A Distributed Interference Management for Crowded WLANs: Opportunistic Interference Alignment

Hu Jin, Bang Chul Jung[†], Jinhyung Oh[*], and Myungsun Song[*]
Dept. Electronics and Communication Engineering, Hanyang University, Ansan, Korea
[†]Dept. Information and Communication Engineering, Gyeongsang National University, Tongyeong, Korea,
[*]Broadcasting and Telecommunications Media Research Laboratory, ETRI, Daejeon, Korea,
Email: hjin@hanyang.ac.kr, [†]bcjung@gnu.ac.kr, [*]{jinhyung, mssong}@etri.re.kr

***Abstract*—Wireless local area networks (WLANs) are becoming denser and thus interference-limited due to heavy traffic from a number of adjacent access points (APs) and stations (STAs). We propose a novel interference management technique for overlapping basic service sets (OBSSs) in such WLANs, which intelligently applies an *opportunistic interference alignment (OIA)* concept to WLANs. Each BSS has an AP and multiple STAs, and operates with a carrier sensing multiple access (CSMA) protocol as commercial IEEE 802.11 WLANs. Both APs and STAs are assumed to have multiple antennas. Specifically, the proposed OIA framework consists of physical (PHY) and medium access control (MAC) layer techniques: transmit beamforming and opportunistic medium access, respectively. First, each STA performs transmit beamforming which minimizes generating interference to other BSSs at the PHY layer. Second, each STA sends packets to its serving AP only when its generating interference to other BSSs is smaller than a pre-determined threshold at the MAC layer. Through extensive simulations, we show that proposed OIA scheme significantly outperforms existing schemes in terms of system throughput. Note that the OIA scheme operates with a *distributed* manner based on local channel state information at each STA and does not require any coordination among BSSs, leading an easier implementation in practice.**

***Index Terms*—WLANs, Interference alignment, CSMA, IEEE 802.11ax, beamforming**

I. INTRODUCTION

IEEE 802.11 wireless local area networks (WLANs) have been widely deployed due to simplicity and efficiency, and most wireless service providers increase investment to extend their public WLAN service areas for offloading cellular data. As a result, a new WLAN standard is being investigated in order to improve spectral and power efficiency in both indoor and outdoor environments, which is named IEEE 802.11ax [1]. Many technologies are being considered such as advanced multiple input multiple output (MIMO), massive MIMO, multi-user MIMO (MU-MIMO) in both downlink and uplink, hybrid automatic repeat request (HARQ), various multiplexing schemes, interference management, in-band full-duplex MIMO, advanced medium access control (MAC) protocols, etc. Among them, the interference management becomes one of the most important techniques since WLANs are expected to be more crowded due to a number of adjacent access points (APs) and stations (STAs) [2].

On the other hand, there has been a lot of effort on characterizing capacity of interference channels in terms of degree-of-freedom (DoF) which is also known as multiplexing gain. Especially, interference alignment (IA) has received much attention because of its capability of achieving the optimal DoF in interference channels [3]. Subsequent studies have shown that IA is also useful in various wireless multi-user networks including MIMO interference channels and cellular networks. In particular, the IA techniques applied to cellular networks have received much attention [4], [5] while they have also practical challenges such as arbitrarily large frequency/time-domain symbol extension [4] or limited number of operating cells [5]. A novel concept of IA called *opportunistic IA (OIA)* was recently proposed for cellular networks, which intelligently combines opportunistic user scheduling and IA techniques [6]–[10]. OIA was shown to asymptotically achieve the optimal DoF if the number of users in a cell is beyond a certain value, i.e., if a certain user scaling condition is guaranteed.

