# Frequency Domain Backoff for Continuous Beamforming Space Division Multiple Access on Massive MIMO Wireless Backhaul Systems

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***Abstract*—This paper newly proposes a frequency domain backoff scheme dedicated to continuous beamforming space division multiple access (CB-SDMA) on massive antenna systems for wireless entrance (MAS-WE). It is one of the practical applications of massive MIMO; ultimately simplified structure for fixed backhaul links. The entrance base station (EBS) has multiple digital base band chains with massive antenna array and construct backhaul links to relay stations (RSs) each of which organizes a small cell. Backhaul links are provided by massive array beamforming and SDMA can be attained even without null-steering such as zero-forcing. It alleviates heavy precoding computation for each scheduled relay station combinations, i.e. sophisticated radio resource management and complicated multiuser scheduling are not required. Although the EBS structure can be ultimately simplified, RSs should work in a distributed manner. One issue remains to be resolved; overloaded multiple access resulting in collision due to its random access nature. The frequency domain backoff mechanism is introduced instead of the time domain one. It can flexibly avoid co-channel interference caused by excessive spatial multiplexing. Computer simulation verifies its superiority in terms of system throughput and packet delay.**

***Index Terms*—Massive antenna systems, Massive MIMO, Wireless backhaul, Continuous beamforming, Frequency domain backoff**

## I. Introduction

Commercialization of the fifth generation mobile communication (5G) has begun and it will trigger various mobile services to further enrich our smart life. Massive multiple-input multiple-output (MIMO) [1,2] is seen as one of the promising enablers for contributing the enhanced mobile broadband (eMBB) and the massive machine type communications (mMTC). Thanks to its plentiful degree of freedom (DoF), massive MIMO has a potentiality to attain large system capacity by higher order space division multiplexing (SDM) as well as coverage expansion by array beamforming. Towards realization of a higher order SDM, i.e. lots of spatial streams, base station (BS) should have lots of digital baseband (BB) chains; such almost fully digital massive MIMO for mobile users requires frequent and extensive channel estimation which sets a difficulty for a practical implementation. As an alternative for practical application of massive MIMO, wireless backhauling has been discussed [3]–[5]. It becomes a significant challenge in order to flexibly support small cells which will be deployed in various areas. Replacing the wired backhaul links between core network and small cell BSs with wireless links would contribute to their rapid installation.

The concept of massive antenna system for wireless entrance (MAS-WE) was also conceived [6,7]; it covers several kilometer radius with high system capacity entrance (backhaul) links to support widely distributed small cells access points via massive MIMO transmission. As depicted in Fig. 1, the entrance base station (EBS) and relay stations (RSs) are installed at fixed and high locations such that the line-of-sight (LoS) environment is obtained. If each RS has a directional antenna, multipath components can be mitigated and the channel state becomes stable as it is composed of a strong direct path and feeble reflected paths [8]. Once channel state information (CSI) is estimated, it can be utilized over long periods for SDM without frequent CSI estimation and feedback. In the literature, accurate CSI estimation scheme via long term averaging was also presented [7]. Major application scenarios of multiuser MIMO are mobile communications where the channel state instantaneously decays according to the Rayleigh distribution [9]. The Rayleigh fading limits a potentiality of diversity gain provided by array antennas. In addition, channel state usually fluctuates due to the user mobility. CSI is outdated by time lag among instants of estimation, feedback and precoding. It severely deteriorates the interference suppression (null-steering) performance and it limits a practicality of MIMO communication [10]. The MAS-WE eliminates the above all issues by setting MIMO application to the fixed wireless backhaul links. In addition, two simplified approaches, i.e. iterative interference cancellation and user scheduling strategy, were proposed [7]. These feasibilities have also been demonstrated via outdoor propagation channel measurements [11,12].

Meanwhile, a spatial multiuser multiplexing via massive MIMO [1,2] is still a significant challenge due to its user scheduling and weighting process. CSI estimation and weight calculation should be performed per user combination. Since the combination of multiplexed users should be frequently updated with respective transmission instance, BS requires a huge computation complexity resulting in excessive processing

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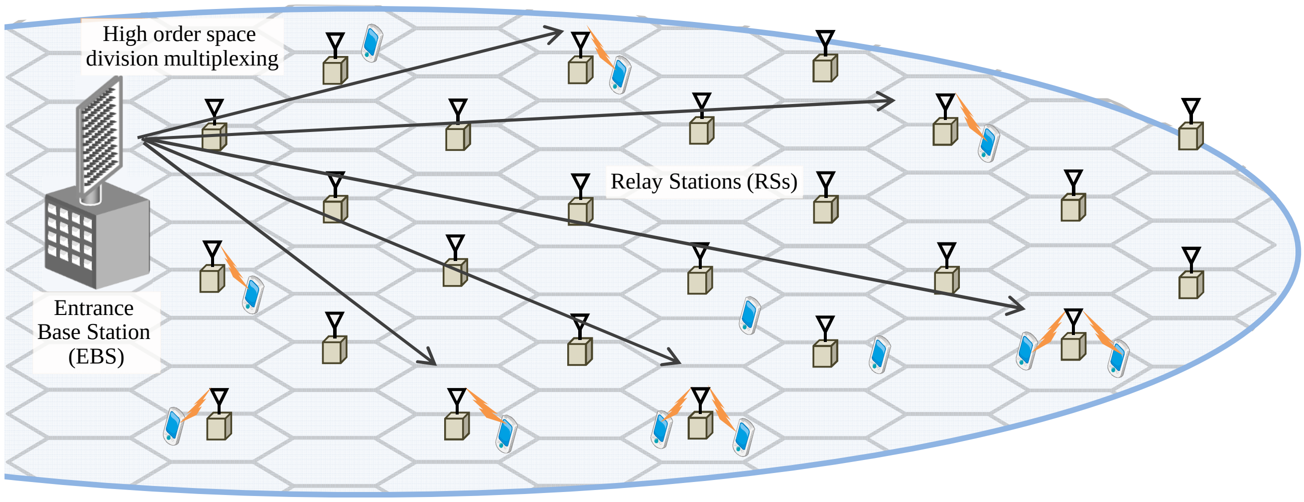



