Optimal Resource Allocation Strategy for ISAC Cellular Network with Multiple User Demands

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Future communication networks are widely considered to be able to provide both high-speed communication service and reliable sensing service. Integrated sensing and communication (ISAC) has been a novel trend due to its possible hardware gain and spectrum gain by the integration of signal communication and sensing capabilities. Appropriate resource allocation strategy is essential for ensuring the quality of both communication and sensing services in terms of ISAC. Existing ISAC-based resource allocation schemes mainly focus on the coexistence of sensing and communication. However, in multi-user ISAC networks, the services required by users are diverse, including sensing-only, communication-only and dual-function cases. To this end, we proposes a resource allocation strategy based on user quality of service(QoS). Specifically, the sum rate of cellular network is maximized via optimizing spectrum resource selection and transmit power, while meeting the sensing QoS. We achieve the optimal solution to the entire problem by first demonstrating that the communication rate in this paper is a monotonically increasing function of sensing power, allowing us to obtain the optimal power allocation scheme. Subsequently, we employ a matching method to obtain the optimal spectrum sharing scheme. Numerical results validate the effectiveness of our proposed algorithm and also unveil a more flexible trade-off in ISAC systems over benchmark scheme.

Introduction: The integration of sensing and communication (ISAC) technology is a key feature of next-generation communication networks, providing both high-speed communication and ubiquitous sensing services[1–4]. This technology enables the integration of signal communication and sensing capabilities, resulting in several benefits [5]. Firstly, the combination of these two functions effectively alleviates spectrum congestion and improves spectrum utilization efficiency[6]. Secondly, the sharing of signal processing technology and hardware architecture allows for integration gain[5]. Finally, the effective combination of sensing and communication functions enables collaborative gain[5]. Base station (BS) equipped with ISAC technology can provide users with high-speed communication data transmission services as well as high-resolution sensing services such as target detection, location, and tracking. This enables a wide range of applications that require accurate location information or target state information [7].

Prior research has often tackled resource allocation in scenarios involving concurrent sensing and communication. Nevertheless, it's crucial to recognize that user requirements frequently exhibit asymmetry, resulting in instances where the need for sensing and communication does not align. Consequently, an excessive focus on either sensing or communication may result in suboptimal utilization of both spectrum and energy resources. In light of this observation, the present study investigates the resources allocation tailored to the specific requirements of both radar and communication users. In summary, the main contributions of this paper are as follows:

- In this study, we investigate the issue of user service in ISAC cellular networks. In these networks, BS provides communication services, while users deliver sensing services based on their individual needs. We formulate this as an optimization problem.
- We categorize users into two groups based on their service requirements: communication service (CS) and sensing services (SS). Our objective is to maximize the sum rate while ensuring constraint on the QoS of sensing. We derive the power allocation scheme based on the monotonic relationship between power allocation and the communication sum rate. Subsequently, we employ the Hungarian algorithm to determine the spectrum sharing matching scheme, thus obtaining the optimal solution to the optimization problem.

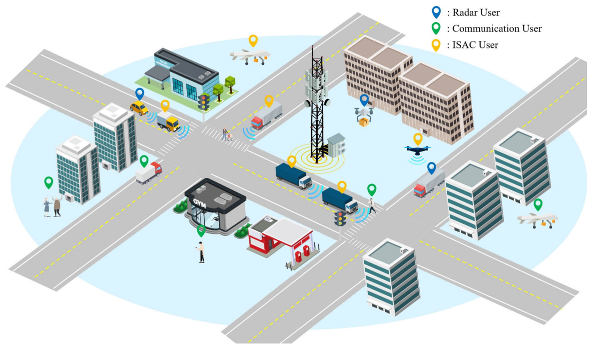


Fig 1 *The illustration of single cellular network ISAC scenario.*

- Finally, we conducted a simulation to evaluate the effectiveness of our proposed resource allocation algorithm.

