Dynamic In-Band Self-Backhauling with Interference Cancellation

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Abstract—**Millimeter wave frequency bands are expected to be used in future 5G networks to provide high data rates. However, higher frequency bands are characterized with high path loss attenuation and sensitivity to the blockages. Thus, deployment of dense networks using smaller cell sizes is important for coverage. To this end, in-band wireless relaying can be used to realize smaller cell sizes at reduced backhaul cost. Wireless relaying may however sacrifice capacity because of half-duplex constraint. In this paper, we investigate the performance of the millimeter wave (mmWave) network employing self-backhaul relay nodes and centralized transmission coordination. In particular, we look at the usage of interference cancellation (IC) receivers to enable backhaul uplink multiple access channel (BU-MAC) and full-duplex (FD) access/backhaul transmission which can boost capacity of relaying. Through simulation results we show,that the $5^{th}\%$ E2E throughput is improved by around 90% with BU-MAC scheme and over 120% in FD scheme. The average throughput of relay downlink increases by around 50% and 80% with BU-MAC and FD schemes respectively.**

I. Introduction

The new generation of mobile communication system, 5G, is expected to utilize millimeter frequency bands because of the large available bandwidth. Millimeter wave (mmWave) frequency bands however pose challenges to system design because of higher path loss attenuation and sensitivity to the blockages [1], [2]. One straightforward way to overcome the propagation challenges is to add more base stations to the network with each cell serving a small radii. However, network densification leads to higher deployment cost, which is mainly driven by the cost for backhaul infrastructure and site maintenance. To ensure good network coverage at a reasonable cost, wireless relaying a.k.a. self-backhaul (sBH) solutions can be beneficial. For low cost wireless relaying, the same radio technology and spectrum can be flexibly used for both access and backhaul (BH) on a transmit time interval (TTI) basis [3], [4]. This solution is referred to as the integrated access and backhaul solution (IAB). Moreover, to cater for instantaneous traffic demands, dynamic time division duplexing (dynamic TDD) can be integrated into the IAB solution. Flexible self-backhaul along with dynamic TDD can however result in various types of inter-cell interference scenarios, e.g. backhaul to access, backhaul to backhaul interference apart from the downlink (DL) to uplink (UL) and conventional inter-cell interference of DL and UL. As a result, inter-cell interference coordination needs to be tightly integrated with radio resource management (RRM).

In-band wireless relaying suffers from an inherent half-duplex (HD) constraint, i.e. an antenna can not transmit and receive at the same time in the same frequency band [5]. For 5G mmWave systems, it is envisioned that the throughput loss arising from the half-duplex constraint can be mitigated to some extent using a multi-panel deployment [6], [7]. For instance a sBH node can simultaneously receive wireless backhaul and uplink access on different panels at the same time using beamforming. In the next slot, backhaul transmission and access downlink is done thereby mitigating the capacity loss of relaying to some extent.

However, the aforementioned scheme still has a limitation of adaptation to bursty traffic especially in case of traffic asymmetry between uplink and downlink. We thus look at further enhancing scheduling flexibility and utilization of panels with interference cancellation (IC) receivers.

To this end, in this paper we make use of successive interference cancellation (SIC) receiver to enable spatial multiplexing between backhaul and access using MIMO multiple access channel (BU-MAC). In the BU-MAC scheme, we receive wireless backhaul and uplink access on the same panel using SIC receiver by exploiting the large received power difference between the backhaul and uplink. The advantage of this scheme is to improve both the spectral efficiency and the scheduling flexibility for relaying.

To overcome the half-duplex loss of relaying, we further look into full-duplex relaying based on cross-panel interference cancellation (CPIC). The full-duplex scheme takes advantage of the prior knowledge of transmitted packet for cancellation, but the performance can still be limited because of imperfect channel estimation. Therefore, we study the effectiveness of interference cancellation receivers in the IAB concept in case of realistic channel estimation

We then apply the aforementioned BU-MAC and full-duplex approaches to coordinated joint scheduling of donor and sBH nodes with flexible TDD switching. We conduct performance evaluation through simulations and quantify the extent to which dynamic TDD interference cancellation, CPIC and BU-MAC are beneficial in mmWave relay systems.

We compare the performance of the above schemes with the coordinated scheme without IC receivers, where the interference coordination is done by beam coordination and time resource scheduling. Simulation results are shown in mmWave street canyon scenario with three panels at each site and with flexible TDD switching. Results show that the $5^{th}\%$ of uplink and downlink E2E throughput is improved by around 90% with backhaul and uplink multiple access scheme and 120% with full-duplex scheme. The SIC-based schemes are also seen to mitigate the half-duplex loss with average downlink throughput gain of around 50% and 80% with BU-MAC and FD schemes respectively.

