} 10}{N_b}\} \quad \text{with} \quad \rho_{RN} = \frac{U_{RN}}{U_c} \tag{5}$$

where $U_{RN}$ and $U_c$ are the total number of RUEs and the total number of all UEs in the cell, respectively. Note that in Equation (5), $N_b$ is put in denominator to determine the resource share per Un subframe. It can be seen that, for a given $N_b$, the RN and MUE resource shares per Un subframe are, respectively, proportional to the total number of RUEs $U_{RN}$ and the total number of MUEs $U_c - U_{RN}$, provided that $\rho_{RN} \leq N_b/10$. In particular, $N_b/10$ sets an upper bound on $\rho_{RN}$ below which resource shares of RNs and MUEs can be flexibly adapted to changes in system conditions and when $\rho_{RN} > N_b/10$ all the resources in a Un subframe will be assigned to RNs, see min operator in Equation (5). Thus, the selection of $N_b$ yields a trade-off, where, for example, a larger $N_b$ means higher flexibility in adapting to system conditions, whereas a reduced access
link capacity, since RUEs experience transmission, gaps during Un subframes.

The over-provisioning of Un subframes is exemplified in Figure 3(b). Besides, it is assumed that the total number of resources in Un and Uu subframes is the same and equal to $M_i$; that is, no particular resource partitioning schemes are considered. Further, MUEs and RNs can be scheduled on different parts of the spectrum, but this is omitted for illustration purposes. In this example, the number of Un subframes is over-provisioned from two (Figure 3(a)) to four, and MUEs are scheduled with RNs in Un subframes (Figure 3(b)). It is worth noting that not all subframes can be configured as Un subframes due to indispensable synchronisation and broadcast channels [24]; however, in Figure 3, the Un subframes are shown to be consecutive for clarity.

### 3.2. Resource sharing techniques on the relay link

After determining the number of Un subframes according to one of the resource splits at DeNB, it is important to investigate how to allocate the available resources to the different RNs. The schemes considered in this work are as follows.

#### 3.2.1. Access instantaneous throughput proportional.

In the access instantaneous TP-proportional (AIT-P) scheme, the resource share of an RN is determined proportionally to the total instantaneous TP achieved on the access link of this RN. Note that access instantaneous TP is defined as the TP achieved on the access link when a resource fair Round Robin (RR) scheduler is considered and all resources are fully utilised. That is, RNs are assigned resources on a demand basis, where the RN with more demand on the access link will be assigned more resources on the relay link. In this manner, $m_{ij}$, the number of resources assigned to UEs $j$ served by RN $i$, can be written in terms of $M_a$, the total number of PRBs on the access link, and $u_i$, the number of UEs attached to RN $i$, as

$$m_{ij} = \frac{M_a}{u_i}, \quad j = 1, \ldots, u_i, \quad i = 1, \ldots, N$$

(6)

where $N$ is the number of active RNs in the overlaying macrocell. Note that $M_a$ is assumed to be identical for all RNs in the system; that is, no particular resource partitioning schemes are considered. The number of resources allocated to RN $i$ can then be obtained as

$$m_i = \Sigma_{j=1}^{u_i} \Sigma_{k=1}^{m_{ij}} R_{ijk} M_i^* \quad \text{for } i = 1, \ldots, N$$

(7)

where $M_i^*$ is the total number of PRBs reserved for the RN during Un subframes (Figure 3) and $R_{ijk}$ is defined as the per-PRB spectral efficiency on the access link of UEs $j$ to its serving RN $i$. $R_{ijk}$ is obtained via an approximation based on Shannon’s capacity formula adjusted by two parameters $B_{\text{eff}}$ and $A_{\text{eff}}$, which are denoted by bandwidth and SINR efficiencies, respectively [25]. It is given as

$$R_{ijk} = S \cdot \begin{cases} 0, & \text{SINR}_{ijk} < \text{SINR}_{\text{min}} \\ \text{BW} \cdot v_{\text{max}}, & \text{SINR}_{ijk} \geq \text{SINR}_{\text{max}} \\ \text{BW} \cdot B_{\text{eff}} \cdot \log_2(1 + A_{\text{eff}} \cdot \text{SINR}_{ijk}), & \text{else} \end{cases}$$

(8)

where $\text{BW}$ is the bandwidth per PRB, $v_{\text{max}}$ is the maximum spectral efficiency depending on the highest available MCS for a given SINR$_{\text{max}}$. Besides, $S$ accounts for LTE UL overhead, for example, because of reference signals.