System Model and Problem Formulation: We consider an OFDMA multi-user network in the uplink transmission as shown in Fig 1. The demends of users in this network can be categorized into communication requirements, sensing requirements and ISAC requirements. We assume that the set of users requiring CS is denoted as $\mathcal{M} = \{1, 2, \ldots, M\}$, the set of users requiring SS is denoted as $\mathcal{J} = \{1, 2, \ldots, J\}$ and the set of users requiring ISAC services is denoted as $Q = \{1, 2, \ldots, Q\}$. However, we represent ISAC service as a combination of both CS and SS. Therefore, we express the CS set and SS set within the entire network coverage as follows:

$$\begin{cases} N = M + Q & \text{Number of CS} \\ K = J + Q & \text{Number of SS} \end{cases} \tag{1}$$

We make h_n represent the channel gain from the user to BS in the uplink communication service n, $h_{n,k}$ represents the interference channel gain from CS n to SS k. Similarly, denote g_k as the channel gain of SS k, $g_{c,k}$ represent the interference channel gain from SS k to BS.

We derive the SINR of CS n and SS k into (2) and (3), respectively.

$$\text{SINR}_n = \frac{P_{c,n} h_n}{\sum\limits_{k \in \mathcal{K}} f_{n,k} P_{s,k} g_{c,k} + \sigma_c^2} \tag{2}$$

$$\text{SINR}_k = \frac{P_{s,k} g_k}{\sum\limits_{n \in N} f_{n,k} P_{c,n} h_{n,k} + \sigma_s^2} \tag{3}$$

where $P_{c,n}$ is the transmit power of the n-th CS and $P_{s,k}$ is transmit power of the k-th SS . σ_c^2 and σ_s^2 are the noise power of sensing channel and communication channel, respectively. $f_{n,k}$ is a binary variable that represents the channel resource block allocation. When $f_{n,k} = 1$ means the n-th CS shared channel resource block with k-th SS and $f_{n,k} = 0$ otherwise. Then the communication rate of the n-th CS is formulated as

$$R_n(f_{n,k}, P_{c,n}, P_{s,k}) = \log_2(1 + \text{SINR}_n) \tag{4}$$

Next, let us consider the performance evaluation metrics for radar sensing. For both estimation and detection problems, the SINR is a crucial metric in radar sensing. With all other parameters held constant, a higher SINR results in an increased probability of detection or improved estimation accuracy. Therefore, it is necessary to ensure that the SINR of radar sensing is greater than a certain threshold to guarantee the accuracy of subsequent estimations,

$$\text{SINR}_k = \frac{P_{s,k} g_k}{\sum\limits_{n \in N} f_{n,k} P_{c,n} h_{n,k} + \sigma_s^2} \geq \Gamma. \tag{5}$$

This paper focuses on maximizing the communication sum rate by optimizing signal power $(P_{c,n}, P_{s,k})$ and channel block allocation factor $f_{n,k}$.

$$\max_{f_{n,k},P_{c,n},P_{s,k}} \sum_{n=1}^{N} R_n(f_{n,k},P_{c,n},P_{s,k}) \tag{6a}$$

$$\text{s.t.} \sum_{n\in\mathcal{N}} f_{n,k} \le 1, \forall k \in \mathcal{K} \tag{6b}$$