The existing IA techniques proposed for cellular networks are centrally controlled by base stations and, hence, suitable modifications on the IA techniques are needed for their applications to random access networks (RANs) such as WLANs. The IA techniques were applied for RANs under two mechanisms: point coordinated function (PCF) [11] and distributed coordinated function (DCF) [12]. In [11], APs are assumed to exchange a certain information through (wired) backbone network in order to realize IA while such a wired backbone may not exist in practice. The IA technique proposed in [12] is applicable only when STAs have different number of antennas, and the performance gain is limited when STAs have similar number of antennas. It was shown that the IA technique can achieves the optimal average DoF in a single RAN [13]. However, the interference among overlapping RANs was not considered. The application of OIA in slotted ALOHA systems was investigated in [14].

In this paper, we propose a novel OIA technique to reduce the interference among overlapping WLANs which operate under DCF mechanism with carrier sense multiple access (CSMA). It was shown that the p-persistent CSMA systems successively emulates the commercial IEEE 802.11 WLAN systems [15], and thus we model the WLANs with the p-persistent CSMA protocol. Specifically, the proposed OIA framework consists of physical (PHY) and MAC layer techniques: transmit beamforming and opportunistic medium access, respectively. Therefore, the proposed OIA can be regarded as a cross-layer solution for the CSMA systems. Note that the proposed OIA significantly outperforms the existing schemes in terms of system throughput even if it operates under a distributed manner and does not require any coordination among APs.

II. SYSTEM MODEL

We consider an uplink CSMA system consisting of K geometrically overlapping basic service sets (OBSSs). Hence, the communication behavior of each BSS may interfere the others due to the broadcasting nature of the wireless channel. In each BSS, N STAs are communicating with an AP where each STA has L antennas to transmit signals which are received by M antennas at each AP. The time is equally divided by σ-duration sensing slots when there is no packet transmission from all STAs in the OBSSs while the packet transmissions occupy the time duration of T if there exists at least one STA's transmission. At each slot, each STA transmits a packet to its serving AP with a probability p, while keeping silence with a probability $1-p$. Due to the random access, there inevitably happens simultaneous transmissions from multiple STAs. Note that the simultaneously transmitting STAs may be served in different BSSs.

Let $H_k^{[i,j]} \in C^{M\times L}$ denote the channel matrix from STA j in the i-th BSS to AP k (in the k-th BSS) where $i,k \in \{1,...,K\}$ and $j \in \{1,...,N\}$. Then, provided that there exist at least one STAs' packet transmissions in the OBSSs, the received signal at AP k, $\mathbf{y}_k \in \mathbb{C}^{M\times 1}$, is expressed as

$$\mathbf{y}_k = \sum_{i=1}^{K}\sum_{j=1}^{N}\mathbf{H}_k^{[i,j]}\mathbf{w}^{[i,j]}x^{[i,j]}I^{[i,j]} + \mathbf{n}_k, \tag{1}$$

where $I^{[i,j]} \in \{0,1\}$ is the indicating function of the activity of STA j in the i-th BSS. $I^{[i,j]}$ becomes zero if the STA is silent while becoming one if the STA is transmitting packets. Therefore, we have $\Pr\{I^{[i,j]}=1\}=p$. Note that the number of active STAs may vary slot by slot due to the random access. Assuming that each STA transmits a single stream, $x^{[i,j]} \in \mathbb{C}$ denotes the information stream of STA j in the i-th BSS while $\mathbf{w}^{[i,j]}$ denotes its beamforming vector. $\mathbf{n}_k \in \mathbb{C}^{M\times 1}$ represents the additive Gaussian noise at AP k. Each AP periodically transmits training signals so that each STA can estimate the *local* channel gains to the K APs based on the reciprocal property of the wireless channel. Note that STA i in the j-th BSS only knows $\mathbf{H}_k^{[i,j]}$ for $k \in \{1,...,K\}$ but not the channel gains between other STAs and APs.

