Multi-user massive MIMO for next-generation WLAN systems

Kyung Jun Kim, Kyung Jun Choi, Seong Ro Lee and Kwang Soon Kim✉

An efficient multi-user multiple-input–multiple-output (MIMO) protocol is proposed and verified to be significantly advantageous over the conventional IEEE 802.11ac protocol for next-generation wireless local area network systems employing massive MIMO and orthogonal frequency division multiple access.

Introduction: In the IEEE 802.11ac wireless local area network (WLAN) systems [1], multi-user (MU) multiple-input–multiple-output (MIMO) is one of the key technologies to enhance the throughput, which is expected to be extended to equip more antennas at an access point (AP) to provide more layers (or streams) for next-generation WLAN systems such as IEEE 802.11ax or beyond. However, the preamble and feedback overhead linearly increase as the number of antennas increases in the conventional MU-MIMO protocol for the current WLANs [1] and it will be non-negligible as next-generation WLAN systems employ massive MIMO schemes. In this Letter, an efficient MU-MIMO protocol is proposed for next-generation WLAN systems employing massive MIMO, in which multiplexing (MUX) groups for pilot signal MUX and simultaneous feedback are performed by an AP among users in each MU-MIMO user group to achieve higher efficiency. Moreover, the long training field (LTF) demultiplexing scheme at each station (STA) and the joint feedback detection scheme at AP considering the orthogonal frequency division multiple access (OFDMA) operation among the APs are proposed [2].

Proposed MU-MIMO protocol: Consider a downlink (DL) MU-MIMO protocol using OFDMA at the existence of legacy STAs for next-generation WLAN systems, where the AP and each STA are, respectively, equipped with N_T and N_R antennas. To enhance channel utilisation efficiency, an AP constructs user groups among non-legacy STAs, performs a channel sensing to find used channel bands, and utilises them for the MU-MIMO data transmissions of user groups. Here, the discrete Fourier transform (DFT) size is N with index set $\boldsymbol{\Omega}_\mathrm{N}$ and the index set of used subcarriers is $\boldsymbol{\Omega}_\mathrm{U}$ ($\subset \boldsymbol{\Omega}_\mathrm{N}$) because of the OFDMA operation. For the proposed MU-MIMO protocol, the AP further constructs MUX groups within each of the selected user group based on the long-term channel information of the STAs in the user group such as the maximum delay spread or the spatial correlation. This MUX group information can be identified to the intended recipients of each MU-MIMO transmission using a modified version of the signal-A field (SIG-A) in Fig. 1, in which the MUX group information with the corresponding cyclic shift (CS) value is further included.

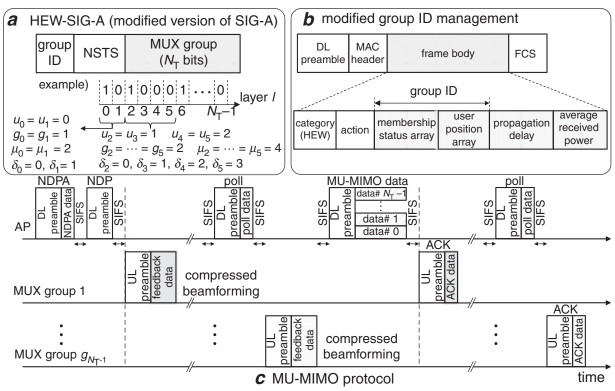

Fig. 1 *Proposed DL MU-MIMO protocol*

Fig. 1 shows the proposed DL MU-MIMO protocol. For the selected user group, the size of each MUX group is selected by the AP and is indicated at the MUX group field in the modified SIG-A as shown in Fig. 1*a*. Each bit in the MUX group field indicates whether a new LTF is used for the corresponding layer (1) or not (0). Since each user knows its position in the selected group ID from the group ID management as shown in Fig. 1*b*, the number of space-time streams field uniquely determines where each layer index in the protocol belongs to (i.e. u_l denotes the user index for the STA having layer l). Then, for the lth layer, the number of '1's from the first to the lth bit in the MUX group field denotes the LTF index g_l, the distance between the left-adjacent (including itself) and right-adjacent '1's denotes the number of multiplexed layers in the LTF, μ_l, and the distance from it to left-adjacent '1'(including itself) determines the CS value $\delta_l \in \{0, 1, \ldots, \mu_l - 1\}$. After a short interframe space (SIFS) from the end of the null data packet announcement frame, the AP sends the null data packet (NDP) frame composed of $g_{N_\mathrm{T}-1}$ code-division multiplexed (CDM) LTFs as shown in Fig. 1*c*.