II. System model

In this paper, we consider in-band wireless relaying (self-backhauling) wherein the same spectrum and radio technology is reused for both access and backhaul at a base station. In particular, we consider dense deployments in mmWave bands above 6 GHz where some base station nodes have wired backhaul and functionalities to be referred to as donor nodes. The relay (sBH) base station nodes have no wired backhaul and hence connect to the donor nodes via wireless self-backhaul using user equipment (UE) functionality. We assume multiple antenna panels at all base station nodes, with each link supporting 2x2 multiple input multiple output (MIMO) along with user-specific wideband beamforming. In the proposed integrated access and backhaul concept, the antenna panels at each base station node can be flexibly allocated to serve access or backhaul on a transmit time interval (TTI) basis. We interchangeably use the term cell to denote a panel, while we use the term node to denote a site which consists of multiple panels.

The decode and forward relaying operation is as follows. In the case of downlink, the donor panel sends data to a sBH receiver panel after applying appropriate beamforming, MIMO rank, modulation and coding scheme on the backhaul link. The decoded and re-mapped data is then transmitted via a sBH panel in the same sBH node using a different beam, MIMO rank and modulation and coding scheme according to the scheduling on the access link. We assume the backhaul link can multiplex backhaul data of multiple users together in one TTI. In the uplink direction, one panel of the sBH node receives data from a single access user in a given TTI. The multiplexed uplink data from multiple panels can then be sent to the donor. Each panel can support a different downlink or uplink user in a given TTI.

The downlink and uplink are unidirectional links between a panel at the base station (donor or sBH node) and a UE. Each UE has a single direct connection only to one panel. A wireless self-backhaul link is a unidirectional link between the transmit array of a donor node and a self-backhaul node. Wideband user specific Eigen beamforming is applied between a transmit array and a receive array of each link [8] to obtain beamformed channel matrix $\mathbf{G}_{kk}$ of dimension $N \times N$, where N is the maximum MIMO rank. We further apply transmitter precoding V_{kk} using the Singular Value Decomposition (SVD) of the beamformed channel matrix $\mathbf{G}_{kk}$ of a link k to obtain $\mathbf{H}_{ki} = \mathbf{G}_{ki}V_{kk},\ \forall i$.

In a TDD system, the received signal $\mathbf{y}_i$ at an receiver of link i is:

$$\mathbf{y}_i = \sqrt{P_i \alpha_{ii}}\mathbf{H}_{ii}^{N \times M_i}\mathbf{x}_i + \sum_{k \in \mathbf{I}} \sqrt{P_k \alpha_{ki}}\mathbf{H}_{ki}^{N \times M_k}\mathbf{x}_k + \mathbf{n}, \quad (1)$$

where $\mathbf{H}_{ii}$ is a effective channel matrix of a serving link i of dimension $N \times M_i$, where $M_i \leq N$ is the number of transmitted streams on the i^{th} link. $\mathbf{n}$ denotes the noise vector with power N_o and $M_i \times 1$ vector $\mathbf{x}_i$ denotes the modulated symbols of transmitter of i^{th} link. In eq. (1) the interfering links $k \in \mathbf{I}, \forall k \neq i$ can be either access uplink, access downlink, backhaul uplink or backhaul downlink. α_{ki} is the pathloss between the transmitter of k^{th} link and the receiver of i^{th} link. P_k denotes the per-subcarrier transmit power of the k^{th} link transmitter. LTE-like open-loop power control is applied for the uplink while the downlink uses a constant power per-subcarrier.

III. Interference cancellation in sBH

Flexible utilization of a panel in a site for downlink, uplink, backhaul receive or backhaul transmit can result in strong inter-cell interference between the sites. Interference cancellation can be used to suppress dynamic TDD downlink to uplink interference as in [10], [11]. For integrated access and backhaul, interference cancellation can be used to further remove backhaul to uplink and backhaul to backhaul interference. In addition, we consider the following enhancements for IAB based on interference cancellation.

The first scheme utilizes full-duplex operation, where interference cancellation is applied at the receiver to cancel intra-node transmit (Tx) to receive (Rx) interference between panels on the top of inter-site interference cancellation. Full-duplex (FD) situation occurs when one panel performs backhaul transmission and a co-sited panel receives uplink or when one panel performs downlink transmission and a co-sited panel receives backhaul. This type of interference can be treated as a 'known interference' and thus need not be decoded for cancellation. It can be removed based on prior knowledge of the transmitted symbols. However, the SIC receiver may still suffer from interference leakage because of imperfect channel knowledge. We thus model channel estimation errors as described below in section III-A. The cross panel interference can be beyond a saturation level of Analog to Digital Converter (ADC) [9] even with antenna isolation of 55 dB [6]. Thus, in case of full-duplex relaying, we lower the transmit power of Tx panels by 20dB in sites operating in FD mode.

The second scheme utilizes MIMO multiple access of backhaul and uplink, wherein the same panel receives sBH and uplink on the same resource. This schemes uses the SIC receiver which first decodes the backhaul signal to perform uplink reception.