III. MULTI-PACKET RECEPTION

Even in a single BSS environment, the collision mitigation among STAs is always a key research issue in designing the random access based CSMA systems. It is known that multi-packet reception (MPR), which is generally implementable with MU-MIMO techniques, is an efficient solution [16]. If each STA transmits a single stream, each AP is able to support maximally M STAs' simultaneous transmissions. When it comes to the OBSSs where the M STAs may be served in different BSSs, the MPR is still valid and each AP is capable of decoding the M streams while it is only interested in the transmissions from the STAs in its BSS. Then, under the p-persistent protocol, the average throughput of the all OBSSs can be obtained as

$$R_{\mathrm{MPR}} = \frac{\sum_{i=1}^{M} mp^m(1-p)^{NK-m}P_{m,M}^{\mathrm{MPR}}}{(1-p)^{NK}\sigma + [1-(1-p)^{NK}]T}, \tag{2}$$

where $P_{m,M}^{\mathrm{MPR}}$ denotes each packet's success probability when there exist m STAs' simultaneous transmissions in the OBSSs. Note that in the right hand side of (2), the numerator is the average number of success packets in each slot while the denominator is the average slot duration. In practice, $P_{m,M}^{\mathrm{MPR}}$ is a function of m and M and decreases as m increases or M decreases due to the reduced DoF. For the analytical expression of $P_{m,M}^{\mathrm{MPR}}$ with Rayleigh fading channels, interested readers may refer [16], [17].

IV. INTERFERENCE NULLING

In this section, we propose an interference nulling (IN) scheme which is designed on top of MPR. First, each AP defines S-dimensional signal space to receive signals from the STAs in its BSS. Hence, the beamforming vector $\mathbf{w}^{[i,j]}$ is designed to make each transmitting STA's signals arriving at the signal spaces of the other APs be zero so that inter-BSS-interference could be eliminated. Let $\mathbf{U}_k = [\mathbf{u}_{k,1},...,\mathbf{u}_{k,S}]$ be the matrix utilized by the k-th AP to extract the signals at the S-dimensional space. Note that $\mathbf{u}_{k,l} \in \mathbb{C}^{M\times 1}$ for $l \in \{1,2,...,S\}$ is orthogonal to each other and $\|\mathbf{u}_{k,l}\|^2 = 1$. Then, $\mathbf{w}^{[i,j]}$ should satisfy

$$\begin{aligned}&\Big[\left(\mathbf{U}_1^H\mathbf{H}_1^{[i,j]}\right)^T, \cdots, \left(\mathbf{U}_{i-1}^H\mathbf{H}_{i-1}^{[i,j]}\right)^T, \left(\mathbf{U}_{i+1}^H\mathbf{H}_{i+1}^{[i,j]}\right)^T,\\ &\cdots, \left(\mathbf{U}_K^H\mathbf{H}_K^{[i,j]}\right)^T\Big]^T \mathbf{w}^{[i,j]} = 0.\end{aligned} \tag{3}$$

Due to the limited number of antennas at the STAs, the dimension of the signal space at each AP S should satisfy the following constraint so that (3) has solutions:

$$S < \min\left\{\frac{L}{K-1}, M\right\}. \tag{4}$$

One interesting property of IN is that it can inherit the advantage of MPR. Let $s_i \doteq \sum_{j=1}^{N} I^{[i,j]}$ and $s \doteq \sum_{i=1}^{K} s_i$ where $I^{[i,j]} \in \{0,1\}$ is the indicating function of the activity of STA j in the i-th BSS as defined in Section II. Then the MPR capability shows the following two usages in IN.

1) If $s < M$, all the APs can perform MPR and subtracts the signals designed to it.
2) If $s_i < S$, the i-th AP can decode the signals from the s_i STAs in its BSS. Note that the number of simultaneously STAs in other BSSs $s - s_i$ does not affect the i-th AP's decoding performance as their arriving signals are zero.