#### 3.2.2. Access user equipment proportional.

The resource shares in an access UE proportional (AUP) resource allocation scheme are defined according to the ratio of $u_i$, the number of UEs attached to RN $i$, to the total number of RUEs $U_{\text{RN}}$ in the cell. Thus, the number of resources assigned to RN $i$ is set as

$$m_i = \frac{u_i}{U_{\text{RN}}} M_i^* $$

(9)

### 3.3. Throughput throttling techniques on the access link

The end-to-end TP of the RUEs depends on the qualities of both the access and relay links. That is, the TP achieved on the better link will be throttled to accommodate only whatever passes through the bottleneck. Accordingly, the end-to-end TP of a RUE $j$ served by an RN $i$ is obtained as

$$\text{TP}_{ij} = \min \left( \text{TP}_{ij}^a, \text{TP}_{ij}^r \right) \quad j = 1, \ldots, u_i, \quad i = 1, \ldots, N$$

(10)

where the user capacity on the access link is defined as $\text{TP}_{ij}^a$ and that on the relay link as $\text{TP}_{ij}^r$. Herein, we consider two TP throttling techniques, namely UEs instantaneous TP proportional (UIT-P) and MMF. The former distributes the TP on an access link quality basis, thus allowing UEs with good access channel to achieve high TP, whereas the latter tries to prioritise the low TP regime in the system by maximising the TP of UEs suffering from bad access channels.

#### 3.3.1. User equipment instantaneous throughput proportional.

In the UIT-P scheme, the end-to-end TP of a user is determined proportionally to its instantaneous access TP, given in terms of the spectral efficiency of the user’s access link. Following Equations (6) and (10), the end-to-end TP of UEs $j$ attached to RN $i$ is

$$\text{TP}_{ij} = \min \left( \sum_{k=1}^{m_{ij}} R_{ijk} \cdot \frac{m_i}{U_{\text{RN}}} \cdot \sum_{k=1}^{m_{ij}} R_{ijk} \cdot \sum_{j=1}^{u_i} \sum_{k=1}^{m_{ij}} R_{ijk} \right) \quad j = 1, \ldots, u_i, \quad i = 1, \ldots, N$$

(11)
where $m_i$ is determined according to the resource sharing technique utilised on the relay link and $R_{ijk}$ is the per-PRB spectral efficiency of the RN $i$.

### 3.3.2. Max–min fairness.

In the MMF scheme, resources are allocated to users in such a way that the users with worse link qualities are prioritised. Consequently, this will increase the end-to-end TPs at low TP regime at the expense of performance degradation at high TP regime. The user TP is then throttled according to the following algorithm analogously to the water filling approach:

1. Determine by means of Equations (6) and (8)
   \[ T_{ij}^p = \sum_{k=1}^{m_i} R_{ijk}, \quad j = 1, \ldots, u_i \]
2. Sort the RUEs served by RN $i$ in an ascending order with respect to $T_{ij}^p$
3. Initialise $j = 1$ and $T_{ij}^* = \sum_{k=1}^{m_i} R_{ijk}$ for RN $i$
4. if $\frac{TP_{ij}^p}{\eta_i - j + 1 + \gamma} > T_{ij}^p$
   - $TP_{ij}^* = T_{ij}^p$
   - $TP_{ij}^* = TP_{ij}^* - T_{ij}^e$
   else
   - $TP_{ij}^* = \frac{TP_{ij}^p}{\eta_i - j + 1 + \gamma}$. \( j = 1, \ldots, u_i \)
   - exit
5. while $j < u_i$ increment $j = j + 1$ and go to step 5.

### 4. SYSTEM MODEL

The simulated network is represented by a regular hexagonal cellular layout with 19 tri-sectored sites (i.e. 57 cells). RNs are regularly deployed at the sector borders. Figure 4 presents deployments of 4 RNs and 10 RNs per sector. Indoor users are assumed, where 25 uniformly distributed UEs are dropped per sector and the full buffer traffic model is applied. In total, 200 user drops (or snapshots) are simulated using a Matlab-based system-level semi-static simulator where statistics are collected from the inner-most sector only to ensure proper modelling of interference. Simulation parameters follow the latest parameter settings agreed in 3GPP [14] and are summarised in Table I.

A frequency reuse factor of one (full reuse scheme) is considered in the network. All available resources in a cell are assumed to be used at all times provided that UEs are not power limited (Section 2.5), and hence, a rather pessimistic interference modelling is considered on the access link. Relay site planning is assumed as modelled in [14]. Directional antennas are utilised at the RNs for relay link transmission, whereas omni-directional antennas are assumed for the access link transmission. Log-normal shadow fading is modelled for non-line-of-sight propagation conditions, whereas fast fading is not simulated.

In addition, it is assumed that the same Un subframe configuration is utilised for all RNs in the network, and it is aligned by the operation and maintenance (O&M) system. Therefore, no RN-to-RN interference is considered. Note that RN-to-RN interference [26, 27] occurs when an RN transmits on its relay link and interferes with a reception on the access link of another RN.

