IEEE 802.11be (Wi-Fi 7): Performance Evaluation of Transmit Beamforming Transceivers with Multi-User Diversity

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Abstract— **In this research, we analyze the performance gains due to the joint implementation of transmit beamforming (TxBF) transceivers and low-complexity multi-user (MU) diversity scheduling scheme in the 2024 IEEE 802.11be amendment (Wi-Fi 7). The physical layer (PHY) configuration assumes TxBF transceivers with either *2*, *4*, *8* or *16* transmit antennas and only one receive antenna; 4096-QAM and low-density parity check (LDPC) codes. The system performance is analyzed over TGn B and TGn D channels with and without Doppler spread. The simulation results for the packet error rate (PER) allow to compare the performance between systems without scheduling and with a scheduling scheme based on the signal-to-noise ratio (SNR) that exploits the MU diversity when either 2 or 8 stations (STAs) are analyzed at each transmit opportunity (TxOP).**

Keywords—802.11be, Transmit Beamforming, Multi-User Diversity, 4096-QAM, LDPC, Doppler Channels.

I. INTRODUCTION

The IEEE Task Group (TG) 802.11be is pushing the limits of wireless local area networks (WLANs) by standardizing enhanced features to improve significantly the goodput of the 2021 802.11ax amendment (Wi-Fi 6) [1]. Regarding the 802.11be physical layer (PHY), the new technologies under investigation include a maximum 320 MHz contiguous bandwidth (BW) in the 6 GHz band; 4096-QAM modulation scheme; Orthogonal Frequency-Division Multiple Access (OFDMA) with allocation of multiple resource units (RUs) for a single user; maximum number of 16 spatial streams (SS) [2]. The 802.11be amendment permits a theorical maximum peak data rate of ~46 Gbps (320 MHz, 4096-QAM, 16x16 MIMO), i.e., a 4.8x increase over the 802.11ax amendment.

Multi-user diversity allows to improve the performance of wireless systems because with the increase of users analyzed by the scheduling scheme there is a high probability to find a user whose channel presents high capacity, increasing the average throughput attainable for a given signal-to-noise ratio (SNR) [3, p. 253]. This have motived us to investigate the performance of transmit beamforming transceivers (TxBF) in the 802.11be PHY when the scheduling scheme takes into account the multi-user (MU) diversity. Section II summarizes the 802.11ax/be PHY simulator that we have been developing. Section III describes a low-complexity joint implementation of MU diversity with TxBF transceivers in the 802.11be PHY. Section IV presents a comprehensive set of simulation results that allow to analyze the possible performance gains due to exploitation of MU diversity in 802.11be PHY with TxBF transceivers. Finally, Section V concludes this paper.

II. IEEE 802.11AX/BE SIMULATOR

Table I shows the main parameters of 802.11ax/be PHY simulator used in this paper. It implements the low-density parity check (LDPC) codes originally specified in the IEEE 2014 802.11ac amendment, which support block lengths of 648 bits, 1296 bits and 1944 bits [4, p. 164]. The LDPC decoder implements the log-domain sum-product algorithm with a maximum number of iterations set to 50 [5]. The TxBF transceivers implement minimum mean squared error (MMSE) precoder and MMSE MIMO detector [6].

TABLE I. IEEE 802.11ax/be PHY simulator parameters.

Parameter	Value	Parameter	Value
Carrier Frequency	5.5 GHz	Bandwidth	20 MHz
Subcarrier Spacing	78.125 kHz	FFT Size	256
OFDM Symbol	12.8 µs	Cyclic Prefix	800 ns
Temporal Synchronization	Autocorrelation	Channel Estimation	MMSE
Channel Codes: LDPC	Code rate: r=1/2, r=2/3, r=3/4, r=5/6	Channel Decoder	Soft-Decision

The wireless channel labeled as $[n_t, n_r, U, K, n_{ss}]$ has the following configuration: *(i)* transmitters with n_t antennas; *(ii)* receivers with n_r antennas; *(iii)* *U* stations (STAs) are taken into account by the scheduling scheme (e.g., *U=1* means that there is no multi-user diversity and *U=8* means that 8 STAs are analyzed by the scheduling scheme); *(iv)* K STAs access the channel simultaneously (i.e., *K=1* for SU-MIMO and *K>1* for MU-MIMO); *(v)* the access point (AP) transmits on the downlink (DL) an equal number of n_{ss} spatial streams (SSs) to each STA. On the other hand, each client transmits n_{ss} SS to the AP when the uplink (UL) is simulated.