However, if $s > M$ and $s_i > S$, the i-th AP is hard to decode the the arriving signals due to the limited available DoF. Reflecting those phenomena, the average throughput of IN can be expressed as follows:

$$\begin{aligned} R_{\mathrm{IN}} &= K \cdot \left\{ \sum_{m=1}^{S} m \binom{N}{m} p^m (1-p)^{N-m} P_{m,S}^{\mathrm{MPR}} \right. \\ &+ \sum_{m=S+1}^{M} m \cdot \binom{N}{m} p^m (1-p)^{N-m} \cdot \\ &\left. \left[\sum_{j=0}^{M-m} \binom{N(K-1)}{j} p^j (1-p)^{N(K-1)-j} P_{m+j,M}^{\mathrm{MPR}} \right] \right\} \\ &/ \left\{ (1-p)^{NK} \sigma + [1-(1-p)^{NK}] T \right\}, \end{aligned} \tag{5}$$

where $P_{m,S}^{\mathrm{MPR}}$ denotes the packet success probability when there are m STAs' simultaneous transmissions while each AP sets S-dimensional signal space to receive signals. In the bracket of the numerator in (5), the first summation shows the average number of success packets decoded from the S-dimensional signal space of each AP while the second summation shows the number of success packets obtained by the MPR decoding with the AP's M available spaces. The denominator still shows the average slot duration. It should be noted that the proposed IN has limited applications due to the constraint as shown in (4).

V. OPPORTUNISTIC INTERFERENCE ALIGNMENT

The constraint shown in (4) limits the application of IN in practice. To overcome this drawback, in this section we propose OIA which consists of two parts: the singular value decomposition (SVD)-based beamforming at the physical layer shown in Section V-A and the opportunistic transmission mechanism at the MAC layer shown in Section V-B. Specifically, the SVD-based beamforming minimizes each STA's interference to other BSSs while the opportunistic transmission mechanism allows the STAs showing relatively small interference other BSSs to transmit in each slot.

A. SVD-based Beamforming

As IN, each AP still sets S-dimensional signal space to receive signals transmitted from the STAs. However, in stead of perfectly nulling the interference to other BSSs, the STAs perform the SVD-based Beamforming to minimize the amount of interference to other BSSs. Again, let $\mathbf{U}_k = [\mathbf{u}_{k,1}, ..., \mathbf{u}_{k,S}]$ be the matrix utilized by the k-th AP to extract the signals at the S-dimensional space.

For STA j in the i-th BSS, the SVD-based beamforming is performed as follows: First, it constructs the channel matrix $\mathbf{G}^{[i,j]}$ which interferes the signal spaces of other APs as follows:

$$\begin{aligned} \mathbf{G}^{[i,j]} = & \left[\left(\mathbf{U}_1^H \mathbf{H}_1^{[i,j]} \right)^T, \cdots, \left(\mathbf{U}_{i-1}^H \mathbf{H}_{i-1}^{[i,j]} \right)^T, \right. \\ & \left. \left(\mathbf{U}_{i+1}^H \mathbf{H}_{i+1}^{[i,j]} \right)^T, \cdots, \left(\mathbf{U}_K^H \mathbf{H}_K^{[i,j]} \right)^T \right]^T. \end{aligned} \tag{6}$$

Second, it performs SVD for $\mathbf{G}^{[i,j]}$,

$$\mathbf{G}^{[i,j]} = \mathbf{\Omega}^{[i,j]} \mathbf{\Sigma}^{[i,j]} \mathbf{V}^{[i,j]}, \tag{7}$$

where $\mathbf{\Omega}^{[i,j]}$ and $\mathbf{V}^{[i,j]}$ are unitary matrices and $\mathbf{\Sigma}^{[i,j]}$ is a diagonal matrix whose elements in the diagonal are the singular values.

