Performance of Amplify-and-Forward and Decode-and-Forward Relays in LTE-Advanced

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Abstract— **Current broadband wireless networks are characterized by large cell sizes. Yet, even in advanced networks, users on the cell edge will face relatively low Signal-to-Interference-plus-Noise-Ratio (SINR). An attractive solution for this problem is provided by multi-hop technologies. In this paper, we consider the performance of full duplex Amplify-and-Forward (AF) and half duplex Decode–and-Forward (DF) Relay Nodes (RNs) from 3G LTE-Advanced perspective. The comparison between AF and DF relaying is important because both approaches are currently under consideration in LTE-Advanced study item in 3GPP. Performance evaluation considers AF RN loop back signal interference and concurrent DF RN transmissions on the access link. Results show that the concurrent transmissions improve the spectral efficiency for DF RN over performing AF RN.**

Keywords-LTE-Advanced; decode-and-forward relay; amplify–and-forward relaying; performance evaluation; loop interference

I. INTRODUCTION

The Long Term Evolution - Advanced (LTE-Advanced) is a new air interface being designed by the Third Generation Partnership Project (3GPP) to fulfill 4G requirements specified by the International Telecommunication Union – Radiocommunication sector (ITU-R). LTE-Advanced will admit higher peak data rates and more users per cell as well as considerably higher peak and average spectral efficiency (SE) than currently employed 3G technologies [1]. Yet, enhancements in radio link technology will not solve the basic problem related to propagation loss: coverage and capacity at the cell border remain relatively small due to low Signal-to-Interference-plus-Noise-Ratio (SINR) [2].

A promising solution to overtake the above mentioned problem is represented by Relay Nodes (RNs). Deploying RNs near the cell edge will help to increase the capacity [3][4] or, alternatively, to extend the cell coverage area [5][6]. RNs diverse in functionality and mode of operation. Conventionally, full duplex Amplify-and-Forward (AF) relays have been used as gap fillers, but it is known that AF relays amplify not only the desired signal but also both interference and noise. Decode-and-Forward (DF) relays, for one, detect the desired signal and then encode and forward it. Therefore, DF relays are applicable also in interference limited environments.

While the introduction of DF relays requires extensive standardization efforts and increases the system complexity, AF relays, on the other hand, suffer from loop interference (LI) that refers to the leakage of transmit signal to receive antenna [7][8]. Due to LI, concurrent transmission and reception at the same frequency band requires two separated antennas in the relay: one for receiving and the other for transmitting. Furthermore, high physical isolation between the antennas has to be guaranteed and therefore, an attractive approach is to use outdoor-to-indoor arrangement, where relay backhaul antenna is placed outside the building while another antenna is used to provide indoor coverage. Since such arrangement is costly and usually feasible only in large office buildings, outdoor antenna systems are applied, where antenna isolation is obtained by creating feasible distance between backhaul and access antennas or by using antenna directivity properties.

In what follows, we carry out a preliminary analytic comparison between full duplex AF and half duplex DF relaying within the LTE-Advanced framework. We have adopted LTE-Advanced framework because the discussion of the role of AF and DF relays has just started there. In this context, we refer to a base station by the 3GPP term enhanced Node B (eNB). We consider a simple scenario where at most two hops are allowed. Such a scenario is most attractive from a practical perspective both in case of DF relaying where the system complexity is strongly related to the number of hops and in AF relaying where interference may start to ping pong between relays. In the following, we refer by direct link to the connection between eNB and the User Equipment (UE), by backhaul link to the connection between eNB and RN, and by access link to the connection between RN and UE. Note that relays are deployed outdoor while indoor users are considered; therefore, penetration loss is assumed on the direct and access links but not on the backhaul link.

The paper is organized as follows. Section II presents an analytic analysis of two-hop relaying. In section III, performance evaluation of both AF and DF relaying as well as comparisons between the two schemes are provided. Limitations of loop interference on AF relaying, advantage of concurrent DF RN transmissions as well as deployment considerations and effects of backhaul link gain are discussed. Section IV concludes the paper and highlights future work.

II. Analysis of Two-Hop Relaying

Comparisons between half duplex relays with direct link showed that AF relays perform better than DF RNs near the receiver [9]. On the other hand, if the direct link is not considered, DF relay outperforms AF one. In this discussion, we compare full duplex AF and half duplex DF relays, and focus on cell middle and edge users. Therefore only the throughputs for UEs connected to the RNs are derived for both AF and DF relays. Interference is neglected in the analytical derivation, as we consider a coverage limited scenario. Loop interference in AF relaying is, however, considered.

