# Distributed Opportunistic Scheduling With Interference Mitigation Antenna Selection for Ultra-Dense D2D Networks

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***Abstract*—This letter proposes a novel distributed opportunistic scheduling with interference mitigation antenna selection (DOS-IMAS) to achieve the optimal multi-user diversity in ultra-dense device-to-device (D2D) networks. The proposed DOS-IMAS opportunistically and sequentially selects $K$ D2D pairs in a fully distributed manner based on interference and desired signal power thresholds. We prove that the proposed DOS-IMAS achieves the optimal multi-user diversity $K \log \mathsf{SNR} \log (n)$ under $n = \omega((MN)^{\frac{1}{\kappa-1}} \mathsf{SNR}^{\frac{K(K-1)}{1-\kappa}})$, where $\mathsf{SNR}$, $\mathsf{n}$, $\mathsf{M}$, and $\mathsf{N}$ denote the signal-to-noise ratio, the total number of D2D pairs in the network, the number of transmit antennas, the number of receive antennas, respectively, and $\kappa \in (0, 1)$. The numerical results validate that the proposed technique outperforms existing scheduling schemes in terms of sum rates.**

***Index Terms*—Ultra-dense network, device-to-device communications, distributed opportunistic scheduling, antenna selection.**

## I. Introduction

RECENT emergence of new paradigm such as Internet of Things (IoT) brings the unprecedented growth in the number of communication devices, which poses several challenges to the current cellular networks especially including spectrum scarcity and interference problems. Device-to-device (D2D) communications have drawn much attention as a promising solution to resolve such challenges in the fifth generation (5G) cellular networks. D2D communications can offer the potential benefits for enhanced system capacity, increased spectral efficiency, effective traffic offloading, and latency reduction by allowing two nearby devices in close proximity to directly communicate without intervention of the base station (BS).

Thus far, lots of studies have been carried out on D2D communications. Most of the works have mainly focused on the network controlled link scheduling [1]–[3] and interference management techniques such as power control and resource allocation [4]–[6] in inband D2D networks, where a central controller controls D2D transmissions. However, such centralized schemes may not be applicable to ultra-dense D2D networks because the central controller is hard to fully know all channel state informations (CSIs) among huge number of D2D links due to high computational complexity and large signaling overheads.

There have also been some trials to address such issues and various distributed scheduling algorithms with the multi-user diversity in D2D communications have been proposed [7], [8], [10], [11]. The multi-user diversity is a user scheduling-based diversity technique which selects the best users at any time instance in terms of channel quality or interference, which can considerably improve the spectral efficiency and network throughputs in D2D networks. The distributed opportunistic scheduling protocols based on local CSI ordering and round robin priority allocation [7] and the interference and signal-to-interference ratio (SIR) thresholds [8]–[10] were proposed. The distributed link scheduling algorithm for energy minimization with throughput constraints was also proposed in overlay D2D networks [11]. However, none of the aforementioned works have successfully addressed optimal multi-user diversity with distributed opportunistic scheduling in ultra dense D2D networks.

Motivated by this, this letter proposes a novel distributed opportunistic scheduling with interference mitigation antenna selection (DOS-IMAS) to achieve optimal multi-user diversity in ultra dense D2D networks. The proposed DOS-IMAS opportunistically and sequentially selects $K$ D2D pairs in a fully distributed manner. At each selection step, each D2D pair selects their transmit and receive antennas to minimize interferences to be generated to and received from previously selected D2D pairs, and then one D2D pair satisfying three threshold criteria is selected. We prove that the proposed DOS-IMAS theoretically achieves the optimal sum rate scaling law $K \log \mathsf{SNR} \log (n)$ under $n = \omega((MN)^{\frac{1}{\kappa-1}} \mathsf{SNR}^{\frac{K(K-1)}{1-\kappa}})$, where $\mathsf{SNR}$ denotes the signal-to-noise ratio, $\mathsf{n}$ is the total number of D2D pairs, $\mathsf{M}$ and $\mathsf{N}$ are the number of transmit and receive antennas respectively, $\kappa \in (0, 1)$ is a constant, and $f(x) = \omega(g(x))$ if $\lim_{x \to \infty} \frac{f(x)}{g(x)} = \infty$. The numerical results validate that the proposed DOS-IMAS outperforms other scheduling schemes in terms of sum rates by efficiently controlling the interference and desired signal power.