In order to minimize the interference to other APs' signal space, the beamforming vector is chosen to the one corresponds to the minimum singular value, i.e.,

$$\mathbf{w}_{\mathrm{SVD}}^{[i,j]} = \arg \min_{\mathbf{v}} \left\| \mathbf{G}^{[i,j]} \mathbf{v} \right\|^2 = \mathbf{v}_L^{[i,j]}. \tag{8}$$

Note that such Beamforming minimizes the interference generated by each STA. When $S < \frac{L}{K-1}$, this beamforming makes the interference signals be zero. Thus, the proposed OIA is indistinguishable from IN. Moreover, when $S \geq \frac{L}{K-1}$, the STAs' transmissions may cause interference to the packet receptions at other APs. We call such interference as leakage interference (LIF). Such interference may reduce the successful decoding probability at the APs. In the next section, we will introduce an opportunistic transmission mechanism to further reduce the effect of LIF on packet receptions. It should be noted that the constraint shown in (4) does not apply to OIA.

B. Opportunistic transmission mechanism

In this section, we propose an opportunistic transmission mechanism to further reduced each STA's interference to other BSSs at the MAC layer. Different from conventional opportunistic transmissions in random access networks which aim to maximize the signal strength received at the AP [18], the proposed mechanism applies the opportunism based on the interference to other cells.

We first define the amount of LIF as follows:

$$\eta^{[i,j]} = \sum_{k=1, k \neq i}^{K} \left\| \mathbf{H}_k^{[i,j]} \mathbf{w}_{\mathrm{SVD}}^{[i,j]} \right\|^2, \tag{9}$$

where $\mathbf{w}_{\mathrm{SVD}}^{[i,j]}$ is obtained from (8). Each STA observes LIF for a long time to store the corresponding cumulative distribution function (CDF) as a lookup table. In each time slot, based on the channel estimation and the CDF table, each STA calculates its LIF value and, then, finds the corresponding CDF value. If the CDF value is smaller than p, it transmits packets. As the CDF values are uniformly distributed in [0, 1][1], the transmission probability still remains as p. A smaller p means a smaller LIF and, therefore, results in a higher successful decoding probability at the APs.

Let $P_{m,j}^{\mathrm{OIA}}$ denote the packet success probability each AP when there are m STAs' simultaneous transmissions in its BSS while there exists j more STAs' transmissions in the

---

[1] Note that it is not an assumption. Any CDF of a continuous random variable has the value in the range [0, 1] and is uniformly distributed.

other BSSs. Then, the average throughput can be expressed as

$$
\begin{aligned}
R_{\mathrm{OIA}} = K \cdot \Bigg\{ & \sum_{m=1}^{M} m \cdot \binom{N}{m} p^{m} (1-p)^{N-m} \cdot \\
& \left[\sum_{j=0}^{M-m} \binom{N(K-1)}{j} p^{j} (1-p)^{N(K-1)-j} \cdot P^{\mathrm{MPR}}_{m+j,M} \right] \\
& + \sum_{m=1}^{S} m \cdot \binom{N}{m} p^{m} (1-p)^{N-m} \cdot \\
& \left[\sum_{j=M-m+1}^{N(K-1)} \binom{N(K-1)}{j} p^{j} (1-p)^{N(K-1)-j} \cdot P^{\mathrm{OIA}}_{m,j} \right] \Bigg\} \\
& / \left\{ (1-p)^{NK} \sigma + [1-(1-p)^{NK}] T \right\} .
\end{aligned}
\tag{10}
$$

In the bracket of the numerator in (10), the first summation shows the average number of success packets from the MPR decoding with all M available spaces of each AP while the second summation shows the average number of success packets observed from the S-dimensional signal space when the total number of simultaneous transmissions is larger than M. The denominator is the average slot duration. Compared to IN, the proposed OIA has no constraint as (4).

VI. PERFORMANCE EVALUATION

We consider a network scenario that consists of $K = 3$ OBSSs each of which has $N = 10$ STAs and one AP. The APs and the STAs are all have 3 antennas, i.e., $M = L = 3$. All the STAs are assumed to show the average received signal-to-noise ratios (SNRs) of 0 dB at APs, i.e. interference limited scenario. The APs perform zero-forcing (ZF) MIMO decoding to receive signals. The successful packet decoding is assumed whenever the received signal-to-interference-plus-noise ratio (SINR) exceeds the threshold of 0 dB. The channel is Rayleigh fading and the channel gain is independently changed to another value for each packet transmission. For the proposed OIA, each STA performs the SVD-based beamforming in each slot and transmits its packet based on the opportunistic transmission mechanism. Due to the random access of p-persistent protocol, the number of interfering STAs varies slot by slot and it also affects the packet decoding behavior at the APs. We performed simulations with MATLAB and examined the performance by observing more than 10^5 T. Otherwise specified, the sensing duration is set to $\sigma = 0.05$ while the packet transmission time is set to $T = 1$.

