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Decision Problems for Joint Transmission in Multi-AP Coordination Framework of IEEE 802.11be

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***Abstract*—**
For the new joint transmission paradigm being discussed under the IEEE 802.11be standardization efforts, we report the findings of our attempt at addressing the possible gains, and strategies, of using such a scheme. We look at the best possible rate achievable under the Joint Transmission approach, and then use these findings to address the problem of performing joint scheduling in a common practical deployment scenario.

I. Introduction and System Model

IEEE 802.11be standardization is exploring options of Multi-AP coordination [1]. Schemes to achieve performance gain by employing coordination in transmission have been used in other context in the past, most prominent example being the CoMP approach in 3GPP LTE Release 11 [2]. Such schemes invariably involve at least two transmitters and at least one receiver. The Key motivation for employing such mechanisms is to gain in network capacity by improving spectral efficiency for the cell-edge users. The cell-edge users are also prone to interference when considering a single frequency network. The exact nature of coordination depends on the scheduling options available at the coordinating transmitters and receiver(s). When using an OFDM based physical layer over a single frequency network with MIMO capability, the following options are available.

Coordinated Scheduling: This is essentially using the OFDM nature of the transmitted signal and ensuring that different transmitters serve *their own* cell edge users by assigning non-overlapping subcarriers to the different users. IEEE 802.11 does not have an existing OFDMA capability where the end-user can selectively process few sub-carriers to get the signal intended for it. This capability is also being incorporated in the standards starting IEEE 802.11ax [3].

Coordinated Beamforming: This scheme can be considered as a network wide MIMO by coordinating multiple APs to beamform the transmission and thus to optimize the overall network performances. This scheme is also applicable when multiple receivers are to be transmitted-to simultaneously.

Joint Transmission: This family of schemes is employed when multiple transmitters are to send a signal simultaneously to the same receiver using the same frequency and time resources.

We use the term *Transmit Coordination* (TC) to refer to the generic mechanisms which can be used to ensure that the transmission from multiple transmitters is jointly controlled. As mentioned above, if the physical layer uses an OFDM approach to modulation, then an equivalent of Coordinated Scheduling of LTE can be used. If MIMO is used, then the approach of coordinated beamforming can be deployed. These mechanisms are useful when multiple end-devices are to benefit from TC *at the same time*. When the objective is to benefit only one user, which is invariably at the so-called *cell edge*, then the mechanism is called *Joint Transmission* - we refer to such a scheme as JT-TC.

For an end-device, we compare the JT-TC performance achieved under the other alternatives:

1) **Single AP Transmission**: This is the scenario where a single AP is transmitting to the end device. It is assumed that this is a noise-limited scenario, i.e., interference is negligible on this frequency. This is referred-to as the **SAPT** scenario.
2) **Single AP Transmission with Interference**: This is the scenario where a single AP is transmitting to the end device but there is another AP transmitting on the same frequency (to a different end device). This is referred-to as the **SAPI** scenario.

It is expected that enabling collaboration among neighbouring APs in an 802.11be deployment will improve utilisation of the various scarce resources including limited time, frequency and spatial. For an overall survey of new IEEE 802.11be (EHT) features including multi-AP coordination, see [4] and [1]. Though the standard is expected to provide minimal explanation and specifications for these features, various enterprise network deployments differ in the manner in which they use the

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standardized features, thus providing a product/service differentiator.

In this paper, we aim at:

1) An in-depth study of the Multi-AP JT-TC approach and its implications on system performance,
2) Network architecture and distributed scheduling mechanisms that would enable a practically deployable and beneficial use of these standard-provided features,
3) Outlining, clearly, the performance gains to be expected from such systems,
4) Defining what is meant by *cell-edge* in the context of IEEE 802.11 network deployment.

Important highlights are that we study the above aspects using a closed-form mathematical formulation for single and multi antenna systems and using simulations with realistic channel models for SISO and MIMO system.

Outline of the paper: In this paper, we first consider a JT-TC system with a single antenna at the two individual transmitters (Section III). The receiver is also assumed to be equipped with a single receiver. For such a system, we provide a comparison of JT-TC and SAPT. In Section IV we provide a direct understanding of how the choice of JT-TC, SAPT and SAPI schemes will impact the system-level deployment considerations. This is done by providing an example system that is similar to the practically encountered IEEE 802.11 enterprise deployment. We then provide extensions of the concepts of the single-antenna system to multi-antenna system and provide theoretical bounds and simulations results from the real implementation of 802.11 physical layer.

II. System Model for JT-TC

Let STA be at a distance r_1 from AP_1 and r_2 from AP_2, and R is the distance between the co-ordinated APs. Also, let transmit power of AP_1 be P_1 and that of AP_2 be P_2 with the total power is limited to $P = P_1 + P_2$. Let the channel matrix from AP_1 (resp. AP_2) to the STA be $\mathbf{H}_1$ (resp. $\mathbf{H}_2$). Assuming M receiving antennas at the STA and N transmit antennas at each APs, the received signal at the STA is given by,

$$\begin{bmatrix} y_1 \\ \vdots \\ y_M \end{bmatrix} = \sum_{i=1}^{2} \sqrt{P_i L_i} \begin{bmatrix} h_{11}^i & h_{1N}^i \\ \vdots & \vdots \\ h_{M1}^i & h_{MN}^i \end{bmatrix} \begin{bmatrix} x_1^i \\ \vdots \\ x_N^i \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_M \end{bmatrix}$$

$$\mathbf{y} = \sqrt{P_1 L_1}\mathbf{H}_1\mathbf{x_1} + \sqrt{P_2 L_2}\mathbf{H}_2\mathbf{x_2} + \mathbf{n} \tag{1}$$

Here L_i is the propagation path loss experienced user from AP_i which as a function of distance r_i from the AP_i. The pathloss model is assumed to be exponential with α parameter ($L_i = r_i^{-\alpha}$). The noise n_i is assumed to AWGN with variance σ^2.