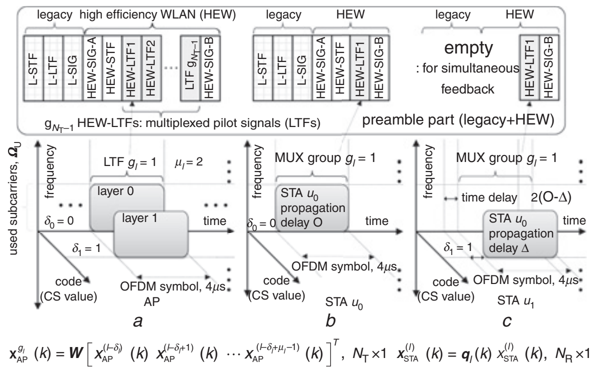

Fig. 2 *New LTF structures for new preamble part*

Fig. 2 shows an example of the new LTF structure. Here, the LTF signal for the lth layer is multiplexed on the g_lth LTF symbol with CS spacing $\Delta_l \triangleq \delta_l N/\mu_l$. A common $N \times 1$ frequency-domain (FD) base sequence $\boldsymbol{p} = [p(0)p(1)\cdots p(N-1)]^\mathrm{T}$ with the properties of a low peak-to-average power ratio and good autocorrelation is shared among the AP and STAs and the training sequence for each layer is obtained by a phase rotation according to the CS value δ_l of the layer. As shown in Fig. 2*a*, the $N_\mathrm{T} \times 1$ FD symbol vector at the kth subcarrier ($k \in \boldsymbol{\Omega}_\mathrm{U}$) of the g_lth LTF can be expressed as $\boldsymbol{x}_\mathrm{AP}^{g_l}(k)$, where $\boldsymbol{W} \triangleq [\boldsymbol{0}_{(l-\delta_l)\times\mu_l}; \boldsymbol{I}_{\mu_l}; \boldsymbol{0}_{(N_\mathrm{T}-l+\delta_l-\mu_l)\times\mu_l}]$ denotes the $N_\mathrm{T} \times \mu_l$ spatial mapping matrix and $x_\mathrm{AP}^{(l)}(k) = 1/\sqrt{\mu_l|\Omega_\mathrm{U}|}p(k)\exp(\mathrm{j}2\pi\delta_l k/\mu_l)$. At the STA to which the lth layer is allocated, MIMO channel estimation is performed by demultiplexing the g_lth LTF. Note that the conventional LTF is used in a poll frame. After an SIFS from the end of the NDP frame or a poll frame, the STAs in the same MUX group simultaneously transmit their compressed beamforming frames after an uplink timing control as in Figs. 2*b* and *c*. Similarly, each STA controls the transmission power by reducing the power by the amount of the difference between itself and the smallest one in the MUX group based on the average received power field in the modified group ID management. As shown in Figs. 2*b* and *c*, the legacy portion, the HEW-SIG-A and the HEW-STF in the preamble are transmitted only by the STA having the zero CS value in the MUX group to avoid a collision. Note that although the received power level may change between the legacy part and the HEW-LTF, it does not cause any problem because the gap is already known at the AP due to the power control mechanism. On the other hand, the LTF signal for each layer of the MUX group is simultaneously transmitted. As shown in Figs. 2*b* and *c*, the $N_\mathrm{R} \times 1$ FD symbol vector at the kth subcarrier ($k \in \boldsymbol{\Omega}_\mathrm{U}$) of the STA having the lth layer for the LTF of the MUX group g is expressed as $\boldsymbol{x}_\mathrm{STA}^{(l)}(k)$, where $\boldsymbol{q}_l(k)$ denotes the $N_\mathrm{R} \times 1$ unitary beamforming steering vector of the lth layer at the kth subcarrier determined by the STA and $x_\mathrm{STA}^{(l)}(k) = 1/\sqrt{|\Omega_\mathrm{U}|}p(k)\exp(\mathrm{j}2\pi\delta_l k/\mu_l)$ which is transmitted after applying the inverse DFT, inserting the length-G cyclic prefix (CP), and applying the earlier mentioned timing and power control. In addition, the HEW-SIG-B as well as the data field for each layer in the MUX group is simultaneously transmitted using the same vector $\boldsymbol{q}_l(k)$ with the timing control only by virtue of the signal separation capability of the AP having multiple antennas. With the feedback reports from STAs in the selected user group, the AP computes the MU-MIMO steering matrix and sends the DL data frame of N_T layers preceded by the same $g_{N_\mathrm{T}-1}$ CDM LTFs used in the NDP frame. After an SIFS from the end of the data frame or a poll frame, the STAs in the same MUX group simultaneously transmit their acknowledgement frames similarly as in the feedback frames.

