Chapter 1

Inband Full-Duplex Self-backhauling in Ultra-Dense Networks

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1.1 Introduction

Traditionally, the backhauling of data in cellular networks has been handled by connecting the base station (BS) or access node (AN) to a core network via a physical cable. This ensures high data rates for the backhaul link, but requires the installing of cables that entails a high cost. This is an especially significant issue in the ultra-dense networks, where the number of ANs is too high for a physical backhaul link to be commercially feasible. To this

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end, the prospect of wireless backhaul connections has been brought up. It would mean that no cables were required, making the corresponding cellular networks more easily scalable to higher densities.

In the current systems, the basic principle behind the wireless backhaul links has been to ensure line-of-sight (LOS) and to use a center frequency different to that utilized in the actual access link between the AN and the user equipments (UEs). Although some of the benefits of wireless connectivity can still be obtained with such an approach, careful planning and additional spectral resources are required. Together, these aspects reduce the cost-efficiency of the wireless backhauling solution, hindering the commercial feasibility of utilizing such an approach in very densely deployed networks.

To this end, one of the paradigms of the upcoming 5G standard is to integrate the access and backhaul links [1]. Therefore, the same spectral resources and radio access technology could be used for serving the UEs as well as for backhauling the data. This facilitates also non-line-of-sight (NLOS) backhaul connections, while not requiring any additional frequencies. Such self-backhauling radio access systems are an integral part of implementing commercially feasible ultra-dense networks as they significantly reduce the cost of the backhaul link.

In this chapter, we investigate how to utilize the recently developed inband full-duplex (IBFD) technology to further improve the efficiency of wireless self-backhauling. In particular, we consider a scenario where one macro BS serves several densely deployed ANs, each of which serves an individual UE. The ANs use a wireless link to backhaul the data from the UEs to the BS and vice versa. Three different self-backhauling strategies are evaluated under Quality-of-Service (QoS) requirements for the UEs by determining the minimal transmit powers with which the QoS requirements can be fulfilled.

Two of these strategies rely on the IBFD technology, while one of them uses time-division duplexing (TDD) to communicate in traditional half-duplex manner. In addition, these AN-based solutions are compared to a half-duplex reference scheme where the BS communicates directly with the UEs.

1.2 Self-backhauling in Existing Literature

Several recent works have considered wireless inband self-backhauling as a possible option for decreasing the cost of the ultra-dense cellular networks of the future [1–11]. As mentioned, the cost savings are incurred by enabling the AN to backhaul all the data with a macro BS without requiring any wired data link. While some works propose performing the wireless backhauling on a separate frequency band at the mmWave frequencies [10, 11], backhauling the data on the same frequency channel as the downlink (DL) and uplink (UL) transmissions will significantly reduce the overall cost of the radio system. What is more, combining this concept with the IBFD technology will result in various alternative solutions for performing the wireless backhauling, some of which could further improve the spectral efficiency of such a network. This makes IBFD-based self-backhauling an intriguing concept for the future 5G systems, as it facilitates higher data rates while also reducing the associated overall costs.

Thus far, most works have considered a relay-type AN that is directly forwarding the signals transmitted by the UL UEs to the BS, or vice versa [2, 3, 5–8, 12–15]. The reason for the popularity of this type of a scheme is likely the fact that such a relay-type AN is more or less directly compatible with the existing networks, as it would essentially just extend the range of the macro BS. This, on the other hand, will obviously result in increased data rates and better coverage.

In particular, in [12], the power control of such a relay-type AN is investigated, and the performance of both HD and IBFD operation modes is then compared. The obtained results indicate that the IBFD AN is capable of obtaining higher throughputs than the corresponding HD system, although a certain amount of SI suppression is obviously required. A similar analysis is performed in [2], where the BS is assumed to have a massive antenna array. There, the optimal power allocation for the BS and the AN is solved iteratively. The work in [7], on the other hand, investigates different beamforming solutions for a BS with massive antenna arrays, although no IBFD operation is assumed in any of the nodes therein.

Moreover, the effect of radio resource management (RRM) on the performance of the relay-type AN is investigated in [6]. There, the RRM tools are used to balance the SI with the other sources of interference, and the resulting solution is shown to outperform the HD benchmark scheme. In [13], the spectral efficiency of a similar system is maximized by solving the optimal power allocation for both IBFD and HD AN. While the power allocation is solved in closed form for the HD case, only an algorithm is proposed for optimizing the transmit powers of the IBFD scenario. Also there the IBFD solution is shown to outperform the corresponding HD case. The work in [4], on the other hand, maximizes the user rates for ANs utilizing frequency-division duplexing (FDD) by optimizing the bandwidth allocation of the backhaul link. A somewhat similar analysis is carried out in [5], where the spectrum allocation is optimized for both half-duplex and full-duplex ANs. The results obtained therein indicate that, with sufficient SI cancellation, the full-duplex ANs outperform their half-duplex counterparts.

The DL coverage of a relay-type self-backhauling AN is then analyzed in [3, 8]. The findings in [8] indicate that, while the throughput of the network with IBFD-capable ANs is almost doubled in comparison to the HD systems, the increased interference levels result in a somewhat smaller coverage. The results obtained in [3] suggest, on the other hand, that on a network level it may be better to have also some ANs that perform the self-backhauling on a different frequency band. This somewhat reduces the interference between the different backhaul links and the DL UEs. Finally, in [15], the throughput and outage probability of a relay-type IBFD AN is analyzed under an antenna selection scheme, where individual transmit (TX) and receive (RX) antennas are chosen at the AN based on a given criterion. Again, the IBFD AN is shown to usually outperform the corresponding HD AN, although this is not the case under all channel conditions.

In this chapter, we investigate different self-backhauling strategies for ultra-dense networks. Namely, as discussed earlier, we consider four different network architectures, three of which utilize ANs to relay the traffic between the UEs and the BS. Moreover, two of the strategies rely on the IBFD technology: one utilizes IBFD-capable ANs while the other assumes an IBFD-capable BS. Of these two, the former corresponds to the relay-type scenario mostly considered in the earlier literature. Therefore, this chapter will comprehensively evaluate the suitability of such a backhauling strategy in the context of ultra-dense networks by comparing it to various alternative solutions.

Table 1.1: Summary of the considered self-backhauling strategies, where it is shown whether the node transmits (TX), receives (RX), or is idle (–) within the time slot in question.