A. Amplify-and-Forward Full Duplex Relay

The system model for AF relaying is illustrated in Fig. 1 with a typical outdoor RN. This example downlink scenario assumes relay deployment on a lamp pole. To guarantee good quality for the backhaul link, a highly directive receive antenna is placed on the top of the pole and pointed towards eNB possibly with a line-of-sight connection. The transmit antenna is placed on the street-level with wider beam pattern towards the covered area while pointing away from the backhaul antenna which minimizes the loop interference.

In what follows, SNR_1 and SNR_2 refer to the Signal-to-Noise Ratios (SNRs) of the first (eNB-RN) and second (RN–UE) hops, respectively. The direct link (eNB-UE) SNR is given by $SNR_{eNB\text{-}UE}$. Similarly, the strength of the loop back interfering signal is quantified in terms of SNR_{LI}, which is the ratio of the interference signal power to the relay input noise power. In practice, SNR_{LI} is defined by the isolation between the relay antennas, antenna gains and the relay transmit power or, equivalently, the relay gain.

In AF relaying, the Signal-to Interference-plus-Noise Ratio (SINR) at UEs connected to RN is obtained as follows. The total useful signal power is a combination of both the signal received directly from eNB and the two-hop signal which is amplified by RN. On the other hand, the total interference plus noise power contains the effect of the loop back signal, relayed noise and UE receiver noise. Extending the analysis in [10] by explicitly including the effect of LI, the end-to-end SINR at UE, which is used to estimate the system SE, is found to be

$$SINR_{AF} = \frac{SNR_1 \cdot SNR_2 + SNR_{eNB-UE}\left(1 + SNR_{LI} + SNR_1\right)}{SNR_1 + \left(1 + SNR_2\right)\left(1 + SNR_{LI}\right)}. \quad (1)$$

Recalling that the multi-path components arriving within the OFDM cyclic prefix add up to the useful signal power, whereas those spread outside generate inter-carrier and inter-symbol interference (ICI and ISI), the formulation in (1) can be seen as both optimistic and pessimistic. On one hand, it is assumed that the end-to-end delay through the relay is shorter than the duration of the cyclic prefix and that the time synchronization in UE is decent. Thus, both eNB and RN contribute to useful signal power. On the other hand, all loop back signals are considered to be interference, which is not the case if the cyclic prefix is long enough to account for multiple loop-back echoes.

It is to be noted that the formulation in (1) assumes that RN gain is selected to guarantee a predefined relay transmission power. However, the end-to-end performance could still be improved by optimizing the relay gain based on the quality of the relay input signal, the isolation between the relay antennas and the desired RN coverage range [11].

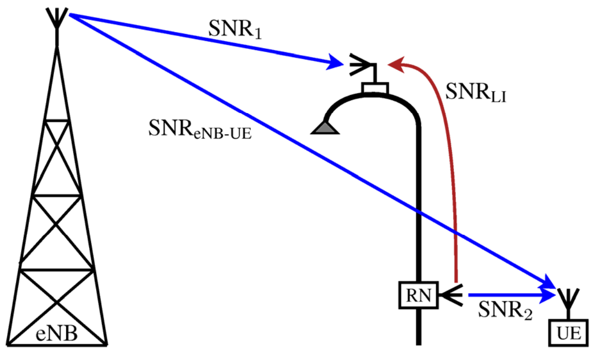

Figure 1. System setup for full duplex AF relaying.

B. Decode-and-Forward Half Duplex Relay

In half duplex DF relaying, resources used on the access link can be reused among n RNs within the overlaying macro cell as shown in Fig. 2. This, however, is not possible with full duplex AF relays, because eNB cannot transmit simultaneously different signals to the different AF RNs. Note that LTE's time-frequency domain split of physical resource blocks (PRBs) is not depicted in Fig. 2; for simplicity, we exclusively use a time domain split. The throughput over two hops is maximized, if throughputs on relay and access links are equal. Assuming equal resource consumption in RNs, we have

$$\rho \cdot SE_1 = \alpha \cdot SE_2, \quad n \cdot \rho + \alpha = 1, \quad (2)$$

where SE_1 and SE_2 refer to the spectral efficiencies on the backhaul and access links, respectively. Factors ρ and α correspond to the time shares in Fig. 2. The latter equality is introduced to normalize resources in the two-hop link. After solving the equations in (2), we find that

$$\rho = \frac{SE_2}{n \cdot SE_2 + SE_1}, \quad \alpha = \frac{SE_1}{SE_1 + n \cdot SE_2}. \quad (3)$$