Fig. 1. Concept of massive antenna systems for wireless entrance (MAS-WE).

delay or energy consumption. Fully exploiting the features of fixed scenarios such as MAS-WE, a new concept of continuous beamforming space division multiple access (CB-SDMA) was previously proposed [13]. EBS has respective digital BB signal processing units dedicated to each RS. Each BB unit continuously applies a fixed beamforming weight for the designated RS. It virtually constructs point-to-point links between EBS and RSs regardless of whether traffic to be transmitted exists. Beamforming indicates that the simplified precoding such as equal gain combining (EGC) which just controls a phase component of each antenna element. It is thanks to a plentiful array combining gain, i.e. massive MIMO can attain SDM even without complicated precoding well known as zero-forcing (channel inversion). With the EGC, weight matrix can be simply constructed by concatenating or inserting a weight vector dedicated to the specified RS which has demand traffic. It also brings beneficial flexibility for multiuser scheduling and radio resource management. CB-SDMA can ultimately reduce overhead and computation complexity; its medium access control (MAC) efficiency can be improved. However, in this system assumption, demand requests for downlink and uplink transmissions occur at random. EGC originally permits inter-user interference (IUI). The SDM order occasionally exceeds an acceptable limit and it degrades signal-to-interference power ratio (SIR) resulting in communication failure. Therefore RSs should work to avoid such an overloaded situation in a distributed manner.

In order to stably operate the CB-SDMA based MAS-WE, a backoff scheme is essential. This paper newly proposes a frequency domain backoff scheme which has better flexibility on radio resource management than the conventional time domain approach. Computer simulation verifies its superiority in terms of achievable system throughput, transmission delay and packet loss rate. Rest of the paper is organized as follows. Section II reviews challenges on multiuser MIMO transmission and clarifies the contribution of this paper. Sections III and IV present summaries of CB-SDMA and the proposed frequency domain backoff scheme, respectively. Section V shows computer simulation results and Section VI then concludes the paper. In this paper, lowercase letters represent scalar quantities, bold letters indicate vectors and matrices, respectively. $|.|$, $(.)^*$, $(.)^T$, and $(.)^H$ represent absolute value, conjugate, transpose, and conjugate transpose, respectively.

## II. Challenges in Multiuser MIMO

With legacy SDMA using multiuser MIMO technique, BS works in a centralized manner and requires calculation and multiplication operations for transmission/reception weight per determined user terminal (UT) combination [14,15]. When the number of UTs is larger than that of SDM order which BS supports, scheduling process is indispensable to maximize the transmission capacity.

Data amount to be transmitted for each UT is various and fluctuates in time. Such various traffic demand can be supported by incorporating with orthogonal frequency division multiple access (OFDMA) which flexibly allocates radio resources to time/frequency domains. On the other hand, considering multiuser MIMO operation, its optimal transmission/reception weights should be determined per time slot and subcarrier, hence, explosive increase of computation burden cannot be overlooked. In addition, such flexible operation necessitates an exchange of control information between transmitter and receiver for radio resource management. It increases overhead and transmission delay.

The most significant issue should be addressed in massive MIMO systems aiming wide area coverage. Control signals are broadcasted to all UTs for association before obtaining beamforming gain. Generally, some kinds of beam selection or search [16]–[19] are utilized for initial association, however, these approaches also enhance overhead. Another problem is channel estimation. CSI for each UT is required to realize spatially multiplexed transmission/reception. The most efficient way for CSI estimation is to utilize scattered pilots or orthogonal training sequences which can be transmitted in one OFDM symbol. Note its possible number is limited depending on a system parameter or channel condition such

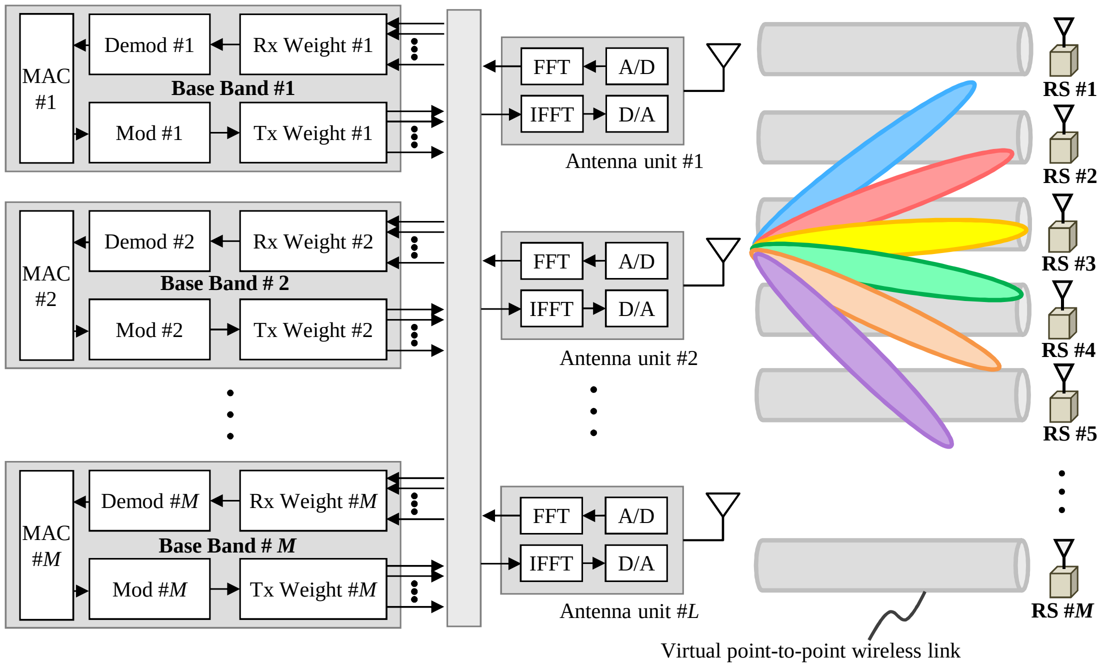



Fig. 2. Continuous beamforming spatial division multiple access (CB-SDMA).

as coherence bandwidth. Excessive number of SDM requires a multiple transmission of pilot symbols whereas it inversely causes depletion of radio resource utilization efficiency. This study is motivated by above challenges in legacy multiuser MIMO communication.