In uncoordinated transmission, the second term in RHS of (1) is interference to the first signal (intended to the user). For a user which is at the edge, *i.e.*, approximately equidistant from both the APs, the signal and interference will be of the same magnitude and SINR will be minimum on average. Joint transmission is a technique to utilize that multi-AP interference to our advantage, by transmitting the same signal from both APs, but by using Joint transmission we will be using more resources (communication and computation) for a single AP. In this paper, we will be considering communication aspects, like BER and channel capacity for selecting the best strategy.

We start with SISO cases and then extend the analysis to MIMO cases.

III. Single Antenna Case: Capacity of the JT-TC System

Consider two transmitters involved in TC and using the JT-TC method. It is implicitly assumed that this is a Single Frequency Network, i.e., both the transmitters are using the same frequency for transmission.

In line with the analysis of [5], when the two APs transmit data jointly, the received SNR is given by,

$$\gamma|_{r,h_1,h_2} = \frac{P_1|h_1|^2 r_1^{-\alpha} + P_2|h_2|^2 r_2^{-\alpha}}{\sigma^2} \tag{2}$$

We will first provide explicit expressions for the expected BER for a realistic channel model for single antenna JT-TC system employing M-QAM. We then provide the corresponding values from our numerical evaluation. We also address the considerations on the achievable rate for this system.

A. Average BER for single antenna Joint Transmission

The average bit error rate (BER) for a user at a distance r_1 from AP_1 and r_2 from AP_2 is given in the following theorem.

Theorem 1. *The* BER *of JT-TC is given by,*

$$\begin{aligned} \mathbb{P}_e^{JT}(r_1, r_2) = & \frac{\alpha_M \sigma^2}{P_1 r_1^{-\alpha} - P_2 r_2^{-\alpha}} \\ & \times \left(\frac{1}{\kappa_M + \kappa_M \sqrt{\frac{2\sigma^2 r_1^\alpha}{\kappa_M P_1} + 1} + \frac{2\sigma^2 r_1^\alpha}{P_1}} \right. \\ & \left. - \frac{1}{\kappa_M \sqrt{\frac{2\sigma^2 r_2^\alpha}{\kappa_M P_2} + 1} + \kappa_M + \frac{2\sigma^2 r_2^\alpha}{P_2}} \right) \end{aligned} \tag{3}$$

Proof. Refer appendix A

□

B. The BER of SAPT Scenario

Corollary 1. *The* BER *for SAPT can be obtained by substituting $P_2 = 0$ in theorem (1), which is given by,*

$$\mathbb{P}_e(r) = \frac{1}{P} \frac{\alpha_M \sigma^2 r^\alpha}{\kappa_M + \frac{2\sigma^2 r^\alpha}{P} + \kappa_M \sqrt{\frac{2\sigma^2 r^\alpha}{\kappa_M P} + 1}} \tag{4}$$

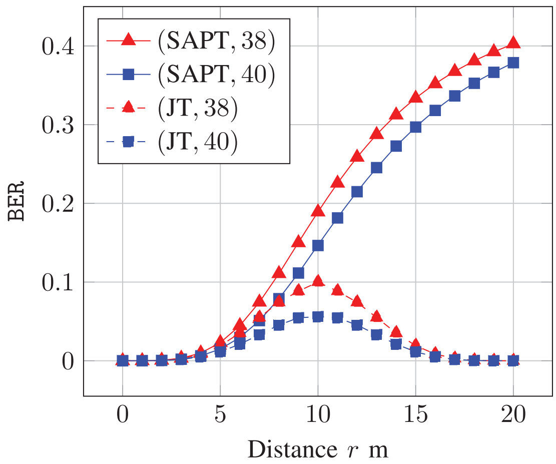


Fig. 1: Bit error rate Vs distance from AP_1 of a user for various values of transmit signal-to-noise ratio $\mathtt{SNR} = P_t/N_o$.

The BER performance of $JT - TC$ and $SAPT$ is provided in Figure 1. We have considered the case where two access points are deployed in a corridor or meeting hall at a distance of 20 meters and there is one STA that moves between the two APs. We can see the benefits of JT-TC, at the cell edge, which is equally apart from both the APs. This analysis can be easily extended to power splitting of AP transmit power ($P = P_1 + P_2$, $P_1 = \beta P$, $P_2 = (1 - \beta P)$), but since the case in practice is the transmit power at AP are hardware-limited, we would essentially be looking at a transmit SNR of 38 dB, thus resulting in further improvement in the BER performance for JT-TC.

C. Average Rate for SISO JT-TC

In joint transmission, interfering signals are effectively converted to useful signals, whereas in conventional systems, nearby APs have to share the spectrum among them to avoid the co-channel interference.