In this industry-oriented paper, we analyze the system performance considering the following channels [4, p. 38]: *(1)* line-of-sight (LOS) TGn B channel, which has a root mean square (rms) delay spread σ_τ of *15 ns,* normally used to model small rooms; *(2)* the non-line-of-sight (NLOS) TGn D channel, a frequency selective channel which has a rms delay spread of 50 ns, commonly used to model typical office environments. The channel coherence bandwidth is given approximately by $B_c = \frac{1}{50\sigma_\tau}$ if the coherence bandwidth is defined as the bandwidth over which the frequency correlation function is above 0.9. Therefore, the TGn B and D channels have a coherence bandwidth of 1.*3 MHz* and *400 kHz*, respectively. Notice that according with Tab. I, the orthogonal frequency division multiplexing (OFDM) has a subcarrier (SC) spacing of *78.125 kHz*. Finally, we also observe that the TGn channels models specify spatial correlation matrices for both sides of the link [2, p. 42].

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The Bell-shaped Doppler power spectrum (DPS) is modeled by the following expression [2, p. 45]:

$$S_d(f) = \frac{\sqrt{A}/(\pi f_d)}{1+A\left(\frac{f}{f_d}\right)}, \quad |f| \leq f_{max}, \tag{1}$$

where $f_d = \frac{v}{c} f_c$ denotes the Doppler spread; f_c is the carrier frequency in Hz; c is the speed of light and v_0 is the environmental speed. The *constant A* equal to 9 means that the DPS is *10 dB* below the peak at Doppler spread frequency. The coherence time for the Bell-shaped DPS is given by $T_c = \left(\sqrt{A}/2\pi f_d\right) \cdot ln(2)$ when it is assumed correlation of 50%. Assuming v_0 fixed to *1.2 km/h*, then $f_d \approx 6\,Hz$ and $T_c = 57\,ms$ for $f_c = 5.25\,GHz$.

Fig. 1 depicts the fields to transmit data packets (DP) implemented in our simulator. We also have implemented the transmission of non-data packets (NDP). The receivers use these NDP to estimate the channel matrix using the MMSE scheme. It is assumed that this realistic estimation of the channel state information (CSI) is fed back for all subcarriers without errors and quantization.

Fig. 1. 802.11be fame format: Legacy Short Training Field (L-STF); Legacy Long Training Field (L-LTF); Legacy Signal Field (L-SIG); Repeated Legacy Signal Field (RL-SIG); Universal Signal Field (U-SIG); EHT signal field (EHT-SIG); EHT-STF; EHT-LTF; EHT data unit; Packet Extension (PE).

III. MULTI-USER DIVERSITY FOR TXBF IN 802.11AX/BE

In this section, the proposed low-complexity scheduling scheme is described assuming a channel BW of 20 MHz, which has 256 subcarriers (SCs) with the following configuration: 6 and 5 guard SC; 3 direct current (DC) SCs; 234 data SCs and 8 pilot SCs [7].

The scheduling scheme is implemented as follows:

1. The access point (AP) transmits a NDP to U STAs.
2. The STAs feed back the CSI for all data SCs and the signal-to-noise ratio (SNR). The SNR is estimated by the STAs for each pilot SC.
3. The AP transmits to the STA that has the higher number of pilots SCs with a larger SNR. The MMSE precoder is calculated using the CSI fed back at step 2.

In summary, this scheduling scheme allows to assess the effects of SNR variation between the STAs on the performance of 802.11be PHY with TxBF transceivers.

IV. PERFORMANCE ANALYSIS

The simulation results shown in this section assume a medium access control protocol data unit (MPDU) of 4000 octets. Unless otherwise noticed, the comparative statements regarding the system performance assume a typical packet error rate (PER) of 1% ($PER_{1\%}$).