## III. CB-SDMA: Continuous Beamforming Spatial Division Multiple Access

Massive MIMO can achieve good SIR performance even under the application of simplified weighting such as EGC [20] or maximal ratio combining (MRC) [21]. Consider MAS-WE application scenario where EBS and RSs are deployed at fixed and high location, above feature can be more feasibly guaranteed than the fading channel environment. Since CB-SDMA performs only beamforming, i.e. no matrix inversion such as zero-forcing (ZF), their derivative weight does not depend on the combination of spatially multiplexed RSs.

It indicates that the weight matrix can be simply constructed by concatenating or inserting a weight vector dedicated to the specified RS which has demand traffic. Exploiting this fact, the uplink signals transmitted from the RSs can be extracted at arbitrary timing. Here, fast Fourier transform (FFT) windowing timing must be synchronized among all RSs under the assumption of OFDM transmission.

Fig. 2 depicts the CB-SDMA based MAS-WE structure. EBS is equipped with an individual digital BB signal processing unit dedicated to each RS and the fixed beamforming weights are continuously applied to transmission/reception signals regardless of RSs' communication status whether active or not. Beamforming raises the signal strength of the intended RS while relatively suppresses the undesired signal levels thanks to random signal synthesis. Therefore, each digital BB unit can detect intended signal by thresholding. If the desired signal is not sent, EBS observes weak signal level regarded as interference. Otherwise, EBS can identify the large level of signal as the desired one. It virtually provides point-to-point wireless backhaul links between EBS and RSs, and enables individual packet based communication.

Virtual point-to-point links can be operated by a time division duplex (TDD) or a frequency division duplex (FDD). With the TDD, implicit feedback [22] is one of the well known approaches for efficient CSI estimation at the EBS side. In this case, EBS should carefully schedule the transmission duration of uplink and downlink according to traffic asymmetry. As for the FDD, it dispenses with such time period separation but cannot utilize the implicit feedback approach; strict feedback based CSI acquisition may request a significant overhead. Both approaches can be applicable, however, CB-SDMA should care about multiple access operation. Since CB-SDMA does not perform null-steering, exceeding the possible SDM capability may degrade overall throughput performance. The previous work elucidated the achievable system throughput performance with regard to acceptable number of CBs and offered load [13]. This paper expands the previous study by additionally introducing MAC scheme to avoid overloaded SDM regime.

## IV. Backoff Control

Focusing on the overloaded situation where SDM order exceeds capability limit of EBS, this paper investigates collision avoidance protocols. Study of interest is uplink; EBS receives multiple signal streams from RSs. As for the downlink transmission, EBS can manage SDM order by itself therefore any additional transmission protocol is not required. Unlike legacy cellular systems, this study assumes the EBS has no negotiation function between RSs aiming at ultimately lightened structure. Instead of eliminating such signaling overhead, RSs dynamically control their transmission resources on time or frequency domain in a distributed manner. In distributed coordination function (DCF) [23] which is generally implemented to Wi-Fi, transmitter detects a packet reception failure due to the collision by hearing an acknowledgment (ACK) feedback from the receiver. If the ACK packet could not be sent back within the predetermined timeout period, the transmitter deems the data transmission to be a failure. After the collision detection, the transmitter autonomously adjusts the transmission timing via backoff mechanism.

Inevitable issue in this case is *hidden terminal* [24]. When transmitters cannot detect existence of each other, they radiate signals at arbitrary timing and these may coincide. These multiple signals reach to the receiver but they cannot be decoded neither; it is collision which collapses efficiency of DCF based multiple access. CB-SDMA originally permits excessive collision of multiple signals since sufficient SIR is ensured by EGC reception. However, a number of simultaneous transmissions from RSs may degrade SIR and it results in non-negligible collisions. It should be avoided but efficacious solution is not discussed so far. Furthermore, backhaul link requires high MAC efficiency to support large packet transmissions by traffic aggregation effect. When performing SDMA with several dozen order in such scenario, the time domain backoff has difficulty to set optimal backoff time in a distributed manner. It may cause frequent retransmission which deteriorates the system capacity. In order to resolve the above drawback, this paper proposes a new frequency domain backoff scheme. Difference of backoff schemes of interest is that interference management is performed in time or frequency domain;

- Time domain backoff: Retransmission after predetermined waiting time.
- Frequency domain backoff: Retransmission after reducing active subcarriers.

Waiting time period (for time domain backoff) and the number of inactive subcarriers (for frequency domain backoff) increase as the retransmission occurs in succession. Following subsections explain these schemes in detail.