The rates can be found out using Shannon's capacity formula as follows. For JT,

$$\mathcal{C}(r) = \mathbb{E}\left[\log_2(1+\gamma)\right] \text{ b/s/Hz} \tag{5}$$

Here, γ is the received SNR.

Theorem 2. *The average rate achieved for a user at a distance r_1 from the AP_1 and r_2 from the AP_2 with JT-TC is given by,*

$$\mathcal{C}^{JT}(r_1, r_2) = \frac{1}{\log(2)} \frac{1}{P_1 r_1^{-\alpha} - P_2 r_2^{-\alpha}} \times \left[P_1 r_1^{-\alpha} e^{\frac{\sigma^2 r_1^\alpha}{P_1}} \Gamma\left(0, \frac{\sigma^2 r_1^\alpha}{P_1}\right) - P_2 r_2^{-\alpha} e^{\frac{\sigma^2 r_2^\alpha}{P_2}} \Gamma\left(0, \frac{\sigma^2 r_2^\alpha}{P_2}\right) \right] \tag{6}$$

where $\Gamma(a, x)$ is the incomplete gamma function[1].

Proof. Substitute (21) in (5) and take the expectation. □

D. Average rate for SAPI Scenario

The achievable rate for single AP transmission with interference (SAPI) from other AP is given by the following theorem[2].

Theorem 3. *The average achievable rate for a user serving by AP_1 at distances r_1 with transmit powers P_1, when uncoordinated AP_2 interfere with it from a distance r_2 with a transmit power of P_2 is given by,*

$$\mathcal{C}^{SAPI}(r_1, r_2) = \int_0^\infty \frac{e^{-\sigma^2(2^t-1)/P_1 r_1^{-\alpha}}}{1 + (2^t - 1)\frac{P_2 r_2^{-\alpha}}{P_1 r_1^{-\alpha}}} \mathrm{d}t. \tag{7}$$

Proof. See appendix B. □

The above theorems can be modified to find the capacity of SAPT without any interference, by substituting $P_2 = 0$ in (6).

Corollary 2. *The average rate achieved for a user at a distance r from an AP, without joint transmission, is given by,*

$$\mathcal{C}^{SAPT}(r) = \frac{e^{\frac{\sigma^2 r^\alpha}{P}} \Gamma\left(0, \frac{r^\alpha \sigma^2}{P}\right)}{\log(2)} \tag{8}$$

Figure 2 provides the comparison of rates achievable with and without JT-TC. We can see that the joint transmission outperform both the other scenarios, especially in cell edge, where an improvement of 5.8 bpsHz compared to SAPI and 1.35 bpHz compared to SAPT can be observed. But in SAPT, no interfering signals are considered, and hence bandwidth needed to be shared with other APs.

In the practical deployment of access points, we can see all these above theorems useful, a practical scenario will be discussed in Section. IV.

[1] $\Gamma(a, x) = \int_x^\infty t^{a-1} e^{-t} \mathrm{d}t$
[2] This single integral expression can be numerically evaluated easily.

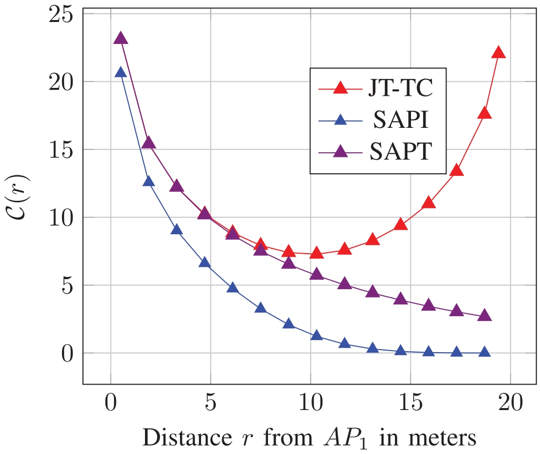


Fig. 2: Average achievable rate $\mathcal{C}$ in b/s/Hz Vs distance from AP_1 of a user for various values of $\mathtt{SNR} = 60$dB.

IV. A System Level Performance Improvement Analysis

Consider the deployment scenario depicted in Figure 3. The figure shows a typical conference room deployment which is covered by 4 access points installed at the 4 corners of the hall. Two APs (color coded blue), AP_2 and AP_4 are assumed to be using the same center frequency (WiFi Channel) for operation and the other APs are using different channels. The colored tiles on the grids on the floor represent the association of end-users (located at that tile, say a chair) to the different APs. The Pink tiles represent the users that are served using JT-TC from the two blue APs (bottom-left and top-right corners), other tile colors represent SAPT from their nearest APs. The blue tiles on the grid are served in a SAPI manner by the nearest blue AP.

The decision problem is that of finding out which users should be served using JT-TC, SAPT and SAPI so that the total system throughput is maximized. Note that we cannot have JT-TC using any other combination of APs as the orange and yellow APs are operating at different frequencies.

In the following, we will assume that the APs and the STA is using single transmit and receive antenna respectively and use the results from Section III to provide a policy to be used for deciding on the use of JT-TC vs SAPI so that the system level performance is improved.