## II. System Model

We consider ultra dense overlay D2D networks, where $n(\to \infty)$ D2D pairs are densely and uniformly distributed in a coverage area of a BS and there exists no interference

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between D2D and cellular communications. The coverage area of a BS can be any area as long as the network is sufficiently dense. The BS is not able to schedule all D2D pairs due to limited communication resources and scheduling complexity, and hence the D2D pairs to be activated should be scheduled in a distributed manner. All transmitters (Txs) and receivers (Rxs) have $M \geq 1$ and $N \geq 1$ antennas, respectively. Each Tx has an independent message to be sent to its designated Rx. Due to limited resources and scheduling complexity, only $K(\ll n)$ D2D pairs are assumed to be allowed to communicate simultaneously, where $K$ can be any positive integer. The D2D pairs are assumed to experience the quasi-static or static channel environments during whole scheduling process and hence a time-invariant frequency flat fading channel is assumed. All D2D pairs are assumed to be synchronized via cellular infrastructure and the time is slotted.

Let $U$ be the set of indices of all D2D pairs in the networks and $S_k$ be the set of indices of selected $k$ D2D pairs such that $1 \leq k \leq K$ and $S_k \subset U$. Then, $S_k^c = U \setminus S_k$ denotes the set of indices of remaining D2D pairs after the $k$-th D2D pair selection step. The proposed scheduler selects $K$ D2D pairs opportunistically and sequentially, so $S_k \subset S_l$ holds for all $l \geq k$ and $|S_k| = k$. Once $K$ D2D pairs are scheduled by the proposed scheduling explained in the next section, then each selected Tx sends a single spatial stream to its designated Rx simultaneously. For notation simplicity, we denote the indices of the selected $K$ D2D pairs as $\mathcal{K} = \{1, 2, \ldots, K\}$, where the element $k \in \mathcal{K}$ denotes the index of the $k$-th selected D2D pair. For $i, j \in \mathcal{K}$, the received signal at the $j$-th selected D2D pair is given by

$$\mathbf{y}_j = \sqrt{\gamma_{j,j}}\ \mathbf{H}_{j,j}\mathbf{w}_j s_j + \sum_{i=1, i\neq j}^{K} \sqrt{\gamma_{i,j}}\mathbf{H}_{i,j}\mathbf{w}_i s_i + \mathbf{z}_j, \quad (1)$$

where $\sqrt{\gamma_{i,j}} (\leq 1)$ denotes the path-loss between the $i$-th D2D Tx and the $j$-th D2D Rx. $\mathbf{H}_{i,j} \in \mathbb{C}^{N\times M}$ indicates the channel matrix between the $i$-th Tx and the $j$-th Rx of which each element is modeled as an independent and identically distributed (i.i.d.) complex Gaussian random variable with zero mean and unit variance, which implies that all small-scale fading channels follow the Rayleigh distribution. $s_j$ indicates the transmitted signal of the $j$-th D2D Tx. $\mathbf{w}_j \in \mathbb{C}^{M\times 1}$ denotes the transmit beamforming vector at the $j$-th D2D Tx and $\mathbf{z}_j \in \mathbb{C}^{N\times 1}$ denotes an Gaussian noise vector at the $j$-th D2D Rx of which elements have zero mean and unit variance. Each Tx has the average power constraint $\mathbb{E}[|s_j|^2] \leq \mathsf{SNR}$.

## III. Distributed Opportunistic Scheduling With Interference Mitigation Antenna Selection

In this section, we propose DOS-IMAS which opportunistically and sequentially selects $K$ D2D pairs in a distributed manner. In each D2D pair selection step, the interference channels to previously selected D2D pairs and desired channel are assumed to be perfectly estimated via pilot signal exchange. The proposed scheduling operates with time division duplex (TDD) mode and thus the channel reciprocity holds.

### A. Transmit & Receive Antenna Selection

In the proposed DOS-IMAS, each D2D pair selects one transmit and receive antenna. That is, each D2D pair chooses one of columns of $\mathbf{I}_M$ and $\mathbf{I}_N$ as the transmit beamforming vector ($\mathbf{w}_s$) and receive beamforming vector ($\mathbf{u}_s$), respectively, where $\mathbf{I}_L = [\mathbf{e}_1, \ldots, \mathbf{e}_L]$ for $L \in \{M, N\}$ denotes $L \times L$ dimensional identity matrix and $\mathbf{e}_l$ denotes the $l$-th column of $\mathbf{I}_L$. For an initial D2D pair selection step, i.e., $k = 1$, each D2D pair $s \in U$ randomly chooses the transmit and receive antennas due to the lack of knowledge for the channels of other D2D pairs. For $2 \leq k \leq K$-th selections steps, each D2D pair selects the Tx and Rx antennas to minimize the generating and receiving interference channel power each.

