

INBAND FULL-DUPLEX RADIO ACCESS SYSTEM WITH SELF-BACKHAULING: TRANSMIT POWER MINIMIZATION UNDER QOS REQUIREMENTS

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ABSTRACT

In this paper, a self-backhauling radio access system is studied and analyzed. In particular, we consider a scenario where a full-duplex access node is serving mobile users simultaneously in uplink and downlink, while also maintaining a wireless backhaul connection. The full-duplex capability of the access node, together with large antenna arrays, allows it to do all of this using the same center frequency. The minimum transmit powers for such a system are solved in a closed form under the condition that certain Quality of Service (QoS) requirements, defined in terms of minimum uplink and downlink data rates, are fulfilled. It is demonstrated with numerical results that, by using the derived expressions for the optimal transmit powers, the probability of fulfilling the QoS requirements is greatly increased, while simultaneously the overall transmit power usage of the system is significantly reduced when compared to a benchmark scheme.

Index Terms— Full-duplex, massive MIMO, self-backhauling.

1. INTRODUCTION

Inband full-duplex communications is widely considered to be an important element in further improving the spectral efficiency of the next generation wireless networks [1–3]. In particular, the progressive operation mode can potentially improve the spectral efficiency by a factor of two, since then the transmitted and received signals are overlapping fully in the time and frequency domains. There are already various demonstrator implementations, which are capable of efficiently suppressing the own transmit signal in the receiver, thus indicating that the problem of self-interference (SI) has already been solved to some extent [4–7]. Hence, the next step is to determine how to best take advantage of the full-duplex capability under residual SI.

One potential application for a full-duplex-capable transceiver is to utilize it as an access node (AN), which is wirelessly backhauling itself without requiring any extra frequency resources [8–11]. Hence, the AN would serve legacy half-duplex mobiles (UEs) while also maintaining a wireless backhaul connection at the same time and on the same center frequency. This type of a system is illustrated in Fig. 1, and it is especially intriguing in the context of densely deployed mobile cells, where setting up a wired backhaul connection may not be feasible. There are already prior works where such a self-backhauling inband full-duplex AN is investigated from various perspectives. For instance, in [8] the downlink (DL) coverage of a network consisting of several self-backhauling ANs is analyzed, while

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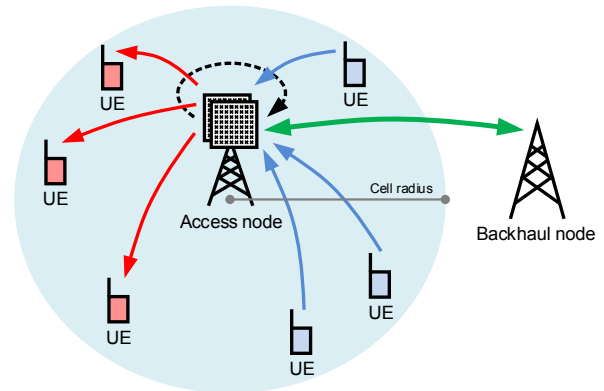


Fig. 1. In the considered system a full-duplex access node is serving legacy half-duplex mobiles while also wirelessly backhauling itself. Some of the interference signals have been omitted in this sketch to improve its readability although they are included in the analysis.

in [9] the achievable uplink (UL) and DL data rates of a single self-backhauling AN under different backhauling strategies are evaluated. Furthermore, [10] analyzes the DL and UL data rates of a similar system under an adaptive self-backhauling scheme, which alternates between half-duplex and full-duplex modes, depending on certain key system parameters. Inband full-duplex self-backhauling is also considered in [11], which evaluates its performance under a potential 5G indoor deployment scenario.