A. Joint Transmission Scenario

Let $S(x, y)$ be the set of APs used for transmission to the user (tile) at location (x, y). The top-left user is located at $(1, 1)$ and top-right user is at $(8, 1)$, see Figure 3. The set $\{S(x, y)\}$ represents a scheduling decision. If $S(x, y)$ contains more than one APs, then these

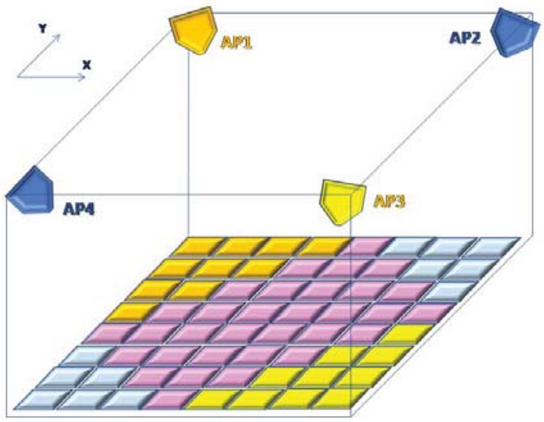


Fig. 3: A deployment scenario.

APs is using the JT-TC mechanism to serve the location (x, y), else either SAPT or SAPI are used depending on the frequency of the channel used by the single AP in $S(x, y)$. In other words, if $\{AP_i, AP_j\} \in S(x, y)$ for some (x, y), then AP_i, AP_j uses the same frequency in downlink and use JT-TC to serve the user at (x, y). Then the objective is to maximize the total throughput assuming an egalitarian service.

For AP_i, let $\hat{S}_i$ be the biggest set $S(x, y)$ to which AP_i belongs, then the following implication holds true:

$$\text{If } \exists (x, y) : AP_i, AP_j \in S(x, y) \text{ then } \hat{S}_j = \hat{S}_i.$$

Consider a node at (x, y) such that $AP_i \in S(x, y)$, then the scheduling problem is that of determining the fraction of AP_i channel use that can be given to (x, y). The total number of nodes served by AP_i is then given by, Let

$$T_i = \sum_{(x,y)\in G} \mathbf{1}((x, y) : AP_i \in S(x, y)),$$

where $\mathbf{1}(R)$ indicator function of the relation R and G is the grid of service area. Then under egalitarian service, AP_i will give $\frac{1}{T_i}$ of its channel use to node (x, y) such that $AP_i \in S(x, y)$.

In the special case depicted in the Figure 3, S(x, y) are denoted by the colored boxes. Then, $T_1 = 10$, $T_2 = 34$, $T_3 = 10$, $T_4 = 34$. Under this assignment scheme, the time-domain scheduling is easy and the total rate of the system is given by,

$$R_{net} = \sum_{i=1}^{4} \frac{1}{T_i} \sum_{(x,y):AP_i\in S(x,y)} R(x, y), \tag{9}$$

where $R(x,y)$ is the achievable rate for a node at (x,y). The problem then is of finding an assignment $\{S(x,y)\}_{(x,y)\in G}$ such that the throughput is maximized. In this paper, we will assume that the sets for SAPT (for AP1 and AP3) are fixed and the problem is of finding whether the remaining tiles should be served in JT-TC or SAPI manner by AP2 and AP4.

More precisely, we consider the scenario where we have two users to serve and they have to be served by AP_2 and AP_4. While using JT-TC, it definitely gives us a higher rate compared to single AP transmission, we can only serve one STA at a time. Whereas while using both APs for different STAs, we can serve them simultaneously, but it also results in higher interference which can decrease the overall capacity. This gives us another constraint for whether to use JT-TC, SAPT, or SAPI. Further, including AP_i in multiple $S(x,y)$ increases T_i, leading to reduce overall throughput.

In the following, we will assume a symmetric scheduling mechanism, i.e., for AP_2 and AP_4 using the same frequency, we will compare for the blue and pink tiles the following scheduling decisions:

$$Sched1: \quad S(x,y) = \{AP_2\}, S(y,x) = \{AP_4\},$$

i.e., SAPI to the tiles at locations (x,y) and (y,x) against

$$Sched2: \quad S(x,y) = S(y,x) = \{AP_2, AP_4\},$$

i.e., JT-TC is used. Note that the $Sched2$ requires two time slots from the two APs to serve two different users, while $Sched1$ requires only one time slot to serve two users. The symmetry assumption in $Sched1$ will be relaxed in a future version of this paper. The scheduling decision now reduces to the problem of determining whether

$$2R_1(x,y) \geq R_2(x,y) \qquad (10)$$

where $R_i(x,y)$ is the rate received by the user at (x,y) under scheduling rule $Schedi$.

To understand the relative values of the rates achieved under $Sched1$ and $Sched2$, we considered a setup where two APs are situated 20 meters apart and two STA are located at a distance $0 \leq d \leq 10$ from the two APs (transmitting on the same frequency). The throughput obtained under joint transmission ($Sched2$) is compared with the sum of the throughput obtained by individual STAs under single AP transmission ($Sched1$). Figure 4 provides the comparison for an individual AP transmit SNR of $101dB$ (corresponding to transmit power of $0dBm$ for a $20MHz$ bandwidth) and shows clearly that it is better to use $Sched1$ when $d < 4.5m$ and use $Sched2$ when $4.5 < d < 10$. Clearly, the exact threshold where this crossover happens will depend on the transmit SNR, the distance between the APs and the statistical characteristics of the channel used.