### 5. PERFORMANCE EVALUATION AND ANALYSIS

Comprehensive system-level simulations have been carried out to evaluate the performance of the different resource sharing techniques within the LTE-Advanced framework. Moreover, 3GPP urban (case 1) and suburban (case 3) scenarios with ISDs of 500 and 1732 m, respectively, are considered [14]. For each scenario, deployments with 4 and 10 RNs per cell are investigated. Furthermore, the eNB-only deployment with RR scheduler is taken as a reference for performance comparisons. We note that a resource fair RR scheduler is utilised in the benchmark so that the achieved relative gains through the studied techniques can be more easily clarified. With a more advanced scheduler in the benchmark, for example, one that prioritises the cell-edge user performance, a trade-off could be attained where the performance is increased at the low TP regime at the cost of a reduction in the cell TP.

Figure 4. Relay node (RN) deployments at the cell border: (a) 4 RNs and (b) 10 RNs. DeNB, donor evolved node B; ISD, inter-site distance.
Table I. Simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td><strong>System parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2 GHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Number of PRBs</td>
<td>48 for data + 2 for control channel</td>
</tr>
<tr>
<td>PRB bandwidth</td>
<td>180 kHz</td>
</tr>
<tr>
<td>Highest MCS</td>
<td>64-QAM, R = 9/10</td>
</tr>
<tr>
<td>Penetration loss</td>
<td>20 dB on direct and access links</td>
</tr>
<tr>
<td>Bandwidth efficiency ((B_n))</td>
<td>0.88</td>
</tr>
<tr>
<td>SINR efficiency ((A_n))</td>
<td>1/1.25</td>
</tr>
<tr>
<td>Overhead scaling (S)</td>
<td>0.75</td>
</tr>
<tr>
<td>Thermal noise PSD</td>
<td>(-174) dBm/Hz</td>
</tr>
<tr>
<td>SINR lower bound</td>
<td>(-7) dB</td>
</tr>
<tr>
<td><strong>eNB/DeNB parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Transmit power</td>
<td>46 dBm</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>14 dBi</td>
</tr>
<tr>
<td>Antenna configuration</td>
<td>Tx-2, Rx-2</td>
</tr>
<tr>
<td>Noise figure</td>
<td>5 dB</td>
</tr>
<tr>
<td>Antenna pattern</td>
<td>(A(\theta) = -\min[12(\theta/\theta_{\text{max}})^2, \ A_{\text{max}}]) (horizontal) (\theta_{\text{max}}=70^\circ) and (A_{\text{max}} = 25) dB</td>
</tr>
<tr>
<td><strong>UE parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Maximum transmit power</td>
<td>23 dBm</td>
</tr>
<tr>
<td>Antenna configuration</td>
<td>Tx-1, Rx-2</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>0 dBi</td>
</tr>
<tr>
<td>Noise figure</td>
<td>9 dB</td>
</tr>
<tr>
<td><strong>RN parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Relay site planning</td>
<td>Considered via higher probability of LOS and 5 dB bonus on NLOS</td>
</tr>
<tr>
<td>Transmit power</td>
<td>30 dBm</td>
</tr>
<tr>
<td>Antenna configuration</td>
<td>Tx-2, Rx-2</td>
</tr>
<tr>
<td>RN-DeNB antenna gain</td>
<td>7 dBi</td>
</tr>
<tr>
<td>RN-UE antenna gain</td>
<td>5 dBi</td>
</tr>
<tr>
<td>Relay link antenna pattern</td>
<td>(A(\theta) = -\min[12(\theta/\theta_{\text{max}})^2, \ A_{\text{max}}]) (horizontal) (\theta_{\text{max}}=70^\circ) and (A_{\text{max}} = 20) dB</td>
</tr>
<tr>
<td>Access link antenna pattern</td>
<td>Omni-directional</td>
</tr>
<tr>
<td>Noise figure</td>
<td>5 dB</td>
</tr>
<tr>
<td><strong>Shadowing</strong></td>
<td></td>
</tr>
<tr>
<td>Shadow fading</td>
<td>Log-normal</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>8 dB on the direct link</td>
</tr>
<tr>
<td>De-correlation distance</td>
<td>50 m</td>
</tr>
<tr>
<td>Correlation factor</td>
<td>0.5 between sites</td>
</tr>
</tbody>
</table>

PRB, physical resource block; MCS, modulation and coding scheme; SINR, signal-to-interference-plus-noise ratio; PSD, power spectral density; eNB, evolved node B; DeNB, donor evolved node B; UEs, user equipment; RN, relay node; LOS, line-of-sight; NLOS, non-line-of-sight; QAM, quadrature amplitude modulation.

would then translate into decreased relative gains at the low TP regime, whereas the relative gains in terms of cell TP would increase.