A. Channel estimation error

We model the channel state information at the scheduler which is outdated and corrupted by noise in a time instance $[t]$ as:

$$\hat{\mathbf{G}}_{ki}[t] = \frac{1}{\sqrt{1+\sigma_E^2}}(\mathbf{G}_{ki}[t-\delta] + \mathbf{E}), \quad (2)$$

where $\mathbf{G}_{ki}$ is the beamformed actual channel between the the transmitter of a link k and a receiver of a link i. $[\delta]$ is the channel estimate outdate delay at the centralized scheduler. $\mathbf{E}$ is a noise matrix with complex-normal values e_{ki} with 0 mean power and σ_E^2 variance: $e_{ki} \sim CN(0, \sigma_E^2)$ [12].$\sqrt{1+\sigma_E^2}$ is an average power normalization scaling factor. The error variance σ_E^2 is estimated with a LTE-like model using pilot Signal to Interference and Noise ratio (SINR):

$$\sigma_E^2 = \frac{c_E}{(\sigma_{ii}^2)}(N_o + \sum_{k \in I} \sigma_{ki}^2), \quad (3)$$

where σ_{ii}^2 is the pilot signal power, N_o is the thermal noise power, and σ_{ki}^2 is the inter-cell interference power, and c_E is a model parameter found to be 0.0544 with a LMMSE estimator in [12] for pedestrian scenarios.

Channel estimation errors will result in interference leakage as well as SINR loss because of mismatch between the estimated channel and the actual channel realization. In our proposed scheduler we compute the IC-based achievable rates after modeling the leakage. Thus, we generate an independent 'noise perturbed channel' at the scheduler as [11]: $\tilde{\mathbf{G}}_{ki}=\frac{1}{\sqrt{1+\sigma^2_{\Delta_{ki}}}}(\hat{\mathbf{G}}_{ki} + \mathbf{\Delta}_{ki})$. The perturbation noise $\mathbf{\Delta}_{ki}$ is an independent random noise with channel estimation error variance modeled as seen at each receiver and calculated as in [12].

IV. Problem definition

We perform centralized resource allocation for flexible TDD switching between access UL/DL and backhaul UL/DL on a panel basis. To this end, we exploit the possibility of strong interference cancellation at the receiver and purposely schedule strong interference which can be canceled. Therefore, we use interference coordination as part of radio resource management to jointly schedule the cells to facilitate strong interference cancellation between cells. Joint scheduling for IC also takes into account beamforming and thus models the back lobes and side lobes after eigen beamforming.

A. *Centralized scheduling for full-duplex backhaul and access*

The imposition of half-duplex constraint across the panels in a site can lead to inefficient utilization of panels in case of bursty traffic. More precisely, the backlogged access traffic of a site may dominate the transmission direction switching of that site, at the cost of serving the backhaul traffic. On the other hand, giving higher priority to backhaul transmission may sacrifice the access data rate and increase the access backlogs. We thus apply full-duplex relaying in the centralized scheduler as well as flexible TDD switching on a panel basis. The main aim of this scheme is to increase the flexibility of multiplexing backhaul and access among co-sited panels.

The centralized resource allocation problem with full-duplex relaying is :

$$\begin{aligned} &\underset{\mathbf{b},\mathbf{M},\mathbf{R}}{\operatorname{argmax}} \sum_{s\in\mathbf{S}}\sum_{p\in\mathbf{P}_s}\sum_{k\in\mathbf{L}_p} w_k b_k \sum_{m=1}^{M_k} r_{km}(\mathbf{b},\mathbf{M}) \\ &s.t.\ \ b_k \in [0,1],\ \sum_{k\in\mathbf{L}_p} b_k \leq 1,\ \forall_{p\in\mathbf{P}_s},\ \forall_{s\in\mathbf{S}} \qquad (4) \\ &(\sum_{p\in\mathbf{P}_s}\sum_{k\in\mathbf{L}_p^{A,Tx}} b_k * \sum_{p\in\mathbf{P}_s}\sum_{k\in\mathbf{L}_p^{A,Rx}} b_k) = 0,\ \forall s\in\mathbf{S}, \end{aligned}$$

where $\mathbf{S}$ represents the set of cooperating nodes in the system comprising both donor and sBH nodes. Each node s comprises a set of co-located panels $\mathbf{P}_s$. The set of unidirectional links $\mathbf{L}_p$ in a panel $p \in \mathbf{P}_s$ consists of access links $\mathbf{L}_p^A$ as well as self-backhaul links $\mathbf{L}_p^B$, thus $\mathbf{L}_p = \mathbf{L}_p^A \cup \mathbf{L}_p^B$.

The transmission direction of p^{th} panel is captured by variable $d_p = \{Tx, Rx\}$, where Tx stands for *transmit* and Rx stands for *receive*. We impose a half-duplex constraint between the panels in a given node only for access transmissions which is shown using the second constraint of (4). Thus, transmission direction is flexible between access and backhaul transmission and across different nodes, and can dynamically change over the scheduled time slots.