We have evaluated these scheduling schemes with extensive Monte-Carlo simulations. Matlab WLAN toolbox provides some pre-defined functions to simulate AP, STA, and the Wi-Fi channel using the IEEE 802.11 documents, [6]. We created transmission channels for each antenna element pair using the TGAC channel object and enabled path loss, [7]. We passed the data signal through the channel and added Gaussian noise of fixed power and received them in their respected receiver antenna. The signals at the receiver were then combined using the MRC scheme (joint-transmission). Then we calculated the BER for different positions of the user between the two APs and plotted it in a graph.

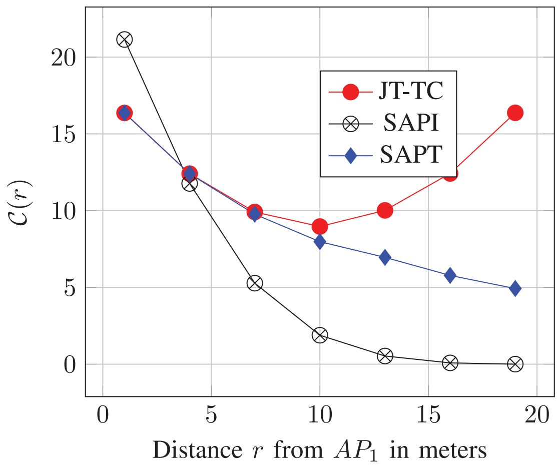


Fig. 4: Figure showing the crossover points for location where Joint transmission should be utilized when transmit SNR = 100 dB. The cross over points of JT and SAPI can be seen to be 4 meters from AP_1.

Figure 5 shows the impact of using such criteria on the scheduling in the two-dimensional grid of Figure 3 and marks the locations where joint transmission by AP_2 and AP_4 yields better throughput. The blue, pink and green tiles are showing two numerical values corresponding to the channel rates for JT-TC and SAPI assumptions, i.e., $Sched2$ and $Sched1$. The tiles for which Equation 10 is satisfied are colored blue (SAPI), else colored pink. The green tiles are the ones where there is not much difference in JT-TC and SAPI. Orange and Yellow tiles are showing the corresponding SAPT rates. This observation can be extended to a more general scenario and we are currently working on such a generalization.

Definition of Cell Edge: As is clear from the observations of this section, we can refer to the STAs in the region *just* qualifying for joint transmission (as per Equation 10) as the cell edge devices in the context of IEEE 802.11be.

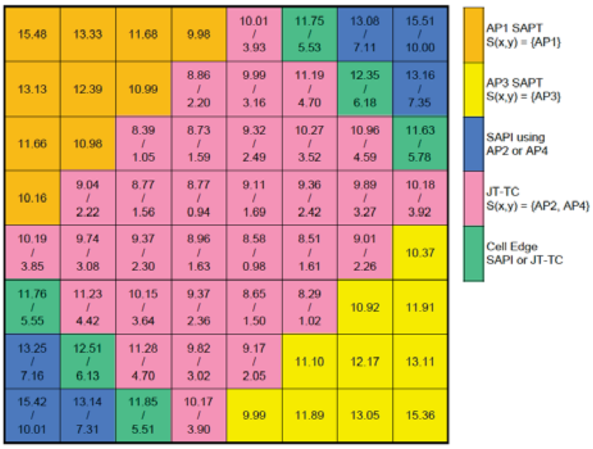


Fig. 5: Figure showing the crossover points for location where Joint transmission should be utilized.

V. Achievable rates with MIMO joint transmission

In this section, we will provide the achievable rates of joint transmission with MIMO systems. Also, we will discuss ZF-DPC based practically feasible suboptimal precoding schemes for MIMO joint Transmission. We have considered APs equipped with N_t antennas and users with N_r antenna. We assume perfect channel knowledge at the users and the APs are transmitting at the same power, P. The link level capacity of MIMO system is given by the well established result [8], [9],

$$R = \mathbb{E}\left[\log\det\left|\mathbf{I}_{N_r} + \frac{\gamma_t}{N_t}\mathbf{H}\mathbf{H}^*\right|\right], \tag{11}$$

where $\gamma_t = P_t/\sigma^2$ the transmit signal to noise ratio. It should be noted that the pathloss is included in the channel matrix, H. We assume coherent combining of channels in JT-MIMO, hence we can use $\mathbf{H} = \mathbf{H}_1 + \mathbf{H}_2$ in (11) to obtain achievable rates, where $\mathbf{H}_1$ and $\mathbf{H}_2$ are channels seen by the user from AP_1 and AP_2.

A. Achievable rates for ZF-DPC based precoding for MIMO-JT

When the channel state informations are available at the transmitters, precoding techniques like dirty paper coding (DPC) can achieve the Shannon limits [10]. Many suboptimal algorithms with reduced complexity, like THP, ZF-DPC are also discussed in the literature for link level MIMO and CoMP [11]–[14].

