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Dual access points association in relay networks to conserve mobile terminals' energy

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Abstract: In this study, the authors consider the benefits of mobile terminals (MTs) with different access points (APs) for uplink and downlink transmission to conserve MTs' energy. In traditional cellular networks, an MT is typically associated with a single AP. However, as wireless networks evolve, heterogeneous and/or overlay deployment scenario become viable and an MT can be associated with different APs for uplink and downlink transmission. The authors call this 'dual APs association'. The authors show that allowing dual APs association provides a significant gain on the uplink system capacity and/or the uplink transmit power savings. As a specific example of the use of dual APs, the authors focus on relay networks and show that considering the relay cost further increases the benefits of this approach. Based on extensive simulations using IEEE 802.16m relay network Evaluation Methodology, the authors demonstrate that dual APs can improve the uplink harmonic capacity by 350% or reduce the uplink transmit power by 7 dB. The authors note, however, that there exists a signalling cost in implementing dual APs association, which needs be overcome to achieve these substantial performance improvements.

1 Introduction

4 G wireless cellular standards such as IEEE 802.16m and 3GPP LTE-Advanced are designed to provide mobile broadband access, which is geared to carry all types of Internet traffic including voice and video [1]. In order to provide better connectivity, various types of access points (APs) with different transmission powers and cell coverage areas are being considered, such as macro, micro, pico, femto and relay APs. Under heterogenous cell deployments, a macro cell may encompass several smaller cells and thus cell coverage areas are overlaid. One of the important problems in such heterogeneous and/or overlay multi-cell environments is properly associating mobile terminals (MTs) with serving APs. This problem is usually called 'user association' [2, 3]. In selecting the serving APs, at least two types of performance metrics should be considered: energy and capacity.

So far, user association has mostly been driven by objectives such as maximising downlink capacity. Since capacity is computed from the received signal-to-interference-plus-noise ratio (SINR), the simplest (and thus widely accepted) rule is to choose the AP that gives the strongest downlink pilot signal. However, increasing attention is being paid to minimising the MTs' energy consumption so as to extend the battery lifetime and reduce the system's 'carbon footprint' [4–6]. Since the uplink RF transmission is one of the main contributors to battery consumption (e.g. 60% in time division multiple access (TDMA) phones [7]), a user association policy merely based on the downlink capacity may be poor from an energy perspective; indeed, uplink RF transmission should be taken into account in selecting the serving AP. As an example of energy-efficient user association, the MT can select the AP that gives minimum path loss to minimise the uplink Tx power consumption.

When the Tx powers of all APs are same, user associations based on (i) maximising downlink capacity and (ii) minimising uplink Tx power, are essentially identical because in both cases the AP with minimum path loss to the associated user is selected. However, when APs have different Tx powers, which is the case in heterogeneous/overlay cell deployments, (i) and (ii) may result in different serving APs for downlink and uplink. This is because unlike heterogeneous downlink Tx powers, the uplink Tx power of the MT is likely the same for all APs. Thus, the MT may have 'asymmetric' APs for downlink and uplink. This will be referred to as 'dual APs' in this paper. The benefits of using dual APs are energy saving and/or increased uplink capacity. We will see that these benefits are greater the more Tx powers of APs differ.

In implementing dual APs association in real systems, it should be noted that uplink and downlink communications are not independent of each other in typical cellular networks; uplink transmission is generally based on scheduling information sent on downlink control channels. For example, when hybrid automatic repeat request (HARQ) is enabled, any data transmission requires acknowledgement to be sent immediately in the opposite direction. This requires very good connectivity between neighbouring APs so that such coupling can be maintained even if downlink and uplink APs are different.

While it may be challenging to implement dual AP in current deployments, efficient backbone communications among APs can be already achieved and is mentioned as the requirement for other advanced radio technologies such as coordinated multiport transmission (CoMP). One of the deployment scenarios where dual APs association can be easily implemented is IEEE 802.16m relay networks because the wireless backhaul between the base station (BS) and the relay station (RS) typically have a small and predictable delay. In addition, MAC coordination between BS–RSs can be easily managed because the BS is the traffic aggregation point for all connected RSs. Another possible deployment scenario is the remote radio head (RRH) deployment as shown in X.1#4 [8], where the RRH has a fibre connectivity to the main BS for radio signal transfer and BS is the central point for all MAC functions. In this deployment, dual-AP access can be considered as carrier aggregation [8] of two cells from BS and RRH.

We show that using dual APs association significantly improves the energy efficiency of MTs. Based on the IEEE 802.16m Evaluation Methodology [9], the uplink Tx power is shown to be reduced by 7 dB, that is, five times lower Tx power to achieve the same SINR at the receiver. In addition to the energy/power saving benefits, dual APs also serve to improve the uplink capacity. For example, our case study shows that the average uplink 'ergodic' capacity is improved by 27% while the average uplink 'harmonic' capacity (which is defined as the inverse of the average 1-bit transmit time) is improved by more than 300%. This substantial gain results from the performance improvement dual APs provide users at the cell edge who experience severe interference and/or large path loss. We show that the benefits of dual APs are even more substantial when relaying costs and inter-cell interference are factored. Finally, we also propose a hybrid user association policy which selects a single AP (to avoid additional dual AP signalling) considering both downlink and uplink performance.