Thus, SE on the two-hop link is of the form

$$SE_{DF} = SE_2 \cdot \alpha \cdot n = \left(\frac{1}{SE_1} + \frac{1}{n \cdot SE_2}\right)^{-1}. \quad (4)$$

Equation (4) shows that the end-to-end SE increases with the number n of concurrent RN transmissions and, in principle, the upper limit for the two-hop link efficiency is set by the efficiency of the backhaul link. Yet, we emphasize that (4) does not take into account the mutual interference between concurrent relay transmissions; therefore, it provides optimistic results, especially when the number of concurrently transmitting relays is large. It is of interest to solve for n in (4),

$$n = \left\lceil \frac{SE_{DF}}{SE_2\left(1 - SE_{DF}/SE_1\right)} \right\rceil. \quad (5)$$

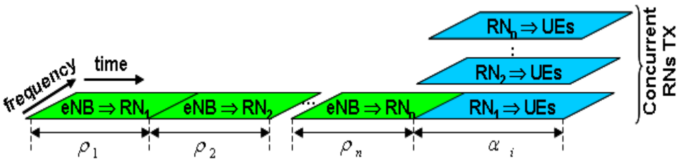

Figure 2. Concurrent transmission of RNs using the same radio resources.

III. Performance Evaluation

A. Comparison methodology

The comparison between AF and DF relaying is carried out by using the analytical formulae (1) and (4). As a performance measure, we consider SE that is computed based on the Shannon approximation

$$SE_{Link} = A \cdot \log_2\left(1 + B \cdot SNR_{Link}\right), \tag{6}$$

where the parameters A=0.88 and B=1/1.25 are, respectively, the bandwidth and SNR efficiency factors that are selected so that (6) fits with the set of LTE adaptive modulation and coding curves. 64-QAM is set as the highest modulation scheme, defining the maximum SE as SE_{max} = 6b/s/Hz.

The reference system is a single-hop network that is designed according to current LTE-Advanced requirements [1]. Adhering to these requirements, for 3GPP *case 1*, where the inter-site distance is 500m, carrier frequency is 2GHz and two transmit and receive antennas are used in DL, the cell edge SE is 0.07b/s/Hz/user, when there are 10 users in the cell; whereas, the average cell SE is 2.4b/s/Hz/cell. It is to be noted that the cell edge value of 0.07b/s/Hz/user is defined as the 5% point of CDF of the user throughput normalized with the overall cell bandwidth, whereas the average throughput is the aggregate throughput of all users in the cell.

Throughout the comparison, we first fix the direct link SE between eNB and UE. That is, we set

$$SE_{eNB-UE} = SE_T, \tag{7}$$

where SE_T is the spectral efficiency defined by the relay location in the overlaying macro cell. Thus, if RN is located on the cell edge, the direct link target SE is set to 0.7b/s/Hz/cell[1]; while it is set to 2.4b/s/Hz/cell if the relay is located on the cell middle.

After fixing the single-hop system SE, we solve the required SNR from (6). This will define the value of the SNR in the direct link of (1). Then we define the SNR on the backhaul link between eNB and RN by

$$SNR_1 = G \cdot SNR_{eNB-UE}, \tag{8}$$

[1] Cell edge spectral efficiency multiplied by the number of users.

where G is the gain achieved from elevation and outdoor location of relay nodes. Namely, RN antennas are at 5m above ground level, which provides 3-7dB gain against link between eNB and UE [12]. Furthermore, we assume indoor users while relays are located outdoors, this gives up to 20dB advantage for backhaul link over eNB-UE link. When SNRs on the direct and backhaul links have been set, AF and DF comparisons are carried out as a function of SNR on the access link.