When using a single transmitter, we perform ZF-DPC as follows: We assume both APs and STA are having the same number of antennas $N_t = N_r = N$. Let the channel matrix be $\mathbf{H}$ and transmit signal vector be $\mathbf{x} = [x_1, x_2, \ldots, x_N]^T$. The signal $\mathbf{x}$ will be precoded before transmission using $\mathbf{W} = \mathbf{Q}^H$, obtained by the $\mathbf{LQ}$ decomposition of $\mathbf{H}$, *i.e.*, $\mathbf{H} = \mathbf{LQ}$. Hence the received vector can be given as,

$$\mathbf{y} = \mathbf{HWx} + \mathbf{n} = \mathbf{Lx} + \mathbf{n}, \tag{12}$$

Let l_{ij} be the element in the ith row and jth column of $\mathbf{L}$, the ith row of the received signal vector $\mathbf{y}$ can be written as

$$y_i = l_{ii}\ s_i + \sum_{j<i} l_{ij}s_j + n_i.$$

The precoder $\mathbf{W}$ cancels interference from streams with indices $j > i$. The remaining interference terms with indices $j < i$ are taken care of by applying DPC. Therefore, the post-processing $\mathtt{SNR}$ for ith stream is given by,

$$\gamma_i = \frac{P|l_{ii}|^2}{\sigma^2}, \tag{13}$$

and then the achievable rate on ith stream is given by

$$R_i = \log[1 + \gamma_i], \tag{14}$$

so that the net achievable rate is

$$R = \sum_i R_i. \tag{15}$$

When used under the JT-TC scheme, the THP approach is to be modified to take into account the LQ decomposition of the channel matrices seen by the receiver, i.e., the LQ decomposition is done for individual channels and precoded streams are sent and combined at the receiver[3]. Thus, the received signal can be written as,

$$\mathbf{y} = \sum_{k=1}^{L} \mathbf{L}^{(k)}\mathbf{x} + \mathbf{n}, \tag{16}$$

where $\mathbf{L}^{(i)}$ is the LQ decomposition of channel $\mathbf{H}^{(i)}$ from ith AP. Therefore in two AP coordination, ith stream will be having a $\mathtt{SNR}$,

$$\gamma_i^{JTM} = \frac{P_1|l_{ii}^{(1)}|^2 + P_2|l_{ii}^{(2)}|^2}{\sigma^2}, \tag{17}$$

where $l_{ij}^{(k)}$ is the element in the ith row and jth column of $\mathbf{L}^{(k)}$.

Theorem 4. *The achievable rate of $N \times N$ MIMO with two AP JT-TC using ZF-DPC is given by*

$$\mathcal{C}^{JM}(r_1, r_2) = \sum_{i=1}^{N-i}\sum_{l=0}^{N-i}\left(\frac{(-1)^l\binom{N-i}{l}}{(b-a)^{N-i+1}((N-i)!)^2}\right.$$
$$\left.\times\int_0^\infty \frac{\Lambda_\beta(z, l+N-i+1)l\log_2(1+z)}{\beta^l e^{z/b} z^{l-N+i}}\mathrm{d}z\right), \tag{18}$$

[3]We can see that $\mathbf{H}^{(i)}$ are uncorrelated with the independent Rayleigh assumption.

where $a = P_1 r_1^{-\alpha}/\sigma^2$, $b = P_2 r_2^{-\alpha}/\sigma^2$ *and* $\Lambda_\beta(z,k)$ *is defined in* (24).

Proof. Refer appendix C. □

The capacity for various configurations of (N_t, N_r) are plotted in Figure.6. The capacity for SAPT with MIMO can be obtained by substituting $P_2 = 0$ in Theorem. 4. We can see the improvement of cell edge rate with JT as in case of single antenna transmissions.

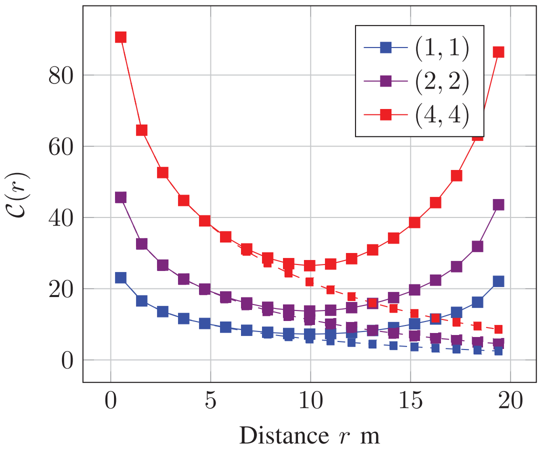


Fig. 6: Average rate $\mathcal{C}$ in b/s/Hz achievable for MIMO-JT-TC Vs distance from AP_1 of a user for various combinations of (N_t, N_r) at $\texttt{SNR} = 60$ dB. The dashed curve corresponds to SAPT for the respective configurations.

The deployment scenario discussed in Section. IV is also considered for MIMO joint transmissions with $(N \times N)$ antenna configurations. The different regions of operations are depicted in Figure. 7. An important observation in this case is that, as the spatial multiplexing rate, N is increased, the region to be served with joint transmission (pink colored) is also increased. This is due to the increased interference created by the multiple independent streams in uncoordinated transmissions (SAPI), which will be more severe at the cell edges where the intended and interfering signals are of almost comparable strengths. This suggests to maximize the joint transmission in MIMO networks for the maximum benefits of MIMO.