Performance evaluation is carried out in terms of the 5th percentile (5%-ile) and 50th percentile (50%-ile) UEs TP CDF levels, and the cell capacity (aggregate user TP, a.k.a. cell TP), which mainly reflect cell-edge, median and cell-centre user performances, respectively. These performance metrics are conventionally utilised in International Mobile Telecommunications Advanced standardisations (e.g. [14]). Moreover, the 50th percentile UEs TP CDF level is particularly critical for performance evaluations in suburban scenarios to assure an optimum performance enhancement [7]. This is due to high inhomogeneity of user experience within the cell, which implies substantially different UEs TP CDF levels. In our work, we focus on techniques to improve the low TP regime to achieve a more homogeneous user experience over the cell area and thus a high level of fairness in the system. Jain’s fairness index [28] is considered as the criterion to reflect the system fairness. An index of one indicates full fairness where all UEs achieve the same TP.

Jain’s fairness index is defined as in Equation (12) to reflect fairness among RUEs, referred to as \(J_{\text{FrN}}\), and as \(J_{\text{sys}}\) in Equation (13) to reveal the fairness in the system as a whole. Recall that \(N\) is the total number of RNs, \(\bar{U}_D\) is the total number of RUEs, \(u_i\) is the number of UEs served by RN \(i\), and \(TP_{ij}\) is the end-to-end TP of user \(j\) in RN cell \(i\). \(U_D\) is defined as the total number of MUEs served on the direct link and \(TP_{ij}\) is the achieved TP of MUE \(i\).

\[
J_{\text{FrN}} = \frac{\left(N \sum_{i=1}^{N} \sum_{j=1}^{u_i} TP_{ij}^2\right)^{\frac{1}{2}}}{\left(N \sum_{i=1}^{N} u_{ij}\right)^{\frac{1}{2}}}
\]

\[
UD \sum_{i=1}^{N} u_{ij} \sum_{j=1}^{TP_{ij}} 2^{TP_{ij}}
\]

\[
J_{\text{sys}} = \frac{\left(N \sum_{i=1}^{N} \sum_{j=1}^{TP_{ij}} U_{ij} + \sum_{l=1}^{U_D} TP_{D,l}\right)^{\frac{1}{2}}}{\left(U_D + UD \sum_{i=1}^{N} \sum_{j=1}^{TP_{ij}} 2^{TP_{ij}} + \sum_{l=1}^{U_D} TP_{D,l}\right)^{\frac{1}{2}}}
\]

In the remainder of this section, we first analyse the resource sharing techniques under the hard resource split assumption at DeNB, and then, further performance enhancements are demonstrated utilising the flexible resource split at DeNB. All resource sharing techniques are associated with a proper UL PC optimisation to guarantee an overall system performance enhancement. Furthermore, in what follows, we define our reference model to utilise AIT-P scheduling of RNs on the relay link and UIT-P TP throttling on the access link. Recall that we refer to our proposed scheme, where AUP scheduling on the relay link along with MMF TP throttling on the access link is utilised, as the hop-optimisation model.
5.1. Resource sharing based on hard resource split at DeNB

The PC optimisation methodology presented in [6, 7] is followed. Accordingly, in urban scenarios, two strategies are considered for the UEs UL transmissions, namely cell coverage-oriented, that is, the 5th percentile UE TP is prioritised, and the 50th percentile UEs TP-oriented settings. On one hand, the cell coverage-oriented setting employs FCPC ($\alpha = 1.0$) and yields a higher 5th percentile UEs TP gain at the expense of reduced UEs TP gain for high percentiles. On the other hand, the 50th percentile UEs TP-oriented setting employs FPC ($\alpha = 0.6$) and yields a higher UEs TP gain for high percentiles at the expense of reduced UEs TP gain for low percentiles. In addition, for the relay link, the PC parameters are set such that a higher capacity can be attained. It is worth noting that the relay link capacity is highly interference limited, and thus, a fine-tuning of PC parameters does not provide notable gains above a certain level of $P_0$ value for the relay link transmissions. We further note that the cell capacity-oriented setting found in [6, 7], that is, $P_0 = -55$ dBm and FPC ($\alpha = 0.6$), is applied for the eNB-only deployment. Furthermore, in suburban scenarios, the trade-off setting presented in [7] is considered for both UEs and RN transmissions and, as well, for the eNB-only deployment. This setting is shown to provide a good balance between low and high UEs TP CDF levels [7]. These optimised PC parameter settings are presented in Table II.

5.1.1. Selection of the number of backhaul subframes.

We proceed with determining the number of Un subframes ($N_b$) yielding the optimum overall system performance. Figure 5 presents the UEs TP CDFs for different Un subframe configurations in a 4-RN urban scenario. In this figure, we also illustrate a novel, very useful concept in performance analysis of heterogeneous networks, which is called proportional CDFs. Namely, the CDFs corresponding to RUEs and MUEs are scaled by the ratio of these.