However, even though there is a relatively wide body of literature available regarding the performance of a self-backhauling full-duplex AN, almost none of the works have explicitly analyzed the transmit power allocation related aspects of such a system. To the best of our knowledge, the only exception is our earlier paper [12], which derives the sum-rate maximizing transmit powers for a greatly simplified system, where similar path loss is assumed for all the UEs, and the effect of the inter-user interference (IUI) between the UL and DL UEs is neglected. Hence, in this work we investigate transmit power allocation under a much more comprehensive system model incorporating all the significant interference sources and assuming different path loss conditions for all the UEs. Furthermore, instead of simply maximizing the sum-rates, here we analyze the system under certain QoS constraints, defined in terms of minimum rate requirements for the DL and the UL. In particular, minimum transmit powers fulfilling the given data rate requirements are derived in a closed form for all the communicating parties. The proposed scheme is also numerically evaluated and shown to outperform a benchmark scheme where fixed transmit powers are used.

2. SYSTEM MODEL

The considered system is illustrated in Fig. 1 and it centers around a full-duplex AN having large transmit and receive antenna arrays and serving legacy half-duplex UEs. Since the AN is full-duplex-capable, the DL and UL UEs are active simultaneously, meaning that the UL and DL transmissions overlap both in time and in frequency. In addition to this, the AN is assumed to simultaneously backhaul itself wirelessly by using the same frequency resource to exchange data with a backhaul node (BN). All of this is made possible by utilizing zero-forcing (ZF) beamforming, since the large antenna arrays allow for efficient spatial multiplexing and partially nulling the SI at the own receiver [12, 13]. In order to keep the analysis tractable, it is assumed that the AN has full knowledge of the channel state information (CSI) in all the relevant communication links. This is obviously not a fully practical assumption, but it allows the derivation of the analytical data rate expressions, and hence general information about the ultimate performance of the considered system can be obtained.

Since a largely similar system model was already considered in [12], the same generic signal-to-noise-plus-interference ratios (SINRs) can also be utilized here. In particular, the SINRs of the signals transmitted by the AN can be expressed as follows:

$$SINR_{t,i} = \frac{L_i (N_t - M_t - N_r) p_i}{\sigma_n^2 + \sigma_{t,i}^2}, \quad (1)$$

where L_i is the path loss of the i th signal stream, N_t is the number of AN transmit antennas, N_r is the number of AN receive antennas, M_t (with $M_t \ll N_t$) is the number of signal streams transmitted by the AN, p_i is the transmit power allocated for the i th signal stream, σ_n^2 is the noise power in all the receivers, and $\sigma_{t,i}^2$ is the variance of an additive interference term. This SINR expression can be applied to the DL UEs and to the signals received by the BN.

In a similar manner, the following expression was derived for the SINRs of the signals received by the AN [12]:

$$SINR_{r,j} = \frac{L_j (N_r - M_r) p_j}{\sigma_n^2 + \sigma_{r,j}^2}, \quad (2)$$

where L_j is the path loss of the j th signal stream, M_r (with $M_r \ll N_r$) is the number of received signal streams, p_j is the corresponding transmit power, and $\sigma_n^2 + \sigma_{r,j}^2$ is the variance of an additive noise-plus-interference term. This expression can be used to calculate the SINRs of all the signals received by the AN.

Unlike in [12], where it is assumed that the path losses between the AN and all the UEs are identical, and that the IUI is negligible, in this analysis we make no such simplifications. Hence based on the generic SINR expression in (1), the total DL data rate of the considered mobile cell can be written as follows:

$$R^d = \sum_{i=1}^D R_i^d = \sum_{i \in DL} \log_2 (1 + SINR_{t,i}),$$

$$R_i^d = \log_2 \left(1 + \frac{\Lambda_t L_i^d p_i^d}{\sigma_n^2 + L_i^{BHd} P_d^{BH} + \sum_{j=1}^U L_{ij}^{ud} p_j^u} \right), \quad (3)$$

where D is the total number of DL UEs, R_i^d is the data rate of the i th DL UE, $\Lambda_t = N_t - N_r - D - M_t^{BH}$ is the degrees-of-freedom of the AN transmitter, M_t^{BH} is the number of backhaul signal streams transmitted by the AN, L_i^d is the path loss between the AN and the i th DL UE, p_i^d is the transmit power allocated for the i th DL signal stream, L_i^{BHd} is the path loss between the BN and the i th DL UE, P_d^{BH} is the total transmit power of the BN, U is the number of UL

