Achievable Rate Evaluation by System Level Simulation for mmWave based Backhaul Network Adopting In-Band Full-Duplex

Seongbae Han*, Jaemin Jung*, Heeyoung Kim*, Seokki Kim†, Seungkwon Baek†, and Sooyong choi*
*School of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea.
Email: {hsb1531, jjmm1000, khy93, csyong}@yonsei.ac.kr
†Electronics and Telecommunications Research Institute (ETRI), Daejeon, Korea.
Email: {kimsk0729, skback}@etri.re.kr

***Abstract*—The millimetre-wave(mmWave) based wireless backhaul operating in an in-band full-duplex (IBFD) mode is evaluated by system level simulation. This paper introduces a system level simulator implementing the mmWave based backhaul network adopting IBFD. We evaluate achievable rates for two link settings. One is designed to minimize the number of self-interference links and the other is designed to maximize the number of self-interference links. Then we verify that the IBFD can increase the acheivable rates of the mmWave based backhaul network. Also we evaluate the effect of link setting on the acheivable rates in the mmWave based backhaul network adopting IBFD.**

I. INTRODUCTION

To support the tens of gigabit-per-second (Gbps) data rates, the capability of backhaul becomes increasingly important not to be bottleneck in the cellular system. Recently, millimetre-wave(mmWave) based backhaul network is considered as a promising technique, since the mmWave based backhaul is able to provide Gbps data rate and offer flexible and cost-effective solution for 5G backhaul networks [2]. To enhance the mmWave based system, many researches have been studied for transmission and reception techniques, such as massive multi-input-multi-output (MIMO), hybrid beamforming, in-band full-duplex (IBFD), etc [3]. Especailly the IBFD has been considered to increase sum capacity of mmWave backhaul network [4]. The adoption of IBFD in mmWave backhaul network is possible if the additional self-interference cancellation (SIC) of 35 to 50dB is supported by SIC techniques [5]. Fortunately, most of existing SIC techniques have cancellation capabilities above 50dB [4].

In this paper, we investigate the system-level simulation for mmWave based backhaul network adopting IBFD. We implement a system level simulator and evaluate the achievable rates on the assumption that SIC is provided and the power level of residual self-interference (SI) is equal to noise power level after the SIC procedure. We evaluate and compare the achievable rate performances of backhaul network adopting IBFD or not. We also evaluate the effect of link setting on the achievable rate performances.

Notation: The operators $(\cdot)^T$ and $||\cdot||_F$ denote transpose and the Frobenius norm, respectively.

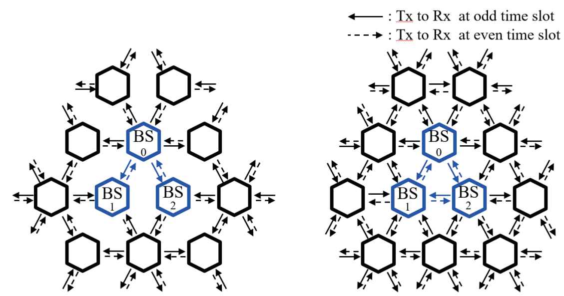

Fig. 1. Deployment and link settings of mmWave backhaul network, (a) conventional link settings without IBFD and (b) link settings with IBFD.

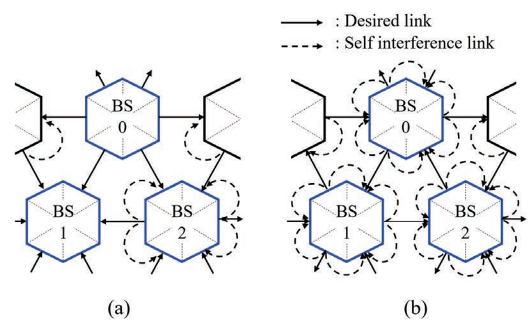

Fig. 2. Desired links and SI links of two link settings for mmWave backhaul network with IBFD, (a) link setting to minimize the number of SI links and (b) link setting to maximize the number of SI links.

II. SYSTEM MODEL

A. Network layout and IBFD model

As described in Fig. 1, we consider a central BS group consisting of three BSs and one tiers of surrounding BSs. Each BS adopts 6 sectors. We consider time division duplex (TDD) mode for each link. Fig. 1 (a) shows the conventional link setting without IBFD. All sectors in a BS should conduct the same operation, transmission or reception, at the same time slot. Therefore, some links cannot be activated, although no SI is inside a BS. Fig. 1 (b) shows the link setting with IBFD. Each sector in a BS can operate in a transmission or reception mode independently at the same time slot. Therefore, all links in the backhaul network can be activated at the same time slot, although SI occurs additionally inside a BS.

Fig. 2 shows the desired and SI links among BS 0, BS 1 and BS 2 of two link settings for the mmWave backhaul network with IBFD. Fig. 2 (a) and (b) show the link settings to minimize the number of SI links and maximize the number of SI links, respectively.