For the $l$-th antenna of a Tx $s \in S_{k-1}^c$ (i.e., $\tilde{\mathbf{w}}_s = \mathbf{e}_l$), its generating interference channel power (GICP) to the previously selected $k$–1 Rxs in $S_{k-1}$ is given by

$$\eta_{\mathrm{GI}}^{k,s}(l) = \sum_{j=1}^{k-1} |\mathbf{u}_j^H \mathbf{H}_{s,j}\tilde{\mathbf{w}}_s|^2 = \sum_{j=1}^{k-1} |\mathbf{u}_j^H \mathbf{h}_{s,j}(l)|^2, \quad (2)$$

where $\mathbf{u}_j$ is the receive beamforming vector of the $j$-th selected Rx and $\mathbf{h}_{s,j}(l) \in \mathbb{C}^{N\times 1}$ is the $l$-th column vector of channel matrix $\mathbf{H}_{s,j}$. The transmit beamforming vector to minimize GICP in (2) is determined as $\mathbf{w}_s = \mathbf{e}_{l_{k,s}}$, where the index $l_{k,s}$ is obtained from $l_{k,s} = \arg\min_{1\leq l\leq M} \eta_{\mathrm{GI}}^{k,s}(l)$. The generating interference power sum of a Tx $s \in S_{k-1}^c$ to the previously selected $k$–1 Rxs in $S_{k-1}$ is given by $I_{\mathrm{GI}}^{k,s} = \sum_{j=1}^{k-1} \gamma_{s,j} |\mathbf{u}_j^H \mathbf{h}_{s,j}(l_{k,s})|^2 \mathsf{SNR}$.

Similarly, for the $q$-th antenna of a Rx $s \in S_{k-1}^c$ (i.e., $\tilde{\mathbf{u}}_s = \mathbf{e}_q$), its receiving interference channel power (RICP) from the previously selected $k$–1 Txs in $S_{k-1}$ is given by

$$\eta_{\mathrm{RI}}^{k,s}(q) = \sum_{i=1}^{k-1} |\tilde{\mathbf{u}}_s^H \mathbf{H}_{i,s}\mathbf{w}_i|^2 = \sum_{i=1}^{k-1} |\mathbf{g}_{i,s}(q)\mathbf{w}_i|^2, \quad (3)$$

where $\mathbf{w}_i$ is the transmit beamforming vector of the $i$-th selected Tx and $\mathbf{g}_{i,s}(q) \in \mathbb{C}^{1\times M}$ is the $q$-th row vector of the channel matrix $\mathbf{H}_{i,s}$. The receive beamforming vector to minimize RICP in (3) is determined as $\mathbf{u}_s = \mathbf{e}_{q_{k,s}}$, where the index $q_{k,s}$ is obtained from $q_{k,s} = \arg\min_{1\leq q\leq N} \eta_{\mathrm{RI}}^{k,s}(q)$. The receiving interference power sum of a Rx $s \in S_{k-1}^c$ from the previously selected $k$–1 Txs is given by $I_{\mathrm{RI}}^{k,s} = \sum_{i=1}^{k-1} \gamma_{i,s} |\mathbf{g}_{i,s}(q_{k,s})\mathbf{w}_i|^2 \mathsf{SNR}$.

For $1 \leq k \leq K$, the desired signal power of an arbitrary D2D pair $s \in S_{k-1}^c$ with their designed transmit and receive vectors $\mathbf{w}_s$ and $\mathbf{u}_s$ is given by

$$D_{k,s} = \gamma_{s,s} |\mathbf{u}_s^H \mathbf{H}_{s,s}\mathbf{w}_s|^2 \mathsf{SNR}, \quad (4)$$

where $S_0^c = U$ for $k = 1$.

### B. Scheduling Procedures

In this subsection, we describe the overall scheduling procedures of the proposed DOS-IMAS. All D2D pairs have the knowledge for the pre-determined threshold values for each scheduling step via the broadcast of the BS.

• *Initial D2D pair selection (k = 1):* Each D2D pair $s \in U$ randomly chooses Tx and Rx antennas, and each Tx generates a random backoff time of which maximum is pre-configured as

$T_{\max}$. Starting from a Tx with a minimum backoff time, each Tx sends its selected antenna index (i.e., $\mathbf{w}_s$) along with pilot signal to its designated Rx and then the designated Rx checks whether $D_{1,s} \geq \epsilon_{\mathrm{D}}$ is satisfied with its randomly selected receive antenna index (i.e., $\mathbf{u}_s$). If such condition is satisfied, then the corresponding Rx sends its selected receive antenna index along with pilot signal back to its designated Tx, and all remaining Txs stop to send their transmit antenna indices and reset the backoff time. The corresponding D2D pair is selected as the first D2D pair and its index is added in $S_1$.