UEs, L_{ij}^{ud} is the path loss between the i th DL UE and the j th UL UE, and p_j^u is the transmit power of the j th UL UE. Hence, the DL data rate in (3) incorporates the effects of both the IUI and the interference produced by the BN transmission.

Similarly, the total UL data rate can be written as:

$$R^u = \sum_{j=1}^U R_j^u = \sum_{j \in UL} \log_2 (1 + SINR_{r,j}),$$

$$R_j^u = \log_2 \left(1 + \frac{\Lambda_r L_j^u p_j^u}{\sigma_n^2 + \alpha_{AN} (P_u^{BH} + \sum_{i=1}^D p_i^d)} \right), \quad (4)$$

where R_j^u is the data rate of the j th UL UE, $\Lambda_r = N_r - U - M_r^{BH}$ is the degrees-of-freedom of the AN receiver, M_r^{BH} is the number of backhaul signal streams received by the AN, L_j^u is the path loss between the AN and the j th UL UE, α_{AN} is the total amount of SI cancellation in the AN, and P_u^{BH} is the transmit power used for backhauling in the AN. Note that this work assumes some given SI mitigation performance, consisting of passive antenna isolation, ZF beamforming at the transmit side to form nulls at the receive antennas, and other possible SI suppression methods.

An important consideration for the full-duplex AN is its capability to backhaul the UL and the DL data. Hence, the backhaul data rates must also be taken into account in the analysis. The data rate of the backhaul signal transmitted by the AN (for backhauling UL data) can be expressed as:

$$R^{u,BH} = \sum_{k \in BH} \log_2 (1 + SINR_{t,k}) =$$

$$M_t^{BH} \log_2 \left(1 + \frac{\Lambda_t L_{BH} P_u^{BH}}{M_t^{BH} (\sigma_n^2 + \alpha_{BN} P_d^{BH} + \sum_{j=1}^U L_j^{BH_u} p_j^u)} \right), \quad (5)$$

where L_{BH} is the path loss between the AN and the BN, α_{BN} is the total amount of SI cancellation in the BN, and $L_j^{BH_u}$ is the path loss between the j th UL UE and the BN. The last determines the interference caused by the UL transmissions at the BN.

Again, in a similar fashion, the data rate of the received backhaul signal streams at the AN (for backhauling DL data) can be written as follows:

$$R^{d,BH} = \sum_{l \in BH} \log_2 (1 + SINR_{r,l}) =$$

$$M_r^{BH} \log_2 \left(1 + \frac{\Lambda_r L_{BH} P_d^{BH}}{M_r^{BH} [\sigma_n^2 + \alpha_{AN} (P_u^{BH} + \sum_{i=1}^D p_i^d)]} \right). \quad (6)$$

Put together, the data rate expressions in (3)–(6) can then be used to determine the optimal transmit powers for the considered system under some given data rate requirements.

3. TRANSMIT POWER OPTIMIZATION

In this work, we consider the minimization of transmit powers under a given per-UE QoS-constraint, defined in terms of the achievable data rate for each individual UE. Denoting the required minimum rates in the DL and in the UL by ρ_d and ρ_u , respectively, the optimization problem can be formulated and solved as discussed next.