Fig. 1 shows the cross-layer average throughput performance by varying the transmission probability p. We can observe that OIA shows much better performance than other schemes while MPR shows the worst. By varying p, we can observe that there exists optimal value that maximizes the throughput for each scheme. OIA tends to achieve the maximum with a larger p as it can accommodate more simultaneous transmissions in OBSSs. For OIA, three cases of $S = 1, 2, 3$ are considered and the setting of $S = 3$ shows the best performance. The maximum throughput of OIA with $S = 3$ is 2.005 packets/T while that of MPR is 1.045 packets/T. Hence, OIA can enhance the throughput by 91.9% compared to MPR in the sce nario considered.

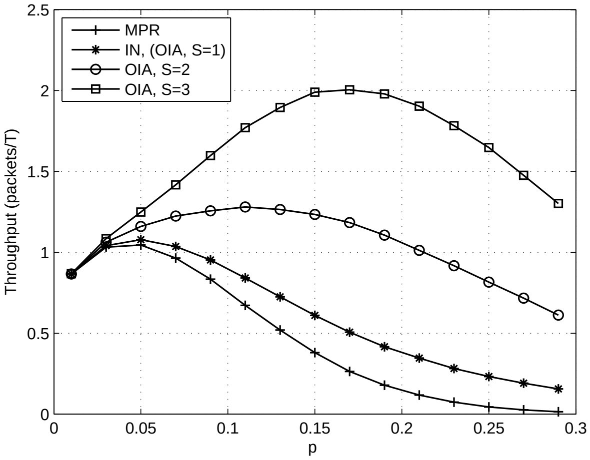

Fig. 1. Throughput over p.

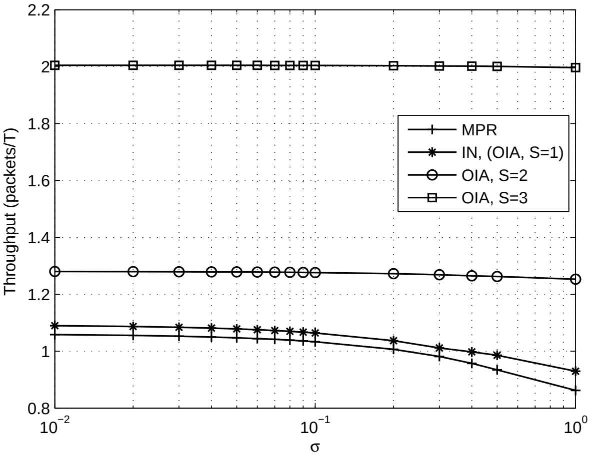

Fig. 2. Throughput over σ.

Fig. 2 shows the maximum cross-layer average throughput performance by varying the sensing slot size σ. Each symbol in fig. 2 is obtained by numerically searching the maximum throughput over all possible p values. As expected, the throughput decreases as σ increases for all the schemes. However, the throughput of OIA with a larger signal space (e.g. $S = 3$) is insensitive to σ. Due to the large transmission probability which results in the maximum throughput with OIA, the channel is always busy as $(1-p)^{NK}$ is quite small and, consequently, the size of σ shows less effect on the throughput performance as shown by (2), (5) and (10). In contrast, the throughput of MPR largely depends on the size of the sensing duration.