2 Dual AP

2.1 System model

We consider an infrastructure-based wireless cellular network where multiple APs serve multiple MSs. Target systems could be, but are not limited to, WiMAX2 or 3GPP-LTE. APs can have different Tx powers and thus different downlink coverage areas. In this paper, we focus on relay networks where two types of APs exist: the BS and the RS. Usually RSs are deployed to extend the coverage of the network, and for cost-effective deployment the RS has a wireless backhaul link to the BS. Even though we study relay networks in this paper, our work can be easily extended to general overlay networks. Fig. 1 shows a typical scenario of the dual APs; the MT is connected to the BS for the downlink, and to the RS for the uplink while BS–RS is a wireless backhaul link.

2.2 Intuition

To develop some intuition of the benefits of dual AP, let us first analyse dual APs association in a one-dimensional (1D) network model. This example is simple but demonstrates the benefits. Suppose that the BS, the RS and the MT are located on a line segment [0,1]. Let the BS be at 0, the RS be at 1 and the MT be somewhere in between.

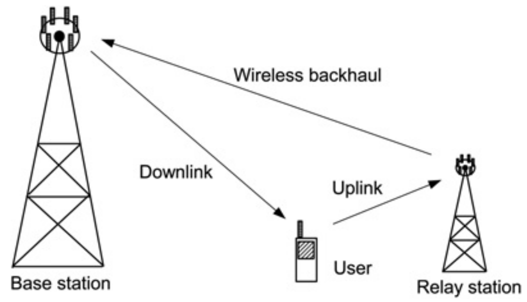

Fig. 1 *System model*

BS and RS cover the interval of (0,1). Let the downlink Tx power of the BS be 1 and that of the RS be $\beta \leq 1$ in the sequel, if not explicitly stated. For simplicity, we use a path loss model given by

$$p_{\rm r} = p_{\rm t}\left[\frac{d}{d_0}\right]^{-\alpha} \quad (1)$$

where $p_{\rm r}$ is the received power, $p_{\rm t}$ is the transmit power, d is the distance, d_0 is the reference distance and α is the path loss exponent [10]. Let $b \in (0, 1)$ denote the cell boundary for downlink; that is, the MT lying in $(0, b)$ is associated with the BS, whereas the MT lying in $(b,1)$ is associated with the RS for downlink communication.

To maximise the downlink Shannon capacity, b should be chosen so that the received SINRs from the BS and the RS are equal at b, so b should satisfy the following equation

$$\frac{[b/d_0]^{-\alpha}}{N_0 + \beta[(1-b)/d_0]^{-\alpha}} = \frac{\beta[(1-b)/d_0]^{-\alpha}}{N_0 + [b/d_0]^{-\alpha}} \quad (2)$$

where N_0 is the noise power. Equation (2) is satisfied when $[b/d_0]^{-\alpha} = \beta[(1-b)/d_0]^{-\alpha}$ and the location of cell boundary is given by

$$b = \frac{1}{1+\beta^{1/\alpha}} \quad (3)$$

Note that in this 1D model the boundary does not change if we ignore the interference terms in the denominators in (2). For simplicity we will not consider interference in our analysis of AP selection in Section 2; we will however consider interference in the 19-cell deployment scenario of IEEE 802.16m relay networks in Section 3.

When $\beta = 1$, that is, the BS and the RS have the same Tx power, the cell boundary is obviously at the middle point, that is, $b = 0.5$. However, as β decreases, b increases, which implies the BS covers a larger downlink area than the RS.

In contrast, the MT needs to be connected to the closest AP to minimise the uplink Tx power (or to maximise the uplink capacity). Then, the uplink cell boundary should be at 0.5 independently of α and β. Thus, if the MT is located on the interval $(0.5, b)$, the MT needs to be connected to the BS for the downlink but to the RS for the uplink. Hereafter we refer to such a region as 'dual APs zone (DAZ)'. In the 1D model, the ratio of DAZ over the length of coverage area, denoted by ϕ, is simply given by $\phi = b - (1/2)$.

Fig. 2 shows the DAZ ratio for various α and β. For example, if $\alpha = 2$ and the Tx power of the RS is 10 dB lower than that of the BS [9], then DAZ is 25%. We will

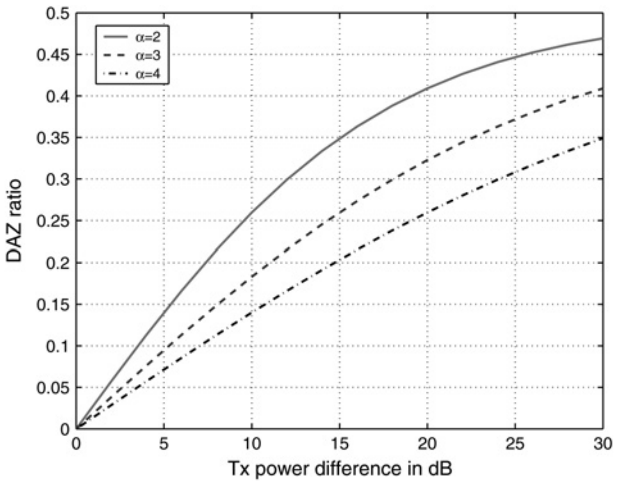

Fig. 2 *DAZ ratio in a 1D model*

see in Section 2.4 that this ratio becomes larger in our 2D model.