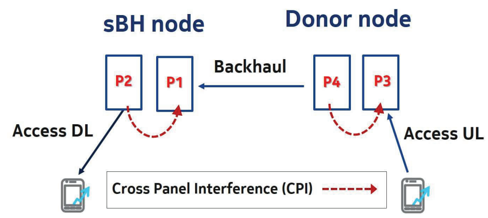

Fig. 1. Full-duplex between access and backhaul transmission.

In (4) the binary scheduling decision of a link k is captured by the variable b_k and stored in vector $\mathbf{b}$. The vector $\mathbf{M}$ captures MIMO rank decisions for all of the links with $M_k \leq N$ representing the number of spatial streams of link k. The matrix $\mathbf{R}$ consists of entries r_{km} denoting spectral efficiency of link k and $m \leq M_k$ MIMO layers. One can note that the achievable rate of a link depends on the interference experienced by the receiver. Thus, we denote the spectral efficiency $r_{km}(\mathbf{b},\mathbf{M})$ as a function of rank as well as the function of scheduled link [11]. The achievable spectral efficiency is computed based on user-specific wideband Eigen based beamforming. A interference rejection combining (IRC) receiver or a SIC-receiver is applied for tackling inter-cell interference, including the cross DL to UL and sBH to UL, and sBH to sBH interference. The variable w_k in (4) represents the current packet delay in the buffer of link $k \in \mathbf{L}_p, \forall p \in \mathbf{P}_s, \forall s \in \mathbf{S}$. The weights w_k soft-prioritize the links (access or backhaul) which currently experience higher packet delays without fully sacrificing spectral efficiency.

The centralized scheduler thus decides each panel to be in transmit or receive mode based on the objective in (4).

Assume a case where one panel (P1) receives backhaul from a donor and other co-sited panel (P2) has an active downlink traffic (as shown in Fig.1). The scheduling hypothesis for that site are then : 1) FD: schedule sBH Rx on P1 and DL on P2, 2) HD: schedule sBH Rx on P1 and UL on P2, 3) HD: sBH or DL Tx on P1 and schedule DL on P2. In the case of donor sites, another UL on P2 or another DL Tx on P1 is more likely to be active for HD options 2 and 3 because of the higher number of direct access users. In the case of sBH sites, panel P2 or P1 may be not realize active traffic in case of HD options leading to the conditions below. Based on the sum delay-weighted objective, FD is chosen when:

$$\begin{aligned} &w_1 log_2(1+\frac{P_1\alpha_{11}|h_{11}|^2}{N_0+\gamma+I_{out}}) + w_2 log_2(1+\frac{0.01P_2\alpha_{22}|h_{22}|^2}{N_0}) \\ &> max(w_1 log_2(1+\frac{P_1\alpha_{11}|h_{11}|^2}{N_0+I_{out}}), w_2 log_2(1+\frac{P_2\alpha_{22}|h_{22}|^2}{N_0})), \end{aligned} \qquad (5)$$

where γ is an interference leakage from CPIC modeled as in equation (3) and thus can be expressed as:

$$\gamma = c_E\Big(\frac{N_0 + P_1\alpha_{11}|h_{11}|^2 + I_{out}}{0.01P_2\alpha_{21}|h_{21}|^2}\Big)0.01 * P_2\alpha_{22}, \qquad (6)$$

where α_{21} is a pathloss between transmitting panel 2 and the receiving panel 1, h_{21} is a single stream channel between these panels and P_1 is a transmit power of panel 1. We thus observe that full-duplex scheduling decisions are affected by interference leakage which is a function of inter-site interference (6).

Thus, using (5), and (6) and after few manipulations, we may obtain the following threshold for inter-cell interference:

$$I_{out} < \min\Bigg(\frac{\frac{c_E}{c_E+|h_{21}|^2} P_1\alpha_{11}|h_{11}|^2}{\left(1+\frac{0.01*P_2\alpha_{22}|h_{22}|^2}{N_0}\right)^{\frac{w_2}{w_1}}-1} - N_0, \\ \frac{P_1\alpha_{11}|h_{11}|^2\left(1-\frac{c_E}{c_E+|h_{21}|^2}\left(\frac{N_0+P_2\alpha_{22}|h_{22}|^2}{N_0+0.01*P_2\alpha_{22}|h_{22}|^2}\right)^{\frac{w_2}{w_1}}\right)}{\left(\frac{N_0+P_2\alpha_{22}|h_{22}|^2}{N_0+0.01*P_2\alpha_{22}|h_{22}|^2}\right)^{\frac{w_2}{w_1}}-1} - N_0\Bigg). \tag{7}$$

We thus see that the condition for FD mode can be affected by the interference from other sites. Moreover the achievable rate of sBH or UL depends on the cancellation and flexible TDD scheduling of other sites. Thus in principle, joint scheduling has to be performed for flexible TDD switching, link scheduling and HD/FD selection among $|S|$ sites. To perform joint scheduling of sites, let us assume there are 3 panels in each site resulting in 2^3 FD Tx/Rx hypothesis per site. For each Tx/Rx hypothesis we have $\prod_{s\in\mathbf{S}}\prod_{p\in\mathbf{P}_s}\frac{L_p}{2}+1(muting)$ link hypothesis. The complexity of full search thus quickly becomes prohibitive and therefore we propose a low complexity scheme as follows. In the proposed heuristic, sub-set of panels are grouped to form clusters and then we go sequentially through the clusters. The main steps of the heuristic are as follows:

Step 1. Identify the set of access and backhaul links with active traffic to be served.