- **Problem (Transmit Power Minimization):**

$$\begin{aligned}
& \underset{\mathbf{p}, P_d^{BH}, P_u^{BH}}{\text{minimize}} && \left(\|\mathbf{p}\|_1 + P_d^{BH} + P_u^{BH} \right) \\
& \text{subject to} && \text{C1: } R_i^d \geq \rho_d, \quad i = 1, \dots, D, \\
& && \text{C2: } R_j^u \geq \rho_u, \quad j = 1, \dots, U, \\
& && \text{C3: } R^{d,BH} \geq \sum_{i=1}^D R_i^d, \\
& && \text{C4: } R^{u,BH} \geq \sum_{j=1}^U R_j^u,
\end{aligned} \tag{7}$$

where \mathbf{p} is a column vector containing the DL and UL transmit powers p_i^d and p_j^u stacked, and $\|\cdot\|_1$ denotes the l_1 -norm. Here, the constraints C1 and C2 ensure that the minimum DL and UL rates are achieved, while the constraints C3 and C4 ensure sufficient self-backhauling capability.

- **Solution:** The solution to the above problem is given by:

$$\mathbf{p}^* = \mathbf{W}^{-1} \mathbf{v}, \tag{8}$$

for which \mathbf{W} and \mathbf{v} are elaborated shortly and $(\cdot)^{-1}$ denotes the matrix inverse; optimized P_d^{BH} and P_u^{BH} follow from \mathbf{p}^* .

In order to arrive at the solution in (8), let us first express the minimum rate requirements in constraints C1 and C2 as transmit power requirements for the AN and each individual UE. In particular, the AN transmit power allocated for serving the i th DL UE must fulfil the following requirement:

$$p_i^d \geq \frac{\bar{\rho}_d \left(\sigma_n^2 + L_i^{BHd} P_d^{BH} + \sum_{j=1}^U L_{ij}^{ud} p_j^u \right)}{\Lambda_t L_i^d}, \tag{9}$$

where $\bar{\rho}_d = 2^{\rho_d} - 1$. Using the same approach, the transmit power of the j th UL UE has the following lower bound:

$$p_j^u \geq \frac{\bar{\rho}_u \left(\sigma_n^2 + \alpha_{AN} \left[P_u^{BH} + \sum_{i=1}^D p_i^d \right] \right)}{\Lambda_r L_j^u}, \tag{10}$$

where $\bar{\rho}_u = 2^{\rho_u} - 1$. Since the objective is to minimize each individual transmit power, all p_i^d and p_j^u are set equal to their lower bounds in (9) and (10). This, on the other hand, means that the data rates obtained by the UEs in the DL and UL are exactly ρ_d and ρ_u , respectively. Consequently, the backhaul rate requirements in constraints C3 and C4 become $R^{d,BH} \geq D\rho_d$ and $R^{u,BH} \geq U\rho_u$. Hence, the backhaul-related transmit power bounds can be written as follows:

$$P_d^{BH} \geq \frac{M_r^{BH} \bar{\rho}_d^{BH} \left(\sigma_n^2 + \alpha_{AN} \left[P_u^{BH} + \sum_{i=1}^D p_i^d \right] \right)}{\Lambda_r L_{BH}}, \tag{11}$$

$$P_u^{BH} \geq \frac{M_t^{BH} \bar{\rho}_u^{BH} \left(\sigma_n^2 + \alpha_{BN} P_d^{BH} + \sum_{j=1}^U L_j^{BH u} p_j^u \right)}{\Lambda_t L_{BH}}, \tag{12}$$

where $\bar{\rho}_d^{BH} = 2^{D\rho_d/M_r^{BH}} - 1$ and $\bar{\rho}_u^{BH} = 2^{U\rho_u/M_t^{BH}} - 1$. Also these transmit powers are chosen as their lower bounds to minimize them under the given constraints. Then, by solving (11) and (12) for P_d^{BH} and P_u^{BH} and substituting these expressions into (9) and (10), a system of $D + U$ equations with $D + U$ unknown transmit powers is obtained.