2.3 Average uplink Tx power reduction in 1D model

Now let us consider the average uplink Tx power with and without dual APs to achieve a target received power at the APs. Let X be a uniformly distributed random variable on (0,1) denoting the location of the MT, and $P(X)$ be a random variable denoting the Tx power of the MT at location X. Then, based on the path loss model in (1), the uplink Tx power is given by $P(X) = p_r[X/d_0]^\alpha$ where p_r is the target received power at the AP. Setting a target received power is appropriate for real-time traffic such as voice or video, which requires sustaining some fixed rate and thus requires a target received SINR. When the AP is selected based on the maximising downlink capacity criterion, the uplink Tx power of the MT at location X, denoted by $P_d(X)$, is given by

$$P_d(X) = \begin{cases} P(X), & \text{if } X \le b \\ P(1-X), & \text{if } X > b \end{cases} \quad (4)$$

where b is given by (3). In contrast, when minimising the uplink Tx power is the AP selection criterion, the uplink Tx, denoted by $P_u(X)$, is given by

$$P_u(X) = \min[P(X), P(1-X)] \quad (5)$$

The uplink Tx power ratio using dual APs over the conventional method is then given by

$$\frac{E[P_u(X)]}{E[P_d(X)]} = \frac{2\int_0^{1/2} p_r x^\alpha \, dx}{\int_0^b p_r x^\alpha \, dx + \int_b^1 p_r (1-x)^\alpha \, dx} \quad (6)$$

$$= \frac{(1/2)^b}{b^{\alpha+1} + (1-b)^{\alpha+1}} \quad (7)$$

Remark 1: Note that power saving ratio is independent of the target received power p_r if interference is not considered in determining the required Tx power.

Fig. 3 shows the Tx power ratio for various α and β. As can be seen, when $\beta = 0.1$, that is, a 10 dB difference in Tx powers [9], a 45% reduction in the uplink Tx power can be realised while achieving the same received power at the AP.

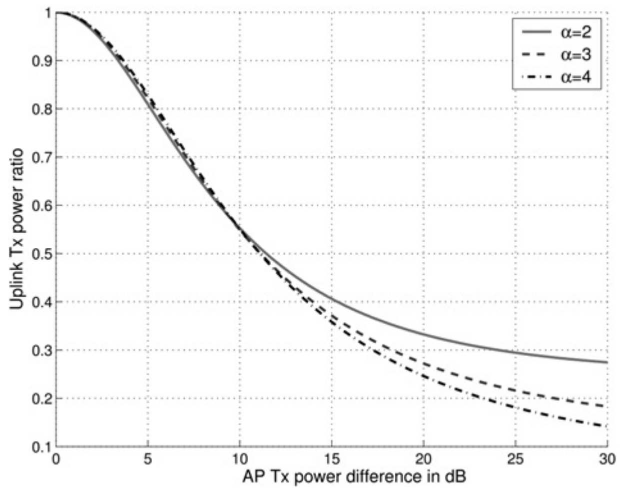

Fig. 3 *Reduced Tx power using dual APs*

2.4 Analysis of DAZ in 2D model

As one might expect, the DAZ ratio becomes higher in 2D than 1D model, which further motivates the use of dual APs in real networks. Fig. 4 shows our 2D model for dual APs. Fig. 4 exhibits the case where a cell is divided into three sectors, each of which has one RS. Note that the IEEE 802.16m Evaluation Methodology also defines a scenario with two RSs per sector, and a similar analysis can be carried out. Suppose that the BS is placed at the origin $A = (0,0)$, and the RS at $B = (1,0)$. Then, using the path loss model in (1), the downlink cell boundary is the collection of the points $C = (x,y)$ where the received SINRs from the BS and the RS are equal. It can be shown by a simple geometry that

$$\overline{AC}:\overline{CB} = 1:\varphi$$

where $\varphi = \beta^{1/\alpha}$ and thus C is on a circle centred at $(1/(1-\varphi^2), 0)$ with a radius $\varphi/(1-\varphi^2)$. For simplicity, we assume that the right most coverage of the BS is the same

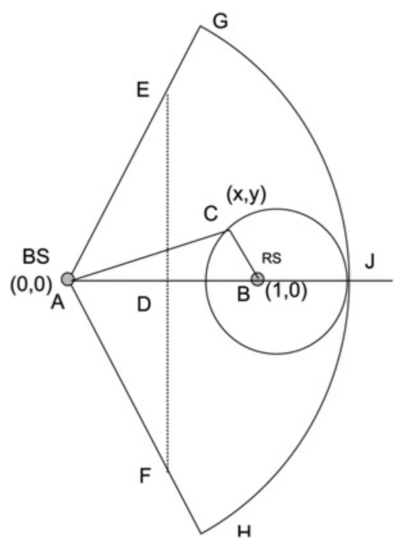

Fig. 4 *2D analysis model*

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to that of the RS, which is denoted by J. Thus, J is the point where the two circles meet and is given by $J = (1/(1-\varphi), 0)$. Note that in this model the coverage areas of the BS and the RS both vary with β. The interior of triangle AEF is the single AP zone where the MT is bidirectionally connected to the BS. Similarly, the interior of the circle of C is the single AP zone of the RS. All other area is the DAZ. By simple geometry, the DAZ ratio ϕ is then given by

$$\phi = 1 - \frac{(\sqrt{3}/4) + \pi(\varphi/(1-\varphi^2))^2}{\pi/(3(1-\varphi)^2)} \tag{8}$$

when $\beta \leq [\sqrt{3}/2]^\alpha$ (When β is bigger than $[\sqrt{3}/2]^\alpha$, which is very unlikely in real systems, the circle C is too big and $\overline{AG}$ and $\overline{AH}$ intersect the circle. In this case the DAZ calculation becomes tedious, so we do not consider it here.). Fig. 5 exhibits the DAZ ratio for the 2-D model, which is significantly larger than that of the 1D model. For example when $\alpha = 2$ and Tx power difference is 10 dB [9], 63% of the sector area corresponds to the DAZ.