Step 2. Arrange the panels in a certain order based on priority and group the panels into clusters. A cluster consists of $|\mathbf{P}|$ panels, and the panels are not necessarily co-located. The clusters are now considered in series, with cluster index $q = 1..Q$.

Step 3. Within a cluster q, go through all combinations of transmit (Tx) and receive (Rx) links in the cluster.

Step 4. Avoid the Tx-Rx combinations of panels which results in duplex collision within a HD site, i.e one panel is on access downlink while the other panel in the same node is on access uplink. For FD sites with the backhaul transmission, we allow for full-duplex relaying. This situation applies when:

- one panel of a node (site) is receiving data (Rx panel) on the backhaul link, while other co-sited panels are transmitting (TX panel) to its direct user on access downlink (sBH node in Fig.1)
- one panel in a node (site) is receiving data (Rx panel) on access uplink, while other co-sited panel is transmitting (Tx panel) on backhaul link (donor node in Fig.1)

Step 5. User-specific wideband Eigen beamforming is applied to each link. Interference is calculated for different link hypothesis in a cluster q as well as for links scheduled in previous cluster iterations $1...q-1$. We compute UL to UL, DL to DL, as well as cross UL/BH and cross DL/BH interference between different panels also taking into account side lobes and back lobes.

Step 6. For cancellation of inter-site interference, rate and rank coordination for interference cancellation is applied as in [10], [11]. The achievable rates after cancellation of inter- and intra-site interference are computed based on SIC receivers with the stronger interference canceled first and after modeling interference leakage.

Step 7. Based on the achievable rates, the delay-weighted scheduling metric is computed as in (4). Note that for the pair of panels with active full-duplex traffic the conditions from (5)-(7) are directly used to speed up the search and determine if the panels should work on HD or FD mode.

Furthermore, in this step, while performing scheduling in a current q^{th} cluster, some of the nodes from clusters $1..q$ clusters are dynamically reconfigured to FD when there is a net gain in metric for clusters $1..q$. The best combination of links maximizing the delay-weighted rate metric in (4) is scheduled for the panels in that cluster q and the transmit powers are assigned. The scheduling information is now stored and used as side information to perform scheduling for the next cluster $q+1$.

B. Centralized scheduling for dynamic access and backhaul multiple access

In the BU-MAC scheme, the relay backhaul link and uplink are jointly received on the same time-frequency resource and antenna panel. The BU-MAC scheme uses SIC receiver which decodes and subtracts the backhaul signal as well as the cross link interference signal from neighbouring sites before performing uplink decoding. At the scheduler, we may now thus schedule a backhaul link up to a maximum rank of N as well as uplink with maximum rank of N on the same resource. At the same time, the backhaul and uplink can utilize the eigen-beamforming gain on respective links. The centralized scheduler now purposely schedules backhaul and uplink multiple access on a panel and cross TDD interference between sites based on the achievable rates after interference cancellation. The centralized problem is expressed as:

$$\begin{aligned} &\underset{\mathbf{b},\mathbf{M},\mathbf{R}}{\operatorname{argmax}} \sum_{s\in\mathbf{S}}\sum_{p\in\mathbf{P}_s}\sum_{k\in\mathbf{L}_p} w_k b_k \sum_{m=1}^{M_k} r_{km}(\mathbf{b},\mathbf{M}) \\ &s.t.\, b_k\in[0,1],\ \sum_{k\in\mathbf{L}_p^{Tx}} b_k \le 1,\ \forall_{p\in\mathbf{P}_s},\ \forall_{s\in\mathbf{S}} \\ &\sum_{k\in\mathbf{L}_p^{A,Rx}} b_k\le 1,\ \sum_{k\in\mathbf{L}_p^{B,Rx}} b_k \le 1,\ \forall_{p\in\mathbf{P}_s},\ \forall_{s\in\mathbf{S}} \\ &\Big(\sum_{p\in\mathbf{P}_s}\sum_{k\in\mathbf{L}_p^{Tx}} b_k * \sum_{p\in\mathbf{P}_s}\sum_{k\in\mathbf{L}_p^{Rx}} b_k\Big) = 0,\ \forall s\in\mathbf{S}, \end{aligned} \tag{8}$$

where the variables are defined as in (4).