$$\sum_{k\in\mathcal{K}} f_{n,k} \le 1, \forall n \in \mathcal{N} \tag{6c}$$

$$f_{n,k} \in \{0,1\}, \forall n \in \mathcal{N}, k \in \mathcal{K} \tag{6d}$$

$$0 \le P_{c,n} \le P_c^{\max}, \forall n \in \mathcal{N} \tag{6e}$$

$$0 \le P_{s,k} \le P_s^{\max}, \forall k \in \mathcal{K} \tag{6f}$$

$$R_n(f_{n,k},P_{c,n},P_{s,k}) \ge R_0, \forall n \in \mathcal{N} \tag{6g}$$

$$\text{SINR}_k \ge \Gamma, \forall k \in \mathcal{K} \tag{6h}$$

Constraints (6b) and (6d) indicate that a channel resource block can be shared between a pair of CS and SS. Constraint (6c) and (6d) indicate that one SS can access at most one channel resource block. Constraints (6b), (6c) and (6d) limit the sharing of multiple resource blocks between CS and SS, which reduces the complexity of inter-user interference in a single ISAC cellular network. $P_c^{\max}$ and $P_s^{\max}$ are the maximum transmit powers of the CS and SS, respectively. (6e) and (6f) ensure that the actual transmission power of the CS and SS does not exceed the maximum power of the system, guaranteeing the safety of the system. R_0 is the minimum communication rate required by the BS to guarantee the minimum communication QoS. Γ is the minimum SINR needed by theSS to establish a reliable detection. The aforementioned constraints ensure that the focus of this paper is on spectrum resource optimization rather than interference management, providing preliminary exploration for more complex and challenging research.

The optimization problem denoted by (6) is a mixed-integer combinatorial optimization problem, which presents significant challenges in terms of resolution. Specifically, the non-convex combinatorial objective function (6a), the nonconvex constraint functions in (6g), (6h), and (6d), and the binary selection constraint (6d) pose substantial obstacle for the design of an efficient resource allocation algorithm.

The Optimization of Resource Allocation: In this section, we solve problem (6) optimally by applying decomposition manner and Hungarian method. We develop a efficiently resource allocation algorithm to maximize the sum rate of CS while taking into account the detection QoS of SS.

Solving $(P_{c,n}, P_{s,k})$: Before solving the power allocation scheme, we initially assume that the sharing of channel resource blocks between CS and SS has already been determined. Assuming that the k-th SS and the n-th CS share a channel resource block, the optimization problem can be reformulated as follows:

$$\max_{P_{c,n},P_{s,k}} \sum_{n=1}^{N} R_n(P_{c,n},P_{s,k}) \tag{7a}$$

$$\text{s.t. } 0 \le P_{c,n} \le P_c^{\max}, \quad \forall n \in \mathcal{N} \tag{7b}$$

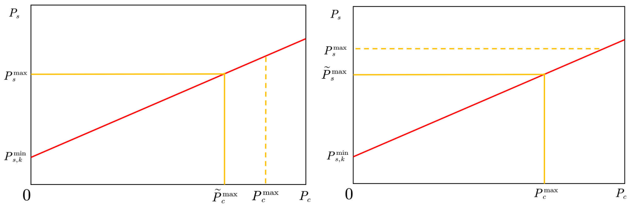
$$0 \le P_{s,k} \le P_s^{\max}, \quad \forall k \in \mathcal{K} \tag{7c}$$

$$\text{SINR}_k \ge \Gamma, \forall k \in \mathcal{K} \tag{7d}$$

We have removed (6g) and will use it as a criterion when solving the channel resource block allocation scheme. This approach also offers the advantage of simplifying the problem. By transforming (7d) with respect to power $P_{c,n}$, we can obtain the following,

$$P_{c,n} \le \frac{1}{h_{n,k}}\left(\frac{1}{\Gamma}P_{s,k}g_k - \sigma_s^2\right). \tag{8}$$

Let $Q(P_{s,k}) = \frac{1}{h_{n,k}}(\frac{1}{\Gamma}P_{s,k}g_k - \sigma_s^2)$. Obviously, $Q(P_{s,k})$ is a monotonously increasing function about $P_{s,k}$. Due to $P_{c,n} \ge 0$, we have $Q(P_{s,k}) \ge 0$, in particular, when $Q(P_{s,k}) = 0$ equals zero, We can get the minimum power $P_{s,k}^{\min}$, which is $P_{s,k}^{\min} = \frac{\sigma_s^2\Gamma}{g_k}$. The maximum available power of RU is not only related to the limitation of power $P_s^{\max}$, but also related to the limitation of power $P_c^{\max}$. According to the specific situation, our analysis is as follows.