A. LOS TGn B Channel without Doppler Spread

Figures 2a and 2b show results for the PER as function of the SNR in dB, assuming DL MIMO LOS TGn B channels without Doppler spread. It is shown results for transceivers with either *2*, *4*, *8* or *16* transmit antennas and only one receive antenna. It is assumed MCS13 *(4096-QAM, LDPC with r=5/6)*. The LDPC soft-decoder implements the low-complexity log-likelihood ratio (LLR) metrics derived and validated in [8] for rectangular Gray-coding 4096-QAM modulation scheme. The scheduler chooses one of two STAs (U=2) at each transmit opportunity (TxOP). The results shown with white geometric figures correspond to the study case when the scheduling scheme is not implemented (i.e., the STAs are chosen randomly at each TXoP).

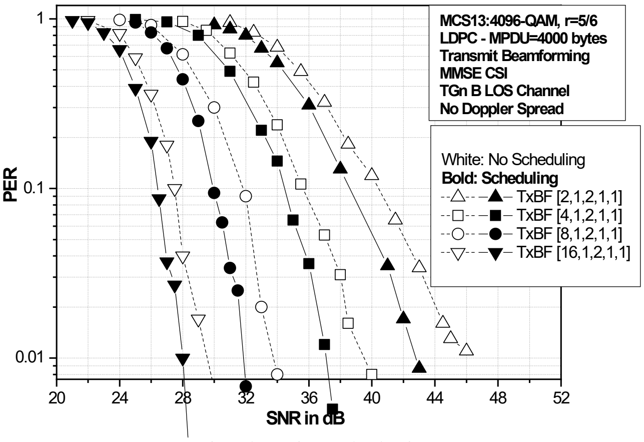

Fig. 2a. Average PER as a function of SNR in dB for LOS TGn B [n_t,1,**2**,1,1] channels without Doppler spread for systems with scheduling (black geometric figures) and without scheduling (white geometric figures).

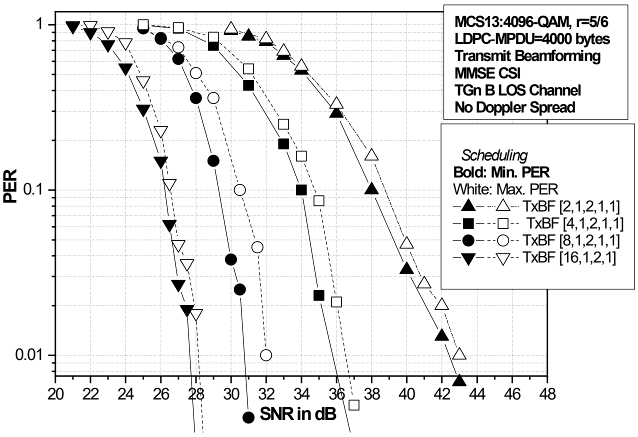

Fig. 2b. Minimum (black geometric figures) and maximum (white geometric figures) PER as a function of SNR in dB for LOS TGn B [n_t,1,**2**,1,1] channels without Doppler spread for systems with scheduling.

Remarks-Fig.2: Analyzing the results depicted in Fig. 2a, we have observed that the scheduling scheme allows a power gain of *~2 dB* for both 8 (●○) and 16 (▼▽) transmit antennas and a power gain of *~3 dB* for both 2 (▲△) and 4 (■ □) transmit antennas. It is observed a trend of saturation in the maximum PER when there are only two transmitting antennas and the scheduling scheme is not implemented (△). Finally, the results shown in Fig. 2b indicate that the differences between the minimum and maximum PER is less than 1 dB, independently of the number of transmit antennas.

Figures 3a and 3b assume the same set up of Figures 2a and 2b, respectively, except that now the scheduler can select one of eight STAs (*U=8*) at each TxOP.