With the first constraint we apply the limitation that only one active link is scheduled per panel in the transmit (Tx) direction. The second constraint imposes that one access uplink and one backhaul link can be simultaneously scheduled on a given panel on the same frequency resource. The third constraint

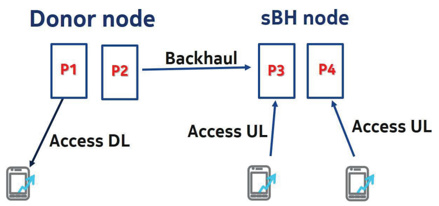

Fig. 2. Example of backhaul and uplink multiple access transmission.

imposes a half-duplex constraint among co-sited panels either receive or transmit at the same time.

The centralized heuristic is as follows.

Steps 1-2 are similar to the centralized scheduling for full-duplex as in Section IV-A. We now perform the following additional steps for BU-MAC scheduling.

Step 3. For a cluster q, go through all combinations of transmit (Tx) and receive (Rx) links in the cluster.

Step 4. The Rx link hypothesis comprises of backhaul and uplink multiple access combinations as well as orthogonal allocations. Fig. 2 illustrates a BU-MAC example.

Step 5. Avoid the Tx-Rx combinations of panels which results in duplex collision at any node, i.e one panel is on Tx while the other panel in the same node is on Rx.

Step 6. Beamforming is applied on the respective access and backhaul links during each hypothesis. The achievable rate of uplink is calculated after interference cancellation of co-scheduled interfering signals. For cancellation, the achievable rates and MIMO rank of backhaul and strong cross-link interferers are also computed using SIC receiver as in [10], [11].

Step 7. Based on the achievable rates, the delay-weighted scheduling metric is computed as in (4). The best combination of links maximizing the delay-weighted rate metric in (4) is scheduled for the panels in that cluster q. The scheduling information is now stored and used as side information to perform scheduling for the next cluster $q + 1$.

V. sBH Deployment Scenario

We now evaluate the performance of above interference cancellation and scheduling schemes in a millimeter wave relay scenario at 28 GHz band. One of the main use cases of millimeter wave relaying is to route the data around dynamic blockages. Thus, we developed a software demo based on the Unity3D rendering engine which was used for pathloss modeling based on a real life scenario with pedestrians and other obstacles. To capture the effect of blockages, we applied edge detection in Unity 3D to determine self body blockages, blockages from nearby pedestrians, and obstacles such as cars and buses in the scene.

A. Propagation modelling

The pathloss modeling in Unity3D models the following possible cases:

- Line of sight (LOS) detection to a user. It is checked if there is LOS to a user, and LOS with single blockage events are further identified. This is done based on object detection on the LOS path. In the case of single blockage events, an attenuation of 35 dB is applied on top of LOS pathloss.
- Diffraction based pathloss modeling based on edge detection. The pathloss values are dependent on the incidence angle on the diffraction ray [2].
- Non line of sight (NLOS) pathloss modeling with a pathloss exponent of 4 is used [13].

The output pathloss to user is taken as the maximum of the above pathloss cases.

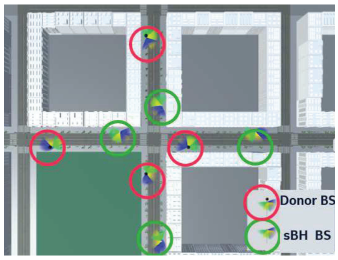

Fig. 3. Simulated street canyon mmWave deployment.

VI. Performance Evaluation

A. Simulation setup

Simulations are conducted in the street canyon scenario as in Fig.3 and using 200 MHz bandwidth. We deploy 4 donor nodes and 4 sBH nodes with each node comprising 3 panels. The inter site distance (ISD) is around 60m. In the scene there are 13 users connected to sBH nodes and 35 users connected directly to the donor nodes. The users are associated with donor nodes only when the SNR is above 30 dB. The traffic is modeled independently for the uplink and the downlink as Poisson distribution with fixed file sizes and 0.5s mean inter-arrival. The uplink file size per user is 2 Mbytes and in downlink the file size per user per arrival is 8 Mbytes. The average target load in terms of resource utilization is 30%. The time stamps of packet arrival and delivery are captured during the course of the simulations for 7 seconds. For the sake of simulation time, scheduling is performed on a time granularity of 1 ms, though the results are expected to also be representative for shorter TTI lengths. The packet discard time is set to 5s. A user's packet is dropped when the user can not be served because of high pathloss to any of the sites or

TABLE I
Table of Simulation Parameter

Parameter	Default value
Carrier frequency	28 GHz
Bandwidth	200 MHz
DL transmit power	27 dBm per panel.
UL transmit power	Pathloss mode slow power control with SNR target of 21 dB is applied. Maximum transmit power 17 dBm.
Antenna configuration	2X2 MIMO directional antenna array (N=2).
BS beamforming	12 degree beam width in azimuth and vertical. Tx Beamforming gain of 23 dB towards one user by beam steering. 90 degree steering range per panel. 30 degree vertical mechanical downtilt.
UE beamforming	UE beamforming gain of 6 dB, both UL and DL.
Traffic	Poisson with 0.5 sec inter-arrival time and DL/UL packet size ratio of 4:1. Fixed packet size of UL=2 Mbytes & DL=8 Mbytes.