(a) (b)

Fig 2 *Maximum available power for CS and SS: (a) $P_c^{\max} \ge P_s^{\max}$; (b) $P_c^{\max} \le P_s^{\max}$.*

To simplify the representation, we denote $\tilde{P}_s^{\max} = \frac{\Gamma(P_c^{\max}h_k+\sigma_s^2)}{g_k}$ and $\tilde{P}_c^{\max} = \frac{1}{h_{n,k}}(\frac{1}{\Gamma}P_s^{\max}g_k - \sigma_s^2)$. Then, we get the optimal power allocation solution of (7) in the following lemma.

Lemma 1. *The optimal power allocation solution to optimization problem* (7) *is given by* (9) *and* (10).

$$P_{c,k}^* = \begin{cases} \tilde{P}_c^{\max}, & \text{if } \frac{1}{h_{n,k}}(\frac{1}{\Gamma}P_s^{\max}g_k - \sigma_s^2) \le P_c^{\max} \\ P_c^{\max}, & \text{if } \frac{1}{h_{n,k}}(\frac{1}{\Gamma}P_s^{\max}g_k - \sigma_s^2) > P_c^{\max} \end{cases} \tag{9}$$

$$P_{s,k}^* = \begin{cases} P_s^{\max}, & \text{if } \frac{1}{h_{n,k}}(\frac{1}{\Gamma}P_s^{\max}g_k - \sigma_s^2) \le P_c^{\max} \\ \tilde{P}_s^{\max}, & \text{if } \frac{1}{h_{n,k}}(\frac{1}{\Gamma}P_s^{\max}g_k - \sigma_s^2) > P_c^{\max} \end{cases} \tag{10}$$

Proof. From (7a), we can obtain that $R_n(P_{c,n}, P_{s,k})$ is a monotonically increasing function of $P_{c,n}$ when $P_{s,k}$ is fixed. However, $R_n(P_{c,n}, P_{s,k})$ is a monotonically decreasing function of $P_{s,k}$ when $P_{c,n}$ is fixed. In particular, according to $P_{c,n} \le Q(P_{s,k})$, we consider the case where $P_{c,n} = Q(P_{s,k})$, this is a monotonically increasing function in the range of $\left[P_{s,k}^{\min}, +\infty\right)$. Substitute $P_{c,n} = Q(P_{s,k})$ into (7a), we have

$$R_n\left(P_{c,n}, P_{s,k}\right) = \log_2\left(1 + \frac{Q(P_{s,k})h_n}{P_{s,k}g_{c,k} + \sigma_c^2}\right) \tag{11}$$

$$\begin{aligned} \frac{Q(P_{s,k})h_n}{P_{s,k}g_{c,k} + \sigma_c^2} &= \frac{\frac{1}{h_{n,k}}(\frac{1}{\Gamma}P_{s,k}g_k - \sigma_s^2)h_n}{P_{s,k}g_{c,k} + \sigma_c^2} \\ &= \frac{P_{s,k}g_k h_n}{h_{n,k}\Gamma(P_{s,k}g_{c,k} + \sigma_c^2)} - \frac{h_n\sigma_s^2}{\Gamma(P_{s,k}g_{c,k} + \sigma_c^2)} \end{aligned} \tag{12}$$

where $\frac{P_{s,k}g_k h_n}{h_{n,k}\Gamma(P_{s,k}g_{c,k}+\sigma_c^2)}$ is a monotonically increasing function in the range of $\left[P_{s,k}^{\min}, +\infty\right)$, $\frac{h_n\sigma_s^2}{\Gamma(P_{s,k}g_{c,k}+\sigma_c^2)}$ is a monotonically decreasing function in the range of $\left[P_{s,k}^{\min}, +\infty\right)$. So, the SINR term SINR_n is a monotonically increasing function in the range of $\left[P_{s,k}^{\min}, +\infty\right)$. Hence, (7a) is monotonically increasing with variable $P_{s,k}$. According to this characteristic, we can obtain that the optimal power allocation point is only obtained on the boundary of feasible region, as shown in Fig 2(a) and Fig 2(b). □

Solving $f_{n,k}$: Due to the removal of constraint (6g) when solving the power allocation scheme, the current power allocation result may not necessarily comply with the minimum communication rate constraint. Thus, we need to abandon the channel allocation solution that are dissatisfied with constraint (6g) in the next step.