Remarks-Fig.3: Stablishing a comparison between the results depicted in Figures 2a and 3a, we can see that the exploitation of MU diversity allows more expressive power gains when it is increased from 2 to 8 the number of clients analyzed by the scheduling scheme at each TxOP: *(i)* power gain of*~4 dB* for n_t=16 (▼▽) and n_t=8 (●○); *(ii)* power gain of *~5 dB* for n_t=4 (■ □) and n_t=2 (▲△). Fig. 3b shows that the discrepancies between the minimum and maximum PER increases with the decrease of the number of transmit antennas: *(i) ~1.5 dB* n_t=16 (▼▽); *(ii) ~3 dB* for n_t=8 (●○); *(iii) ~5 dB* for n_t=4 (■ □). Comparing the results shown in Figures 2b and 3b, we can see, as expected, an increase in the discrepancy between the minimum and maximum PER when the number of STAs analyzed by the scheduling scheme is increased. Although, as shown in Fig. 2a, the average PER is reduced when U=8 due to the substantial decrease of the minimum PER for U=8. Finally, it is noticed a saturation in the maximum PER when the transceivers have only two transmitted antennas (△) and the scheduling scheme is not implemented, as similarly observed in Fig. 2b for U=2.

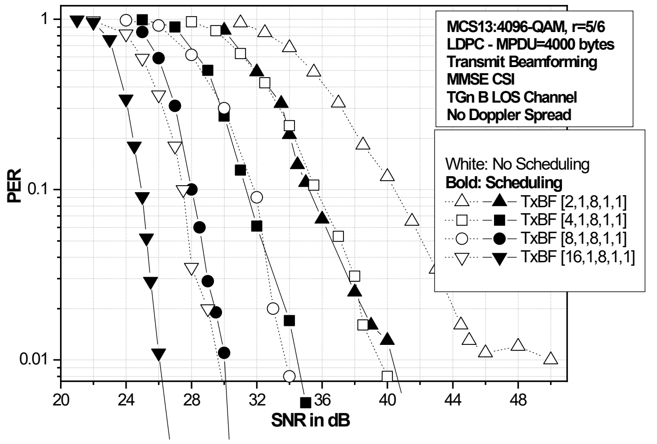

Fig. 3a. Average PER as a function of SNR in dB for LOS TGn B [n_t,1,**8**,1,1] channels without Doppler spread for systems with scheduling (black geometric figures) and without scheduling (white geometric figures).

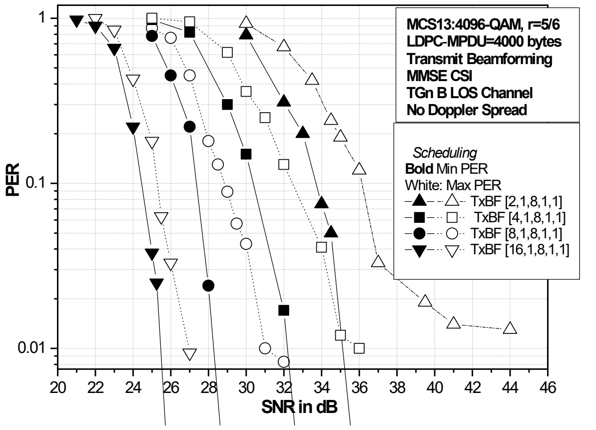

Fig. 3b. Minimum (black geometric figures) and maximum (white geometric figures) PER as a function of SNR in dB for LOS TGn B [n_t,1,**8**,**1**,1] channels without Doppler spread for systems with scheduling.

B. NLOS TGn B Channel with Doppler Spread

Fig. 4 allows to analyze the joint effects of Doppler spread and channel state information (CSI) feedback delay on the performance of 802.11ax/be PHY with TxBF transceivers with and without scheduling scheme. It is assumed U=2 and LOS TGn B channels with CSI feedback delay of 20 ms.

Remarks-Fig.4: These results show that even when the scheduling analyzes only two STAs (U=2), there are expressive power gains due to the scheduling scheme: *(i) 2.0 dB* for n_t=16 (▼▽); *(ii) 2.5 dB* for n_t=8 (●○); *(iii)* 3*.5 dB* for n_t=4 (■ □). Notice, differently of observed in Fig. 1a, there is a floor on PER for systems without scheduling due to the Doppler spread and feedback delay of 20 ms when the transceiver has 4 transmit antennas (□). Finally, although the results are not shown due to space restrictions, we have observed differences less than 1.5 dB between the minimum and the maximum PER for this study case when the scheduling scheme is implemented.