Figure 5. User equipment (UEs) throughput (TP) cumulative distribution functions (CDFs) considering different backhaul subframe (Un subframe) configurations in 4-relay-node (RN) deployments: urban scenario, MUEs, macrocell-served UEs; RUEs, RN-served UEs; eNB, evolved node B; TTI, transmission time interval.

Table II. Optimised power control parameter configurations for relay nodes (hard resource split at donor evolved node B), macrocell-served user equipments (Uu) and relay node-served user equipments.

<table>
<thead>
<tr>
<th>Urban Scenarios</th>
<th>Suburban Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell coverage-oriented setting</td>
<td>50th percentile UE TP-oriented setting</td>
</tr>
<tr>
<td>MUE (Uu)</td>
<td>RUE</td>
</tr>
<tr>
<td>$P_0$ [dBm]</td>
<td>$96$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$1.0$</td>
</tr>
<tr>
<td>$P_{\text{max}}$ [dBm]</td>
<td>$23$</td>
</tr>
</tbody>
</table>

UE, user equipment; TP, throughput; RN, relay node; MUE, macrocell-served user equipment; RUE, RN-served user equipment; (Uu), during Uu subframes; (Un), during Un subframes.
MUEs performance becomes the limitation when four Un subframes are used, as only six subframes remain available for the MUEs. In this case, the RUEs performance is significantly increased resulting in a higher TP gain at high percentiles. Besides, it is seen that the case with two Un subframes achieves the best gain at the low TP regime. As the emphasis in LTE-Advanced is a more homogeneous user experience, the optimum number of Un subframes is chosen to be two. Similarly, the optimum number of Un subframes is found for other scenarios, and these settings are given in Table III along with the RN coverage areas (i.e., $\mu_{RN}$).

### 5.1.2. Performance assessment.

Assuming the hard resource split at DeNB according to Sections 3.1.1 and 5.1.1, we first evaluate the performance of the different resource sharing strategies and TP throttling techniques presented in Sections 3.2 and 3.3. It is worth noting that these techniques will only shape the performance of RUEs, and thus, the performance of MUEs will not be impacted.

The simulation results for urban scenarios are shown in Figure 6(a). The percentage gains at depicted percentiles of UEs TP CDFs are presented with respect to the eNB-only deployment in Figure 6(a) for the 4-RN and 10-RN deployments. In the 4-RN deployment with the 50th percentile UEs TP-oriented PC, it is observed that the reference and hop-optimisation models yield, respectively, 63% and 118% TP gains at the 5th percentile UEs TP CDF, and 37% and 47% TP gains at the 50th percentile UEs TP CDF. That is, the hop-optimisation model achieves significant TP gains at the 5th percentile UEs TP CDF (extra 55%) and moderate gains at the 50th percentile UEs TP CDF without degrading the cell capacity (cf. Cell TP) compared with the reference model. The 5th percentile TP gain can be further increased at the expense of somewhat reduced the 50th percentile TP gain and a slight degradation in cell capacity, when the cell coverage-oriented PC is utilised. A similar performance enhancement is also observed in the 10-RN deployment. Nevertheless, compared with the case in the 4-RN deployment, it is seen that the hop-optimisation model yields higher relative gains at the 50th percentile UEs TP CDF over the reference model. Furthermore, the CDFs based on the Jain’s fairness index are plotted in Figure 6(b) for the 10-RN deployment. It is observed that the hop-optimisation model results in significantly higher fairness in the system compared with both eNB-only deployment and the reference model. In addition, the system fairness can be further enhanced using the cell coverage-oriented PC scheme. Besides, the mean Jain’s fairness indices for different deployments are tabulated in Table IV. Therein, the 50th percentile UEs TP-oriented PC and cell coverage-oriented PC settings are depicted by PC 1 and PC 2, respectively.

<table>
<thead>
<tr>
<th>Deployment scenario</th>
<th>RN coverage area (%)</th>
<th>Number of Un subframes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard split</td>
<td>Flexible split</td>
<td></td>
</tr>
<tr>
<td>Urban—4 RNs</td>
<td>29.5</td>
<td>2</td>
</tr>
<tr>
<td>Urban—10 RNs</td>
<td>45.5</td>
<td>4</td>
</tr>
<tr>
<td>Suburban—4 RNs</td>
<td>43.5</td>
<td>4</td>
</tr>
<tr>
<td>Suburban—10 RNs</td>
<td>67.0</td>
<td>6</td>
</tr>
</tbody>
</table>

RN, relay node.

---

**Table III.** Optimum backhaul subframe configurations for different resource splits at donor evolved node B.

---

Figure 6. (a) Throughput (TP) percentage gains over evolved node B (eNB)-only in 4-relay-node (RN) and 10-RN deployments; (b) Jain’s fairness index in 10-RN deployment; urban scenario. UEs, user equipment; PC, power control; RUEs, RN-served UEs; CDF, cumulative distribution function.
Table IV. Mean Jain's fairness indices for the investigated scenarios.