Strategy	**Time slot 1**					**Time slot 2**				
Half-duplex BS without ANs	**BS**	**DL ANs**	**UL ANs**	**DL UEs**	**UL UEs**	**BS**	**DL ANs**	**UL ANs**	**DL UEs**	**UL UEs**
	TX	n/a	n/a	RX	–	RX	n/a	n/a	–	TX
Half-duplex BS with half-duplex ANs	**BS**	**DL ANs**	**UL ANs**	**DL UEs**	**UL UEs**	**BS**	**DL ANs**	**UL ANs**	**DL UEs**	**UL UEs**
	TX	RX	RX	–	TX	RX	TX	TX	RX	–
Full-duplex BS with half-duplex ANs	**BS**	**DL ANs**	**UL ANs**	**DL UEs**	**UL UEs**	**BS**	**DL ANs**	**UL ANs**	**DL UEs**	**UL UEs**
	TX+RX	RX	TX	–	–	–	TX	RX	RX	TX
Half-duplex BS with full-duplex ANs	**BS**	**DL ANs**	**UL ANs**	**DL UEs**	**UL UEs**	**BS**	**DL ANs**	**UL ANs**	**DL UEs**	**UL UEs**
	TX	TX+RX	–	RX	–	RX	–	TX+RX	–	TX

1.3 Self-backhauling Strategies

Herein, we describe the three different strategies for serving the UEs with an intermediate AN that is backhauling the data with a macro BS. For reference, we consider also a basic scheme where the BS is directly serving the UEs in a conventional macro cell fashion. Moreover, in two of the backhauling strategies, either the BS or the ANs must be IBFD capable, while one of the schemes has no such requirements. Table 1.1 provides a high-level description of each self-backhauling strategy, while the sections below give further details.

In the analysis presented in this chapter, the BS is assumed to have massive antenna arrays, alongside with perfect channel state information (CSI). The assumption of perfect CSI is obviously optimistic, but it allows the derivation of analytical data rate expressions that provide information about the ultimate performance limits of the considered system. Namely, this assumption means that, apart from SI, none of the signals received or transmitted by the BS interfere with each other, which represents a best-case scenario. Nevertheless, the effect of residual SI is still considered, as no full knowledge of the SI coupling channel is assumed. Furthermore, the ANs and the UEs will generate significant mutual interference as each of them has only a single antenna.

In this chapter, we assume that the wireless system employs TDD to separate the transmissions when operating in half-duplex mode. However, the analysis would be identical if FDD was utilized. Therefore, the results presented herein apply also to FDD systems as long as the division of frequencies between the two communication directions can be adjusted.

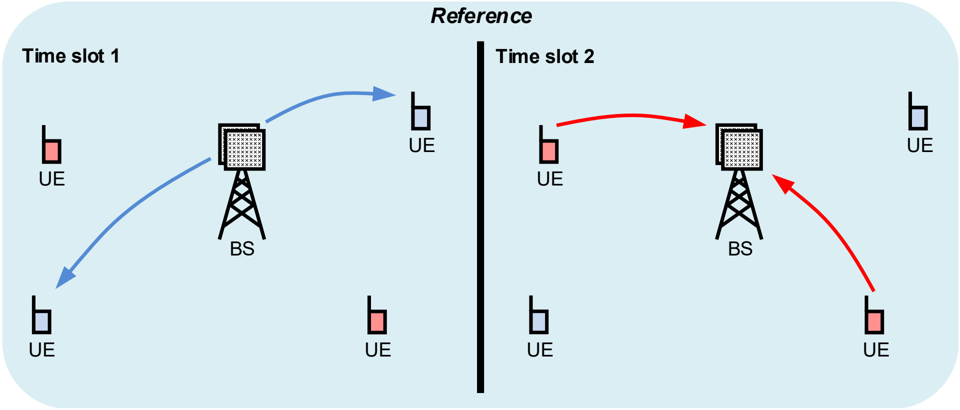

Figure 1.1: The reference scenario, where the BS serves the UEs directly using TDD to separate UL and DL.

Half-Duplex Base Station without Access Nodes

In general, the considered scenario involves a macro BS that has massive antenna arrays at its disposal, and that is exchanging data with UEs both in UL and DL. Therefore, an obvious reference solution is the case where a half-duplex-capable BS serves these UEs directly itself, without any intermediate nodes. This strategy is depicted in Fig. 1.1, where both the DL and UL time slots are shown. All of the alternative solutions presented in this section will be compared to this basic reference scheme.

Half-Duplex Base Station with Half-Duplex Access Nodes

In all of the forthcoming alternative strategies, the basic idea is to introduce so-called ANs into the network to act as intermediate nodes between the UEs and the BS. Moreover, deploying the ANs densely will ensure that each UE is close to at least one AN, resulting in reduced path loss. Figure 1.2 illustrates such a backhauling strategy, where all the nodes are legacy half-duplex radio

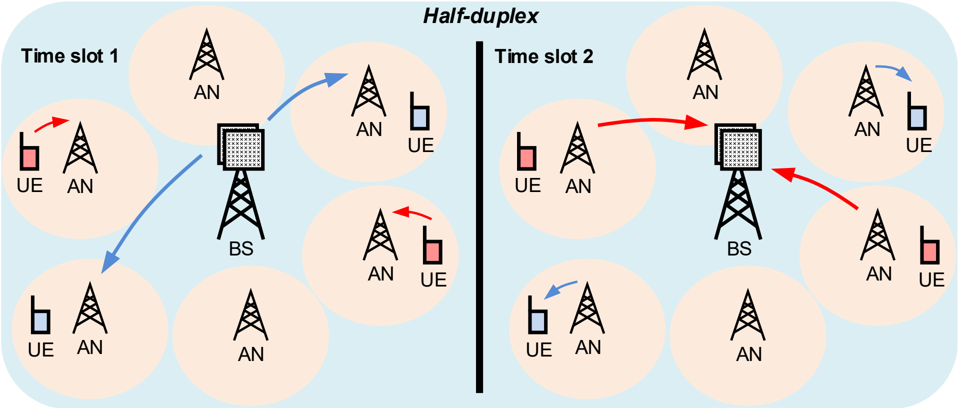

Figure 1.2: The half-duplex self-backhauling solution, where the densely deployed ANs handle the traffic between the BS and the UEs such that no IBFD capabilities are required.

devices. This strategy is particularly suitable for very lost-cost deployments, where only half-duplex devices are available.