Using straightforward manipulations, which are omitted from this paper for brevity, the system of equations for the unknown DL and UL transmit powers is expressed in matrix form as follows:

$$\mathbf{W} \mathbf{p} = \mathbf{v}, \tag{13}$$

for which the solution is as shown in (8).

In order to next express the matrix \mathbf{W} , let us denote the $D \times D$ and $U \times U$ identity matrices by \mathbf{I}_D and \mathbf{I}_U , respectively. Then \mathbf{W} can be written in blockwise form as

$$\mathbf{W} = \begin{bmatrix} \mathbf{I}_D + \mathbf{A} & \mathbf{B} \\ \mathbf{C} & \mathbf{I}_U + \mathbf{E} \end{bmatrix}, \tag{14}$$

where

$$\mathbf{A} = -\frac{\alpha_{AN} \bar{\rho}_d \bar{\rho}_d^{BH} M_r^{BH}}{\Lambda_t \Lambda_r L_{BH} (1 - \alpha_{AN} \alpha_{BN} \phi)} \mathbf{q}_{BH/d} \mathbf{1}_D^T, \tag{15}$$

$$\mathbf{B} = -\left(\frac{\bar{\rho}_d}{\Lambda_t} \right) \left(\alpha_{AN} \phi \mathbf{q}_{BH/d} \mathbf{L}_{BH u}^T + \mathbf{L}_{ud} \circ \mathbf{q}_d \mathbf{1}_U^T \right), \tag{16}$$

$$\mathbf{C} = -\frac{\alpha_{AN} \bar{\rho}_u}{\Lambda_r (1 - \alpha_{AN} \alpha_{BN} \phi)} \mathbf{q}_u \mathbf{1}_D^T, \tag{17}$$

$$\mathbf{E} = -\frac{\alpha_{AN} \bar{\rho}_u \bar{\rho}_u^{BH} M_t^{BH}}{\Lambda_t \Lambda_r L_{BH} (1 - \alpha_{AN} \alpha_{BN} \phi)} \mathbf{q}_u \mathbf{L}_{BH u}^T, \tag{18}$$

and the other terms are defined as follows:

$$\phi = \frac{M_r^{BH} M_t^{BH} \bar{\rho}_d^{BH} \bar{\rho}_u^{BH}}{\Lambda_t \Lambda_r L_{BH}^2}, \tag{19}$$

$$\mathbf{q}_{BH/d} = \left[\frac{L_1^{BHd}}{L_1^d} \quad \frac{L_2^{BHd}}{L_2^d} \quad \dots \quad \frac{L_D^{BHd}}{L_D^d} \right]^T, \tag{20}$$

$$\{\mathbf{L}_{ud}\}_{ij} = L_{ij}^{ud}, \tag{21}$$

$$\mathbf{L}_{BH u} = \left[L_1^{BH u} \quad L_2^{BH u} \quad \dots \quad L_U^{BH u} \right]^T, \tag{22}$$

$$\mathbf{q}_d = \left[\frac{1}{L_1^d} \quad \frac{1}{L_2^d} \quad \dots \quad \frac{1}{L_D^d} \right]^T, \tag{23}$$

$$\mathbf{q}_u = \left[\frac{1}{L_1^u} \quad \frac{1}{L_2^u} \quad \dots \quad \frac{1}{L_U^u} \right]^T. \tag{24}$$

Furthermore, $\mathbf{1}_U$ and $\mathbf{1}_D$ are column-vectors consisting of U and D ones, respectively, and \circ denotes the Hadamard product.