To investigate the effect of the SVD-based beamforming and the opportunistic transmission mechanism individually, we consider two schemes which only reflects one of the two functions: OIA without transmit beamforming (OIA w/o BF) and OIA without the opportunistic transmission (OIA w/o OT). Fig. 3 shows the average throughput over varying the

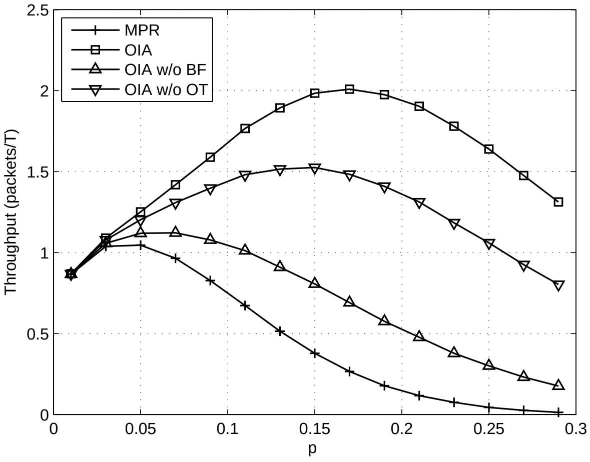

Fig. 3. Cross layer throughput over p.

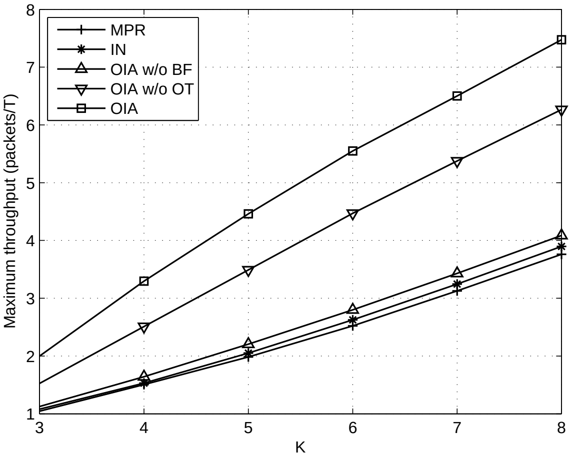

Fig. 4. Throughput over K.

transmission probability. The size of signal space is set to $S = 3$. The maximum throughput of ‘OIA w/o BF’ is 1.1217 packets/T while that of ‘OIA w/o OT’ is 1.5253 packets/T. Hence, we can conclude that the transmit beamforming has a larger impact in enhancing the throughput performance. Compared to MPR, ‘OIA w/o BF’ shows 7% enhancement while ‘OIA w/o OT’ shows 46.0%. However, OIA further improves the throughput of ‘OIA w/o BF’ by 31.5% from which we can observe the synergy between the transmit beamforming and the opportunistic transmissions.

Fig. 4 shows the maximum average throughput over the number of OBBSs K where we set $S = M = L = K$. The maximum throughput is obtained by numerically searching all possible p values. We can still observe that the adoption of the opportunistic transmission only brings small throughput enhancement compared to MPR while the effect of the transmit beamforming is significant. Moreover, the opportunistic transmission can magnify the effect of transmit beamforming in reducing inter-BSS-interference.

VII. CONCLUSION

In this paper, we proposed a novel opportunistic interference alignment scheme for OBSSs with p-persistent CSMA protocol. First, OIA applies the SVD-based beamforming to minimize each transmitting STA’s interference to other BSSs at the physical layer. Second, OIA further reduces the amount of interference by opportunistically allowing the transmissions of the STAs who show relatively small interference to other BSSs at the MAC layer. Through extensive simulations, it was shown that the proposed OIA protocol significantly outperforms the conventional schemes in terms of system throughput even if it operates with a distributed manner.

ACKNOWLEDGMENT

This work was supported by ICT R&D program of MSIP/IITP [B0101-15-1272, Development of Device Collaborative Giga-Level Smart Cloudlet Technology] and [12-921-01-301, Short Range Wireless Transmission Technology with Robustness to Radio Interferences].