• *$2 \leq k \leq K$-th D2D pair selection:* For $2 \leq k \leq K$-th selection step, each D2D pair $s \in S_{k-1}^c$ selects the transmit and receive antennas (i.e., $\mathbf{w}_s$ and $\mathbf{u}_s$) according to the methods described in Section III-A by overhearing the transmitted Tx and Rx antenna indices in previous selection steps. Each Tx $s \in S_{k-1}^c$ checks if $I_{\mathrm{GI}}^{k,s} \leq \epsilon_{k-1}$ is satisfied and then Txs satisfying such condition generate the backoff time as $T_{\max} \cdot \frac{I_{\mathrm{GI}}^{k,s}}{\epsilon_{k-1}}$. Note that the smaller $I_{\mathrm{GI}}^{k,s}$ generates the smaller backoff time. Starting from a Tx with a minimum backoff time, each Tx generating backoff time sends its selected antenna index (i.e., $\mathbf{w}_s$) along with pilot signal to its designated Rx and then the designated Rx checks if $D_{k,s} \geq \epsilon_{\mathrm{D}}$ and $I_{\mathrm{RI}}^{k,s} \leq \epsilon_{k-1}$ with its selected receive antenna index (i.e., $\mathbf{u}_s$). If such conditions are simultaneously satisfied, then the corresponding Rx sends its selected receive antenna index along with pilot signal back to its designated Tx and all remaining Txs stop to send their transmit antenna indices and reset the backoff time. The corresponding D2D pair is selected as the $k$-th D2D pair and its index is added in $S_k$. This process is repeated until $k = K$.

• *Data transmission and decoding:* After $K$ D2D pairs are successfully selected, the scheduled Txs simultaneously send their independent data with their selected transmit antennas and then the designated Rxs decode them by using selected receive antennas.

## IV. Sum Rate Scaling Law Analysis

In this section, we analyze the achievable sum rate scaling law of the proposed DOS-IMAS.

*Theorem 1:* When the Tx and Rx have $\mathsf{M}$ and $\mathsf{N}$ antennas, the proposed DOS-IMAS with $\epsilon_{\mathrm{D}} = \kappa \log(n)\mathsf{SNR}\gamma_{\min}$ and $\epsilon_{k-1} = \sqrt[k-1]{e(k-1)\Gamma(k-1)2^{k-1}}$ for $2 \leq k \leq K$ asymptotically achieves the sum rate scaling law $\Theta(K\log(\mathsf{SNR}\log(n)))$ in high $\mathsf{SNR}$ regime if the network size $\mathsf{n}$ scales as $n = \omega((MN)^{\frac{1}{\kappa-1}}\mathsf{SNR}^{\frac{K(K-1)}{1-\kappa}})$, where $\gamma_{\min}$ is the minimum pathloss in the network of a finite area and $\kappa \in (0,1)$.

*Proof:* In order that total $K$ D2D pairs are successfully scheduled by the proposed DOS-IMAS, there should exist at least one D2D pair satisfying $\mathcal{C}_{1,3}$ in the first D2D pair selection step and at least one D2D pair simultaneously satisfying the following three criteria for $2 \leq k \leq K$-th selection step: i) $\mathcal{C}_{k,1} : I_{\mathrm{GI}}^{k,s} \leq \epsilon_{k-1}$, ii) $\mathcal{C}_{k,2} : I_{\mathrm{RI}}^{k,s} \leq \epsilon_{k-1}$, and iii) $\mathcal{C}_{k,3} : D_{k,s} \geq \epsilon_{\mathrm{D}}$. Accordingly, the probability that $K$ D2D pairs are successfully scheduled by DOS-IMAS is given by

$$\mathcal{P}_{\text{DOS-IMAS}} = \left[1 - \left(1 - \mathbb{P}[\mathcal{C}_{1,3}]\right)^n\right] \times \prod_{k=2}^{K} 1 - \left(1 - \mathbb{P}[\mathcal{C}_{k,1}]\mathbb{P}[\mathcal{C}_{k,2}]\mathbb{P}[\mathcal{C}_{k,3}]\right)^{n-k+1}. \quad (5)$$