VI. Conclusion

In this paper, we have considered the Joint Transmission mechanism of multi-AP coordination. We have provided clear criteria for a decision on the use of JT-TC as against SAPI. We have not addressed the problem of time-domain scheduling across the APs participating in such coordination, and have done the study based on an egalitarian sharing model. We are currently working on extending the analysis to provide an optimal STA assignment and Multi-AP coordination decision to optimize the system throughput.

Appendix A
Proof of the Theorem 1

The BER of an M-QAM can be generally expressed as

$$\mathbb{P}_e(\gamma) = \alpha_M Q\left(\sqrt{\kappa_M \gamma}\right), \tag{19}$$

where α_M and κ_M are constants and are given in Table 6.1 in [15] for different M-modulations schemes. The distribution of $\gamma|_{r,h_1,h_2}$ given in 2 can be derived by using the linear combination property of exponential random variables, $Z = aX + bY$,

$$f_Z(z) = \frac{\lambda}{a-b}\left[e^{-\lambda z/a} - e^{-\lambda z/b}\right] \tag{20}$$

Thus the distribution of γ is given by,

$$\begin{aligned} f_\gamma(\gamma) = &\frac{\sigma^2}{P_1 r^{-\alpha} - P_2 r_2^{-\alpha}} \\ &\times\left[e^{-\gamma\sigma^2 r^\alpha/P_1} - e^{-\gamma\sigma^2 r_2^\alpha/P_2}\right] \end{aligned} \tag{21}$$

By substituting (21) in (19) and taking expectation over γ, the proof is complete.

Appendix B
Proof of Theorem 3

Proof. We have for a positive random variable X, $\mathbb{E}(X) = \int_0^\infty \mathbb{P}(X > t)\mathrm{d}t$. Using the fact that the rate, $R = \log_2(1 + \texttt{SINR})$, is always positive, we can write $\mathbb{E}(R) = \int_0^\infty \mathbb{P}\left[\texttt{SINR} > 2^t - 1\right]\mathrm{d}t$.

The $\texttt{SINR}$ in this case is given by,

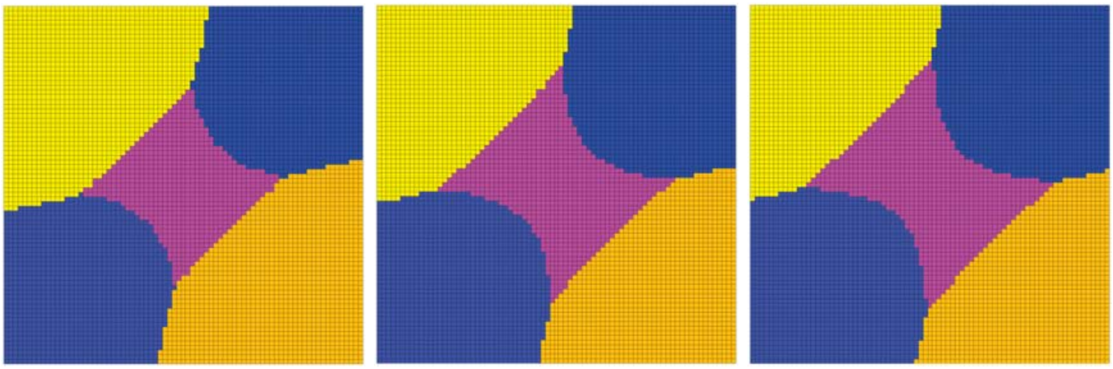
$$\gamma|_{r_1,r_2,h_1,h_2} = \frac{P_1|h_1|^2 r_1^{-\alpha}}{\sigma^2 + P_2|h_2|^2 r_2^{-\alpha}}$$

$$\begin{aligned} \mathbb{P}[\texttt{SINR} > z] &= \mathbb{P}\left[|h_1|^2 > \frac{z r_1^\alpha}{P_1}\left(\sigma^2 + P_2|h_2|^2 r_2^{-\alpha}\right)\right] \\ &\overset{(a)}{=} \mathbb{E}_h\left[\exp\left(-\frac{z r_1^\alpha}{P_1}\left(\sigma^2 + P_2|h_2|^2 r_2^{-\alpha}\right)\right)\right] \\ &\overset{(b)}{=} \mathbb{E}_h\left[e^{-z r_1^\alpha \sigma^2/P_1}\exp\left(-|h_2|^2 z\frac{P_2 r_1^\alpha}{P_1 r_2^\alpha}\right)\right] \\ &= e^{-z r_1^\alpha\sigma^2/P_1}\left(\frac{1}{1 + z\frac{P_2 r_2^{-\alpha}}{P_1 r_1^{-\alpha}}}\right) \end{aligned} \tag{22}$$

The step (a) is using the tail probability of exponential distribution[4] and step (b) is by using the Laplace transform of exponential distribution[5].

Now by using the property of positive random variables, the proof is complete. □

[4] $\mathbb{P}(X > \theta) = \exp(-\theta)$ if $X \sim \exp(1)$.
[5] $\mathbf{L}_X(s) = \mathbb{E}(\exp(-sX))$, when $X \sim \exp(1)$, $\mathbf{L}(s) = 1/(1+s)$



(a) 1×1 (b) 2×2 (c) 4×4

Fig. 7: Demonstration of a deployment scenario. Comparison of regions of MIMO joint transmission and cell edges for various configurations of $(N_t \times N_r)$ at $\texttt{SNR} = 60$ dB. Blue regions with SAPI, orange and yellow with SAPT and pink with MIMO JT-TC.