In principle, using the ANs to relay the traffic of the access links results in reduced TX powers for all parties, especially so as the dense deployment of ANs ensures smaller path losses. However, the challenge of this type of a scheme are the various sources of interference. Namely, since all the nodes use the same frequency band, they will also interfere with each other when transmitting and receiving simultaneously. The BS avoids this as it has large antenna arrays which facilitate accurate beamforming, but the ANs and the UEs have no such benefit. Therefore, referring to Fig. 1.2, in the first time slot the UL UEs interfere with the reception of the DL ANs, while in the second time slot the DL ANs interfere with each other and the DL UEs. In order to manage these various interference sources while also fulfilling the QoS requirements, careful transmit power allocation is needed. Such power allocation is especially crucial in ultra-dense networks where the significance of interference is much larger. This is investigated in more detail

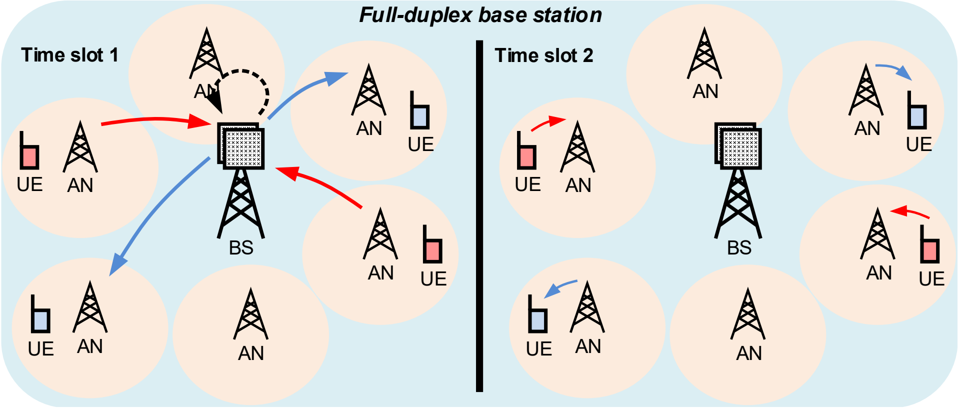

Figure 1.3: A full-duplex self-backhauling solution, where the ANs communicate first with an IBFD-capable BS, after which they serve the UEs.

in Section 1.4.

Full-Duplex Base Station with Half-Duplex Access Nodes

In the next scheme, depicted in Fig. 1.3, the BS must be IBFD capable as it simultaneously communicates with both DL and UL ANs in the first time slot. Thanks to its massive antenna arrays, it can perform part of the SI cancellation by forming nulls into the positions of its RX antennas, while the rest of the SI can be cancelled using any of the widely reported techniques. In the other time slot, the ANs serve then the UEs, as depicted in Fig. 1.3. This strategy results also in a relatively low-cost deployment since only the BS must be capable of full-duplex operation, while the ANs and the UEs can be legacy half-duplex devices.

Moreover, also in this self-backhauling strategy, the various interference links call for careful transmit power allocation, especially when considering ultra-dense networks. In particular, in the first time slot, the UL ANs interfere with the reception of the DL ANs, while in the second time slot

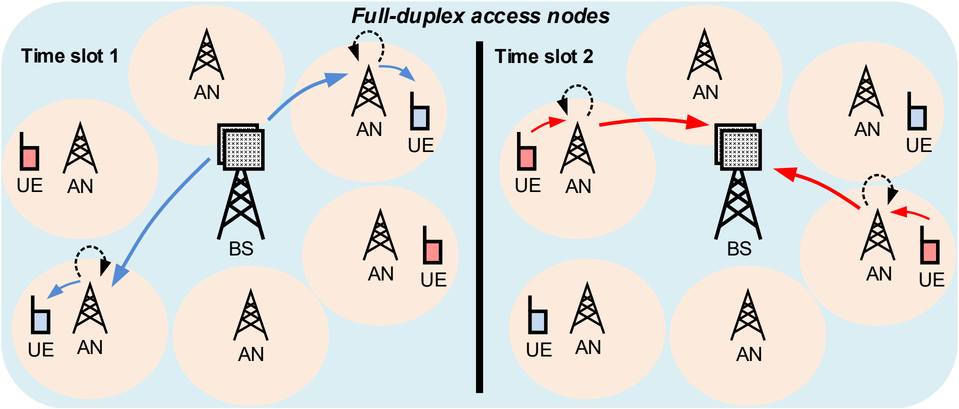

Figure 1.4: A full-duplex self-backhauling solution, where IBFD-capable ANs relay the traffic between the UEs and the BS.

the UL UEs and the DL ANs produce interference at the DL UEs and the UL ANs. However, as opposed to the purely half-duplex strategy, now the residual SI at the BS must also be taken into account, in addition to the other interference terms.

Half-Duplex Base Station with Full-Duplex Access Nodes

The fourth considered backhauling solution is the one depicted in Fig. 1.4, where the ANs are essentially IBFD relays forwarding the data between the BS and the UEs. Therefore, in this case, the ANs must be capable of IBFD operation. The time slots are divided between DL and UL such that in the first time slot the AN forwards the signals from the BS to the DL UEs, while in the second time slot it forwards the UL signals to the BS. Utilizing this strategy will result in an increased cost of deployment since now each AN must be equipped with the necessary SI cancellation capability. However, as will be shown in Section 1.5.2, the benefit of this strategy is the decreased transmit power consumption, which is likely to outweigh the additional costs incurred by the IBFD-capable ANs.

Now, in addition to the residual SI at the AN, the ANs and UEs again produce interference to each other, as some nodes must receive data while others are transmitting it on the same frequency band. Since this analysis considers a very dense deployment of the ANs, it is crucial to manage such interference within the network. The transmit power allocation scheme discussed next in Section 1.4 takes these interference links into consideration and aims at minimizing their harmful effects.

1.4 Transmit Power Optimization under QoS Requirements

Herein, the heterogeneous network is analyzed in terms of transmit power minimization under QoS requirements, defined as a minimum data rate for each UE. This facilitates the comparison of the transmit power efficiencies of the alternative solutions under the same circumstances and requirements. The generic optimization problem, which can be used to minimize the transmit powers of all the alternative self-backhauling strategies, can be formulated as follows:

Problem (Transmit Sum-Power Minimization):

$$\begin{aligned}
\underset{\mathbf{p}_{\mathrm{u}},\mathbf{p}_{\mathrm{u}}^{\mathrm{AN}},\mathbf{p}_{\mathrm{d}}^{\mathrm{AN}},p_{\mathrm{d}}^{\mathrm{BS}},\eta}{\text{minimize}} \quad & \sum \mathbf{p}_{\mathrm{u}} + \sum \mathbf{p}_{u}^{\mathrm{AN}} + \sum \mathbf{p}_{d}^{\mathrm{AN}} + p_{\mathrm{d}}^{\mathrm{BS}} \\
\text{subject to} \quad & \text{C1: } R_i^{\mathrm{d}} \geq \rho_{\mathrm{d}},\ i = 1,\ldots,D, \\
& \text{C2: } R_j^{\mathrm{u}} \geq \rho_{\mathrm{u}},\ j = 1,\ldots,U, \\
& \text{C3: } R_i^{\mathrm{d,AN}} \geq R_i^{\mathrm{d}},\ i = 1,\ldots,D, \\
& \text{C4: } R_j^{\mathrm{u,AN}} \geq R_j^{\mathrm{u}},\ j = 1,\ldots,U,
\end{aligned} \tag{1.1}$$