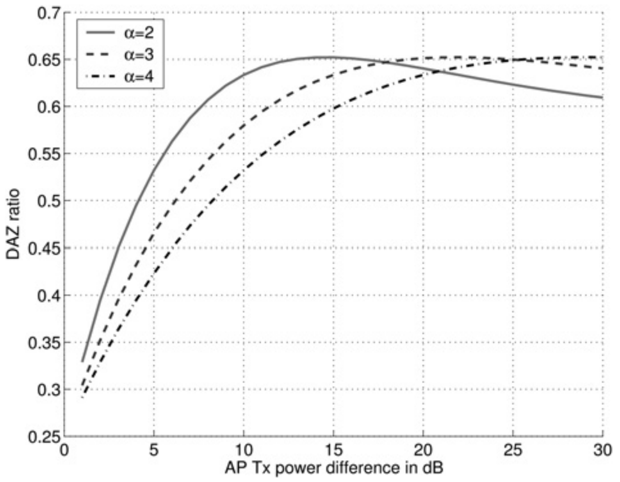

Fig. 5 *DAZ ratio in 2D model*

2.5 Relaying cost

So far we have not considered the impact of the relaying cost, and thus the results are applicable to general overlay networks. However, in selecting the serving AP, it is more reasonable to also consider the relaying costs because a two-hop routing (BS–RS–MT) is costlier than one-hop (BS–MT). Intuitively, when the relaying cost is factored, the BS coverage area is expected to expand to avoid an unnecessary additional hop. To quantify this we use the following metric.

Let C_{bm}, C_{br} and C_{rm} be the link capacity when the Tx/Rx pairs are BS/MT, BS/RS and RS/MT, respectively. Then, the cell boundary as determined from a downlink perspective is the location where the following equation holds

$$\frac{1}{C_{\text{bm}}} = \frac{1}{C_{\text{br}}} + \frac{1}{C_{\text{rm}}} \tag{9}$$

This can be interpreted as follows; time is a shared resource, so we want to equalise the 1-bit transfer time from the BS to the MT, either via the direct link or the relay link. Note that this criterion is identical to (2) when C_{br} is set infinity. This is the case of overlay networks where APs are connected by wired links. Similarly, the uplink boundary is the location satisfying the following equation

$$\frac{1}{C_{\text{mb}}} = \frac{1}{C_{\text{mr}}} + \frac{1}{C_{\text{rb}}} \tag{10}$$

where C_{mb}, C_{mr} and C_{rb} are the link capacities when the Tx/Rx pairs are MT/BS, MT/RS and RS/BS, respectively.

Fig. 6 shows the impact of the relaying cost on the downlink and uplink boundaries: (a) without factoring relaying cost, (b) when factoring the relaying cost. Capacities are computed using the path loss model in (1) and the Tx power parameters defined in the 802.16m Evaluation Methodology [9], that is, 46 dBm for the BS, 23 dBm for the MT. The BS is placed at the origin, and the RS is 500 m away. By varying the Tx power of the RS (y-axis in Fig. 6), the uplink and downlink boundaries on [0,500] are plotted. Comparing Figs. 6*a* and *b* shows that