Appendix C
Proof of Theorem 4

The squared absolute value of diagonal elements of the **LQ** decomposition of a Rayleigh matrix of order $N \times N$, $|l_{ii}|^2$ is $\Gamma(N-i+1,1)$ distributed[6]. Here the channel coefficient are scaled by pathloss, $r_j^{-\alpha/2}$, therefor, $|l_{ii}^{(j)}|^2$ will be scaled by $r_j^{-\alpha}$.

The distribution of γ_j^{JTM} given in (17) can be derived by using the linear combination property of random variables, $Z = aX + bY$, *i.e.*,

$$f_Z(z) = \frac{1}{ab}\int_0^z f_X(x/a) f_Y((z-x)/b)\mathrm{d}x$$

Therefore,

$$\begin{aligned} f_{\gamma_i}(z) &= \frac{e^{-z/b}}{(ab)^{N-i+1}((N-i)!)^2} \\ &\times \int_0^z x^{N-i}(z-x)^{N-i} e^{-x\beta}\mathrm{d}x \\ &\overset{(a)}{=} \frac{e^{-z/b} z^{N-i}}{(b-a)^{N-i+1}((N-i)!)^2} \\ &\times \sum_{l=0}^{N-i} \binom{N-i}{l} \frac{(-1)^l \Lambda_\beta(z, l+N-i+1)}{(\beta z)^l} \end{aligned} \tag{23}$$

where step (a) is by substituting the binomial expansion of $(z-x)^N$, $\beta = 1/a - 1/b$ and $\Lambda_\beta(z,k)$ is given by,

$$\Lambda_\beta(z,k) = (\Gamma(k) - \Gamma(k, z\beta)) \tag{24}$$

Here $a = P_1 r_1^{-\alpha}/\sigma^2$, $b = P_2 r_2^{-\alpha}/\sigma^2$ and by substituting (23), in (15) and use (14), proof is complete.

[6] $\Gamma(\alpha,\beta)$ is the Gamma distribution with shape parameter α and scale parameter β. The pdf of Gamma distribution is given by, $f(x;\alpha,\beta) = \frac{\beta^\alpha x^{\alpha-1} e^{-\beta x}}{\Gamma(\alpha)}, x > 0, \alpha, \beta > 0,$

References

[1] E. M. Khorov, I. Levitsky, and I. F. Akyildiz, "Current status and directions of IEEE 802.11be, the future Wi-Fi 7," *IEEE Access*, vol. 8, pp. 88 664–88 688, 2020. [Online]. Available: https://doi.org/10.1109/ACCESS.2020.2993448

[2] *Coordinated multi-point operation for LTE physical layer aspects (Release 11), 3GPP TR 36.819, 2011*.

[3] B. Bellalta, "IEEE 802.11ax: High-efficiency WLANS," *IEEE Wireless Communications*, vol. 23, no. 1, pp. 38–46, 2016.

[4] C. Deng, X. Fang, X. Han, X. Wang, L. Yan, R. He, Y. Long, and Y. Guo, "IEEE 802.11be – Wi-Fi 7: New challenges and opportunities," *IEEE Communications Surveys Tutorials*, pp. 1–1, 2020.

[5] Q. Cui, H. Song, H. Wang, M. Valkama, and A. A. Dowhuszko, "Capacity analysis of joint transmission CoMP with adaptive modulation," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 2, pp. 1876–1881, Feb 2017.

[6] *MATLAB WLAN Toolbox*, The MathWorks, Inc., 2018. [Online]. Available: https://www.mathworks.com/help/wlan/

[7] G. Breit, "TGac channel model addendum," *IEEE802.11-09/0308r8*, 2009. [Online]. Available: https://ci.nii.ac.jp/naid/10027986088/en/

[8] E. Telatar, "Capacity of multi-antenna Gaussian channels," *European Transactions on Telecommunications*, vol. 10, no. 6, pp. 585–595, 1999. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/ett.4460100604

[9] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. USA: Cambridge University Press, 2005.

[10] M. Costa, "Writing on dirty paper (corresp.)," *IEEE Trans. Inf. Theor.*, vol. 29, no. 3, p. 439–441, Sep. 2006. [Online]. Available: https://doi.org/10.1109/TIT.1983.1056659

[11] U. Erez and S. Brink, "A close-to-capacity dirty paper coding scheme," *IEEE Trans. Inf. Theor.*, vol. 51, no. 10, p. 3417–3432, Oct. 2005. [Online]. Available: https://doi.org/10.1109/TIT.2005.855586

[12] Q. H. Spencer, A. L. Swindlehurst, and M. Haardt, "Zero-forcing methods for downlink spatial multiplexing in multiuser MIMO channels," *IEEE Trans. Signal Process.*, vol. 52, no. 2, pp. 461–471, 2004. [Online]. Available: https://doi.org/10.1109/TSP.2003.821107

[13] H. Harashima and H. Miyakawa, "Matched-transmission technique for channels with intersymbol interference," *IEEE Transactions on Communications*, vol. 20, no. 4, pp. 774–780, 1972.

[14] M. Tomlinson, "New automatic equaliser employing modulo arithmetic," *Electronics Letters*, vol. 7, no. 5, pp. 138–139, 1971.

[15] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.