B. Impact of loop interference

Fig. 3 depicts SE for cell edge users of full duplex AF relaying for different values of loop interference, assuming that the backhaul link is 16dB better than the direct link. It is seen that the loop interference reduces the AF relaying efficiency, especially at high access link SNR. The performance of AF relaying decreases rapidly if serious loop interference (above -5dB) takes place. This may happen when e.g. AF relay antenna installation is not done properly or the transmit/receive antenna isolation is difficult to obtain, due to site or cost limitations. Compared to an idle AF relaying scheme, i.e. considering a negligible SNR_{LI}=-50dB loop interference level, a reduction at access link SNR=20dB of around 0.7b/s/Hz end-to-end SE is noticed for loop back signal of SNR_{LI}=0dB. A loss of about 0.3b/s/Hz is experienced at SNR_{LI}=-5dB. The -5dB level is considered realistic in some AF relaying schemes, and it will be used in the comparisons that follow.

C. Deployment Prioritization

In this analysis, we validate the deployment of DF RNs on the cell edge, and show the plausibility of deploying AF RNs around the middle of the cell. Fig. 4 presents the end-to-end spectral efficiency for both AF and DF relaying schemes at both locations. A loop back signal SNR_{LI} of -5dB is assumed for AF relaying. In DF relaying scheme, a single DF RN is considered, i.e. no concurrent transmission. The gain on the backhaul link with respect to the direct link is set to 16dB.

For cell edge relay node deployments, DF relaying provides a better performance, as compared to the expected direct link spectral efficiency, for access link SNR higher than 0dB. However, as DF relay nodes are moved closer to the middle of

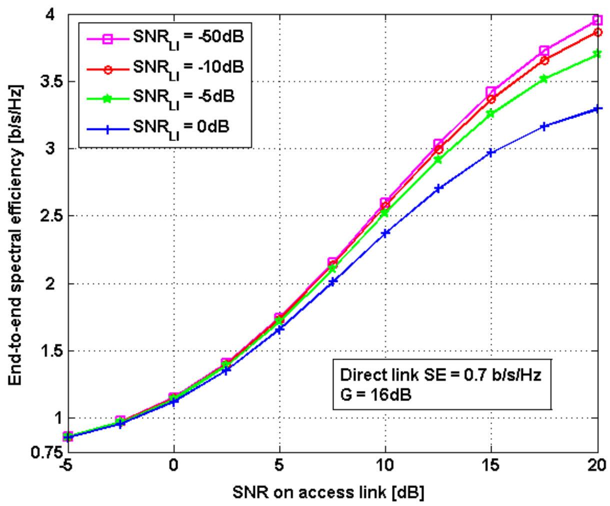

Figure 3. Effect of loop interference on SE of AF RN.

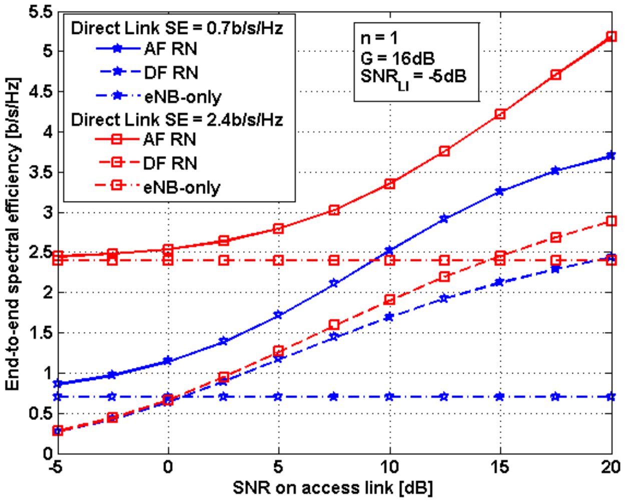

Figure 4. Deployment prioritization considering AF and single (n=1) DF relay nodes.

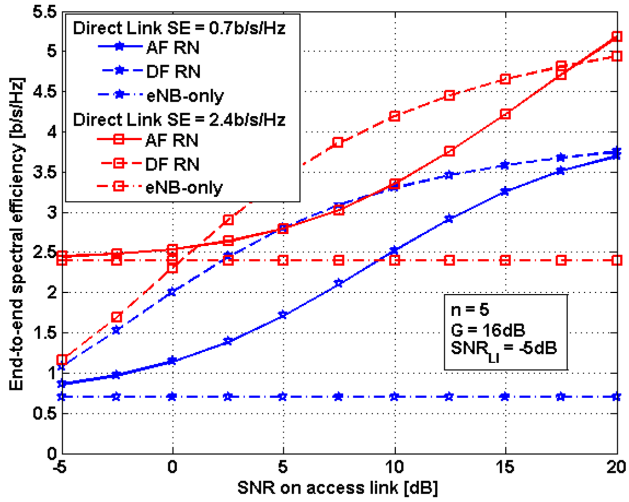

Figure 6. Deployment prioritization considering AF and 5 concurrently transmitting DF RNs.

the cell, DF relaying lags in performance behind the macro eNB scheme for access link SNR up to 15dB. Thus, Decode-and-Forward RN deployments are more attractive at cell edges. On the other hand, AF relaying always outperforms the direct link for both deployments, with still higher SE when deployed at the middle of the cell. Therefore, AF RN deployments, as opposed to DF RN deployments, are more suitable near the middle of the cell. It is worth noting that in both deployments AF relaying performs better than DF relaying assuming single DF RN transmission.