Let us define the GICP and RICP of $s \in S_{k-1}^c$ with designed beamforming vectors $\mathbf{w}_s$ and $\mathbf{u}_s$ as $J_{\mathrm{GI}}^{k,s} = \sum_{j=1}^{k-1} |\mathbf{u}_j^H \mathbf{H}_{s,j}\mathbf{w}_s|^2 = \sum_{j=1}^{k-1} |\mathbf{u}_j^H \mathbf{h}_{s,j}(l_{k,s})|^2$ and $J_{\mathrm{RI}}^{k,s} = \sum_{i=1}^{k-1} |\mathbf{u}_s^H \mathbf{H}_{i,s}\mathbf{w}_i|^2 = \sum_{i=1}^{k-1} |\mathbf{g}_{i,s}(q_{k,s})\mathbf{w}_i|^2$, respectively. Then, the probability $\mathbb{P}[\mathcal{C}_{k,1}]$ in (5) is lower bounded by

$$\mathbb{P}\big[\mathcal{C}_{k,1}\big] \overset{(a)}{\geq} \mathbb{P}\left[\sum_{j=1}^{k-1} |\mathbf{u}_j^H \mathbf{H}_{s,j}\mathbf{w}_s|^2 \leq \frac{\epsilon_{k-1}}{\mathsf{SNR}}\right] \triangleq F_{J_{\mathrm{GI}}^{k,s}}\Big(\frac{\epsilon_{k-1}}{\mathsf{SNR}}\Big), \quad (6)$$

where $F_{J_{\mathrm{GI}}^{k,s}}$ is the cumulative distribution function (CDF) of the random variable $J_{\mathrm{GI}}^{k,s}$. The inequality (a) comes from $\forall \gamma_{s,j} \leq 1$. Similarly, $\mathbb{P}[\mathcal{C}_{k,2}]$ is lower bounded by

$$\mathbb{P}\big[\mathcal{C}_{k,2}\big] \geq F_{J_{\mathrm{RI}}^{k,s}}\Big(\frac{\epsilon_{k-1}}{\mathsf{SNR}}\Big), \quad (7)$$

where $F_{J_{\mathrm{RI}}^{k,s}}$ is the CDF of the random variable $J_{\mathrm{RI}}^{k,s}$. The probability $\mathbb{P}[\mathcal{C}_{k,3}]$ can be lower bounded by

$$\mathbb{P}[\mathcal{C}_{k,3}] \geq \mathbb{P}\Big[\gamma_{\min}|\mathbf{u}_s^H \mathbf{H}_{s,s}\mathbf{w}_s|^2 \geq \frac{\epsilon_{\mathrm{D}}}{\mathsf{SNR}}\Big] \overset{(b)}{=} e^{-\frac{\epsilon_{\mathrm{D}}}{\gamma_{\min}\mathsf{SNR}}}, \quad (8)$$

where $\gamma_{\min}$ is the minimum pathloss value of the network with finite area. The equality (b) holds from $|\mathbf{u}_s^H \mathbf{H}_{s,s}\mathbf{w}_s|^2$ follows the exponential distribution with unit mean because $\mathbf{u}_s$ and $\mathbf{w}_s$ are isotropically distributed for desired channel.

Using (6), (7), and (8), $\mathcal{P}_{\text{DOS-IMAS}}$ is lower bounded as

$$\mathcal{P}_{\text{DOS-IMAS}} \geq \left[1 - \left(1 - e^{-\frac{\epsilon_{\mathrm{D}}}{\gamma_{\min}\mathsf{SNR}}}\right)^n\right] \times \prod_{k=2}^{K} 1 - \left[1 - F_{J_{\mathrm{GI}}^{k,s}}\Big(\frac{\epsilon_{k-1}}{\mathsf{SNR}}\Big) F_{J_{\mathrm{RI}}^{k,s}}\Big(\frac{\epsilon_{k-1}}{\mathsf{SNR}}\Big) e^{-\frac{\epsilon_{\mathrm{D}}}{\gamma_{\min}\mathsf{SNR}}}\right]^{n-k+1}. \quad (9)$$