where

- $\mathbf{p}_{\mathrm{u}}$ is a vector containing the transmit powers of the UL UEs;
- $\mathbf{p}_{\mathrm{u}}^{\mathrm{AN}}$ is a vector containing the transmit powers of the UL ANs;
- $\mathbf{p}_{\mathrm{d}}^{\mathrm{AN}}$ is a vector containing the transmit powers of the DL ANs;
- $p_{\mathrm{d}}^{\mathrm{BS}}$ is the DL transmit power of the BS;
- R_i^{d} is the DL data rate of the ith DL UE in bps/Hz;
- R_j^{u} is the UL data rate of the jth UL UE in bps/Hz;
- ρ_{d} is the DL data rate requirement of an individual UE in bps/Hz;
- ρ_{u} is the UL data rate requirement of an individual UE in bps/Hz;
- $R_i^{\mathrm{d,AN}}$ is the data rate of the backhaul link between the BS and the ith DL AN in bps/Hz;
- $R_j^{\mathrm{u,AN}}$ is the data rate of the backhaul link between the BS and the jth UL AN in bps/Hz;
- D is the total amount of DL UEs;
- U is the total amount of UL UEs;
- η is the duplexing parameter that determines the relative lengths of the two time slots.

The constraints C1 and C2 ensure the QoS of the UEs, while the constraints C3 and C4 ensure sufficient backhauling capability in the ANs. Due to the ultra-dense deployment of the ANs, this type of an optimization procedure is crucial in facilitating any data transfer within the network since the interference will be intolerably powerful, unless dealt with properly. Therefore, determining the optimal transmit power allocation, and consequently minimizing the effect of interference, ensures that the QoS requirements can be fulfilled.

The objective function can be obtained in a rather straightforward manner by determining the relationship between the achieved data rates, the related transmit powers, and the duplexing parameter. The alternative self-backhauling strategies differ mostly in the structure of the interference terms, as each of them divides the transmissions between the two time slots in a different way. Moreover, the residual SI only affects the strategies where full-duplex operation is utilized. As a result, the exact form of the optimization problem is different for each self-backhauling strategy. Although similar optimization problems have been solved in closed form for somewhat more simpler systems [16], in this work the optimization will be performed numerically.

In principle, the optimization procedure involves first determining the minimum transmit powers for a given duplexing parameter η. This results in a linear system of equations, from which the solution of this subproblem can be obtained. Then, the obtained optimal transmit powers for any given duplexing parameter are used to form another objective function with respect to η, the solving of which gives the global optimum solution of the complete optimization problem. The resulting optimal values are defined as $\mathbf{p}_\mathrm{u}^*$, $(\mathbf{p}_\mathrm{u}^\mathrm{AN})^*$, $(\mathbf{p}_\mathrm{d}^\mathrm{AN})^*$, $(p_\mathrm{d}^\mathrm{BS})^*$, and η^*.

It should be noted that this formulation of the optimization problem minimizes the overall transmit power consumption within the whole cell, without considering the transmit powers of the individual nodes. Therefore, if the objective is to minimize the transmit powers of, say, the UEs, the optimization problem in (1.1) can be modified by increasing the cost of the UE transmit powers in the objective function. Or, to provide another example, if the transmit power of the BS is of no interest, it can be entirely removed from the objective function. Nevertheless, in this chapter, such variations of the optimization procedure are omitted for brevity.

In some cases, however, the required QoS requirements cannot be fulfilled with any finite transmit powers. In the above optimization problem, these cases manifest themselves as negative optimal transmit powers, which are obviously physically impossible. Such scenarios are referred to as *infeasible* network geometries, since then the required minimum data rates cannot be achieved due to the strength of the various interference links.

1.5 Performance Analysis

1.5.1 Simulation Setup

Next, the proposed system is evaluated with the help of Monte Carlo simulations, considering the different self-backhauling strategies. To concentrate on a simple and straightforward scenario for this initial analysis, in the simulations the ANs and UEs are randomly and uniformly positioned into a circular cell of given size, at the center of which is the BS. Each UE is then allocated an AN based on the closest distance. In this work, it is assumed that an individual AN only serves one UE, as it is unlikely to have two UEs in the same cell due to the high density of the ANs. However, if it happens that two UEs share the same cell, then one of the UEs is allocated to the next closest AN, the preference being given to the DL UEs. For simplicity, it is assumed that there are no external interference sources, e.g., from adjacent

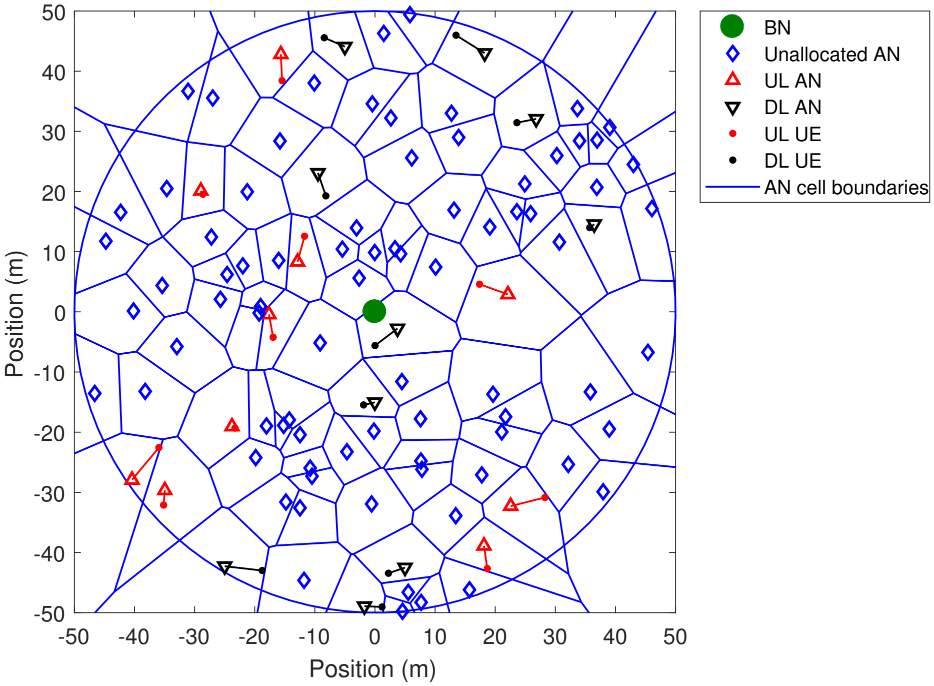

Figure 1.5: An example realization of the random AN/UE positions, together with the AN cell boundaries.

cells. Extending this analysis to consider different node distributions and interference from other cells is an important future research direction in the area of ultra-dense networks.