D. Impact of concurrent DF RN transmissions

An important advantage of half duplex DF relaying is in the opportunity to use concurrent RN transmissions on the access link with different data contents. Although the DF spectral efficiency in (4) does not take into account the interference between DF relays, it provides guidelines to evaluate the efficiency of DF relaying when concurrent transmissions take place. Fig. 5 shows the significant enhancement in performance for an increasing number of concurrently transmitting DF relay

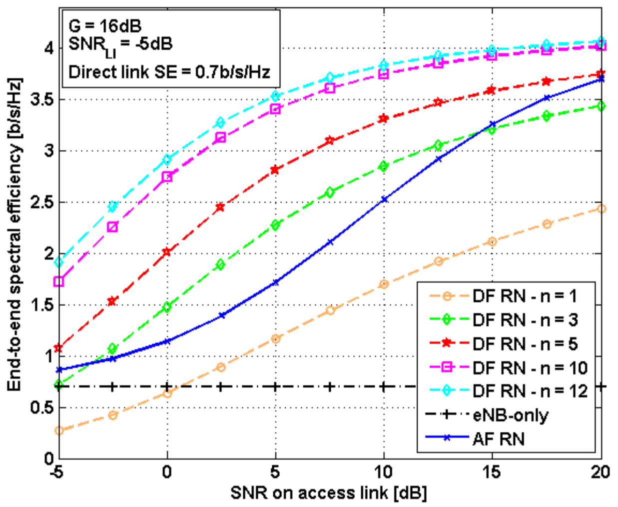

Figure 5. Spectral efficiency versus access link SNR considering different number of concurrent DF RN transmissions.

nodes. Whereas, a single DF RN lags in performance behind AF RN and also behind that of the eNB-only scheme for low access link SNR, DF RN deployments outperform noticeably both for 5 or more concurrent transmissions, considering access link SNR in the range [-5dB, 20dB]. A 3 concurrently transmitting DF relaying scheme performs better than AF relaying at mid and low access link SNR. The comparison was carried out assuming cell edge RN deployments, $SINR_{LI}$=-5dB AF RN loop interference and 16dB gain on the backhaul link as compared to the direct link. In the following analysis, DF relaying schemes will be considered with 5 concurrent transmissions.

It is also interesting to consider the effect of the concurrent transmissions on the access link on the deployment strategy in DF relaying schemes. Fig. 6 depicts the performance of AF and DF relaying schemes at the middle and edges of the cell. The significant gain from the 5 concurrent DF RN transmissions is clear as compared to the performance of a single DF RN shown in Fig. 4. At the cell edge, DF relaying with 5 concurrently transmitting RNs outperforms both AF relaying and traditional eNB-only scheme for the considered access link SNR range, even at very low SNR regime. Similarly, for deployments near the middle of the cell, the concurrent transmissions enhanced the performance of DF relaying with a noticeable gain over eNB-only scheme for access link SNR roughly above 0dB. Thus, the gain from concurrent transmissions in DF relaying can be translated into shifts in deployment from the cell edges more towards the middle of the cell. In such a case, DF RNs are also favored over AF RNs, and users at the low SNR regime can be served by eNB, since AF RN provides marginal gain at such SNR levels.