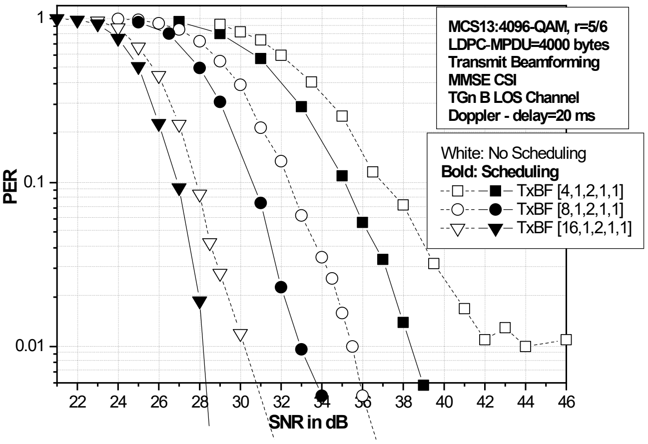

Fig. 4. Average PER as a function of SNR in dB for LOS TGn B [n_t,1,**2**,1,1] channels with Doppler spread and feedback delay of 20 ms. It is shown results for systems with scheduling (black geometric figures) and without scheduling (white geometric figures).

Figures 5a and 5b show results for the PER as function of the SNR in dB, assuming U=8 and LOS TGn B channels with Doppler spread and CSI feedback delay of 20 ms.

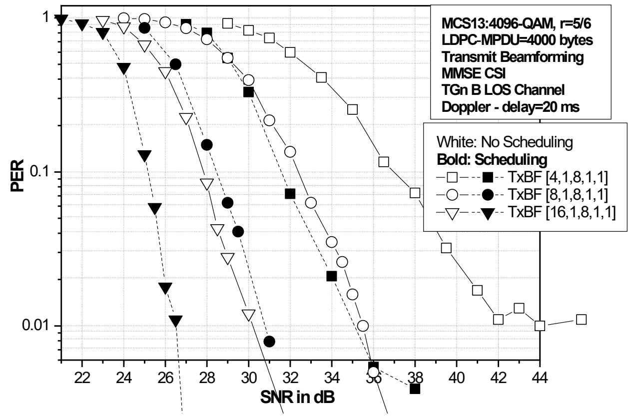

Fig. 5a. Average PER as a function of SNR in dB for LOS TGn B [n_t,1,**8**,1,1] channels with Doppler spread and feedback delay of 20 ms. It shown results for systems with scheduling (black geometric figures) and without scheduling (white geometric figures).

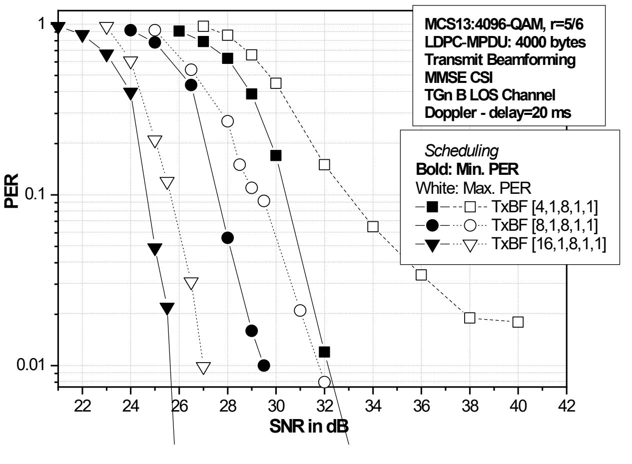

Fig. 5b. Minimum (black geometric figures) and maximum (white geometric figures) PER as a function of SNR in dB for LOS TGn B [n_t,1,**8**,**1**,**1**] channels with Doppler speed and feedback delay for systems with scheduling.

Remarks-Fig.5: The results shown in Fig. 5a indicate that the proposed scheduling scheme allows the following power gains when it has de possibility to analyze 8 STAs (U=8) to schedule 1 STA at each TXoP: *(i) 3.5 dB* n_t=16 (▼▽); *(ii) 4.5 dB* for n_t=8 (●○); *(iii) 6.5 dB* for n_t=4 (■ □). Fig. 4b ratifies the observation done at *Remark-Fig.3,* i.e., the differences between the minimum and maximum PER increases with the decrease in the number of transmitting antennas: *(i) 1.5 dB* n_t=16 (▼▽); *(ii) 2.0 dB* for n_t=8 (●○). It is observed an error floor in the maximum PER (□) when the transceiver has 4 transmit antennas. This suggests the necessity of implementing rate adaptation schemes that dynamically decreased the MCS when the maximum PER does not decrease with the increase of SNR. Finally, notice that these results assume 4096-QAM and LDPC code with code rate *r=5/6*, i.e., a demanding PHY configuration due to the high-signaling cardinality and high code rate.