### A. Time Domain Backoff

Here describes the time domain backoff scheme specialized for CB-SDMA principle. One time slot is associated to an OFDM symbol duration and backoff is controlled on a time slot basis. Packet is composed of multiple OFDM symbols. Traffic is assumed to be originated at each time slot. Since RSs work in distributed manner, EBS receives uplink packets from each RS at different time slots. If a number of RSs transmit packets simultaneously, SDM order exceeds allowable limit and SIR cannot satisfy requirement resulting in reception failure. This study assumes that RSs can recognize transmission failure when EBS detects collision, e.g. sending back ACK/NACK frame via different control channel. Then random backoff control is performed prior to the retransmission. Fig. 3 exemplifies time domain backoff procedure in asynchronous

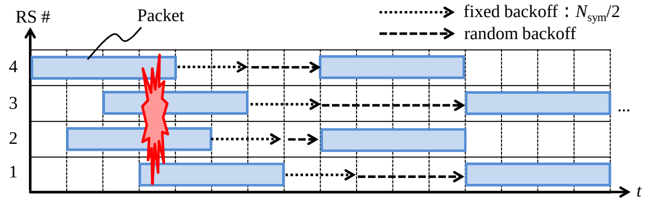



Fig. 3. Time domain backoff.

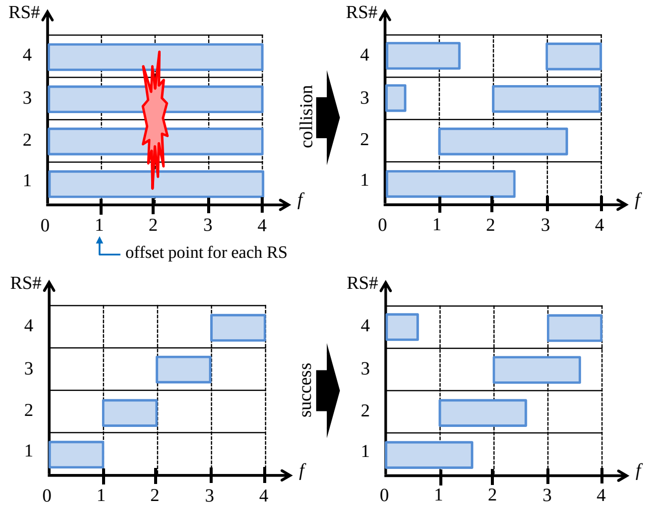



Fig. 4. Frequency domain backoff.

transmissions. As illustrated, a reception failure (collision) occurs when a part of packet experiences overload of SDM order. In this case, even though the 4th RS performs retransmission after several time slots, collision may occur again between packets still being transmitted from the 1st or the 3rd RSs. Retransmission should be done by setting standby in a fixed period before the randomize procedure in order to avoid such collision reappearance. This conception derives the following backoff control function;

$$N_{BO} = \frac{N_{sym}}{2} + N_{ret} N_{rand} \tag{1}$$

Fixed backoff time is assumed to be half of the packet length $N_{sym}$. $N_{rand}$ is a random variable taking integer values with uniform distribution in the range $[0, N_{max}]$. Random backoff period is linearly increased with the retransmission count $N_{ret}$. If the retransmission exceeds $N_{ret}$ times, the packet is discarded and is regarded as the packet loss.

### B. Proposal: Frequency Domain Backoff

Some literature proposed a frequency domain backoff concept, however, it is applied only to the control frame for transmitter–receiver handshake [25]–[27]. Their main purpose is to reduce the overhead of backoff time required for carrier sense multiple access with collision avoidance (CSMA/CA) in a single pair communication, i.e. single-input single-output (SISO). On the other hand, the key target of this paper is the multiuser MIMO communication and the proposed frequency domain backoff dynamically changes the number and position of active subcarriers even in a data part.

Fig. 4 shows the conceptual work flow of the proposed frequency domain backoff and its algorithm is presented in Fig. 5. OFDM can flexibly control the number of active subcarriers, $N_{SC}$, in which data symbol is assigned. Key idea of the proposal is to avoid excessive SDM of arbitrary frequency components by controlling the number of active subcarriers. We define the above mechanism as frequency domain backoff. An accessory benefit of this scheme is that the receiver (EBS) can obtain forward error correction (FEC) capability. Even when a certain subcarriers exceed allowable SDM order, these erroneous part can be compensated via FEC function with the aid of other subcarriers which successfully satisfied SIR requirement. Although the time domain backoff necessitates an optimization of its backoff parameter dependent to the packet length, the frequency domain backoff is irrespective of that. Only to appropriately adjust the number and allocation of active subcarriers can easily achieve SDM requirement. Above features bring expectation that the proposed approach can effectively support large traffic demand without capacity degradation.

This study defines an available active subcarrier ratio (number) as 100% (850), 80% (680), 60% (510), 40% (340), and 20% (170). Each RS decreases 40% (340) of active subcarriers after the collision detection and increases 20% (170) when EBS succeeded the reception of corresponding packet. Indices of active subcarriers, i.e. frequency resource element, dedicated to each RS are predetermined as shown in Fig. 4. It is considered to be better to use the fixed indices of subcarriers in order to avoid intensive use of active subcarriers. The possible idea is to provide offset for active subcarrier location per RS as shown in the figure.

$$N_{offset} = \left\lfloor \frac{N_{SC}(0)}{M} \right\rfloor \tag{2}$$

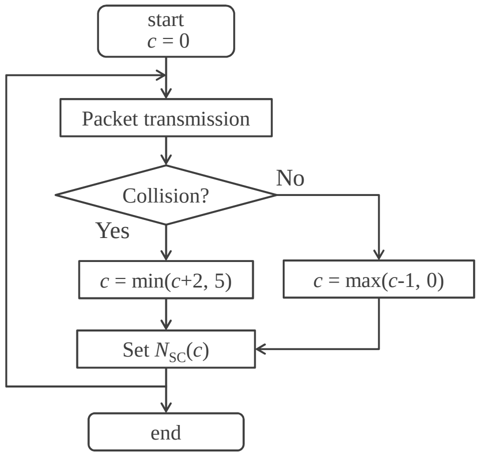
$N_{SC}(0)$ indicates the number of all subcarriers available and $\lfloor . \rfloor$ denotes the floor function. $N_{offset}$ is the offset of subcarrier index counted from the left-end, i.e. the first subcarrier position. Started from this subcarrier position, each RS increases or decreases the number of active subcarriers. This assumption does not lose a generality since RSs in MAS-WE are deployed before communication service start; pre-configuration is possible such that excessive collision per subcarrier can be avoided at heavy traffic situation.