We notice that $J_{\mathrm{GI}}^{k,s}$ and $J_{\mathrm{RI}}^{k,s}$ are the minimum of $\mathsf{M}$ and $\mathsf{N}$ independent Chi-square random variables with 2($k$–1) degrees of freedom, respectively. Let us define $L_{k-1}$ as a Chi-square distributed random variable with 2($k$–1) degrees of freedom, where $2 \leq k \leq K$. Then, the CDF of $L_{k-1}$ is given by $F_{L_{k-1}}(l) = \frac{\gamma(k-1, l/2)}{\Gamma(k-1)}$, where $\Gamma(z) = \int_0^\infty t^{z-1}e^{-t}dt$ is the Gamma function and $\gamma(z,x) = \int_0^x t^{z-1}e^{-t}dt$ is the lower complete Gamma function. Hence, the minimum distribution of $a$ independent Chi-square random variables with 2($k$–1) degrees of freedom can be represented as $G_{L_{k-1}}^a(l) = 1-(1-F_{L_{k-1}}(l))^a$. Hence, (9) can be re-written by (10) which is placed in the bottom of the page, where $l_{k-1} = \epsilon_{k-1}/\mathsf{SNR}$.

In the high SNR regime ($\mathsf{SNR} \to \infty$), $0 \leq l_{k-1} < 2$ holds for $2 \leq k \leq K$ and thus (10) can be further lower bounded by using [12, Lemma 1] as (12), shown at the bottom of the next page, where $C_{k-1} = (e(k-1)\Gamma(k-1)2^{k-1})^{-1}$ is a positive

$$\left[1 - \left(1 - e^{-\frac{\epsilon_{\mathrm{D}}}{\gamma_{\min}\mathsf{SNR}}}\right)^n\right] \prod_{k=2}^{K} 1 - \left[1 - G_{L_{k-1}}^M(l_{k-1}) G_{L_{k-1}}^N(l_{k-1}) e^{-\frac{\epsilon_{\mathrm{D}}}{\gamma_{\min}\mathsf{SNR}}}\right]^{n-k+1} \quad (10)$$

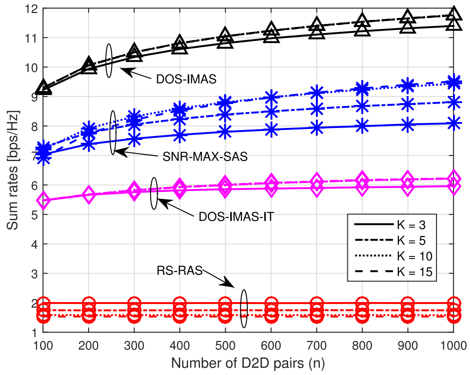


Fig. 1. Comparison of sum rates of four different scheduling schemes for various $K$.

constant, the inequality (c) follows from $(1-x)^a \le 1+ax$ for $0 \le x \le 1$ and $a \ge 1$ and (d) follows from the fact that we choose $\epsilon_{\mathrm{D}} = \gamma_{\min}\kappa\mathsf{SNR}\log(n)$ and $\epsilon_{k-1} = \sqrt[k-1]{\frac{1}{C_{k-1}}}$ for $2 \le k \le K$, where $\kappa \in (0,1)$. Note that (12) goes to zero in the high $\mathsf{SNR}$ regime (i.e., $\mathsf{SNR} \to \infty$) for a finite value of $\mathsf{n}$. However, the probability term for each $k$ goes to one if $MNn^{1-\kappa}$ scales like $\omega(\mathsf{SNR}^{2(k-1)})$, which can be easily derived from the relation of $\lim_{x\to\infty}(1-\frac{a}{x})^x = e^{-a}$. Considering all selection steps $2 \le k \le K$, if $MNn^{1-\kappa}$ scales like at least as $\omega(\mathsf{SNR}^{\sum_{k=2}^{K} 2(k-1)}) = \omega(\mathsf{SNR}^{K(K-1)})$, i.e., the total network size scales like $n = \omega((MN)^{\frac{1}{\kappa-1}}\mathsf{SNR}^{\frac{K(K-1)}{1-\kappa}})$, then the probability (12) goes to one.

If total $K$ D2D pairs are successfully scheduled, their achievable sum rates are given by

$$R_{\mathrm{s}} = \sum_{j=1}^{K}\log\left(1+\frac{\gamma_{j,j}|\mathbf{u}_j^H\mathbf{H}_{j,j}\mathbf{w}_j|^2\mathsf{SNR}}{1+\sum_{i=1,i\neq j}^{K}\gamma_{i,j}|\mathbf{u}_j^H\mathbf{H}_{i,j}\mathbf{w}_i|^2\mathsf{SNR}}\right). \quad (13)$$

Since the GICP and RICP of the scheduled D2D pair are regulated by a constant threshold, the achievable sum rate in (13) can be lower-bounded by $R_{\mathrm{s}} \ge \sum_{j=1}^{K}\log(1+\frac{\epsilon_{\mathrm{D}}}{1+\sum_{k=2}^{K}2\epsilon_{k-1}})$. Thus, as $\mathsf{n}$ goes to infinity, DOS-IMAS asymptotically achieves the sum-rate scaling law of $K\log(\log(n)\mathsf{SNR})$ in the high $\mathsf{SNR}$ regime. ■

*Remark:* If we choose large $\kappa(\to 1)$, then the achievable sum rate increases, but the necessary user scaling law to successfully schedule $K$ D2D pairs increases. On the contrary, for small $\kappa(\to 0)$, the achievable sum rate becomes smaller, but the necessary user scaling law to successfully schedule $K$ D2D pairs decreases.