E. Impact of Bakchaul link gain

Fig. 7 presents the performance of AF and DF relaying for different backhaul link gains. RN deployments are assumed at cell edge, with -5dB $SINR_{LI}$ and n=5 concurrent DF RN transmissions. It is clear that at mid access link SNR, DF RN gains more from the backhaul link SNR increase than AF RN. On the other hand, AF relays benefit more at high access link

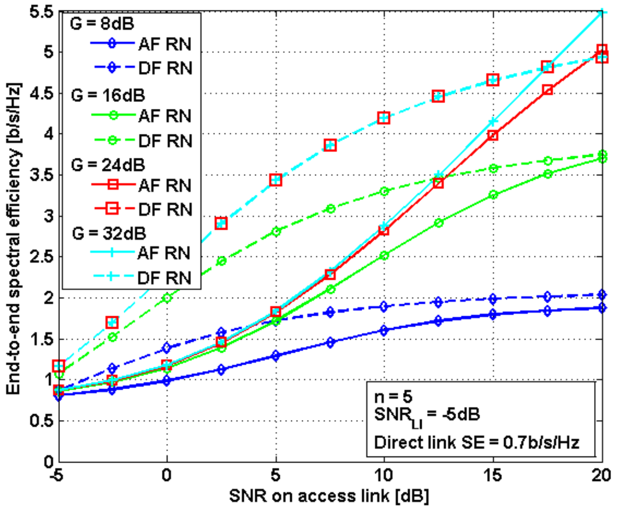

Figure 7. Spectral efficiency of AF and DF relaying vs SNR on the access link considering 8dB, 16dB, 24dB and 32dB gains on the backhaul link.

SNRs, and even outperform DF RNs, when the spectral efficiency on the backhaul link is limited by SE_{max} the maximum efficiency of the modulation scheme.

F. Considerations on concurrent DF transmissions

In what preceded, the significant gain from concurrent DF RN transmissions was highlighted. Fig. 8 illustrates the required number of concurrent DF relay transmissions that is needed to achieve at least the same spectral efficiency as with AF relaying, for different access and backhaul link SNR. For that purpose it is assumed that AF and DF end-to-end spectral efficiencies are equal and use equation (5) where the two-hop DF spectral efficiency is calculated from equation (6) with SNR given in (1). Clearly, a practically moderate number of concurrent DF transmissions (n=5) is required for most of the access link and backhaul link SNR spectra. However, when

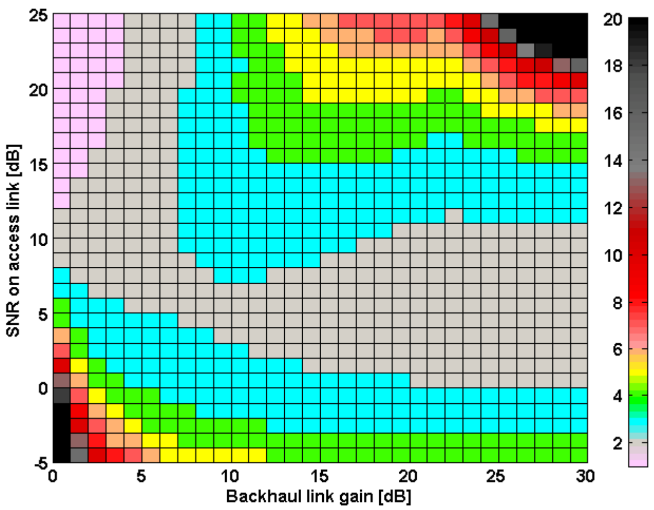

Figure 8. Number of concurrent transmissions required by DF RN to achieve same performance as AF RN considering different SNRs on the access and backhaul links. RN deployments are at cell edge, with SNR_{LI}=-5dB. n=20 is set in this figure as an upper limit, for illustration purposes.

both access and backhaul links SNR are either very low or very high, the required number of concurrent transmissions is unfeasible, and AF RNs outperform DF RNs. This is due to the resource consumption on the backhaul link for DF RNs.

IV. CONCLUSION AND FUTURE WORK

We discussed amplify-and-forward (AF), and decode-and-forward (DF) relaying within LTE-Advanced framework and carried out performance comparison based on analytical evaluations. It is noticed that while full duplex AF relays provide a straightforward mean to increase signal strength they also amplify noise and interference, and require careful and costly installation due to loop back interference between transmit and receive antennas. On the other hand, the required standardization effort is minimal when compared to DF relays that can be introduced only after appropriate standardization.

Deduced analytical results take into account the limitations of loop back interference for AF relays and show the advantage of concurrent transmissions on the access link for DF relays. Performance results indicate that concurrently transmitting DF RNs are more attractive in both cell middle and edge deployments. However, AF RNs outperform DF ones for very high access and backhaul links SNR.

Future work will consider the effect of interference due to concurrent DF RN transmissions. Further, resource partitioning will be studied in case where not all RNs transmit concurrently.

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