Mathematical Formulation for Intelligent Resource Allocation in Wireless Communications Systems

We consider a multi-channel cellular system which allows direct communication among users, i.e., device to device (D2D) communication. In our system model, we assume that the number of channels is K, and for each channel, one cellular user equipment (CUE) transmits data to the base station (BS), i.e., uplink transmission. The number of D2D user equipments (DUEs) is set to N where each DUE consists of one transmitter and one receiver, and $\mathbb{I}$ denotes the set of D2D transmitters. Moreover, the channel gain between the i-th transmitter and the j-th receiver for channel k is denoted as $h^k_{i,j}$, where the index 0 is assigned to the CUE and BS, e.g., $h^k_{0,j}$ is the channel gain between the CUE and j-th DUE for channel k.

The transmit power of the DUEs allocated to each channel is denoted as P^k_i where k and i are the index of the channel and the DUE, respectively. Moreover, we assume that the maximum transmit power of DUEs is P_{T} such that $\sum\limits_{k\leq K} P^k_i \leq P_{\mathrm{T}}$ for all i. Furthermore, we assume that the transmit power of CUE is fixed to P_{M}. In addition, we denote W and N_0 as the bandwidth and the noise spectral density, respectively. Accordingly, in our system model, the spectral efficiency (SE) of DUE i, SE_i, can be written as

$$\mathrm{SE}_i = \sum_{k\leq K} \log_2\left(1 + \frac{h^k_{i,i}P^k_i}{N_0W + \sum_{l\in\mathbb{I}\setminus\{i\}} h^k_{l,i}P^k_l + h^k_{0,i}P_{\mathrm{M}}}\right). \tag{1}$$

Moreover, the energy efficiency (EE) of DUE i, EE_i can be written as

$$\mathrm{EE}_i = \frac{\mathrm{SE}_i}{\sum\limits_{k\leq K} P^k_i + P_{\mathrm{C}}}, \tag{2}$$

where P_{C} is the circuit power of the DUE.

In our work, we consider the optimization with three different objectives which are 1) maximization of SE, 2) maximization of EE, or 3) minimization of the total transmit power. Moreover, we take three constraints into account. First, the transmit power allocated to each channel should be non-negative and the sum of the transmit power for a single DUE must not exceed the maximum transmit power, P_{T} (i.e., the transmit power constraint). Second, the amount of interference caused to the cellular transmission must be less than the threshold I_{T} (i.e., the interference constraint). Third, each D2D transmission should satisfy the minimum QoS requirement, i.e., the SE achieved by each DUE must be greater than the threshold, R_{T} (i.e., QoS constraint).

Accordingly, the optimization problem to maximize the SE of DUEs can be formulated as follows:

$$\begin{aligned}
\underset{P_i^k}{\text{maximize}} \quad & \sum_{i \in \mathbb{I}} \text{SE}_i \\
\text{s.t.} \quad & \sum_{k \leq K} P_i^k \leq P_{\text{T}} && \forall i \in \mathbb{I} \\
& 0 \leq P_i^k && \forall i \in \mathbb{I},\ k \leq K \\
& \textstyle\sum_{l \in \mathbb{I}} h_{l,0}^k P_l^k \leq I_{\text{T}} && \forall k \in \mathbb{K} \\
& \text{SE}_i \geq R_{\text{T}} && \forall i \in \mathbb{I}.
\end{aligned} \tag{3}$$

Similarly, the optimization problem to maximize the EE of DUEs can be formulated as follows:

$$\begin{aligned}
\underset{P_i^k}{\text{maximize}} \quad & \sum_{i \in \mathbb{I}} \text{EE}_i \\
\text{s.t.} \quad & \sum_{k \leq K} P_i^k \leq P_{\text{T}} && \forall i \in \mathbb{I} \\
& 0 \leq P_i^k && \forall i \in \mathbb{I},\ k \leq K \\
& \textstyle\sum_{l \in \mathbb{I}} h_{l,0}^k P_l^k \leq I_{\text{T}} && \forall k \in \mathbb{K} \\
& \text{SE}_i \geq R_{\text{T}} && \forall i \in \mathbb{I}.
\end{aligned} \tag{4}$$

Finally, the optimization problem to minimize the total transmit power of DUEs can be formulated as follows:

$$\begin{aligned}
\underset{P_i^k}{\text{minimize}} \quad & \sum_{i \in \mathbb{I}} \sum_{k \leq K} P_i^k \\
\text{s.t.} \quad & \sum_{k \leq K} P_i^k \leq P_{\text{T}} && \forall i \in \mathbb{I} \\
& 0 \leq P_i^k && \forall i \in \mathbb{I},\ k \leq K \\
& \textstyle\sum_{l \in \mathbb{I}} h_{l,0}^k P_l^k \leq I_{\text{T}} && \forall k \in \mathbb{K} \\
& \text{SE}_i \geq R_{\text{T}} && \forall i \in \mathbb{I}.
\end{aligned} \tag{5}$$

The optimization problems formulated in (3) - (5) are nonconvex such that they are extremely hard to be solved analytically with low computational complexity. Moreover, given that the optimal solutions depend on the channel gain, the optimal transmit power has to be re-derived whenever the channel gain changes.