The vector $\mathbf{v} = [\mathbf{g}^T \quad \mathbf{h}^T]^T$ is a vertical concatenation of two column-vectors, namely \mathbf{g} and \mathbf{h} , which are expressed as follows:

$$\mathbf{g} = \frac{\bar{\rho}_d \sigma_n^2}{\Lambda_t} \left[\mathbf{q}_d + \left(\frac{1}{1 - \alpha_{AN} \alpha_{BN} \phi} \right) \times \left(\frac{\bar{\rho}_d^{BH} M_r^{BH}}{\Lambda_r L_{BH}} + \alpha_{AN} \phi \right) \mathbf{q}_{BH/d} \right], \tag{25}$$

$$\mathbf{h} = \frac{\bar{\rho}_u \sigma_n^2}{\Lambda_r (1 - \alpha_{AN} \alpha_{BN} \phi)} \left(1 + \frac{\alpha_{AN} M_t^{BH} \bar{\rho}_u^{BH}}{\Lambda_t L_{BH}} \right) \mathbf{q}_u. \tag{26}$$

Note that, since the path losses considered in this analysis are randomly generated, it is extremely unlikely that the matrix \mathbf{W} is singular, and hence a solution to the problem in (7) practically always exists. However, under some extreme circumstances, it is possible that the optimal transmit powers appear in fact negative, which physically means that the data rate requirements cannot be achieved with finite positive transmit powers under those particular parameter values. In other words, this means that the system corresponding to these parameters is not feasible to begin with. For brevity, we must omit a more detailed analysis of this aspect herein (beyond the numerical results below), but we consider it an important future work item.

Table 1. The essential default system parameters.

| Parameter | Value |
|---|------------|
| Number of AN transmit/receive antennas (N_t/N_r) | 200/100 |
| Number of DL and UL UEs ($D = U$) | 10 |
| Number of DL/UL backhaul streams (M_r^{BH}/M_t^{BH}) | 12/6 |
| Receiver noise floor (σ_n^2) | -90 dBm |
| Amount of SI cancellation ($\alpha_{AN} = \alpha_{BN}$) | 120 dB |
| Per-UE DL/UL rate requirement (ρ_d/ρ_u) | 8/2 bps/Hz |
| Cell radius | 50 m |
| Distance between the AN and the BN | 75 m |

Table 2. A comparison between using minimized transmit powers as per the proposed scheme and using fixed transmit powers.

| | Proposed scheme | Fixed transmit powers |
|-----------------------------|--------------------|-----------------------|
| QoS fulfillment probability | 94.9 % | 60.4 % |
| AN transmit power | 30.2 dBm (average) | 53.0 dBm |
| UE transmit power | 6.1 dBm (average) | 30.5 dBm |
| BN transmit power | 5.4 dBm (average) | 28.0 dBm |

4. NUMERICAL RESULTS AND CONCLUSIONS

In order to numerically evaluate the considered system, the transmit powers given by (8) are solved for various random UE positions, using the parameters specified in Table 1 unless otherwise mentioned. In particular, the specified amount of DL and UL UEs is randomly positioned within the cell radius, and the different path losses are then calculated based on the relevant distances. To ensure a practical system, the DL and UL UEs are scheduled from the opposite sides of the cell, which results in a smaller level of IUI [14]. This is an acceptable solution, since the UEs can then alternate between DL and UL modes at regular intervals, meaning that, regardless of their position in the cell, each UE gets served both in the DL and in the UL.

The measurement-based path loss model presented in [15] for a center-frequency of 3.5 GHz is adopted in the simulations. The line-of-sight (LOS) path loss model is used for the backhaul link, while all the other path losses are calculated assuming the non-line-of-sight (NLOS) model. Having then solved the optimal transmit powers using the realized path losses, the whole process is repeated 50 000 times in order to calculate the different transmit powers under various random UE positions and thus obtain information regarding the average performance of the system.

Firstly, to illustrate the benefits of the proposed power control solution, Table 2 compares it to a scheme where fixed transmit powers are used. In particular, in the latter case the transmit powers of the UEs, the different DL streams, and the backhaul streams are set to fixed values, regardless of the UE positions. The optimal values of these fixed transmit powers are obtained with a simple grid search, the optimality criterion being the QoS fulfillment probability. Overall, it is clear from Table 2 that calculating the transmit powers with (8) significantly improves the probability of achieving the QoS requirements while also resulting in lower power usage. This indicates that careful selection of the transmit powers, based on the UE positions, is greatly beneficial in this type of a system.