## V. Computer Simulation

Here we observe effectiveness of the proposed scheme via computer simulations where physical (PHY) and MAC layers' behaviors are implemented.

### A. Simulation Condition

EBS is equipped with $L$ antenna elements and $M$ CBs are constructed; up to $M$ RSs are spatially multiplexed using the same frequency channel. Define transmission and reception signal vectors for the uplink as $\mathbf{S} = (s_1, s_2, \ldots, s_M)^T \in \mathbb{C}^{M\times1}$




| $c$ | $N_{SC}(c)$ |
|---|---|
| 0 | 850 |
| 1 | 680 |
| 2 | 510 |
| 3 | 340 |
| 4 | 170 |

Fig. 5. Flowchart of frequency domain backoff.

and $\mathbf{R} = (r_1, r_2, \ldots, r_M)^T \in \mathbb{C}^{M\times1}$, their relationship is expressed as,

$$\mathbf{R} = \mathbf{W}(\mathbf{HS} + \mathbf{N}) \tag{3}$$

where

$$\mathbf{H} = \begin{pmatrix} h_{11} & h_{12} & \cdots & h_{1M} \\ h_{21} & \ddots & & \\ \vdots & & h_{ij} & \vdots \\ & & \ddots & \\ h_{L1} & & \cdots & h_{LM} \end{pmatrix} \tag{4}$$

$$\begin{aligned} \mathbf{W} &= \begin{pmatrix} w_{11} & w_{12} & \cdots & w_{1L} \\ w_{21} & \ddots & & \\ \vdots & & w_{ij} & \vdots \\ & & \ddots & \\ w_{M1} & & \cdots & w_{ML} \end{pmatrix} \\ &= \frac{1}{\sqrt{ML}} \begin{pmatrix} \frac{\tilde{h}^*_{11}}{|\tilde{h}_{11}|} & \frac{\tilde{h}^*_{21}}{|\tilde{h}_{21}|} & \cdots & \frac{\tilde{h}^*_{L1}}{|\tilde{h}_{L1}|} \\ \frac{\tilde{h}^*_{12}}{|\tilde{h}_{12}|} & \ddots & & \\ \vdots & & \frac{\tilde{h}^*_{ji}}{|\tilde{h}_{ji}|} & \vdots \\ & & \ddots & \\ \frac{\tilde{h}^*_{1M}}{|\tilde{h}_{1M}|} & & \cdots & \frac{\tilde{h}^*_{LM}}{|\tilde{h}_{LM}|} \end{pmatrix} \end{aligned} \tag{5}$$

$\mathbf{N} = (n_1, n_2, \ldots, n_M)^T \in \mathbb{C}^{M\times1}$ denotes an additive white Gaussian noise (AWGN) vector. When an RS has no data traffic to transmit, $s_j = 0$. $\mathbf{H} \in \mathbb{C}^{L\times M}$ represents the uplink channel matrix assuming LoS channel environment. The EBS has 100 antenna elements and employs a parallelogram planar array (PPA) [28,29] configuration which yields reduced spatial correlation characteristics. Using a far field expression, channel coefficient between the $i$-th EBS antenna element and the $j$-th RS is given by [30],

$$\begin{aligned} h_{ij} = \exp\left[\frac{2\pi j}{\lambda}\left\{(m-1)d\cos\phi_j\sin\theta_j\right.\right. \\ \left.\left. + \left\{(n-1) + (m-1)d_p\right\} d\cos\theta_j\right\}\right] \end{aligned} \tag{6}$$

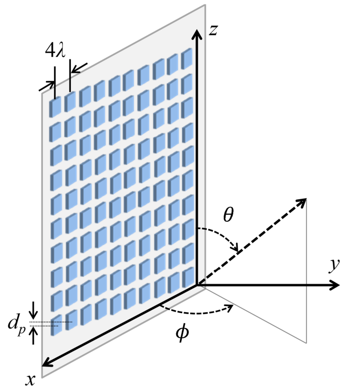



Fig. 6. Parallelogram planar array (PPA) structure.

where $m$ and $n$ denote row-wise and column-wise indices of EBS antenna elements, respectively. As illustrated in Fig. 6, when the PPA faces to the $y$-axis, $\phi$ denotes the azimuth angle direction of the RS from the $x$-axis toward the $y$-axis and $\theta$ denotes the zenith angle from the $z$-axis toward the $y$-axis. $d$ and $d_p$ stand for inter-element spacing and row-wise offset to provide PPA structure, respectively. Let $\lambda$ denotes the wavelength, $d$ is set to $4\lambda$ with reference to literature [29]. $d_p$ is set to 0.1. Channel estimate value, $\tilde{h}_{ij}$, is given by,

$$\tilde{h}_{ij} = h_{ij} + \sigma\varepsilon \tag{7}$$

where $\sigma\varepsilon$ is CSI estimation error due to the channel time fluctuation or the additive noise effect. $\varepsilon$ is a zero-mean complex Gaussian random variable with variance of $\sigma^2$. Its variance value is assumed to be −16 dB for conservative design as considered in [7]. $\mathbf{W} \in \mathbb{C}^{M\times L}$ is the reception weight matrix based on the EGC. Data traffic is offered to each RS with the occurrence probability of $\alpha/N_{sym}$ $(0 \le \alpha \le 1)$ for each transmission time slot; normalized total offered load is then given as $M\alpha$. Detailed simulation parameters are listed in Table I. RSs are uniformly distributed within the range of $45° \le \phi \le 135°$ (horizontal) and $90° \le \theta \le 95°$ (looking down). Thanks to the low spatial correlation nature provided by the PPA, the simplified threshold based RS scheduling is applied [31,32]. Combination of RSs is determined such that their spatial correlation is lower than the threshold of 0.3. Signal-to-noise power ratio (SNR) for each link is assumed to be 10 dB and it is defined as per antenna element, i.e. SISO case. Beamforming gain of approximately 20 dB is then provided by 100 antenna array. High SNR is expected; this system is dominated by interference since it does not perform null-steering (interference cancellation). 16QAM with coding rate of 1/2 is fixedly used to ensure the stable communication. Retransmission limit is set to 10. Retransmitted packet exceeding the limit is immediately discarded and counted as a packet loss. Evaluation metrics are defined as follows;