B. Antenna model

We consider a uniform rectangular antenna array comprising N_p panels per each sector and $N_H N_V$ cross-polarized antenna elements per each panel, where N_H and N_V are the number of cross-polarized antenna elements in a row and a column, respectively. Then the total number of antenna elements can be calculated as $N_e{=}2N_P N_H N_V$. It is assumed that all sectors use the same number of antenna elements for transmission and reception. The detailed antenna radiation pattern is referred from in [6].

C. Link measurement model

1) Signal model: For the transmission and reception model, we consider hybrid beamforming based MIMO-OFDM system. The analog beamforming is appiled per transceiver radio unit (TXRU) [7]. We consider N_{ru} TXRUs per sector at transmitter (Tx) and receiver (Rx). When N_s data streams (layers) are transmitted to a receiver, the received symbol vector of the lth subcarrier for the receiver of the kth link is given as

$$\begin{aligned}\mathbf{y}_k[l] =&\mathbf{G}_k[l]\mathbf{M}_k^T\mathbf{V}_k^T(\mathbf{H}_k[l]\mathbf{W}_k\mathbf{M}_k\mathbf{P}_k[l]\mathbf{x}_k[l]\\ &+\sum_{i\in I_k}\mathbf{H}_i[l]\mathbf{W}_i\mathbf{M}_i\mathbf{P}_i[l]\mathbf{x}_i[l]+\mathbf{n}[l]),\end{aligned}\tag{1}$$

where $\mathbf{y}_k[l]$ is an $N_s \times 1$ baseband received symbol vector, $\mathbf{G}_k[l]$ is an $N_s \times N_p$ digital equalization matrix, $\mathbf{M}_k$ is an $N_{\text{ru}} \times N_p$ port virtualization matrix, $\mathbf{V}_k$ is an $N_e \times N_{\text{ru}}$ analog beamforming matrix at the receiver, $\mathbf{H}_k[l]$ is an $N_e \times N_e$ frequency domain channel matrix, $\mathbf{W}_k$ is an $N_e \times N_{\text{ru}}$ analog beamforming matrix at the transmitter such that $\|\mathbf{W}_k\|_F^2 = 1$, $\mathbf{P}_k[l]$ is an $N_p \times N_s$ digital precoding matrix such that $\|\mathbf{P}_k[l]\|_F^2 = 1$, $\mathbf{x}_k[l]$ is an $N_s \times 1$ baseband transmit symbol vector, $\mathbf{n}[l]$ is an $N_s \times 1$ noise vector, and I_k is the set of interference link for the kth link. I_k can be divided into two groups, one for the SI links $I_{k,SI}$ and the other for inter-BS-interference (IBI) links $I_{k,IBI}$. IBI refer to interference to sectors in other BSs.

In this paper, we assume that SIC techniques are applying to each BS and the SI can be cancelled to the noise power level. We define SIC ratio as χ. Therefore, the power of residual SI can be expressed as $(1-\chi)P_{Tx}$, where P_{Tx} denotes the transmit power. Using the residual SI calculated by χ, (1) can be rewriten as

$$\begin{aligned}\mathbf{y}_k[l] =&\mathbf{G}_k[l]\mathbf{M}_k^T\mathbf{V}_k^T(\mathbf{H}_k[l]\mathbf{W}_k\mathbf{M}_k\mathbf{P}_k[l]\mathbf{x}_k[l]\\ &+\sum_{i\in I_{k,SI}}\mathbf{H}_i[l]\mathbf{W}_i\mathbf{M}_i\mathbf{P}_i[l]\mathbf{x}_i[l]\\ &+\sum_{j\in I_{k,IBI}}\sqrt{1-\chi}\mathbf{x}_j[l]+\mathbf{n}[l]).\end{aligned}\tag{2}$$

TABLE I
SIMULATION PARAMETERS.

Parameter	Value
Carrier frequency (f_c)	40 GHz
Bandwidth & FFT size	200 MHz, 1024
Inter-site distance (d_{ISD})	1000 m
Channel model	3D SCM UMa, LOS [11]
Height of BS	25 m
Number of antenna elements per sector	512
Polarized antenna model	Model 2 (Sec. 7.1.1 [12])
Maximum antenna element gain	8 dBi
Sampling frequency	491.52 MHz
Subcarrier spacing	480 kHz
Number of subcarriers	384
Number of subcarriers per one RB	12
Receiver type	MMSE
Channel estimation	Ideal without error
Thermal noise	-174 dBm/Hz
Maximum number of layers	4
Traffic model	Full buffer

We also consider the limited feedback based hybrid beamforming. The beam index (BI), precoding matrix index (PMI), channel quality indicator (CQI) and rank indicator (RI) are used to feedback the channel state information (CSI). For the analog beamforming, we employ the analog codebook as the uniform quantization in angle space defined in [8]. For the digital precoding, we consider the LTE release 8 codebook supporting up to 4 layers [9]. The BI and PMI are determined based on the analog codebook and digital codebook, respectively. The MCS is determined based on the CQI and RI. We consider modulation to 1024-quadrature amplitude modulation (QAM) and the MCS table is refered from Table I in [6].