<table>
<thead>
<tr>
<th>Deployment Scenario</th>
<th>Mean Fairness Index for RUEs</th>
<th>Mean System Fairness Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>model PC 1 PC 2 model PC 1 PC 2</td>
<td></td>
</tr>
<tr>
<td>Urban—4 RNs</td>
<td>0.7330 0.9833 0.9833 0.7358 0.8403 0.8680</td>
<td></td>
</tr>
<tr>
<td>Urban—10 RNs</td>
<td>0.6932 0.9728 0.9716 0.6702 0.8575 0.8657</td>
<td></td>
</tr>
<tr>
<td>Suburban—4 RNs</td>
<td>0.7374 0.9757 0.6347 0.7710</td>
<td></td>
</tr>
<tr>
<td>Suburban—10 RNs</td>
<td>0.6790 0.9709 0.7045 0.8761</td>
<td></td>
</tr>
</tbody>
</table>

RN, relay node; RUEs, RN-served user equipment; PC, power control.

The proposed hop-optimisation model achieves, as well, significant TP gains in suburban scenarios as presented in Figure 7(a). We first note the significant performance enhancement at the 5th percentile UEs TP CDF over the eNB-only deployment after RNs are deployed. This behaviour shows that RN deployments can effectively cope with the coverage issues due to large ISD. In the 4-RN deployment, the reference and hop-optimisation models achieve, respectively, 297% and 310% TP gains at the 5th percentile UEs TP CDF, and 95% and 136% TP gains at the 50th percentile UEs TP CDF. That is, the hop-optimisation model outperforms the reference model both at the 5th percentile and 50th percentile UEs TP CDF levels (see extra gains depicted by Δ in Figure 7(a)). Lower gain at the 5th percentile UEs TP CDF is due to the limitation of the cell-edge MUEs. On the other hand, in the 10-RN deployment, the gains for the reference and hop-optimisation models read, respectively, as 1090% and 1664% at the 5th percentile UEs TP CDF, and 142% and 196% at the 50th percentile UEs TP CDF. This implies that the hop-optimisation model significantly outperforms the reference model both at the 5th percentile and 50th percentile UEs TP CDF levels (see extra gains depicted by Δ in Figure 7(a)). Furthermore, in both 4-RN and 10-RN deployments a negligible loss is observed in the cell capacity when the proposed model is used. In addition, according to the fairness CDFs plotted in Figure 7(b) for the 10-RN deployment, it is seen that the hop-optimisation model results in significantly higher fairness in the system compared with both eNB-only deployment and the reference model. Recall that the mean Jain’s fairness indices for different deployments are tabulated in Table IV.

5.2. Resource sharing based on flexible resource split at DeNB

The preceding analysis has shown that the proposed hop-optimisation model achieves significantly higher gains compared with the reference model in all of the considered scenarios. Therefore, we consider the hop-optimisation model in the following and further show the impact of the flexible resource split scheme.

The optimisation strategies in case of the flexible resource split scheme are more involved. The reason is threefold. First, as mentioned before, interference characteristics during Uu and Un subframes can be substantially different, which implies different PC parameters for the co-scheduled MUEs and further tuning of those pertaining to RNs during Un subframes. Second, co-scheduled MUEs and RNs may have significantly different received power levels at the serving DeNB, and hence, the receiver dynamic range of the serving DeNB should also be taken into account. Third, the choice of MUEs selection scheme for co-scheduling can impact the resultant system performance drastically. Nevertheless, the possibility of MUEs
5.2.1. Selection of the number of backhaul subframes.

In line with [8], the over-provisioning of Un subframes aims at adapting up to λ percentile of F(ρ_{RN}), which is the CDF of ρ_{RN}. The resultant number of Un subframes, N_b, is then determined taking the upper bound ρ_{RN} ≤ N_b/10 (Section 3.1.2) into account as

\[ N_b = \text{round}(10 \cdot F^{-1}(\lambda)) \text{ with } 0 < N_b \leq 6, \ N_b \in \mathbb{N}^+ \] (14)

With the λ = 90th percentile target, N_b is determined for different scenarios. In Figure 8, CDFs of ρ_{RN} are plotted for the considered scenarios. It is seen that the λ = 90th percentile CDF level corresponds to ρ_{RN} = F^{-1}(0.9) ≈ {0.42, 0.59, 0.57, 0.79} for [Urban 4-RN, Urban 10-RN, Suburban 4-RN, Suburban 10-RN] deployments, respectively. Following Equation (14), N_b values are then found and tabulated in Table III for the investigated scenarios. However, because of constraints on N_b given in Equation (14), the target λ level cannot be achieved for the considered scenarios. Accordingly, achievable target CDF levels, denoted by \( \lambda^* = F(N_b/10) \), are depicted in Figure 8. We recall that \( \lambda^* \) values mark the levels up to which the resource split can be flexibly tuned. It is worth noting that for Urban 4-RN deployment, the flexibility of the scheme can be further increased for N_b > 4; however, for such values, access link limitation is observed because of increased number of transmission gaps, and thus, N_b > 4 is not preferred.