- System throughput: Packet reception is succeeded when contiguous $N_{sym}$ OFDM symbols are completely received without error. Let $N_{suc,j}$ and $N_{sim}$ denote the number of received packet for the $j$-th RS and observed time slots in simulation, respectively, normalized system throughput is given as,

$$\Gamma = \frac{\sum_{j=1}^{M} N_{suc,j} N_{sym}}{N_{sim}} \tag{8}$$

When system throughput, $\Gamma$, is equal to offered load, $M\alpha$, it indicates that maximum throughput is achieved in error free.
- Retransmission rate: It is defined as an averaged ratio of the number of retransmissions for the $j$-th RS, $N_{ret,j}$, to that of total transmission, $N_{tx,j}$, counted during the simulation period.

$$\Psi = \frac{1}{M}\sum_{j=1}^{M}\frac{N_{ret,j}}{N_{tx,j}} \tag{9}$$

- Average delay: Average delay is defined as the number of time slots taken for a packet transmit completion including awaiting time required for backoff.
- Packet loss rate: Packet loss rate is defined as a ratio of the number of discarded packets, $N_{dis,j}$, to total received and to be received packets.

$$\Theta = \frac{1}{M}\sum_{j=1}^{M}\frac{N_{dis,j}}{N_{rx,j} + N_{dis,j}} \tag{10}$$

TABLE I
SIMULATION PARAMETERS

| Parameters | values |
|---|---|
| Carrier frequency | 5.2 GHz |
| Bandwidth | 20 MHz |
| Transmission scheme | OFDM |
| Number of FFT point | 1024 |
| Number of subcarrier | 850 |
| Modulation | 16QAM |
| Forward error correction | Convolutional Coding, R=1/2<br>Soft decision Viterbi decoding |
| EBS antenna structure | Parallelogram planar array [29],<br>Inter-element spacing: $d = 4\lambda$<br>Row-wise offset: $d_p = 0.1$ |
| Number of EBS antennas | 100 (10 × 10) |
| Number of RS antennas | 1 |
| RS distribution | Uniformly distributed within;<br>Azimuth: $45° < \phi < 135°$<br>Zenith: $90° < \theta < 95°$ |
| Channel model | LoS |
| CSI estimation error | $\sigma^2 = -16$ dB |
| SNR | 10 dB@SISO |
| RS scheduling | Correlation threshold: 0.3 [31] |
| Beamforming | EGC |
| Retransmission limit | 10 |

Evaluation in this paper assumes that successful data transmission or failure/collision are ideally notified to the transmitter (RS).

### B. Fundamental Characteristics

First, Fig. 7 anew plots system throughput versus total offered load, $M\alpha$, with respective CB number, $M$. This preliminary result does not consider neither backoff nor retransmission with $N_{sym} = 1$. It is almost equivalent to that disclosed

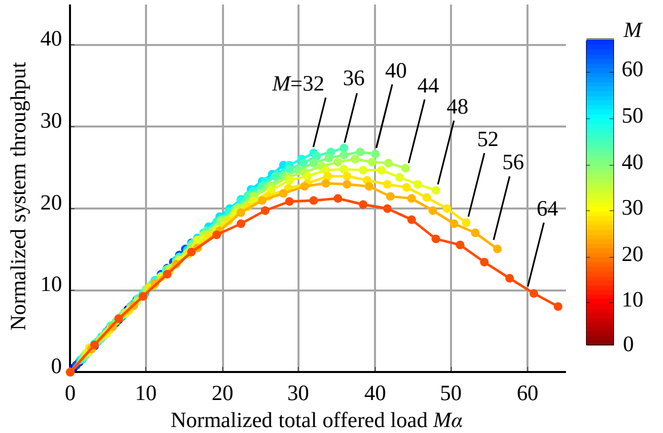



Fig. 7. Throughput performance without backoff scheme.

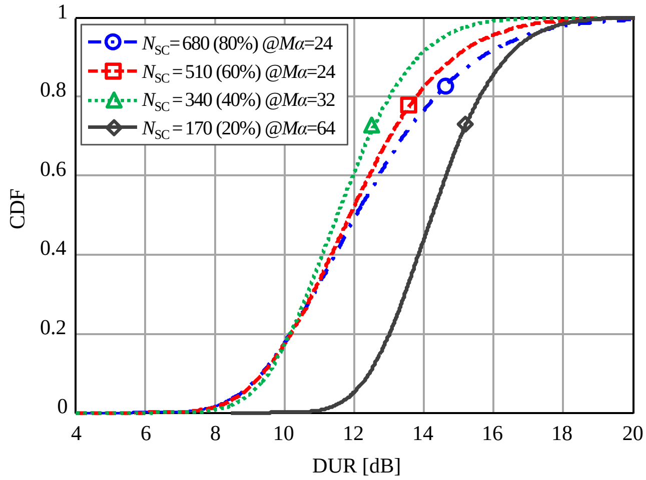



Fig. 8. Active subcarrier detection probability ($M$ = 64).