Additional Simulation Results

In this section, we have provided simulation results which were not added to the manuscript due to the limitation of journal.

First, in Figs. 1-3, we show the performance of our proposed scheme as a function of number of D2D user equipments (DUEs), N, when the number of channels, K, is 10 and the size of area,

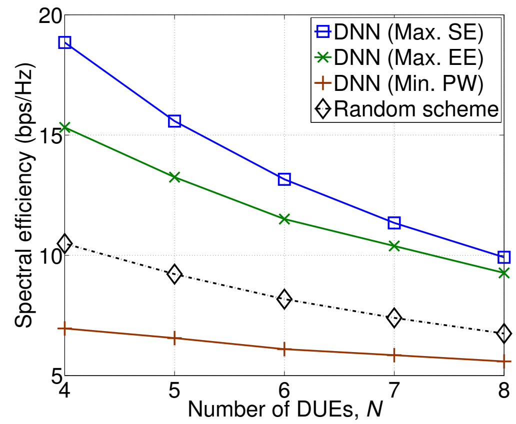

Fig. 1. Spectral efficiency vs. N when D = 30 m and K = 10.

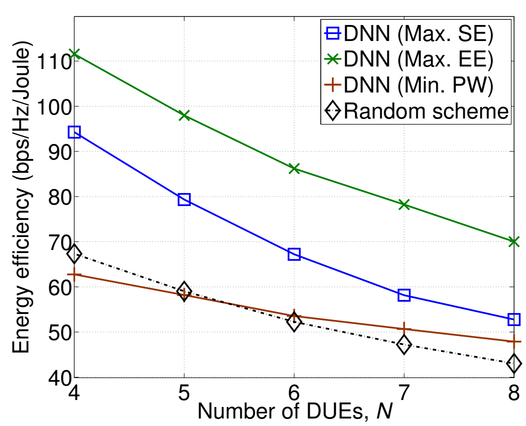

Fig. 2. Energy efficiency vs. N when D = 30 m and K = 10.

D, is 30 m. In these simulation, we are unable to evaluate the performance of ES scheme due to the excessive computation time. For example, the required computation time for ES scheme is larger than 30 seconds for one channel realization when $N = K = 4$, such that obtaining one simulation points requires approximately 7 days. Consequently, we are also unable to show the performance of DNN based RA using SL because the label data for training which is collected using ES scheme, cannot be obtained.

First of all, we can find that the our proposed DNN-based RA achieves desired goals. Specifically, the DNN-based RA for SE maximization shows the highest SE, the DNN-based RA for EE maximization shows the highest EE, and the DNN-based RA for transmit power minimization shows the lowest total transmit power. Especially, we can observe that our proposed scheme can achieve sufficiently higher performance compared to the random scheme. These simulation

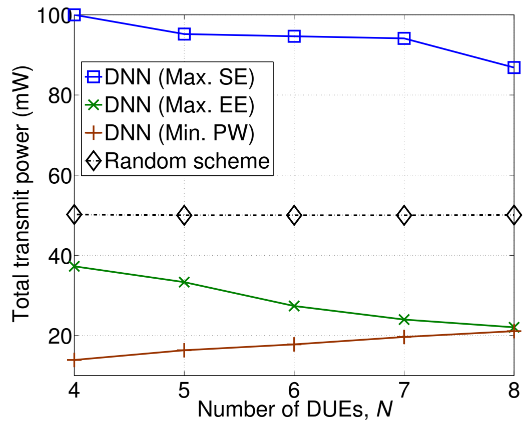

Fig. 3. Total transmit power vs. N when D = 30 m and K = 10.

results justify the usefulness of our proposed DNN-based RA.

Moreover, as can be seen from the simulation results, the average SE and EE decrease as the number of DUEs increases because more interference is incurred among DUEs. Moreover, we can find that the total transmit power of DNN with the maximization of SE (Max. SE) and the maximization of EE (Max. EE) decreases as the number of DUEs increases in order to meet the constraint on the interference regarding cellular transmission, i.e., $\sum_{l\in\mathbb{I}} h_{l,0}^k P_l^k \le I_{\mathrm{T}}$. However, for the DNN with the minimization of transmit power (Min. PW), the QoS constraint regarding DUEs, $\mathrm{SE}_i \ge R_{\mathrm{T}}$, is more critical such that the total transmit power increases as N increases.