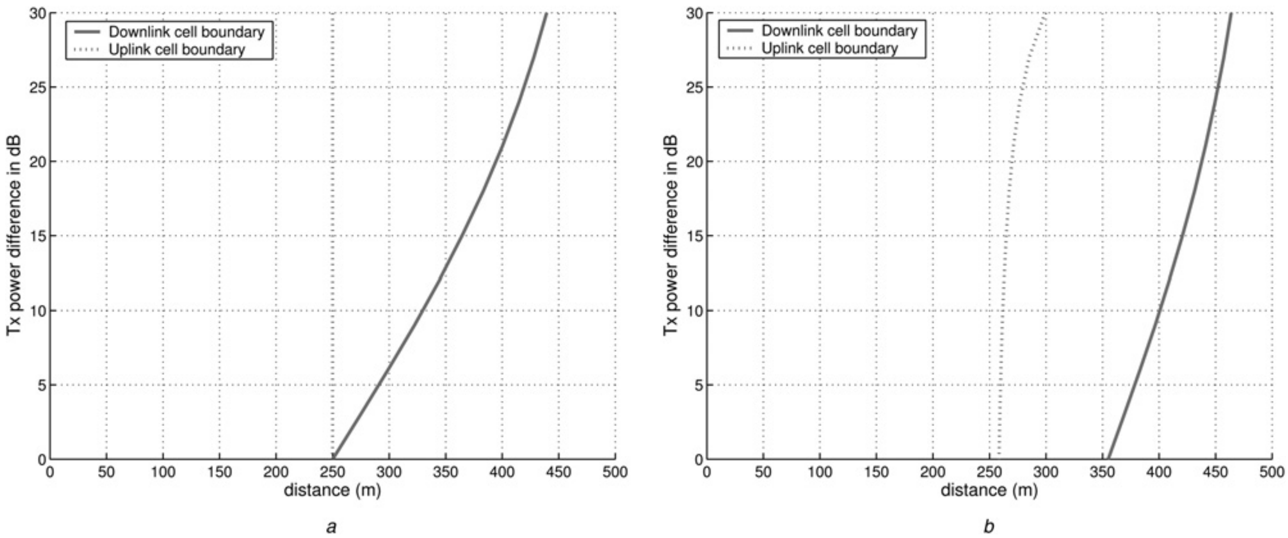

Fig. 6 *Impact of relaying cost on the cell boundaries*

a Relaying cost excluded
b Relaying cost included

Table 1 System parameters

carrier frequency	2.5 GHz
operating bandwidth	10 MHz
frequency reuse	1 × 3 × 1
number of RS per sector	2
number of sectors	3
number of cells	19
BS site-to-site distance	1500 m
BS Tx power per sector	46 dBm
MT Tx power	23 dBm
BS antenna gain (boresight)	17 dBi
BS antenna height	32 m
BS to RS distance	562.5 m
RS Tx power	26∼46 dBm
RS antenna height	32 m
RS antenna gain to BS (directional)	20 dBi
RS antenna gain to MT (omni)	7 dBi
MT antenna gain (omni)	0 dBi
noise figure + cable loss	7 dB
penetration loss	10 dB
noise spectral density	−174 dBm/Hz

the downlink coverage of the BS expands significantly when the relaying cost is considered. This is because the relaying cost reduces the benefit of relay links and the connection needs to be biased to the direct link. In contrast, the uplink boundary remains almost same, with the relaying cost not playing a critical role. This is because the backhaul link capacity (RS–BS) is a lot better than the direct link (MT–BS), and thus using the relay link is mostly beneficial.

Remark 2: Factoring the relaying cost expands DAZ and further motivates the use of dual APs.

3 IEEE 802.16m relay networks

In this section we investigate the benefit of dual APs in the context of IEEE 802.16m relay networks. According to the deployment scenario in [9], one cell has three sectors, each of which has two RSs. The key system simulation parameters are summarised in Table 1 as in [9]. Path loss models for BS–RS, BS–MT, RS–MT links are also quoted from [9].

3.1 Demonstration of DAZ

Figs. 7*a* and *b* show the DAZ without and with consideration of relaying costs, respectively. For simplicity here we compute the AP's coverage area in a single cell scenario; the BS is at the centre of the hexagon and 6 RSs are placed along the corners. The distance between the BS and the RS is 562.5 m while the length of a side of the hexagon is $1500/\sqrt{3}$ m. The Tx power of the BS, RS and the MT are 46, 36 and 23 dBm, respectively. As we have already seen in Fig. 6, factoring relaying cost expands the DAZ further. Fig. 7*a* shows that 32% of the total coverage area is DAZ when relaying costs are not considered while Fig. 7*b* shows that 51% of the cell coverage area is DAZ when relaying costs are factored. This verifies the result shown in Fig. 6 and is summarised in Remark 2. Unlike the straight line boundary $\overline{EF}$ in Fig. 4, the boundaries between the BS and the RSs here are bent. This is because the BS has higher antenna gain and so its coverage area expands further.

3.2 Capacity and power gains under inter-cell interference

Next let us consider a multi-cell deployment scenario of relay networks under inter-cell interference as shown in Fig. 8. We are interested in the uplink performance enhancement in terms of capacity and power since downlink performances are same as before. To account for inter-cell interference, 19 cells were considered. The centre cell is surrounded and interfered by the first tier with 6 cells and the second tier with 12 cells. The downlink interference is from BSs and RSs when they transmit at their maximum power, and interference is considered in computing (9). Uplink interference comes from MSs that are randomly placed. We assume that only one MT is scheduled in each sector; since a cell has three sectors, there are in total $19 \times 3 - 1$ interfering MSs. The uplink interference is considered for two different cases, separately. When we compute the uplink capacity gain, we assume that all the MTs transmit