One example realization of the network architecture is presented in Fig. 1.5, where the macro cell area has been divided to smaller cells based on which AN is the closest. Furthermore, the radius of the macro cell is represented by the large circle. The DL and UL UE positions are also illustrated, together with the allocation of the ANs. Note that each UE gets served both in the DL and in the UL by having them alternate between the two modes at regular intervals. The path losses for the different links are calculated based on the corresponding distances and the adopted path loss model. By calculating the optimal transmit powers over various random network realizations, the cumulative distribution functions (CDFs) of the corresponding quantities can then be obtained. The CDF describes the probability with which the transmit power is lower than the abscissa.

Table 1.2 lists all the default system parameters, which are used in the simulations unless otherwise mentioned. Moreover, the path loss model is taken from [17], where a measurement-based model for a center frequency of 3.5 GHz is reported, considering both LOS and NLOS conditions. Denoting the distance in meters by d_{m}, the former path loss model is defined as

$$L_{\mathrm{LOS}} = 42.93 + 20\log_{10}(d_{\mathrm{m}}),$$

while the latter is

$$L_{\mathrm{NLOS}} = 33.5 + 40\log_{10}(d_{\mathrm{m}}).$$

In the simulations, the LOS model is applied to the links between the AN and the BS and between the AN and the allocated UE, while the NLOS model is used for all the other links. The forthcoming CDFs are obtained by generating 10^4 random UE locations for which the optimal transmit powers are calculated. Furthermore, to ensure a fair comparison between the different schemes, the transmit powers of the different schemes are weighted by the proportion of time spent in the corresponding time slot, as this more realistically illustrates their overall transmit power usage.

1.5.2 Numerical Results

Considering then the realized transmit powers of the different self-backhauling strategies, Fig. 1.6 shows the transmit powers of the individual communicating parties using the default system parameters. In terms of the UE transmit

Table 1.2: The essential default system parameters. Many of the parameter values are also varied in the evaluations.

Parameter	**Value**
Number of BS TX/RX antennas	200/100
Number of DL and UL UEs	10
Number of ANs	100
Receiver noise floor	−90 dBm
Amount of SI cancellation in the AN	−100 dB
Amount of SI cancellation in the BS	−100 dB
Per-UE DL/UL rate requirement	2/0.5 bps/Hz
Cell radius	50 m
Number of Monte Carlo simulation runs	10^4

power consumption, the half-duplex solution is very closely matched with the one with full-duplex ANs. However, having full-duplex capable ANs significantly reduces the transmit power requirements of the BS, thereby rendering it the preferable option in terms of the total power usage. The strategy with a full-duplex BS is inferior to both of these solutions, as it cannot obtain the QoS requirements for most network geometries. This is evident from the CDFs saturating to a value below 1, indicating that roughly 75% of the random network geometries are such that the QoS requirements cannot be fulfilled with any finite transmit powers. In fact, also the solutions with half-duplex devices and full-duplex ANs suffer from this same phenomenon, the former obtaining the minimum data rates for

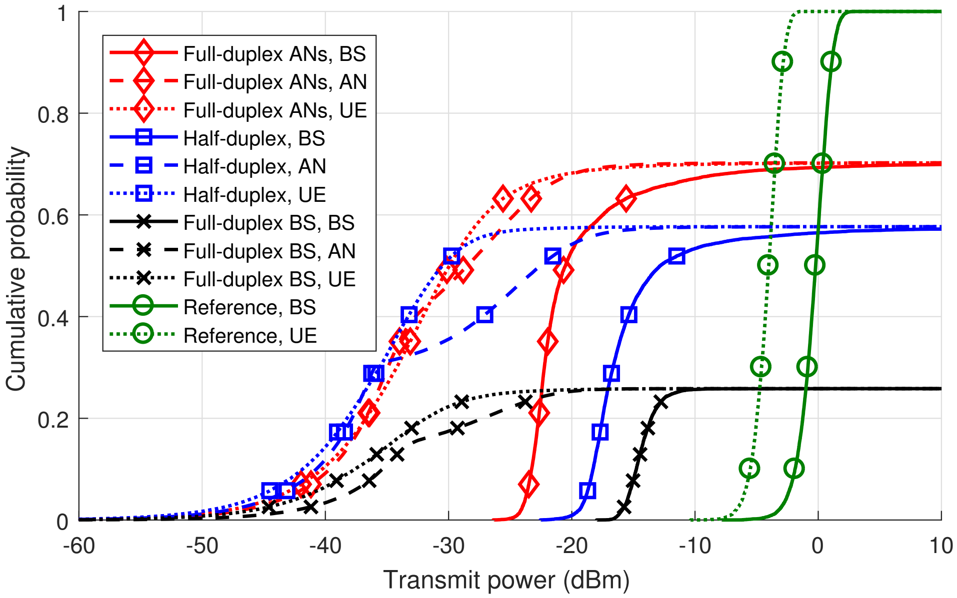

Figure 1.6: CDFs of the individual parties' transmit powers with the different self-backhauling strategies.

nearly 60% of the network geometries while the latter obtains them for 70% of the geometries. As opposed to this, the reference scheme without any ANs can always obtain the QoS requirements, although it uses significantly higher transmit powers to achieve this compared to the solutions utilizing the ANs. Therefore, as long as the infeasible network geometries can be identified and avoided, the solution with full-duplex ANs is clearly the most favorable option.

To analyze the effect of the UE density, Figure 1.7 illustrates the self-backhauling solutions from a different perspective, showing the CDFs of their total transmit power usage for different amounts of UEs. In terms of the total transmit power, the solution with full-duplex ANs is clearly the preferable option, as it outperforms the other solutions both in obtaining

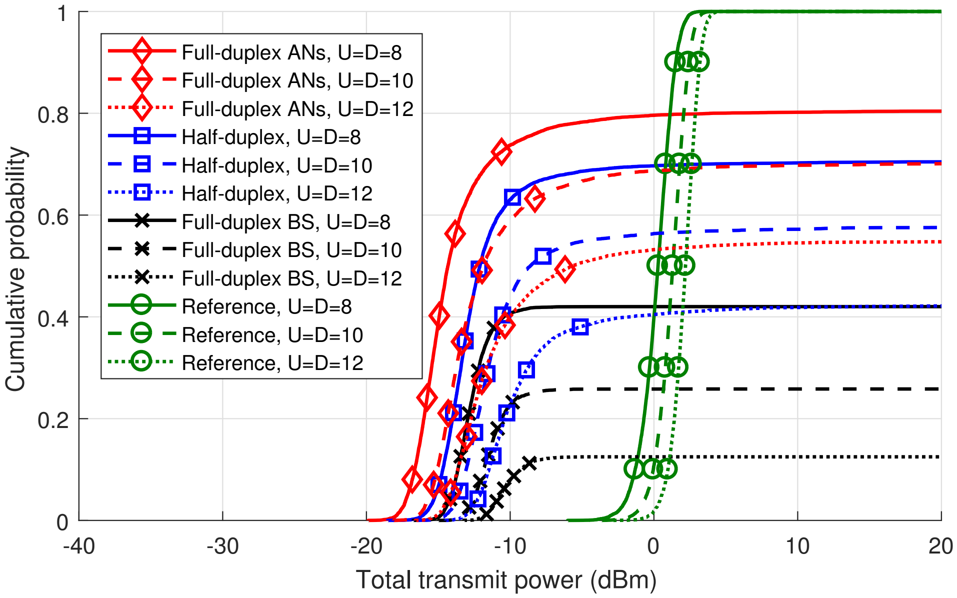

Figure 1.7: CDFs of the total used transmit power with the different self-backhauling strategies, shown for different numbers of UEs.