In Fig. 2, the cumulative distribution functions (CDFs) for the total DL and UL transmit powers obtained with the proposed scheme are then shown for different SI cancellation levels in the AN. It can

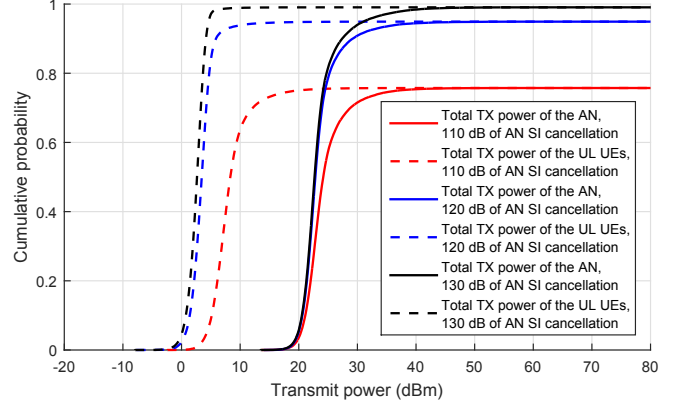


Fig. 2. The CDFs for the total UL and DL transmit powers with different amounts of AN SI cancellation.

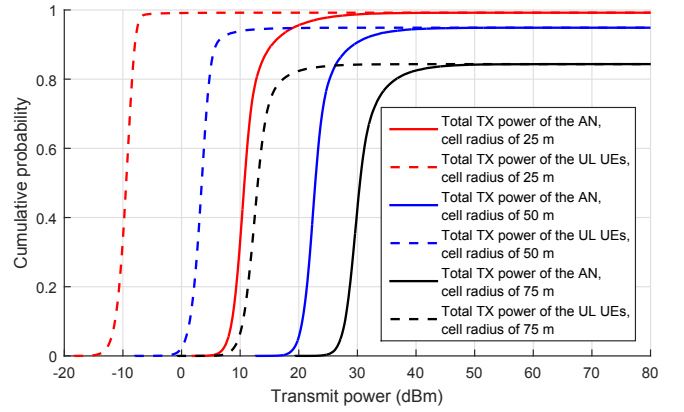


Fig. 3. The CDFs for the total UL and DL transmit powers with different cell radii. The distance between the AN and the BN is maintained as $\frac{3}{2}$ times the cell radius.

be observed that the total UL transmit power is quite heavily affected by the AN SI cancellation performance. The reason for this lies in the fact that the UL data rate is directly affected by the residual SI level, and hence higher UL transmit powers are needed under worse SI cancellation performance to reach a given data rate. The SI cancellation performance at the AN also affects the probability of fulfilling the QoS requirements with finite transmit powers, which is evident from the fact that the CDFs saturate to a value that is less than 1. This value is the probability that the system is feasible for random UE positions. It can be observed that, with less SI cancellation at the AN, it becomes less and less probable that the QoS requirements can be fulfilled for a random positioning of the UEs. Hence, the feasibility of self-backhauling is highly dependent on the SI cancellation performance, and it is something that should be taken into account when considering this type of a system.

Figure 3 then shows the CDFs of the DL and UL transmit powers with different cell sizes. As can be expected, the radius of the cell has a rather significant impact on the transmit power levels required to achieve the given data rates, both in the DL and in the UL. For instance, the median UL transmit power is increased by nearly 10 dB when the cell radius is increased from 50 m to 75 m. The difference is almost the same for the DL transmit power. This clearly indicates that the cell size for a self-backhauling AN is limited if high transmit power efficiency is required. Thereby, this type of an inband self-backhauling solution is best suited for the more densely deployed ANs, since then the cell sizes are obviously smaller.

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