Tab. II summarizes the target SNR in dB to obtain a PER of 1% considering channels with and without Doppler spread and systems with and without scheduling. These results emphasize the expressive power gains (e.g.., between 3.5 to 6.5 dB for U=8) due to the implementation of the proposed low-complexity scheduling scheme over realistic channels with Doppler spread and feedback delay.

TABLE II. SNR necessary in dB to obtain an average PER of 1% for systems with and without scheduling scheme (U=2 and U=8) as a function of the number of transmit antennas for LOS TGn B channels without and with Doppler spread (feedback delay of 20 ms).

Doppler	**No Scheduling**			**Scheduling:** U=2 **(U=8)**		
	n_t=16	n_t=8	n_t=4	n_t=16	n_t=8	n_t=4
No	29 dB	33.5 dB	39 dB	28 dB **26 dB**	32 dB **30 dB**	37 dB **34.5 dB**
Yes	30 dB	35.5 dB	42 dB	28 dB **26.5 dB**	33 dB **31 dB**	38.5 dB **35.5 dB**

C. NLOS TGn D Channels

In this subsection, we assess the performance of the proposed scheduling scheme considering the highly frequency selective NLOS TGn D channel.

Figures 6a and 6b show results for the average PER as function of SNR in dB over DL MIMO NLOS TGn D channels with and without Doppler spread, respectively. It is shown results for transceivers with either *4*, *8* or *16* transmit antennas and only one receive antenna. The scheduler chooses one of two STAs (U=2) at each TxOP.

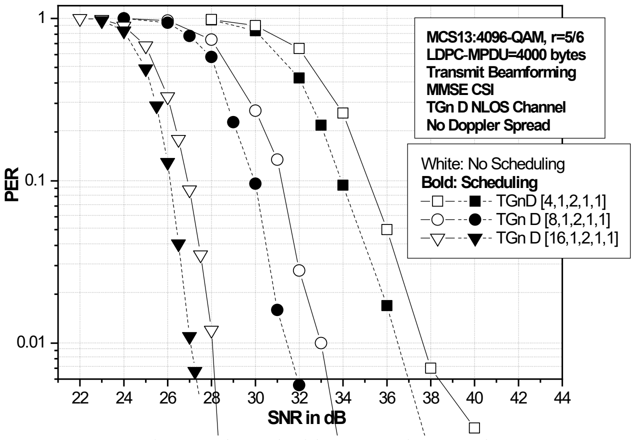

Fig. 6a. Channel without Doppler spread.

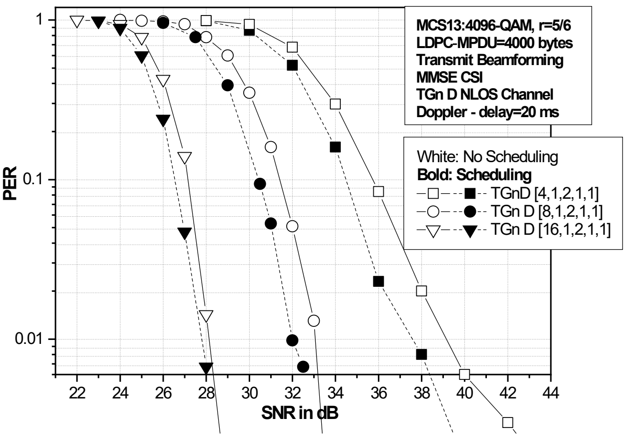

Fig. 6b. Channel with Doppler spread and feedback delay of 20 ms.

Fig. 6. Average PER as a function of SNR in dB for NLOS TGn D [n_t,1,**2**,1,1] channels for systems with scheduling (black geometric figures) and without scheduling (white geometric figures).