Next, we have compared the performance of our proposed scheme with that of WMMSE-based scheme. To this end, we have removed the interference and QoS constraint and also taken into account single channel system. The modified optimization problem is written as follows:

$$\begin{aligned} \underset{P_i}{\text{maximize}} \quad & \sum_{i\in\mathbb{I}} \log_2\left(1+\frac{h_{i,i}P_i}{N_0W+\sum_{l\in\mathbb{I}\setminus\{i\}} h_{l,i}P_l + h_{0,i}P_{\mathrm{M}}}\right) \\ \text{s.t.} \quad & 0 \le P_i \le P_{\mathrm{T}} \qquad \forall i \in \mathbb{I}, \end{aligned} \tag{6}$$

where the superscript k is dropped since we considered the single channel system.

The optimization problem in (6) can be solved by the WMMSE-based RA proposed in [1]. In Figs. 4 and 5, we show the average SE of DUEs by varying the number of DUEs, N, when D = 30 m, and 60 m, respectively. Moreover, we also show the computation time in Fig. 6. In the performance evaluation, we have also considered DNN based RA using SL.

As can be seen from the simulation results, our proposed scheme and DNN with SL shows similar SE with the WMMSE-based scheme and higher SE compared to random scheme, which

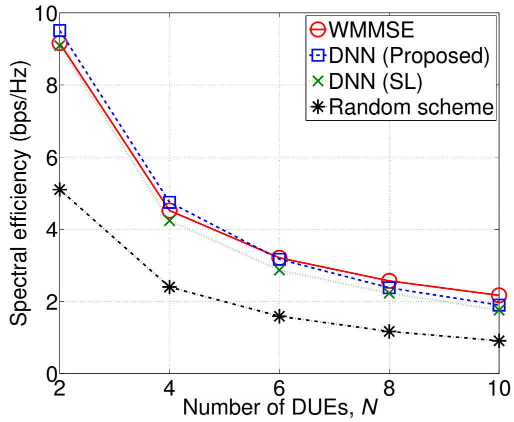

Fig. 4. Spectral efficiency vs. N when D = 30 m.

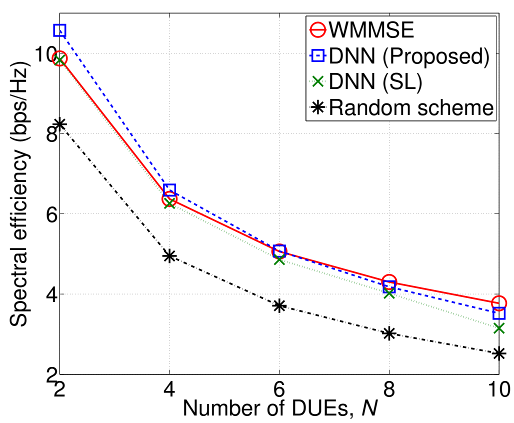

Fig. 5. Spectral efficiency vs. N when D = 60 m.

highlights the necessity of proper resource allocation. Especially, we can find that the SE of our proposed scheme is higher than that of WMMSE scheme when N is small while the SE of DNN with SL is always smaller than that of WMMSE. However, as N increases, the SE of our proposed scheme becomes smaller than that of WMMSE scheme mainly due to the lack of computation capability of DNN structure since we consider smaller DNN structure. Moreover, we can find that the SE decreases as the number of DUEs increases, due to the increased interference among DUEs. For the same reason, the SE of considered schemes when D = 30 m is lower than that of SE when D = 60 m. Furthermore, we can find that the computation time of WMMSE based scheme can be smaller than that of DNN based scheme for small N, however, as N increases, the computation time of DNN based scheme becomes smaller than

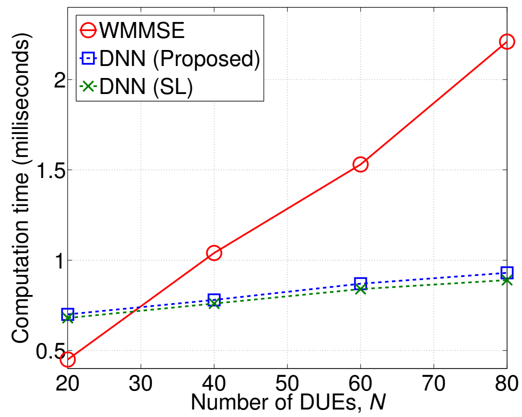

Fig. 6. Computation time vs. N.

that of WMMSE based scheme. From these results, we can confirm that our proposed scheme is beneficial when the number of users is large, e.g., ultra-dense network (UDN).

References

[1] H. Sun, X. Chen, Q. Shi, M. Hong, X. Fu, and N. D. Sidiropoulos, "Learning to optimize: Training deep neural networks for wireless resource management," *arXiv preprint arXiv:1705.09412*, 2017.