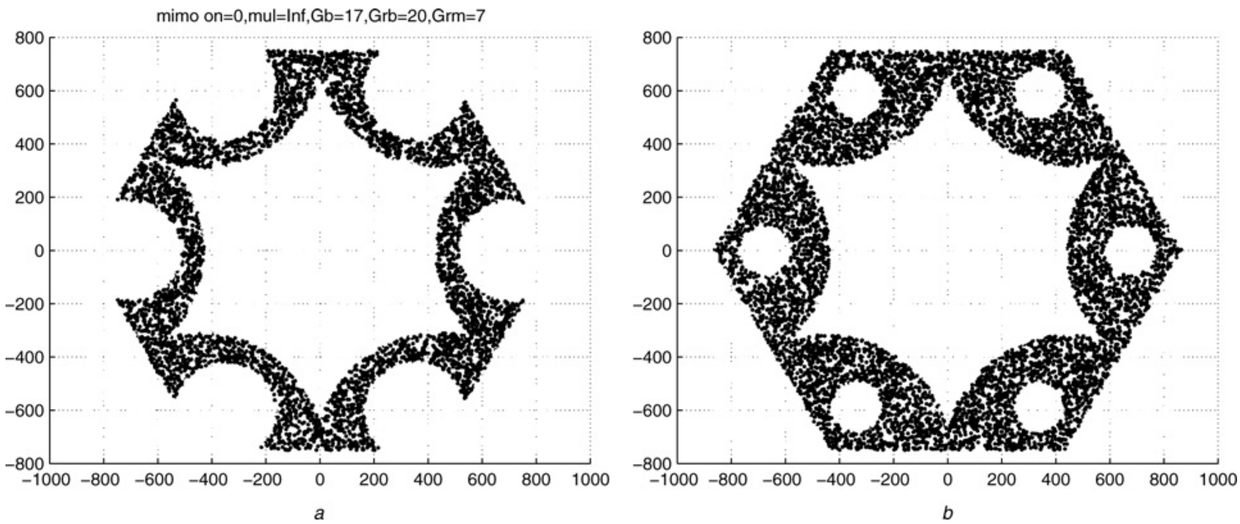

Fig. 7 *Dual APs zone*

a Relaying cost excluded
b Relaying cost included

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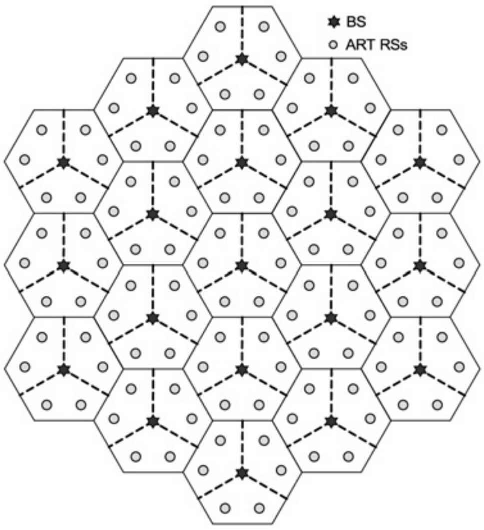

Fig. 8 *Relay networks deployment scenario*

at their maximum Tx power, that is, no power control for simplicity. When we consider the uplink Tx power saving ratio, we assume that the MTs do power control so as to achieve some fixed SINR at the target AP. Note that when we apply (10) to AP selection for uplink, we do *not* consider interference in computing $C_{\rm mr}$, $C_{\rm mb}$ and $C_{\rm rb}$ because uplink interference changes depending on the locations of the interfering MTs (i.e., scheduled MTs in other cells); the timescale of AP selection should be much larger than that at which interference varies.

3.2.1 Gains in the average ergodic capacity: Fig. 9 shows the uplink capacity computed for the baseline (single AP) and the proposed (dual APs), respectively. Tx power of the RS varies from 26 to 46 dBm, that is, upto a 20 dB difference from that of the BS. The uplink capacity is computed when all the MSs transmit at their maximum power. This scenario mainly corresponds to the case where the uplink traffic is best effort and thus maximising throughput is desired. Fig. 9*a* shows the ergodic uplink capacity averaged over many realisations of randomly placed MSs. As can be seen, the capacity obtained by the baseline policy decreases monotonically as the Tx power difference between BS and RS increases. By contrast, the capacity obtained by the dual APs policy remains almost the same. When the Tx power difference is 10 dB as defined in 802.16m Evaluation Methodology, the dual APs policy achieves 23.8 Mbps while the baseline achieves 18.7 Mbps, corresponding to a 27% improvement in uplink capacity. This performance gain increases further as the Tx power of the RS decreases.

3.2.2 Gain in the harmonic average capacity: Fig. 9*b* shows the harmonic uplink capacity, which is defined as the inverse of the average 1-bit transmit time. It can capture the average file transfer time seen by a typical MT. Note that from Jensen's inequality, harmonic capacity cannot exceed the ergodic capacity. Comparing Figs. 9*a* and *b* shows that the harmonic capacity is a lot lower than the ergodic capacity in the case of the baseline policy. In contrast, the dual APs policy does not show much degradation. Hence, the harmonic capacity gain of dual APs over the baseline is very substantial. For example, at 10 dB Tx power difference, the harmonic capacity of the dual APs policy is over 15 Mbps while that of the baseline is 3.5 Mbps, which is more than four times difference. This huge gain comes from the edge users' performance; since the harmonic capacity is the inverse of the average 1-bit transmit time, it is strongly affected by the users who see poor capacity, for example, edge users. As a corner case, if any of the users experiences zero capacity, the average harmonic capacity becomes zero. To exclude this kind of extreme, the harmonic capacity is computed by averaging 95 percentile of users who see good capacity (and thus 5 percentile of users with poor capacity are excluded).

3.2.3 Uplink Tx power savings: Fig. 10 shows the uplink Tx power of the baseline policy and that of the dual APs policy, respectively. The uplink Tx power is computed assuming that each MT requires a fixed bit rate. This scenario corresponds to the case where the network supports real-time voice or video connections. The target received SINR at either the BS or RS is 0 dB in our