Remarks-Fig.6: First, we can see that for the frequency selective NLOS TGn D channel without Doppler spread the power gains due to proposed scheduling scheme for U=2 is less than 1.5 dB when the scheduler have statistics to analyze only two STAs (see also Tab. III). Second, notice that the performance is not impacted significantly by the channel aging due to the Doppler spread (e.g., maximum performance degradation of 1.5 dB and 1.0 dB for systems without and with scheduling, respectively, for transceivers with 4 transmitting antennas). However, the performance gains due to the scheduling scheme are reduced due to the channel aging (e.g., power gain is reduced from 1.5 dB to 1 dB for transceiver with 8 transmit antennas and insignificant performance improvement of 0.3 dB as observed for n_t=16). Finally, we have noticed, although not shown due to space restrictions, that the differences between minimum and maximum PER is less than 0.5 dB when the scheduling scheme is implemented for channels with and without Doppler spreads.

TABLE III. SNR necessary in dB to obtain an average PER of 1% for systems with and without scheduling scheme (U=2 and U=8) as a function of the number of transmit antennas for NLOS TGn D channels without and with Doppler spread (feedback delay of 20 ms).

Doppler	**No Scheduling**			**Scheduling:** U=2 **(U=8)**		
	n_t=16	n_t=8	n_t=4	n_t=16	n_t=8	n_t=4
No	28 dB	33 dB	37.5 dB	27.0 dB **26.8 dB**	31.5 dB **30.4 dB**	36.5 dB **35.0 dB**
Yes	28.1 dB	33.0 dB	39.0 dB	27.8 dB **27.0 dB**	32.0 dB **31.0 dB**	37.5 dB **37.0 dB**

Fig. 7 uses the same configuration of Fig. 6a, except that now the scheduler can analyze eight STAs (*U=8*) to schedule one STA at each TxOP, assuming a TGn D [n_t,1,8,1] channel without Doppler spread.[

Remarks-Fig. 7: We observe analyzing the results shown in Fig. 7 and Tab. IV for channels without Doppler spread that the gains due to the scheduling scheme improve due to the increase from 2 to 8 of the number of STAs analyzed by the scheduling scheme: 1.2 dB for n_t=16; 2.6 dB for n_t=8 and 2.5 dB for n_t=4 for channels without Doppler spread.

The results shown in Fig. 8a for the average PER and Fig. 8b for the minimum and maximum values of the PER allow infer the effects of Doppler spread over NLOS TGn D channels for systems with and without scheduling when U=8.

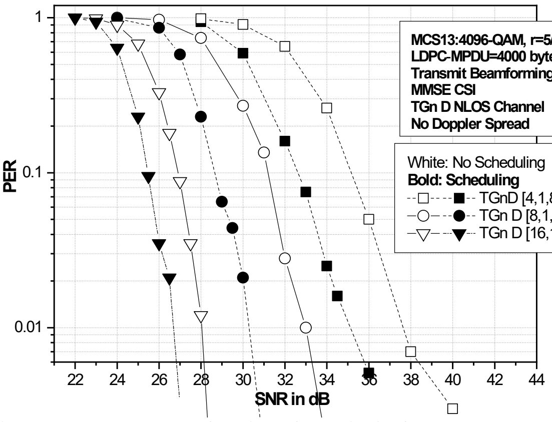

Fig. 7. Average PER as a function of SNR in dB for NLOS TGn D [n_t,1,**8**,1,1] channels without Doppler spread assuming systems with (black geometric figures) and without (white geometric figures) scheduling.

Remarks-Fig.8: The results shown in Fig. 8a for channels with Doppler spread, and summarized in Tab. IV for a $PER_{1\%}$, indicate the following gains due tom the scheduling scheme for U=8: ~1 dB for n_t=16; 2 dB for n_t=8 and n_t=4. This indicates a reduction in the performance gain due to the scheduling, as shown in Tab. III, of 0.3 dB for n_t=16; 0.6 dB for n_t=8 and 1.5 dB for n_t=4. Fig. 8b indicates that the differences between the minimum and maximum PER increases significantly with the reduction of the number of transmit antennas.