We substitute $P_{s,k}^*$ and $P_{c,n}^*$ in constraint (6g), let

$$R_n^*(P_{c,n}^*, P_{s,k}^*) = \begin{cases} R_n^*(P_{c,n}^*, P_{s,k}^*), & R_n(f_{n,k}, P_{c,n}, P_{s,k}) \ge R_0 \\ -\infty, & R_n(f_{n,k}, P_{c,n}, P_{s,k}) < R_0 \end{cases} \tag{13}$$

The objective of the optimization problem is to maximize the sum rate, (13) serves as a penalty function. If the current power allocation results do not satisfy (6g) for a given $f_{n,k}$, then $R_n^*(P_{c,n}^*, P_{s,k}^*)$ takes a value of negative infinity. This indeed compels the optimization function to reject any power allocation scheme that does not meet (6g). After

Table 1. Simulation parameters

	M	J	Q	SINR	$P_c^{\max}$	$P_s^{\max}$	R_0
Value	5	2	5	15 dB	30 dBm	30 dBm	1 bps/Hz

filtering out all eligible sharing solution using constraint (6g), equation (6) is reformulated as

$$\max \sum_{n=1}^{N}\sum_{k=1}^{K} f_{n,k} R_n^*(f_{n,k}) \tag{14a}$$

$$\text{s.t.} \sum_{n\in N} f_{n,k} \le 1, \quad \forall k \in \mathcal{K} \tag{14b}$$

$$\sum_{k\in \mathcal{K}} f_{n,k} \le 1, \quad \forall n \in \mathcal{N} \tag{14c}$$

$$f_{n,k} \in \{0,1\}. \quad \forall n \in \mathcal{N}, k \in \mathcal{K} \tag{14d}$$

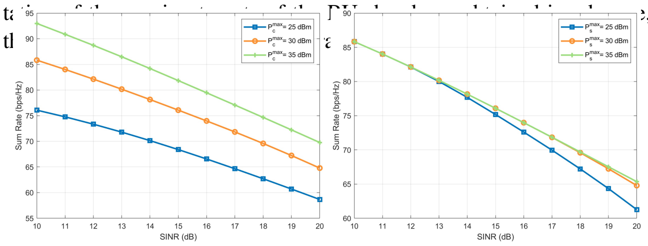
(14) is an equivalent maximum weighted bipartite matching (MWBM) problem [8] and we can use the Hungarian algorithm to solve it efficiently in polynomial time [9].

Algorithm 1 Optimal Resource Allocation

Input: $\boldsymbol{h}_k, \boldsymbol{s}_k, \boldsymbol{u}, \boldsymbol{g}, \eta, n_k^c, n^r, \boldsymbol{P}^c, \boldsymbol{P}^r$
Initialization: Set $f_{n,k}$ to feasible values
for $n = 1 : N$ **do**
  for $k = 1 : K$ **do**
    Calculate $P_{c,n}^*$, $P_{s,k}^*$ according to Lemma 1 by fixed $f_{n,k}$
    Check whether the obtained power allocation scheme $P_{c,n}^*$, $P_{s,k}^*$ satisfies detection QoS constraint by (13)
    Obtain $f_{n,k}$ by using Hungarian algorithm
  end for
end for
Output: $P_{c,n}^*$, $P_{s,k}^*$ and $f_{n,k}$.