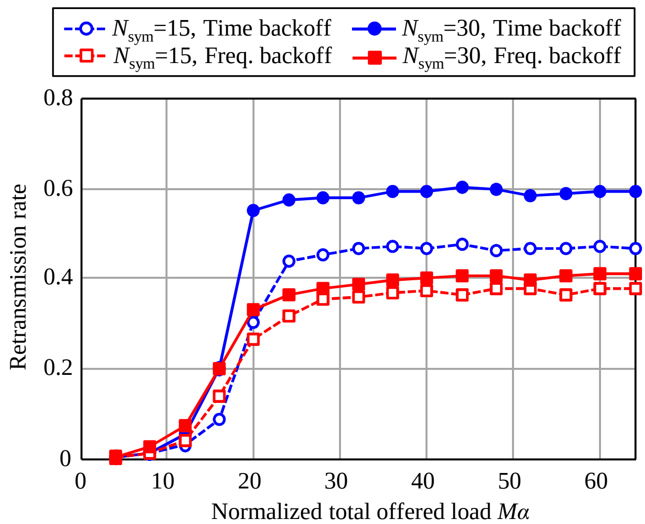



Fig. 9. Retransmission rate ($N_{sym}$ = 15, 30).

in the previous work [13] but it contains more detailed PHY and MAC layers' behaviors. We can verify its validity. When $M\alpha$ is up to around 16, system throughput increases linearly since satisfactory SIR is obtainable. $M\alpha$ = 32 almost takes a maximal value irrespective of CB number, $M$. It indicates that the system has the capability of 32 SDM order in this case and preferable number of CBs is 32 or less. Of course it can be further enhanced by increasing the number of EBS antenna elements. Excessive increase in offered load for large $M$ raises collision probability which deteriorates SIR performance and signal detection accuracy. This effect can be seen over the peaks in the figure. Increase of CB number implies physical circuit scale expansion, therefore, $M$ should be optimized based on allowable SDM order. From the result, we can design fundamental system parameters through the number of CB, EBS antenna elements, and target system throughput.

Lost transmitted packets due to the excessive spatial multiplexing should be retransmitted. Backoff scheme, which equivalently controls the value of $\alpha$, is then introduced to prevent system throughput degradation in such overloaded situation. Following evaluation discusses its effectiveness in terms of retransmission rate, system throughput and average delay.

### C. Active Subcarrier Detection Probability

Here arises an issue in the frequency domain backoff; EBS should detect the location of active subcarriers since RSs autonomously/dynamically control them. We focused on the fact that the signal reception level of active subcarriers is expected to be large enough due to the EGC whereas that level of inactive ones is the result of random combining and is feeble. Therefore, large level discrepancy can be observed and this feature can be exploited for active subcarrier detection at the EBS without any control signaling. The second evaluation confirms its possibility. Fig. 8 shows cumulative distribution functions (CDFs) of desired-to-undesired signal power ratio (DUR). It is the reception signal power ratio between the active and inactive subcarriers at the CB number $M$ = 64. Result plots some cases of the number of active subcarriers, $N_{SC}$, and normalized offered loads, $M\alpha$, upon the frequency domain backoff successfully works. When $N_{SC}$ = 680 and 510 at saturated throughput region ($M\alpha$ = 24), we can obtain DUR > 7 dB at CDF= 1% region. It certainly indicates the possibility of active subcarriers detection. Even limiting the number of active subcarriers according to the increase of offered load, obtainable DURs are still useful.

EBS continuously applies EGC beamforming weight, therefore, EBS can make sure that detected active subcarrier is always from the designated RS. In other words, EGC strengthens only the desired signal regardless of what are signals from other RSs and what are active/inactive subcarriers. Result disclosed in Fig. 8 indicates that EBS only does receive the signal of active subcarriers in valuable strength and it is always the desired one.

### D. System Throughput and Average Delay

Fig. 9 examines the retransmission rate characteristics on the time and frequency domain backoff schemes with two cases of packet length as $N_{sym}$ = 15 and 30, respectively.

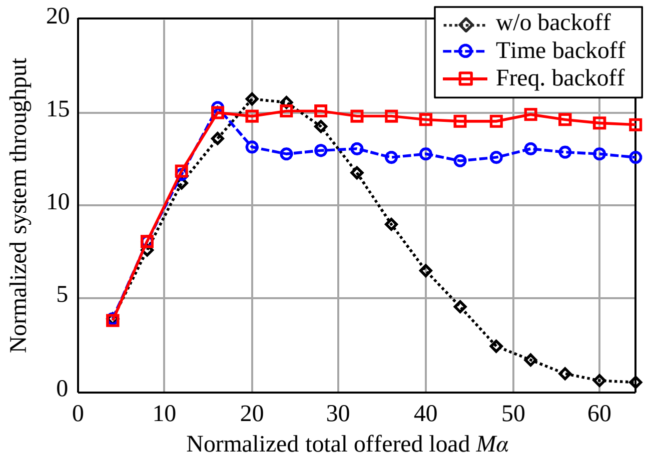



Fig. 10. System throughput performance with backoff scheme ($N_{sym}$ = 30).

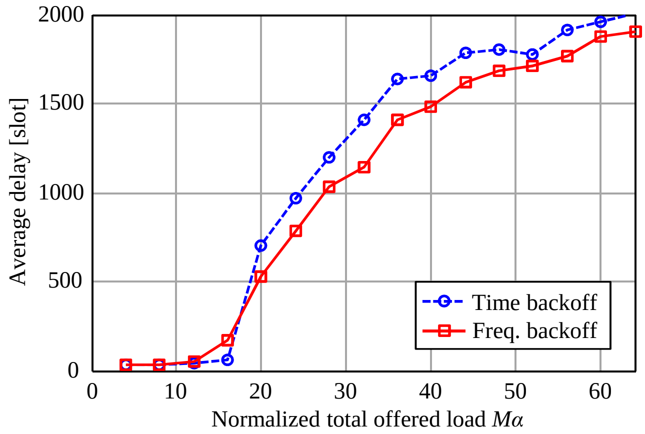



Fig. 11. Average delay performance ($N_{sym}$ = 30).