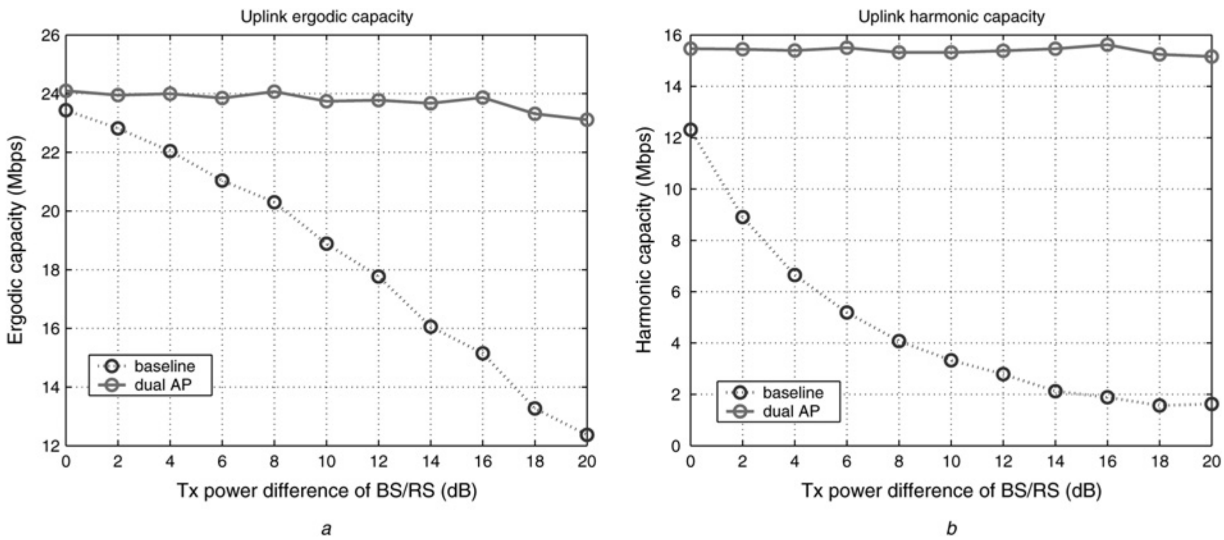

Fig. 9 *Uplink capacities in a 19-cell scenario*

a Ergodic capacity
b Harmonic capacity

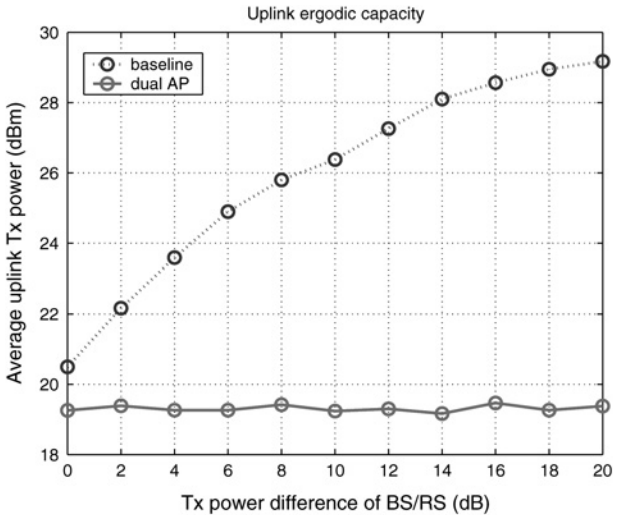

Fig. 10 *Uplink Tx power saving in a 19-cell scenario*

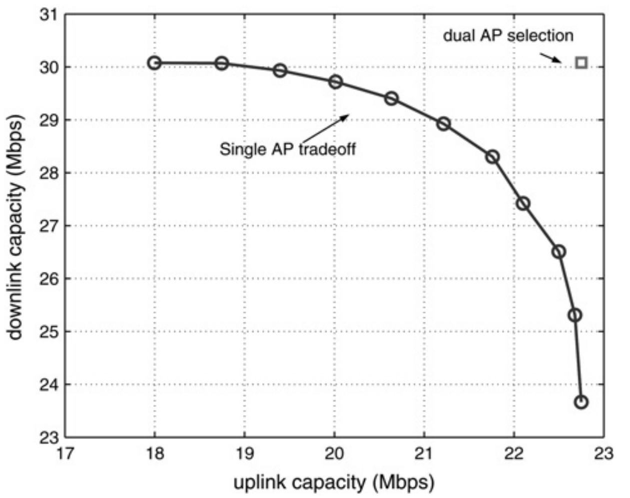

Fig. 11 *Ergodic capacity region of uplink and downlink for different θ (19-cell scenario)*

simulation (Note from Remark 1 that the power saving ratio is independent of the target received SNR. In the presence of interference, if the target received SINR is higher, the power saving gain becomes larger. This is because the dual APs reduce uplink Tx power so that inter-cell interference is also reduced.). As can be seen in Fig. 10, the uplink Tx power of the dual APs remains almost constant while that of the baseline increases as the Tx power difference of BS/RS grows. For example, when Tx power difference is 10 dB, the MT can reduce its Tx power by 7 dB, which is a promising performance gain. This result strongly suggests that dual APs policy should be implemented in relay networks although there may be additional signalling costs – the evaluation of these cost remains as a future work.

3.3 Hybrid decision

In addition to dual AP association, we also consider a hybrid user association policy. In this scenario, the MT is connected to only one AP in order to avoid signalling overheads associated with using dual APs. In selecting the AP, the MT considers both the uplink and downlink performance. As an example, we use the following decision metric. Let C_d^j and C_u^j be the j-hop downlink and uplink capacity, respectively, which are determined from the criteria described in (9) and (10). Let θ be the parameter that specifies the preference on the uplink in selection the AP. Then,

$$j^* = \arg\max_{j \in \{1,2\}} C_u^j \theta + C_d^j (1 - \theta) \tag{11}$$

is the decision criterion, that is, when $j^* = 1$ the MT is connected to the BS directly while when $j^* = 2$, the MT is connected to the RS. Note that $\theta = 0$ corresponds to the AP selection purely from downlink perspective, and $\theta = 1$ is from purely uplink perspective; θ can be a system design parameter specifying the operator's preference on uplink and downlink performance. Fig. 11 shows how the uplink and downlink ergodic capacity changes as θ varies. We see the trade-off between downlink and uplink capacity. Also shown in the figure is the performance when the dual APs are implemented; the uplink and downlink capacities of (22.8 and 30 Mbps) (square point in this figure) are achieved. Clearly, the dual APs selection strictly dominates the hybrid strategy, suggesting this is well worth pursuing.