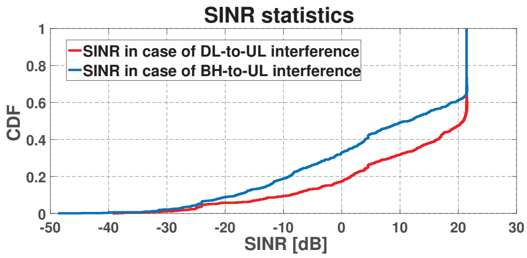

Fig. 4. SINR statistic for uplink.

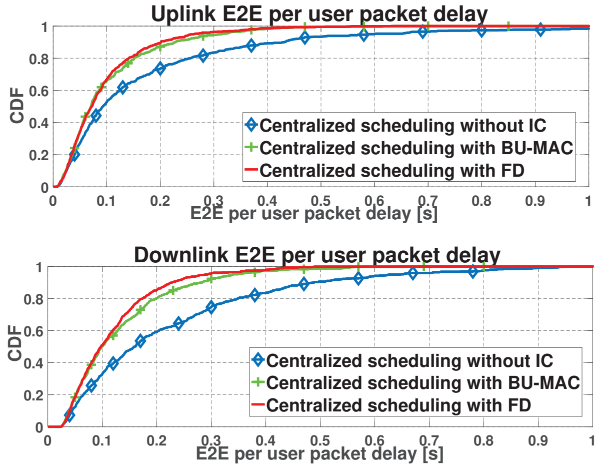

Fig. 5. E2E per user packet delay CDFs.

panels. Please see Table I for a short description of simulation parameters. The following schemes are evaluated:
1) Centralized scheduling without IC,
2) Centralized scheduling with IC and BU-MAC,
3) Centralized scheduling with IC and FD.

B. Results discussion

1) Interference statistics: In Fig.4 we first present SINR statistics for uplink in the scenario without BU-MAC or FD. From Fig.4 it can be seen that around 15% of uplink links are the subject of possible strong interference (i.e. SINR below -3dB) coming from inter-site downlink interference. In case of backhaul interference around 30% of uplink links can be strongly interfered. Thus, with the traffic load of around 30% the chances of cross-link strong interference occurrence are very low. Therefore, in case without BU-MAC and FD advanced IC receivers could be underutilized.

We now present the delay and throughput performance of IC-aware centralized schemes (with BU-MAC or FD) in the sBH scenario and compare it to the centralized scheduling scheme without interference cancellation receivers.

2) E2E delay results: The cumulative distribution function (CDF) of the end-to-end (E2E) uplink and downlink packet delays of evaluated schemes is shown in Fig. 5. The E2E per user packet delay was measured as a difference of the file arrival time at the source node and the time when the entire file was delivered to the target receiver.
BU-MAC: It can be seen that the uplink E2E packet delay with backhaul and uplink multiple access IC scheme is reduced from 0.599s to 0.314s (47.6% gain) in the 95^{th} percentile and from 0.093s to 0.071s (24% gain) in the median as compared to the scheme without IC. Significant gains are also visible in downlink with 47% and 38% delay reduction in $95^{th}\%$ and the median respectively as compared to the scheme without IC. The uplink gains are mostly because access uplink users do not have to duplex in time with Rx backhaul transmission to the same panel and thus can be served with reduced scheduling delay. The downlink performance improves because of better uplink performance via flexible UL/DL slot scheduling.
Full-duplex: The SIC-receiver with full-duplex and cross-site interference cancellation also brings significant gains as compared to the baseline scheme without IC. In $95^{th}\%$ the gain is 56 % and in the median 22% as compared to the scheme without IC. In the downlink the gain is of around 55% and 38% in the $95^{th}\%$ and the median respectively. In case of full-duplex with IC the significant gains in uplink and downlink are because of the better adaptation to the current traffic direction demands of direct donor and sBH users.
In the next section we will discuss the throughput performance separately for direct donor node users and sBH users.

3) Throughput performance: The numerical E2E throughput results are presented in Table II. With the throughput results we look at the performance of direct donor users and sBH users separately. The E2E throughput is calculated as the ratio between transmitted packet size and the E2E delay of that packet. Table II summaries percentage gains of IC schemes as compared to the baseline scheme without IC.
The effectiveness of FD and BU-MAC schemes are dominated by the amount of backhaul transmission. Because of traffic asymmetry, the backhaul direction from donor to sBH carries more traffic. Thus, from Table II we see moderately higher gains for sBH users as compared to the direct donor users.