## V. Numerical Results

In this section, we show some numerical examples to validate our analytical results in the previous section and the feasibility of the proposed DOS-IMAS in the practical range of network size $\mathsf{n}$. We randomly distributed $\mathsf{n}$ D2D pairs in finite two dimensional unit square kilometer. The system parameters are set as $K = 10$, $M = N = 3$, $\kappa = 0.5$, and $P = 10$ (dB), unless otherwise stated.

Fig. 1 compares the sum rates of the proposed DOS-IMAS with those of three other benchmark scheduling schemes for various $K$ versus the number of D2D pairs $\mathsf{n}$:

- Random scheduling with random antenna selection (RS-RAS): Each Tx and Rx randomly selects their antennas and the BS selects random $K$ D2D pairs among $\mathsf{n}$ D2D pairs.
- SNR maximization scheduling and antenna selection (SNR-MAX-SAS): Each Tx and Rx selects their antennas to maximize the SNR of desired channel and the BS selects the best $K$ D2D pairs in terms of SNRs in a centralized way.
- DOS-IMAS with interference thresholds $\epsilon_{k-1}$ only (DOS-IMAS-IT): Total $K$ D2D pairs are selected by the proposed DOS-IMAS with interference threshold conditions only, i.e., $\epsilon_{\mathrm{D}} = 0$.

This figure shows that the sum rates of SNR-MAX-SAS, DOS-IMAS-IT, and DOS-IMAS increase as $\mathsf{n}$ increases while those of RS-RAS are static. This is because SNR-MAX-SAS, DOS-IMAS-IT, and DOS-IMAS obtain the multi-user diversity gains by selecting the best D2D pairs among entire D2D pairs based on their own scheduling strategies, while the RS-RAS cannot obtain any diversity gain due to random scheduling and antenna selection. Interestingly, the sum rates of SNR-MAX-SAS, DOS-IMAS-IT, and DOS-IMAS are gradually increased but saturated as $K$ increases. This is because the desired signal power and interference power simultaneously increase as the number of activated D2D pairs for SNR-MAX-SAS, while DOS-IMAS-IT and DOS-IMAS have the limited number of D2D pairs satisfying the stringent thresholds conditions for finite $\mathsf{n}$. This figure also shows that DOS-IMAS is superior to other schemes for finite $\mathsf{n}$ in terms of the sum rates, which validates that the proposed scheduling scheme effectively controls the desired channel power and interferences.

Figs. 2, 3, and 4 compare the sum rates, the sum interferences, and the average number of selected D2D pairs of the proposed DOS-IMAS for various $\kappa$, $\mathsf{M}$, and $\mathsf{N}$. Those figures show that the sum rates and average number of selected D2D pairs increase as $\mathsf{n}$ increases, while the sum interference decreases. Fig. 4 shows that only some D2D pairs among total $K$ D2D pairs are scheduled for finite $n(\le 1000)$. This is because the proposed DOS-IMAS schedules the D2D pairs based on the thresholds for desired signal power and interferences, which incurs some scheduling failure probabilities at the D2D pair selection step for finite $\mathsf{n}$.

$$\ge \left[1-\left(1-e^{-\frac{\epsilon_{\mathrm{D}}}{\gamma_{\min}\mathsf{SNR}}}\right)^n\right]\prod_{k=2}^{K}1-\left[1-\left\{1-\left(1-C_{k-1}(l_{k-1})^{k-1}\right)^M\right\}\left\{1-\left(1-C_{k-1}(l_{k-1})^{k-1}\right)^N\right\}e^{-\frac{\epsilon_{\mathrm{D}}}{\gamma_{\min}\mathsf{SNR}}}\right]^{n-k+1} \quad (11)$$

$$\overset{(c)}{\ge}\prod_{k=2}^{K}1-\left[1-\left(C_{k-1}(\epsilon_{k-1})^{k-1}\right)^2\frac{MNe^{-\frac{\epsilon_{\mathrm{D}}}{\gamma_{\min}\mathsf{SNR}}}}{\mathsf{SNR}^{2(k-1)}}\right]^{n-k+1}\overset{(d)}{=}\prod_{k=2}^{K}1-\left[1-\frac{MNn^{-\kappa}}{\mathsf{SNR}^{2(k-1)}}\right]^{n-k+1} \quad (12)$$