2) Performance measurement: In this paper, we calculate the achievable rate of each link. To calculate the achievable rate of each link, we first calculate CSI including BI, PMI, RI and CQI from channel response. The detailed procedure to obtain the CSI is referred from [6]. Based on the CSI, the precoding matrix, analog beamforming, modulation and coding rate are selected and we calculate the SINR per subcarrier from (2). From the SINR per subcarrier, we calculate effective SINR and achievable rate based on the mutual information based effective SINR mapping (MIESM) methed used in [10].

III. SIMULATION RESULTS

In this section, we present system level simulation results. Simulation parameters for the simulations are listed in Table I. To observe the performance gains of IBFD according to link setting, we evlauate the achievable rates for three link settings, called as 'non-IBFD', 'min SI link' and 'max SI link'. The 'non-IBFD' is described in Fig.1 (a) and 'Min SI link' and 'Max SI link' are described in Fig. 2 (a) and (b), respectively. The achievable rates are measured for the links among BS 0, BS 1 and BS 2 depicted in Fig.1.

Fig. 3 shows the cumulative distribution functions (CDF) of achievable rate of each link. The CDFs for three link settings are similar to each other. The 'Min SI link' has probability of 0.51 that a link has achievable rate under 3 bps/Hz. The

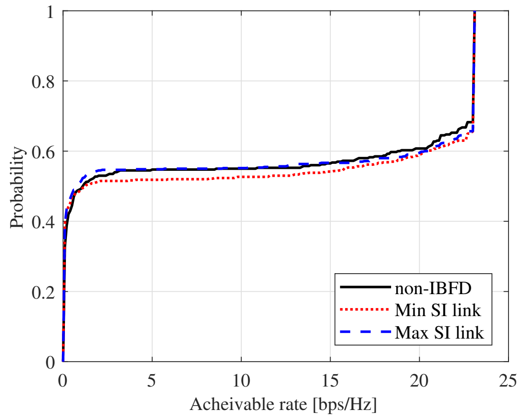

Fig. 3. CDF of achievable rate of each link for three link settings, 'non-IFBD', 'Min SI link' and 'Max SI link'.

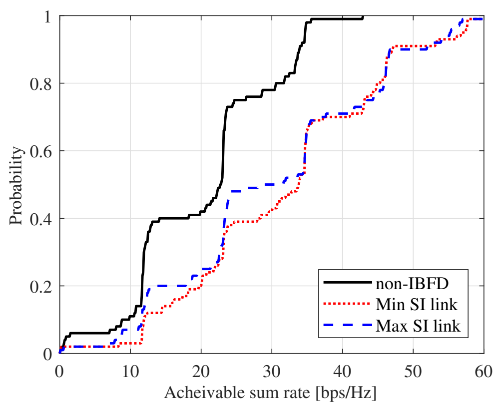

Fig. 4. CDF of achievable sum rate for three link settings, 'non-IFBD', 'Min SI link' and 'Max SI link'.

'Max SI link' and 'non-IBFD' have probability of 0.55 that a link has achievable rate under 3 bps/Hz. Therefore, we can observe that the 'Min SI link' has the ewer low-quality links than the other link settings.

Fig. 4 shows CDFs of the achievable sum rates and Table II shows the average acheivable rates for three link settings. The 'Min SI link' and 'Max SI link' outperform 'non-IBFD' in terms of the achievable sum rates. In Table II, the average achievable sum rates of 'Min SI link' and 'Max SI link' are about 1.5 times higher than that of 'non-IBFD'. The performance gain is obtained by increase of number of desired link, since the number of measured links of 'Min SI link' and 'Max SI link' is 1.5 times lager than that of 'non-IBFD'. Also we observe that 'Min SI link' has the higher achievable sum rates than 'Max SI link'. Therefore, the number of SI links should be decreased to increase the achievable rates of network.

IV. Conclusion

We have simulated the mmWave backhaul network by using a system level simulator. The IBFD, massive MIMO, limited feedback based hybrid beamforming and MCS up to 1024-QAM are considered in the system level simulation. We focused on the performance gains of IBFD for mmWave backhaul networks. We evaluated the achievable rates of mmWave backhaul network adopting IBFD and verified that the IBFD can increase the network capacity. Also we observed that the link setting should be determined with consideration for the number of SI links. The link setting algorithm for various deployments is required to increase the performances of IBFD.

TABLE II
Average achievable rates.

Link setting	non-IBFD	Min SI link	Max SI link
Average achievable rate (bps/Hz)	10.0802	10.5836	10.0824
Average achievable sum rate (bps/Hz)	20.1603	31.7509	30.2471

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