a lower transmit power and in fulfilling the QoS requirements. It should be noted, however, that with 24 UEs in the cell in total, even this solution cannot obtain the required data rates for more than 55% of the network geometries. Similar to the observations made in Fig. 1.6, the reference scheme without any ANs can always fulfill the data rate requirements, albeit with a considerable increase in the total transmit power.

Let us then investigate the SI cancellation requirements of the ANs in more detail. To this end, Fig. 1.8 illustrates how the total transmit power usage of the solution with full-duplex ANs is affected by the amount of SI cancellation in the ANs. For reference, the total transmit powers of the other solutions are also shown, using the default system parameters. The main observation from Fig. 1.8 is that a very small amount of SI cancellation

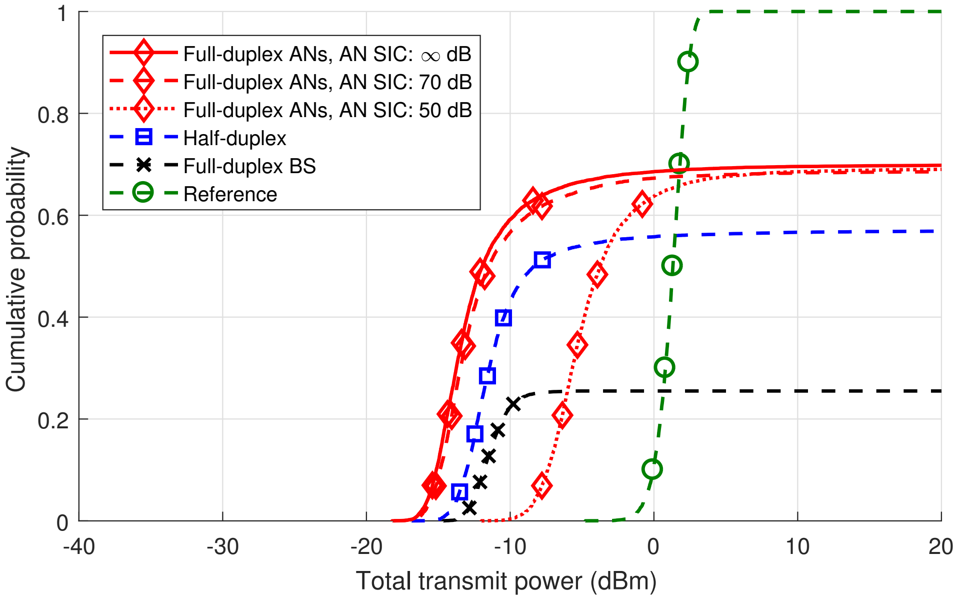

Figure 1.8: CDFs of the total used transmit power with the different self-backhauling strategies, shown for different amounts of AN SI cancellation.

suffices for the full-duplex ANs. Namely, while 50 dB of cancellation in the AN is not enough to outperform the half-duplex solution, there is no significant difference in the transmit power consumption between the cases of 70 dB of SI cancellation and perfect SI cancellation. The primary reason for this is the interference produced by the other nodes, which is already dominating the SI with 70 dB of cancellation. Moreover, another important reason for the low SI cancellation requirement is the fact that the transmit powers are minimized, which means that the SI power is lower to begin with. This is an encouraging finding, as such a low amount of SI suppression can likely be obtained even when using a shared TX/RX antenna and performing only digital SI cancellation [18, 19]. Such full-duplex ANs can therefore be implemented without a significant increase in the cost over half-duplex ANs.

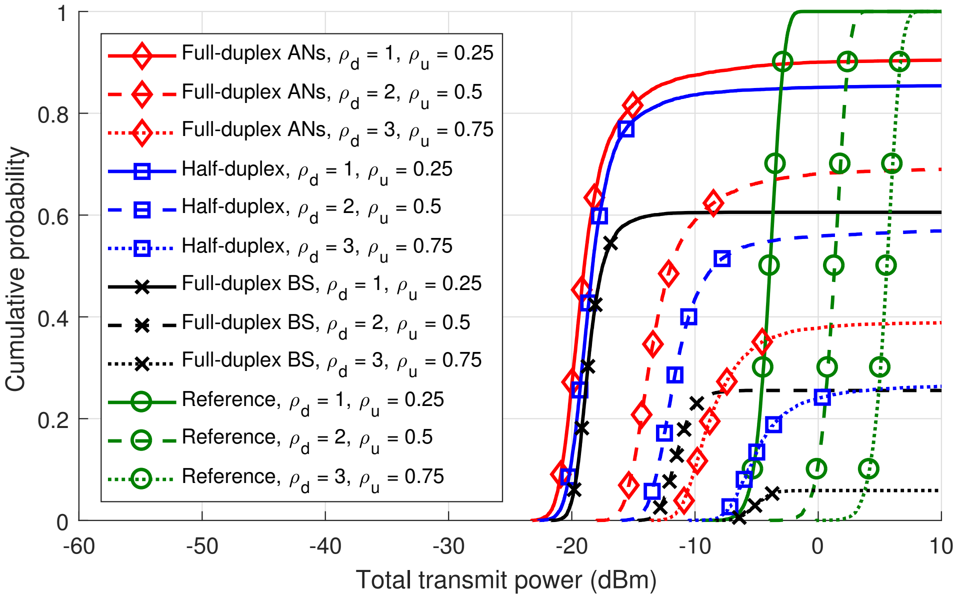

Figure 1.9: CDFs of the total used transmit power with the different self-backhauling strategies, shown for different data rate requirements.