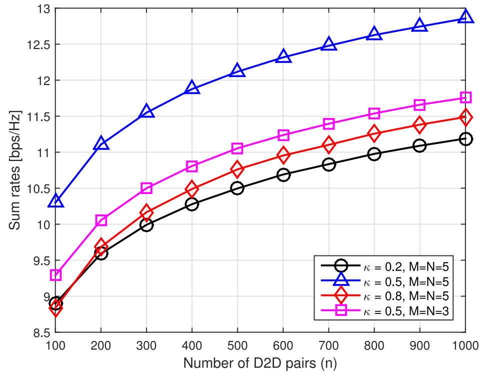


Fig. 2. Sum rates of proposed DOS-IMAS for varying $\kappa$, $\mathsf{M}$, and $\mathsf{N}$.

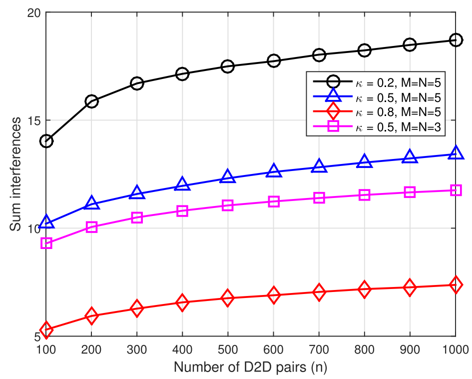


Fig. 3. Sum interference of proposed DOS-IMAS for varying $\kappa$, $\mathsf{M}$, and $\mathsf{N}$.

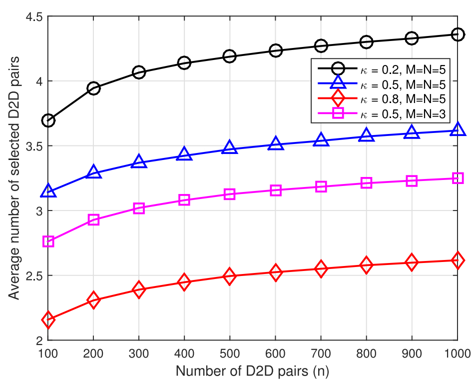


Fig. 4. Average number of selected D2D pairs of proposed DOS-IMAS for varying $\kappa$, $\mathsf{M}$, and $\mathsf{N}$.

However, as $\mathsf{n}$ increases, the chance of successfully scheduling whole $K$ D2D pairs increases. Therefore, our derived theoretical scaling law of $\mathsf{n}$ as a function of $K$ in Theorem 1 tells that how fast the network size should be grown to schedule whole $K$ D2D pairs with probability one.

Figs. 3 and 4 also show that the sum interferences and the average number of selected D2D pairs increase as $\mathsf{M}$ and $\mathsf{N}$ increase while decrease as $\kappa$ increases. The larger number of antennas increases the chance to satisfy the interference threshold conditions with better interference mitigation at each D2D pair selection step. Therefore, it increases the average number of selected D2D pairs, which increases the sum interferences despite of better interference mitigation. Interestingly, even though the sum interferences and the average number of selected D2D pairs gradually decrease as $\kappa$ increases, the sum rates increase and then decrease (See Fig. 2). This implies that both selecting small number of D2D pairs with high desired signal power and deminishing the network interference at the expense of sacrificing the average number of selected D2D pairs is more beneficial for relatively small value of $\kappa$ in terms of sum rates, but which is reversed for high value of $\kappa$. Therefore, choosing the optimal $\kappa$ is necessary depending on the network size.

## VI. Conclusion

This letter proposed the novel distributed opportunistic scheduling with interference mitigation antenna selection to achieve optimal multi-user diversity in ultra dense D2D networks, where the D2D pairs choose their antennas to minimize interferences. The proposed scheme opportunistically and sequentially selects $K$ D2D pairs with interference and desired signal power thresholds in a fully distributed manner. It was proved that the proposed scheme theoretically can achieve optimal multi-user diversity under a certain user scaling law. The proposed scheduling scheme was demonstrated to outperform other scheduling schemes in terms of sum rates by efficiently controlling the interference and desired signal power.

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