In principle the FD scheme intends to completely overcome the loss because of half-duplex constraint. In the downlink of

TABLE II
E2E PER USER THROUGHPUT RESULTS

COORDINATION SCHEME	Uplink [Mbps]		Downlink [Mbps]	
	$5^{th}\%$	Avg	$5^{th}\%$	Avg
Direct donor users				
Centralized scheduling without IC (baseline)	28.93	314.80	145.82	741.95
Centralized scheduling with IC and BU-MAC (gain)	52.61 (82%)	363.99 (16%)	273.50 (88%)	946.50 (27%)
Centralized scheduling with IC and FD (gain)	66.60 (130%)	359.69 (14%)	295.55 (102%)	949.10 (28%)
sBH users				
Centralized scheduling without IC (baseline)	14.90	170.90	72.95	256.81
Centralized scheduling with IC and BU-MAC (gain)	47.69 (220%)	222.48 (30%)	128.67 (76%)	391.43 (52%)
Centralized scheduling with IC and FD (gain)	43.05 (189%)	226.70 (32%)	154.53 (112%)	455.22 (77%)
Direct donor + sBH users				
Centralized scheduling without IC (baseline)	27.10	278.08	97.75	602.01
Centralized scheduling with IC and BU-MAC (gain)	50.84 (87%)	327.32 (18%)	185.00 (89%)	790.86 (31%)
Centralized scheduling with IC and FD (gain)	60.88 (125%)	325.08 (17%)	217.91 (123%)	810.60 (35%)

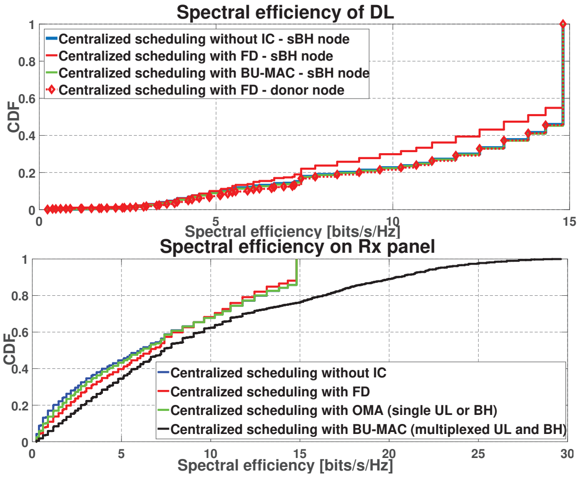

Fig. 6. Spectral efficiency results.

the scheme without IC the donor users achieved around 2.8 times higher mean downlink throughput as compared to the sBH users. The gap is now reduced with the FD scheme to approximately a factor of 2. The above performance gap is because of multiple reasons: a) Because of the association bias, the donor users are guaranteed a 30 dB SNR while the sBH may realize a lower SNR. b) In case of FD transmission, we reduce the transmit power by 20 dB because of CPI target which further reduces the achievable Tx spectral efficiency as shown in Figure 6. c) Moreover, around 15% of time, the same panel is used for backhaul reception and downlink access transmission to a user, thus imposing a half-duplex constraint on the sBH traffic.
The uplink performance is also improved by the full-duplex scheme by 125% and 17% in the $5^{th}\%$ and the median respectively as compared to the scheme without IC.

In the case of uplink, significant throughput gains of around 220% are seen with the proposed BU-MAC scheme for sBH users. Furthermore, the performance gap between direct donor users and sBH users is now only 9%. The BU-MAC scheme also shows downlink performance gain which is mainly on account of the flexible TDD switching gains and more backhaul scheduling opportunities.

The sum spectral efficiency of co-scheduled backhaul and uplink on same resources based on SIC-receiver is shown in Figure 6. The median sum spectral efficiency of orthogonal multiple access (OMA) with only backhaul or uplink is 6.58 bits/sec/Hz, while for BU-MAC is 7.4 bits/sec/Hz, which around a 20% gain. In Table III the decision statistics for BU-MAC and full-duplex transmission for sBH and donor nodes are presented. The statistics shown the amount of time BU-MAC or FD is actually selected as percentage of scheduling opportunity. This is computed as the ratio between the number of slots scheduled with BU-MAC or FD to the number of slots with active traffic for BU-MAC or FD.

VII. Conclusion

In this paper, we studied the performance of in-band self-backhauling (sBH) in mmWave system using interference cancellation receivers. We presented scheduling schemes utilizing backhaul and uplink multiple access channel (BU-MAC) and full-duplex cancellation, where successive interference cancellation is performed based on realistic channel estimation. The aforementioned IC-based schemes were then exploited using a centralized scheduler for donor and sBH cells along with flexible TDD scheduling. Results in a street canyon scenario shows significant performance gains for sBH users with the above IC-based schemes as compared to the fully coordinated scheme without IC. The $5^{th}\%$ of uplink and downlink E2E throughput improves by around 90% with BU-MAC scheme and 120% in full-duplex. The IC-based schemes are also seen to mitigate the half-duplex loss of sBH users with multi-panel deployment. The average throughput of relay dowlink is seen to gain by around 50% and 80% with BU-MAC and full-duplex scheme respectively.

TABLE III
Table of FD and BU-MAC statistic

SCHEME	sBH nodes	donor nodes
BU-MAC transmission occurrence	39.2%	43.7%
FD transmission occurrence	34%	14%

VIII. Acknowledgment

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