The maximum backoff values for the time domain approach in (1), $N_{max}$ (slots), are set to $N_{max}$ = 20 for $N_{sym}$ = 15 and $N_{max}$ = 30 for $N_{sym}$ = 30, respectively. As seen by the figure, the retransmission rate of the time domain backoff is raised by enlarging the packet length from 15 to 30. Meanwhile, that increasement of the proposed frequency domain backoff is lower than the time domain one and is almost independent to packet length. Following evaluations focus on performances of $N_{sym}$ = 30 with forecasting long packetization from the viewpoint of MAC efficiency.

Figs. 10 and 11 plot normalized system throughput and average packet delay performances versus offered load, respectively. Fig. 10 also includes the result without backoff control. We can observe superiority of the frequency domain backoff in both metrics. Introducing backoff scheme can avoid deterioration of throughput even over the overloaded situation and the proposed scheme can keep the peak value. Backoff control imposes excessive time slots for completion of packet transmission. In the overloaded situation, the time domain backoff requires more awaiting time to effectively avoid collision whereas the frequency domain backoff can alleviate such impact. Additionally, FEC is considered to contribute to mitigating IUI impact. Unlike the time domain backoff where all subcarriers are interfered with one another, IUI in the frequency domain backoff affects specific active subcarriers. There exist subcarriers less affected by IUI and these accuracies can compensate for erroneous component of other subcarriers. Although this evaluation employed the rate 1/2 convolutional code, any type of FEC codes, e.g. Turbo, LDPC and Polar codes, are applicable.

We can understand that the frequency domain backoff is able to directly track the fluctuation of offered traffic by controlling the number of active subcarriers. On the other hand, the time domain backoff is means to avoid collision temporarily and hence it has difficulty to thoroughly adjust the possible SDM order. Furthermore, its parameter optimization such as $N_{max}$ strongly depends on the packet duration which practically has variety for each application or requirement. The proposed scheme can exclude such parameter optimization and can achieve stably improved performances with simplified operation. These features also precisely contribute to MAC delay performance improvement as shown in Fig. 11.

Meanwhile, throughput performance per RS directly depends on the number of active subcarriers. Therefore if decreasing the active subcarriers according to the backoff function, the datarate for the corresponding RS is also decreased. Main objective of this paper is to maintain the maximally achievable system throughput even at the overloaded situation. The computer simulation results confirmed that the objective of this study has been accomplished.

### *E. Packet Loss Rate*

Finally, Fig. 12 shows the packet loss rate performance with offered load. The time domain backoff is suffered from unavoidable retransmission and it results in increased packet loss rate. It unfortunately affects on effective delay enlargement triggered by a retransmission at the upper layer such as transmission control protocol (TCP). The proposed frequency domain backoff can keep significantly reduced packet loss rate almost zero. It can guarantee a reliable communication with reduced delay and better throughput performances. Above results verified effectiveness of the proposed frequency domain backoff scheme which can realize simplification of system design as well as stable operation.

### *F. Discussion*

Evaluations so far employed a fixed modulation order of 16QAM. Adaptive modulation and coding (AMC) is expected to further improve the robustness in the system of interest. It is because acceptable SIR can be decreased which means the possible SDM order can be increased. Generally, spatial multiplexing can better contribute to enhance the transmission capacity rather than raising bit rate per stream. Although it will depend on adopted modulation order and coding rate, overall system throughput performance is expected to be improved.

The proposed approach including CB-SDMA can be technically applied to the mobile access scenario. Although the MAS-WE in this study assumed the use of 5.2 GHz band, it

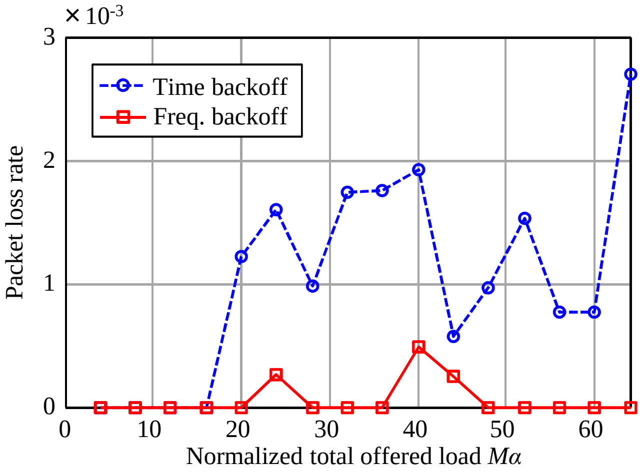



Fig. 12. Packet loss rate ($N_{sym}$ = 30).

can cover several kilometer radius by exploiting massive array combining gain. For instance, achievable coverage with 128 elements each of which radiates 12 dBm power (33.1 dBm in total) is 3 km radius or more. The preliminary study [7] disclosed its spatial multiplexing performance. Therefore this system configuration and schemes can be applied to the mobile access scenario with macro cells and can be expected to provide a large system capacity better than the current cellular system.

## VI. Conclusion

This paper proposed the frequency domain backoff scheme for CB-SDMA structured massive MIMO wireless backhaul systems. CB provides virtual point-to-point links between EBS and RSs via EGC based beamformng. Resource management is entrusted to RSs with distributed coordination function. It can simplify complicated MAC and pre/postcoding overheads of EBS while achieving good system throughput performance. There exists an acceptable CB number that can maximize the system throughput performance. Although overloaded spatial multiplexing deteriorates throughput, it can be avoided by the backoff control. The proposed frequency domain backoff flexibly controls the number and allocation of active subcarriers to autonomously optimize the spatial multiplexing order with satisfying SIR requirement. Computer simulation exhibited superior performance of the proposed scheme compared to the conventional time domain backoff in terms of system throughput, average delay and packet loss. The proposed scheme can be one of the most promising means to contribute to simplification of large scale MIMO communication systems.

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