Proposed LTF demultiplexing and joint detection schemes: Let $\boldsymbol{h}_l^{(u)}(k)$ be the $N_R \times 1$ channel vector between STA u and the lth transmit antenna of the AP. Moreover, $\boldsymbol{H}^{(u)}(k) = [\boldsymbol{h}_0^{(u)}(k)\boldsymbol{h}_1^{(u)}(k)\cdots\boldsymbol{h}_{N_T-1}^{(u)}(k)]$ is the $N_R \times N_T$ channel matrix for the STA u and the AP. In addition, $\boldsymbol{H}_l(k)$ is the $N_T \times N_R$ channel matrix between the STA having the lth layer and the AP and $\boldsymbol{h}_l(k) = \boldsymbol{H}_l(k)\boldsymbol{q}_l(k)$ is the effective channel vector for the lth layer at the AP. Then, the $N_R \times 1$ received FD symbol vector after the CP removal and DFT at the kth subcarrier ($k \in \boldsymbol{\Omega}_U$) for the gth LTF in the NDP frame at the STA u can be expressed as $\boldsymbol{y}^{(u)}(k)$ as in Fig. 3, where $\Upsilon^{(u)}$ is the average received power at the STA u and $\boldsymbol{n}^{(u)}(k)$ is the $N_R \times 1$ independent identically distributed (i.i.d.) complex white Gaussian noise (CWGN) vector. Besides, the $N_T \times 1$ received FD symbol vector after the CP removal and DFT at the kth subcarrier ($k \in \boldsymbol{\Omega}_U$) for the MUX group g in the compressed beamforming frame at the AP can be expressed as $\boldsymbol{y}(k)$ as in Fig. 3, where Υ_l is the average received power of the signal from the STA having the lth layer and $\boldsymbol{n}(k)$ is the $N_T \times 1$ i.i.d. CWGN vector.

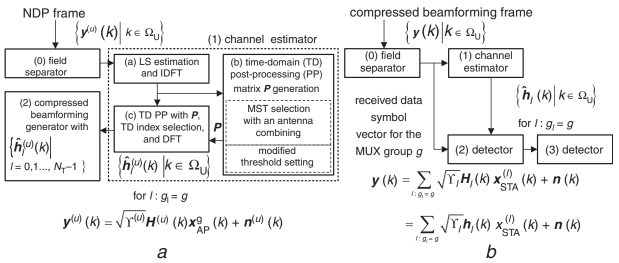

Fig. 3 *Proposed LTF demultiplexing and joint detection schemes*

The proposed LTF demultiplexing scheme makes an effort to separate μ_l $N_R \times 1$ channel estimates $\{\widehat{\boldsymbol{h}}_l^{(u)}(k)|g_l = g\}$ from $\boldsymbol{y}^{(u)}(k)$ of the gth LTF by applying an extended version from the DFT-based channel estimator in [3] considering the leakage effect because of the OFDMA operation while keeping the low complexity, in which the antenna combined in the most significant tap selection with an appropriately modified threshold considering the antenna combining technique as shown in Fig. 3*a* to generate the compressed beamforming information from $\{\widehat{\boldsymbol{h}}_l^{(u)}(k)|l = 0, 1, \ldots, N_T - 1\}$ after receiving all multiplexed LTFs from the AP. Moreover, with $\boldsymbol{y}(k)$, he proposed joint detection scheme first separates the LTF and feedback data fields, obtains μ_l $N_T \times 1$ channel estimates $\{\widehat{\boldsymbol{h}}_l(k)|g_l = g\}$ from the LTF of the MUX group g, and performs a MU-MIMO detection followed by decoding to obtain the feedback data field. To overcome the co-channel interference, the proposed channel and minimum-mean-square error (MMSE) soft-output MIMO detector [4] followed by a Viterbi decoder are adopted as shown in Fig. 3*b*.

Performance evaluation: For the simulation, $N_T = 16$ and an 80 MHz bandwidth are assumed. Here, $N = 256$, $G = 64$ and the most commonly used IEEE 802.11ac channel model B are used. A nearby AP and a legacy STA are assumed to preoccupy the primary 20 MHz channel so that the non-legacy STAs around them should utilise the remaining 60 MHz channel using the OFDMA operation for the MU-MIMO, i.e. $|\boldsymbol{\Omega}_U| = 178$. In addition, the total transmit power and the thermal noise power are, respectively, set to 17 dBm and −174 dBm/Hz with a noise figure of 10 dB at the receiver. To evaluate the performance of the proposed MU-MIMO protocol by comparing it with the conventional IEEE 802.11ac equipped with the optimal MMSE estimator, a toy example is considered where 22 associated STAs are placed as given in Table 1. Here, the first 12 and the remaining 10 STAs are grouped into two user groups and the MUX grouping is also summarised. In Table 1, the signal-to-interference plus noise ratio (SINR) loss [dB], defined as the performance degradation in terms of the average received SINR when the regularised zero-forcing (ZF) beamforming is assumed, is summarised for STAs 0–3 because of the mismatch in the feedback channel. The results show that the proposed protocol works very well at sufficiently low SINR loss in spite of the improved efficiency because of the LTF demultiplexing even with the proposed channel estimator by overcoming the reduced transmit power per layer due to the MUX and a possible leakage due to the OFDMA operation.