5.2.2. Performance assessment.

In this section, the performance is analysed considering random MUEs selection for co-scheduling. We then start with illustrating PC optimisation strategy during Un subframes, taking TP gains and DeNB receiver dynamic range into account. In Figure 9, the results for the 10-RN deployment in urban scenario are provided. Therein, PC optimisation during the Un subframes is depicted where FPC is utilised, and a parameter sweep is applied for the P_0 values of RNs (P_0^{RN}) at two different P_0 values of co-scheduled MUEs (P_0^{MU}). During Uu subframes, the 50th percentile UEs TP-oriented setting is used (Table II). The percentage gains at the 50th percentile UEs TP CDF over eNB-only deployment (left vertical axis) and DeNB receiver dynamic ranges (right vertical axis) are presented. Two settings are marked, which yield comparable results in terms of the shown performance measures, that is, the maximum 50th percentile UEs TP CDF and the minimum DeNB receiver dynamic range. Besides, these settings also achieve similar percentage gains at the 5th percentile UEs TP CDF level over eNB-only deployment (around 205%) and mean UEs TP values (around 850 kbps). Nevertheless, the second setting is selected because the P_0 values during Uu and Un subframes become the same so that no extra signalling is required to update the P_0 values for Un subframes. The corresponding P_0 values along with the achieved gains over eNB-only deployment are provided in Table V (Random MUEs Selection Scheme).

Because of the full frequency of reuse, the total inter-cell interference at DeNB is of particular concern for the resultant system performance. During each of the Uu and Un subframes, we group all interferers into two distinct groups denoted by \( \eta_1 \) and \( \eta_2 \). To be specific, \( \eta_1 \) and \( \eta_2 \) correspond to, respectively, the MUEs in other cells and RNs in all cells during Uu subframes and the co-scheduled MUEs in other cells and RNs in other cells during Un subframes. The total instantaneous interference-over-thermal (IoT) level per PRB at DeNB can then be written in linear domain as

\[ \text{IoT}_{\text{DeNB}} = \frac{I + P_N}{P_N} = \frac{I_{\eta_1} + I_{\eta_2} + P_N}{P_N} \] (15)
Table V. Performance of flexible resource split at donor evolved node B in urban scenarios.

<table>
<thead>
<tr>
<th>MUE Selection Scheme</th>
<th>PC Scheme</th>
<th>TP Gain (%) over eNB-only</th>
<th>$R_0$ (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90th percentile</td>
<td>50th percentile</td>
<td>5th percentile</td>
</tr>
<tr>
<td>Random</td>
<td>4 RNs</td>
<td>FPC</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FCPC</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>10 RNs</td>
<td>FPC</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FCPC</td>
<td>31</td>
</tr>
<tr>
<td>Cell centre</td>
<td>4 RNs</td>
<td>FPC</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FCPC</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>10 RNs</td>
<td>FPC</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FCPC</td>
<td>46</td>
</tr>
<tr>
<td>Cell edge</td>
<td>4 RNs</td>
<td>FPC</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FCPC</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>10 RNs</td>
<td>FPC</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FCPC</td>
<td>32</td>
</tr>
</tbody>
</table>

MUE, macrocell-served user equipment; RN, relay node; PC, power control; FPC, fractional PC; FCPC, full compensation PC; TP, throughput; eNB, evolved node B; (Uu), during Uu subframes; (Un), during Un subframes.

where $I_{n_1}$ and $I_{n_2}$ are the interferences caused by node groups $n_1$ and $n_2$, respectively, and $P_N$ is the thermal noise power. Equation (15) can be rewritten as

$$\text{IoT}_{\text{DeNB}} = \frac{I_{n_1} + P_N}{P_N} + \frac{I_{n_2} + P_N}{P_N} - 1$$

Subsequently, to highlight the difference in interference characteristics during Uu and Un subframes, we plot mean IoT CDFs in Figure 10. It is first seen that the IoT proportion of the MUEs is dominating the total mean IoT at DeNB. Second, it is observed that the total mean IoT at DeNB tends to be less during Un subframes than that during Uu subframes. Another observation during Un subframes is that the mean IoT levels from RNs are comparable with or less than those of the MUEs. The reason is stemming from the low transmit power levels of RNs, thanks to decreased path loss towards the serving DeNB due to relay site planning, and higher antenna gains, as well as the directional antennas installed at RNs for backhauling. We note that this reveals a key advantage of co-scheduling. Namely, because of the decreased total mean IoT at DeNB during Un subframes, the co-scheduled MUEs are substantially higher than those during Uu subframes provided that a proper PC setting is applied.
5.2.3. Impact of macrocell-served user equipment selection schemes.