4 Discussion on implementing dual APs

So far we have been focusing on the data communication of the MT. Control signalling coordination between two APs is, however, also important because data communication depends on control signalling. In this section we discuss a

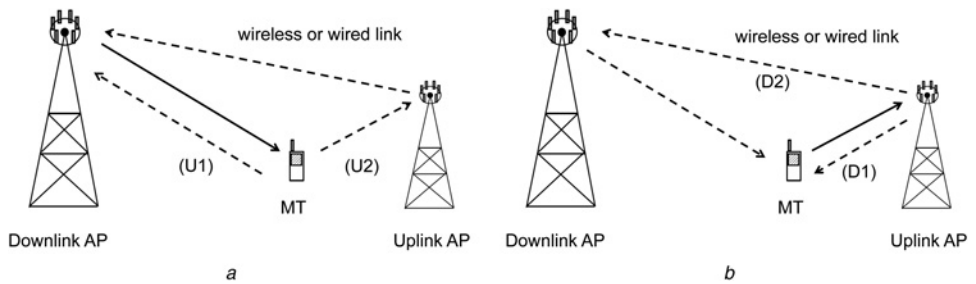

Fig. 12 *Control signalling scenarios in overlay network*

a Downlink data communication with uplink control signalling
b Uplink data communication with downlink control signalling
Solid line is for data communication, and dashed line is for control signalling

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way of implementing dual APs considering control signalling. We expand the concept of dual APs into overlay networks by replacing the BS and the RS with downlink AP and uplink AP, respectively. While the MT is in the dual AP zone, downlink AP is responsible for downlink data communication and requires uplink control signalling feedback from the MT. Similarly, uplink AP is responsible for uplink data communication and needs to send downlink control signalling feedback to the MT.

Concerning control signalling feedback, we have four scenarios as follows. For downlink data communication, downlink AP needs to have uplink control signalling, and two options (U1) and (U2) are illustrated in Fig. 12*a*. (U1) Uplink control signalling can be directly sent by MT to downlink AP via robust transmission. This implies that control signalling does not follow dual AP principle. In this case, coordination is generally required so that no concurrent uplink data transmission to uplink AP at the same time, and to ensure enough coverage given MT's limited transmission power. (U2) Uplink control signalling can be transferred from MT to uplink AP, and then uplink AP transmits to downlink AP with a small penalty on latency; however, if the link between uplink AP and downlink AP is a wired connection such as cable/optical fibre, which is indeed the case in the overlay networks of 3GPP–LTE Advanced [11], latency increase would be negligible. Similarly, for uplink data communication, uplink AP needs to send downlink control signalling to the MT, and two options (D1) and (D2) are illustrated in Fig. 12*b*. (D1) Downlink control signalling can be directly sent by uplink AP to the MT via robust transmission. This implies that the control signalling does not follow dual AP principle. (D2) Downlink control signalling can be transferred from uplink AP to downlink AP, and then downlink AP transmits to the MT with a small penalty on latency; this latency can be negligible if the link between two APs is a wired connection.

Here are some examples for delivering uplink scheduling information, HARQ feedback, channel quality indicator (CQI) feedback and uplink ranging. In these examples, we assume that the link between two APs is wireless, so these are examples for the worst cases for dual AP implementation.

- *HARQ feedback:* when HARQ timing is critical, (U1) and (D1) can be used for fast HARQ feedback.
- *Uplink scheduling information:* uplink data transmission requires scheduling information to be sent from AP in the downlink. This could be independently managed and broadcasted reliably in the downlink from the uplink AP as in (D1). This could also be jointly managed by inter-AP coordination and broadcasted in the downlink from the downlink AP as in (D2), for example, centralise scheduling at the BS in the relay network or coordinated scheduling in multiple BSs case.
- *CQI feedback:* CQI report for downlink channel quality is an independent operation in uplink without strong timing requirement. Hence, it could be either (U1) or (U2) depending on latency requirement.
- *Uplink ranging:* This is not generally timing critical. (U2) can be a sufficient solution.

5 Conclusion and future work

We showed that using dual APs association significantly improves the uplink energy efficiency and/or capacity. Unlike the homogeneous deployment scenario where all APs have the same Tx power and thus roughly the same coverage areas, future wireless networks will be based on heterogeneous deployments. In this case, a large Tx power difference (e.g. 10 dB) between APs necessitates different selection of APs for uplink and downlink. One of the possible deployment scenarios is that of wireless relay networks, and we proposed a decision metric based on harmonic capacity. We demonstrated that allowing dual APs in an IEEE 802.16m relay network reduces the average uplink transmission power by 7 dB or improves the uplink harmonic capacity by 350%. It should be noted that the performance gain may be achieved at the expense of increased signalling cost. Considering the fact that, however, upcoming wireless standards IEEE 802.16m and 3GPP LTE-Advanced have efficient backbone communications, implementing dual AP association is expected to be feasible soon.

Even though in this paper we have focused on evaluating the performance of dual AP in IEEE 802.16m replay network, the performance benefits of dual AP should also apply to other 4 G wireless networks. For example, the dual AP concept could be applied to 3GPP LTE-Advanced technology where heterogeneous types of cells such as macro, micro and pico cells coexist. In addition, the use of RRH in LTE Rel-11 cooperative multi-point transmission [11] facilitates the implementations of design options defined in Section 4. Note that RRHs are the geographically distributed nodes that are connected to a BBU/eNodeB via high-speed cable/optical fibre, and the BBU/eNodeB jointly processes the signals from/to RRHs. We leave its performance evaluation as future research.

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