In Table 2, the average throughput performance of the proposed MU-MIMO protocol is compared with the IEEE 802.11ac in the toy example by assuming ZF beamforming transmission at the AP. Here, the average throughput [Mbits] is obtained by simulation considering both the channel estimation effect and the effect caused from the detection error in the compressed feedback frames for the case of using 64 frames with each frame length of N_{Data}. As can be seen from Table 2, the proposed protocol can reduce the required feedback duration by allowing simultaneous transmission with only little loss in the used modulation and coding set option. Thus, by efficiently reducing the preamble and feedback overhead without sacrificing performance, the proposed protocol can achieve much higher efficiency, especially for a small data frame length.

Table 1: Toy example, SINR loss comparison for STAs 0–3

User group $q=0$	MUX group $m=0$				$m=1$		$m=2$		$m=3$			
STA index (u)	0	1	2	3	4	5	6	7	8	9	10	11
Distance [m]	10	20	20	30	20	20	20	30	10	20	30	30
N_R	1	1	1	1	2	2	2	2	1	1	1	1
CS (δ_l)	0	1	2	3	0,1	2,3	0,1	2,3	0	1	2	3
User group $q=1$	$m=0$		$m=1$		$m=2$				$m=3$			
STA index (u)	12	13	14	15	16	17	18	19	20	21		
Distance [m]	30	30	10	20	10	20	20	30	20	30		
N_R	2	2	2	2	1	1	1	1	2	2		
CS (δ_l)	0,1	2,3	0,1	2,3	0	1	2	3	0,1	2,3		
SINR loss [dB]	$u=0$			$u=1$			$u=2$			$u=3$		
Conventional	0.1281			0.1476			0.1485			0.1530		
Proposed	0.8133			0.8495			0.8451			0.9422		

Table 2: Average throughput performance comparison, required feedback duration comparison for $m=0$ and $q=0$

Throughput	$N_{Data} = 2000$ [bytes]			$N_{Data} = 3895$ [bytes]		
User group (q)	0	1	Average	0	1	Average
Conventional	173.5	203.5	187.3	310.9	359.5	333.4
Proposed	349.5	357.5	353.2	521.0	534.2	526.6
Improvement [%]	200.4	175.7	188.6	167.6	148.6	157.9
Typical MCS	Conventional: 5/6, 256QAM			Proposed: 5/6, 64QAM		
Duration [μs]	1084			260		

Conclusion: In this Letter, an efficient MU-MIMO protocol is proposed for WLAN systems employing massive MIMO and OFDMA. The simulation results confirm that the proposed protocol provides a much higher throughput compared with the conventional IEEE 802.11ac.

Acknowledgments: This work was supported in part by the ICT R&D programme of MSIP/IITP (2014-044-006-004, Next Generation WLAN System with High Efficient Performance) and in part by the MSIP, Korea, under the C-ITRC (IITP-2015-H8601-15-1006) supervised by the National IT Industry Promotion Agency (NIPA).

9 March 2015
doi: 10.1049/el.2015.0808
One or more of the Figures in this Letter are available in colour online.

Kyung Jun Kim, Kyung Jun Choi and Kwang Soon Kim (*Department of Electrical and Electronic Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, Republic of Korea*)

✉ E-mail: ks.kim@yonsei.ac.kr

Seong Ro Lee (*Department of Information and Electronics Engineering, Mokpo National University, Jeonnam 534-729, Republic of Korea*)

References

1 IEEE: 'Proposed TGac draft amendment', 2011, IEEE802.11-10/1361r3
2 IEEE: 'Discussions on the better resource utilization for the next generation WLANs', 2012, IEEE802.11-12/0068r0
3 Kim, K.J., Hwang, H.G., Choi, K.J., and Kim, K.S.: 'Low-complexity DFT-based channel estimation with leakage nulling for OFDM systems', *IEEE Commun. Lett.*, 2014, **18**, (3), pp. 415–418
4 Choi, K.J., and Kim, K.S.: 'Hierarchical tree search for runtime-constrained soft-output MIMO detection', *IEEE Trans. Veh. Technol.*, 2013, **62**, (2), pp. 890–896