Different strategies can be employed for the MUEs selection such as the link quality. Herein, we exemplify two MUEs selection schemes. In the example schemes, cell-edge or cell-centre MUEs are selected to be scheduled with RNs in Un subframes. In order to classify the MUEs as cell-edge UEs, the periodic measurements of reference signal received power (RSRP) and reference signal received quality (RSRQ) can be used [29].

Similarly, in the considered example schemes, reference signal received power measurements are employed to classify the MUEs as cell edge or cell centre. Specifically, for each MUEs the numbers of neighbour macrocells and RN cells are determined such that the DL signal strength of the neighbour macrocell or RN cell is 6 dB lower than the DL signal strength of the serving cell. The MUEs with the largest number of such neighbours, where the number pertaining to macrocells is prioritised, are considered as cell-edge MUEs, and the rest of the MUEs are considered as cell-centre UEs. For example, assume that MUEs 1, which has two such macrocell and three RN cell neighbours, and MUEs 2, which has three such macrocell and two RN cell neighbours. According to the aforementioned grouping scheme, MUEs 1 and MUEs 2 will be considered as cell-centre MUEs and cell-edge MUEs, respectively. Then, depending on the target scheme, either cell-edge or cell-centre MUEs are first scheduled with RNs in Un subframes. In order to classify the cell-edge or cell-centre MUEs are first scheduled with RNs in Un subframes in such a way that the resource fairness is assured. It is to be noted that co-scheduling cell-edge or cell-centre MUEs has different impacts on the interference characteristics during Uu and Un subframes. This is as well demonstrated in Figure 13 for 10-RN urban deployment utilising FCPC. In this figure, the changes in the mean IoT levels due to the MUEs selection scheme are depicted by mean IoT indicators where a pointer direction towards zero implies no change in the mean IoT level with respect to the random MUEs selection scheme. Furthermore, a pointer direction towards plus or minus indicate a relative increase or a decrease in the mean IoT level, respectively.

As also depicted by the mean IoT levels, for the cell-centre MUEs selection scheme, the total mean IoT at DeNB decreases in Uu subframes as cell-edge MUEs are dominating the inter-cell interference, whereas it...

Figure 11. User equipment (UEs) throughput (TP) cumulative distribution functions (CDFs) in (a) 4-relay-node (RN) deployment and (b) 10-RN deployment; urban scenario. FPC, fractional power control; FCPC, full compensation power control; eNB, evolved node B.

Figure 12. User equipment (UE) throughput (TP) cumulative distribution functions (CDFs) in 4-relay-node (RN) and 10-RN deployments; suburban scenario. Res., resource; Sel., selection; eNB, evolved node B; MUEs, macrocell-served UE.
In this work, we have investigated different resource sharing techniques taking into account UL PC optimisation. We have proposed a combination of resource allocation on the relay link based on the number of attached RUEs and a TP throttling scheme achieving MMF in the end-to-end two-hop communication. Furthermore, we have demonstrated a flexible resource split at DeNB based on over-provisioning of Un subframes and co-scheduling of MUEs, seen necessary only if it yields a good trade-off between different TP regimes.

Next, the impact of the MUEs selection for co-scheduling is analysed in suburban scenarios (Figure 12; Table VI). Unlike urban scenarios, the suburban scenarios are not interference limited because of large ISD, and the performance is mainly defined by the received signal-to-noise ratio. Consequently, power limited cell-edge MUEs shape the low TP regime. Therefore, the path loss of a MUE is taken as the criterion to classify it as a cell-edge or cell-centre MUEs. That is, the MUEs experiencing the largest path losses, which are mainly the power-limited UEs, are selected first for co-scheduling in the cell-edge MUEs selection scheme. As the cell-centre MUEs selection scheme does not provide a good trade-off between high and low TP regimes, we focus on the cell-edge MUEs selection scheme in the following. When the cell-edge MUEs selection scheme is employed, the performance can be further improved above the 25th percentile and 7th percentile UEs TP CDF levels for 4-RN and 10-RN deployments, respectively, at the cost of reduced performance at lower TP percentiles. Crucially, the cell-edge MUEs selection scheme enables an increased $P_0^{\text{MUE}}$ value during Uu subframes, which is the main reason for the performance enhancement (see Cell-Edge MUEs Selection Scheme in Table VI). We note that such an increase in $P_0$ value is otherwise not desirable because of power limitation of cell-edge MUEs. It is also worth noting that the $P_0^{\text{MUE}}$ setting of the co-scheduled MUEs should be set differently than that of the other MUEs in most of the considered cases in suburban scenarios.

### 6. CONCLUSION

In this work, we have investigated different resource sharing techniques taking into account UL PC optimisation.
REFERENCES


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