Considering then the QoS requirements, Fig. 1.9 shows the CDFs of the total transmit power consumption for different UE data rate requirements. As can be expected, lower data rate requirements translate to lower transmit power consumption, the system with full-duplex ANs providing again the highest performance. With the lowest considered rate requirement of $\rho_{\mathrm{d}} = 1$ and $\rho_{\mathrm{u}} = 0.25$, the different AN-based solutions are quite closely matched, but as the rate requirements are increased, the gap between the networks with full-duplex ANs and those with half-duplex ANs becomes wider. Therefore, utilizing full-duplex ANs for such a self-backhauling radio access system is especially beneficial with higher data rate requirements. Nevertheless, it should also be noted that the data rate requirements cannot be fulfilled under all network geometries. A possible solution would be to downgrade to the reference scheme under these infeasible scenarios. This would mean that higher transmit powers would be used when necessary to ensure that the QoS remains on the required level, while utilizing the full-duplex ANs whenever they can provide the required data rates with smaller transmit powers.

Next, Fig. 1.10a illustrates the effect of the UE density by showing the probability of feasibility of the different self-backhauling solutions with respect to the number of UEs in the cell.[2] The medians of the corresponding sum transmit powers are shown in Fig. 1.10b. Firstly, it can be observed from Fig. 1.10a that the number of supported UEs is higher the larger the cell is. This indicates that the limiting factor of the considered system is the interference between the different communicating parties, whose effect is decreased when the cell radius is increased. As for the individual self-backhauling strategies, the network with full-duplex ANs is again the best solution, supporting always the highest number of UEs for a given probability of feasibility. For instance, with a cell radius of 50 m, full-duplex ANs can provide the required data rates for 10 UL and 10 DL UEs with a probability of 70%, while the half-duplex ANs can support the same number of UEs with a probability of 55%.

Investigating the medians of the sum transmit powers in Fig. 1.10b, the network with full-duplex ANs can be observed to be also the most power efficient solution under most circumstances. The only exceptions are the scenarios where the number of UEs approaches the boundary after which more than 50% of the network geometries are infeasible. Beyond this point, the median sum transmit power tends to infinity and the corresponding curves in

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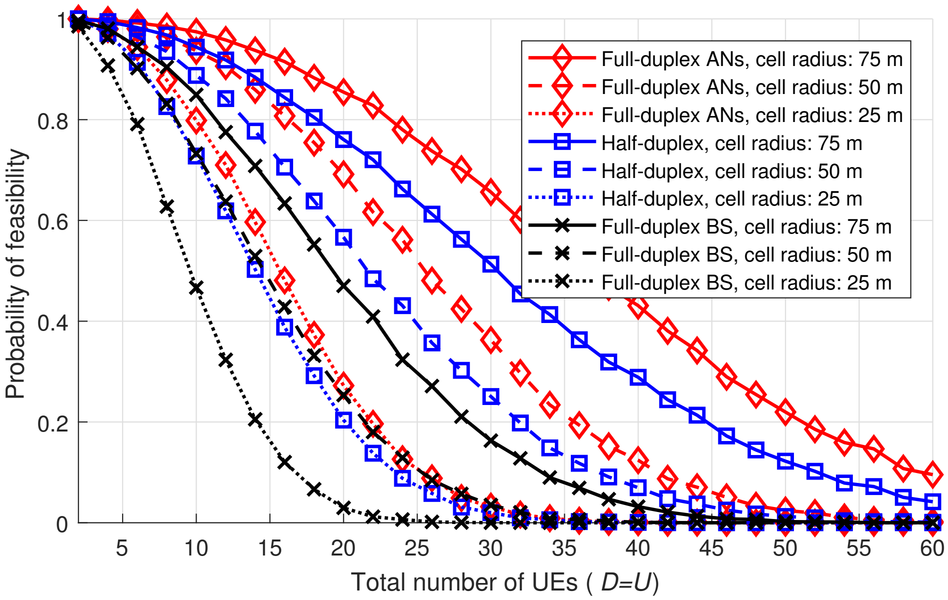
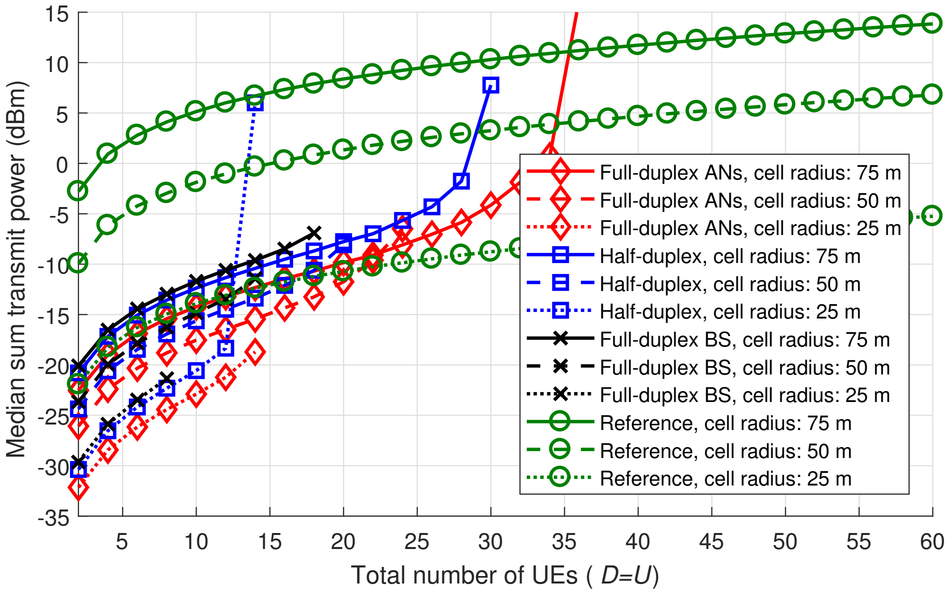
[2] Note that the reference scheme is always feasible and is therefore excluded from Figs. 1.10a and 1.11a.



(a)