REFERENCES

[1] http://www.ieee802.org/11/PARs/P802.11ax.pdf

[2] E. Perahia, *et al.*, “High efficiency WLAN overview,” *IEEE 802.11-14/0214r2*, Feb. 2014.

[3] S. A. Jafar and M. J. Fakhereddin,“ Degrees of freedom for the MIMO interference channel,” *IEEE Trans. on Inf. Theory*, vol. 53, no. 7, pp. 2637-2642, Jul. 2007.

[4] C. Suh and D. N. C. Tse, “Interference alignment for cellular network,” Allerton Conference on Communciation, Control and Computing, pp. 1037-1044, 2008.

[5] C. Suh, M. Ho, and D. N. C. Tse, “Downlink interference alignment,” *IEEE Trans. Commun.*, vol. 59, no. 9, pp. 2616-2626, Sep. 2011.

[6] B. C. Jung and W.-Y. Shin, “Opportunistic interference alignment for interference-limited cellular TDD uplink, *IEEE Communications Letters*, vol. 15, no. 2, pp. 148-150, Feb. 2011.

[7] B. C. Jung, D. Park, and W.-Y. Shin, ”Opportunistic interference mitigation achieves optimal degrees-of-freedom in wireless multi-cell uplink networks,” *IEEE Trans. Commun.*, vol. 60, no. 7, pp. 1935-1944, Jul. 2012.

[8] H. J. Yang, W.-Y Shin, B. C. Jung, and A. Paulraj, “Opportunistic interference alignment for MIMO interfereing multiple-access channel,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2180-2192, May 2013.

[9] H. J. Yang, W.-Y. Shin, B. C. Jung, C. Suh, and A. Paulraj, “Opportunistic downlink interference alignment,? *preprint*, [Online]. Available: http://arxiv.org/abs/1312.7198.

[10] H. J. Yang, B. C. Jung, W.-Y Shin, and A. Paulraj, “Coodbook-based opportunistic interference alignment,” *IEEE Trans. Signal Process.*, vol. 62, no. 11, pp. 2922-2937, Jun. 2014.

[11] S. Gollakota, S. D. Perli, and D. Katabi, “Interference alignement and cancellation,” *SIGCOMM2009*, pp. 159-170, 2009.

[12] K. C.-J. Lin, S. Gollakota, and D. katabi, “Random access heterogeneous MIMO network,” *SIGCOMM2011*, pp. 146-147, 2011.

[13] V. Pourahmadi, A. S. Motahari, and A. K. Khandani, “Degrees of freedom of MIMO-MAC with random access,” *IEEE Trans. Commun.*, vol. 61, no. 5, May 2013.

[14] H. Jin, S.-W. Jeon, and B. C. Jung, “Opportunistic interference alignment for random access networks,” *IEEE Trans. Veh. Tech.* (To appear).

[15] J.-B. Seo, H. Jin, and Victor C. M. Leung, “Throughput upper-bound of slotted CSMA systems with unsaturated finite population,” *IEEE Trans. Commun.*, vol. 61, no. 6, pp. 2477-2487, Jun. 2013.

[16] H. Jin, B. C. Jung, H. Y. Hwang, and D. K. Sung, “A MIMO-based collision mitigation scheme in uplinnk WLANs,” *IEEE Commun. Lett.*, vol. 12, no. 6, pp. 417-419, Jun. 2008.

[17] H. Jin, B. C. Jung, and D. K. Sung, “A tradeoff between single-user and multi-user MIMO schemes in multi-rate uplink WLANs,” *IEEE Trans. Wireless Commun.*, vol. 10, no. 10, pp. 3332-3342, Oct. 2011.

[18] C.-S Hwang and J. M. Cioffi, “Opportunistic CSMA/CA for achieving multi-user diversity in wireless LAN, *IEEE Trans. Wireless Commun.*, vol. 8, no. 6, pp. 2972-2982, Jun. 2009.