Optimality and Complexity Analysis: In this paper, we propose Algorithm 1 to maximize the uplink sum rate in a single ISAC cell. Specifically, our algorithm first determines the globally optimal power allocation, after which the Hungarian algorithm is employed to find the globally optimal channel match. Computational complexity is critical to the usefulness of the algorithm. For this reason, we analyze the complexity of Algorithm 1. As mentioned earlier, we assume $N \ge K$. The complexity of algorithm 1 is $O(NK + N^3)$, where $O(KM)$ is the algorithm complexity of optimal power allocation, $O(M^3)$ is the complexity of Hungarian method to compute channel reuse.

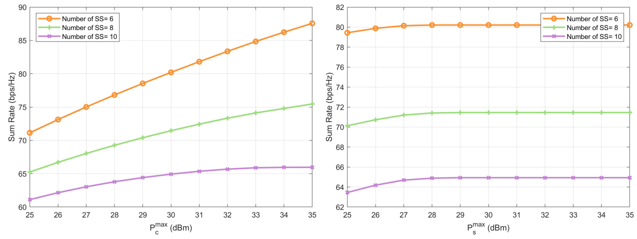
Performance Evalution: In this section, simulation results are presented to validate the proposed joint resource allocation algorithm for multi-user ISAC network. In a cellular cell centered around a base station, we randomly generate multiple uplink CUs, RUs, ISAC users and their respective channel coefficients. Among the generated users, M CUs, J RUs, and Q ISAC users are randomly selected. The approximate orien-ta[...], tl[...]



(a) (b)

Fig 3 *Sum rate with varying sensing SINR Γ: (a) $P_c^{\max}$ = [25, 30, 35] dBm with $P_s^{\max}$ = 30 dBm; (b) $P_s^{\max}$ = [25, 30, 35] dBm with $P_c^{\max}$ = 30 dBm.*

Fig 3 illustrates the performance of our proposed algorithm under various sensing SINR Γ. Specifically, Fig 3(a) maintains the $P_s^{\max}$ constant while altering the $P_c^{\max}$ for CS. Conversely, Fig 3(b) varies $P_s^{\max}$ for SS while keeping $P_c^{\max}$ constant. From Fig 3, it is evident that increasing $P_c^{\max}$ can significantly enhance the sum rate performance. However, an increase in SINR Γ noticeably diminishes the sum rate performance. Although augmenting $P_s^{\max}$ can also improve the sum rate of CS, it is constrained by $P_c^{\max}$, thereby limiting its enhancement potential.



(a) (b)

Fig 4 *Sum rate with varying maximum transmit power: (a) $P_s^{\max}$; (b) $P_c^{\max}$.*

Fig 4 showcases the impact of the number of SS on the sum rate in ISAC network. It indicates that as the number of SS increases, the sum rate decreases. This is attributed to the fact that SS share spectrum resources with CS, resulting in co-frequency interference, which consequently reduces the sum rate. From Fig 4 (a), it can be observed that increasing $P_c^{\max}$ can enhance sum rate in ISAC network. However, when the number of CS equals the number of SS, the sum rate reaches an upper limit. This limitation arises due to the constraints imposed by sensing SINR and $P_s^{\max}$, which prevent the avaiable communication power from increasing indefinitely. Fig 4 (b), on the other hand, reveals that, at a given $P_c^{\max}$, increasing $P_s^{\max}$ can enhance the sum rate, although the improvement is limited. Additionally, the extent of enhancement is positively correlated with the number of SS demands.

Conclusion: In this study, we investigate the spectrum sharing and power allocation design in multi-user ISAC networks. Given the diverse needs of users, it is impractical to provide both communication and perception services to all users in practice. Instead, spectrum sharing and power allocation should be implemented according to the actual needs of users. To address this issue, we consider the differentiated QoS requirements in ISAC networks, formulate an optimization problem, and aim to design a resource allocation scheme that only meets the multiple demands of multi-users. We propose an algorithm to maximize the network communication rate while ensuring the quality of service for all perception users.

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