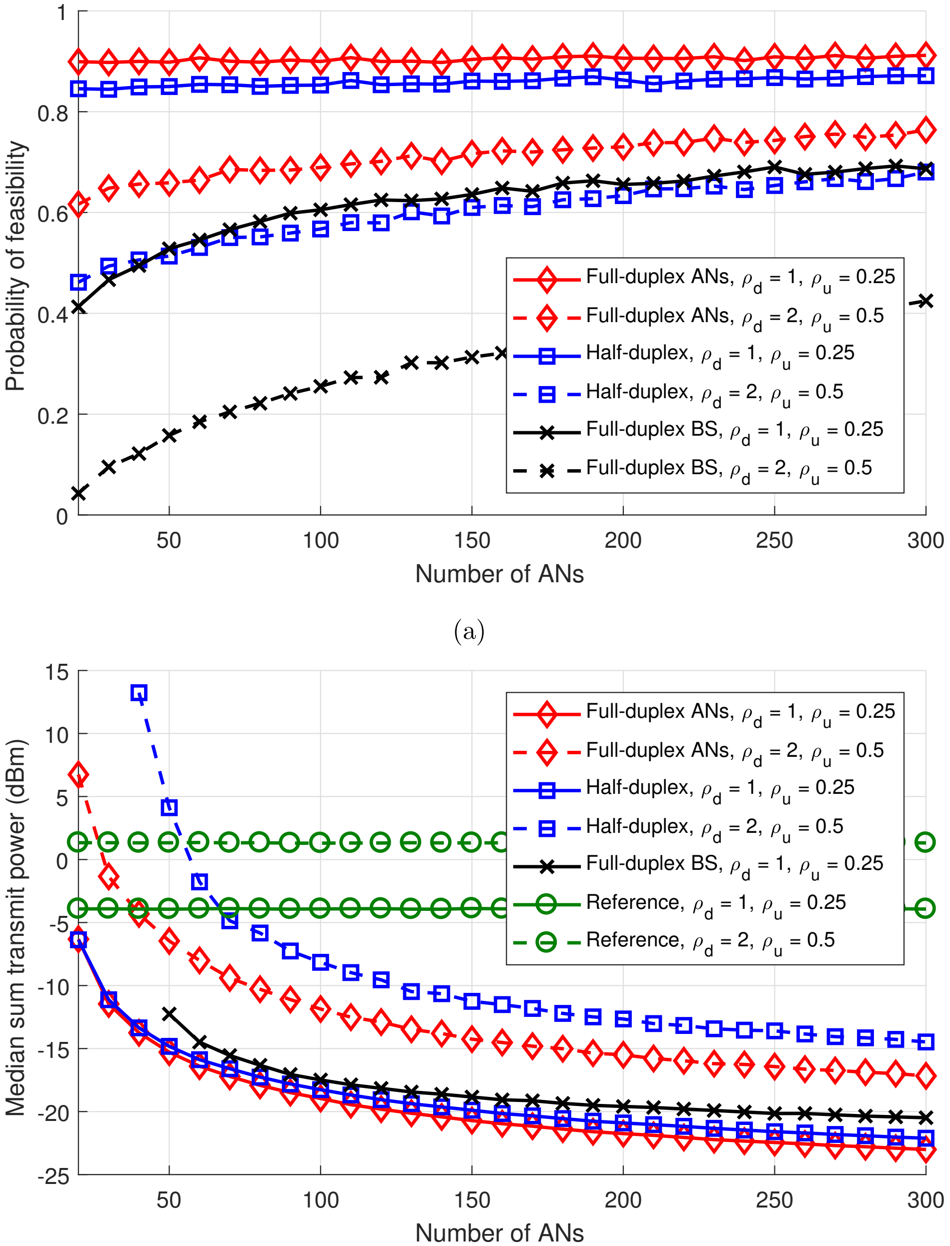
(b)

Figure 1.10: (a) Probability of feasibility and (b) median of the sum transmit power with respect to the number of UEs, shown for different cell radii.

Fig. 1.10b become undefined. As opposed to this, the reference scheme is never infeasible, but it requires considerably higher transmit powers. Altogether, utilizing full-duplex ANs to provide the radio access seems therefore the most preferable option in terms of transmit power consumption and number of supported UEs, as long as steps are taken to ensure the feasibility of the network geometry.

Finally, Fig. 1.11a shows the probability of feasibility with respect to the number of ANs, while Fig. 1.11b shows the medians of the corresponding sum transmit powers. Firstly, Fig. 1.11a indicates that the probability of feasibility is not dramatically affected by the density of the ANs, although more ANs does translate to a slightly higher probability of feasibility. However, with the considered system parameters, it seems that 100 ANs is enough to obtain a sufficiently high probability of feasibility with most self-backhauling strategies. Furthermore, again, the case with full-duplex ANs obtains the highest probability of feasibility among the considered self-backhauling strategies, especially with the higher data rate requirements.

As for the overall transmit power consumption, Fig. 1.11b indicates that a larger number of ANs always translates to a lower median sum transmit power. This is an intuitive result as more densely deployed ANs mean that the distance between a randomly positioned UE and the closest AN is smaller, resulting in reduced path losses. The lowest transmit powers are obtained by utilizing full-duplex ANs, while the reference scheme without any ANs requires the highest transmit powers under most circumstances. However, if the number of ANs is very small, the transmit power consumption of the AN-based strategies might be higher than that of the reference scheme. In fact, Fig. 1.11b shows that, in many cases, the median transmit powers of the networks with half-duplex ANs tend to infinity if the number of ANs is too



(a)

(b)

Figure 1.11: (a) Probability of feasibility and (b) median of the sum transmit power with respect to the number ANs, shown for different data rate requirements.

small. The most extreme example of this is the network with a full-duplex BS, as its median transmit power tends to infinity regardless of the number of ANs when the data rate requirements are $\rho_{\mathrm{d}} = 2$ and $\rho_{\mathrm{u}} = 0.5$. Therefore, the corresponding curve is not visible in Fig. 1.11b.

To conclude, the most important observations based on the numerical results are the following.

- Utilizing ANs to relay the traffic between the UEs and the BS reduces the transmit power consumption under most circumstances compared to a case where the BS serves the UEs directly. However, this requires careful transmit power allocation and favorable network geometry.
- Full-duplex ANs can obtain the QoS with lower overall transmit power consumption than half-duplex ANs, requiring only 70 dB of SI cancellation in doing so.
- Having a full-duplex capable BS is not helpful under the considered scenarios. Therefore, the BS and the UEs should rely on legacy half-duplex processing.
- The AN density should be significantly higher than the UE density to ensure that the interference links remain sufficiently weak in comparison to the data links.

1.6 Summary

In this chapter, we investigated different self-backhauling strategies for cellular networks with densely deployed ANs that relay data between the UEs and a macro BS. Three different self-backhauling strategies were considered:

one where all the nodes are half-duplex-capable, one where only the BS is full-duplex-capable, and one where all the ANs are full-duplex-capable. The optimal transmit power allocations under minimum QoS requirements were then determined for all these strategies as well as for a reference scheme without any ANs. The results indicate that utilizing full-duplex ANs is the most transmit power efficient solution, and it outperforms also the case where the BS communicates directly with the UEs. However, the drawback of utilizing the ANs as intermediary nodes is the fact that the QoS requirements cannot be obtained at all under some network geometries, due to the interference links. Nevertheless, as long as the system is designed such that the network geometry remains favorable, the findings of this chapter clearly demonstrate the benefits of deploying the ANs densely to minimize the transmit power consumption of ultra-dense wireless networks.

As for the potential future research directions, the analysis presented in this chapter could be extended to consider a multi-cell scenario with several BSs. In addition, the effect of alternative node distributions and path loss conditions should also be investigated to ensure that the results obtained herein can be generalized. Moreover, to address the problem of infeasible network geometries, a hybrid solution utilizing the optimal self-backhauling strategy for the prevailing node locations could be developed and evaluated.

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