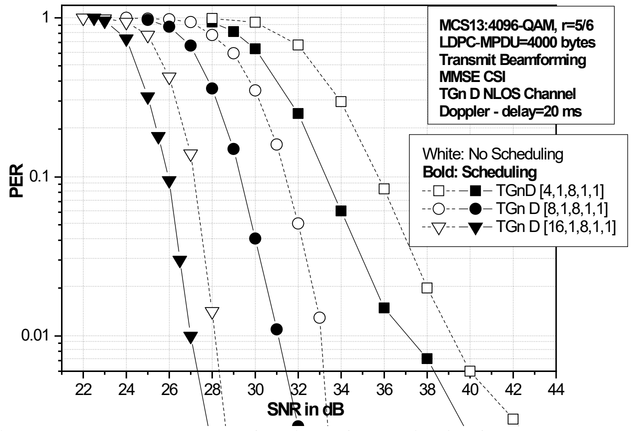

Fig. 8a. Average PER as a function of SNR in dB for NLOS TGn D [n_t,1,**8**,1,1] channels with Doppler spread and feedback delay for systems with (black geometric figures) and without white geometric figures) scheduling.

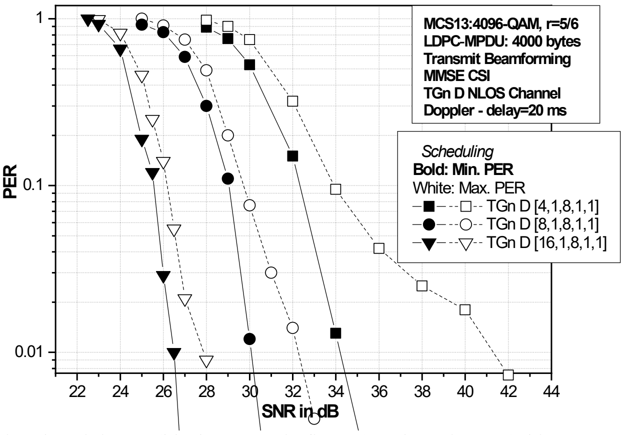

Fig. 8b. Minimum (black geometric figures) and maximum (white geometric figures) PER as a function of SNR in dB for NLOS TGn D [n_t,1,**8**,**1**,1] channels with Doppler spread and feedback delayfor systems with scheduling.

TABLE IV. Performance gains in dB due to the scheduling scheme.

Doppler	**Scheduling: U=2** TGn B/**TGn D**			**Scheduling: U=8** TGn B/**TGn D**		
	n_t=16	**n_t=8**	**n_t=4**	**n_t=16**	**n_t=8**	**n_t=4**
No	1.0 dB **1.0 dB**	1.5 dB **1.5 dB**	2.0 dB **1.0 dB**	3.0 dB **1.2 dB**	3.5 dB **2.6 dB**	4.5 dB **2.5 dB**
Yes	2.0 dB **0.3 dB**	2.5 dB **1.0 dB**	3.5 dB **1.5 dB**	3.5 dB **1.1 dB**	4.5 dB **2.0 dB**	6.5 dB **2.0 dB**

V. CONCLUSIONS

In this paper, we have analyzed the performance gains due the joint implementation of TxBF transceivers and low-complexity SNR based multi-user (MU) diversity scheduling scheme in the 802.11be amendment.

We have concluded, for both LOS TGn B channels (channels with low frequency selectivity) and NLOS TGn D channels (highly frequency selective channels), that the performance gains due to the scheduling schemes w.r.t the systems without scheduling decreases with the number of transmit antennas and increases with the number of STAs analyzed by the scheduling scheme (see Tab. IV). Notice that the target SNR to achieve a given PER reduces significantly with the increase of the number of transmit antennas (see Tables II and III).

We also have observed that the performance gains due to the proposed scheduling decreases with the increase of frequency diversity, i.e., a greater improvement due to the scheduling scheme is observed for LOS TGn B channels (see Tab. IV).

Assuming a Doppler frequency of 6 Hz and the CSI feedback of 20 ms, we have observed that channel aging does not impact significantly the system performance for LOS TGn B channels. However, the performance gains due to MU diversity is reduced for the highly frequency selective NLOS TGn D channels with Doppler spread and feedback delay.

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