Joint Resource Allocation Based on F-OFDM for Integrated Communication and Positioning System

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Abstract. OFDM signal can provide communication and ranging services at the same time, but it is limited by sub-carriers and power resources, and cannot meet service requirements adaptively. In order to better improve the communication and positioning performance, a joint communication and ranging resource allocation strategy based on F-OFDM for integrated communication and positioning system is proposed. Firstly, F-OFDM is used to construct a communication and positioning integrated network under protocol interference. Then, link grouping is performed, and a joint sub-carrier and power optimization model is established based on independent sub-bands. The simulation results show that the resource allocation strategy proposed in this paper can significantly improve the ranging performance of the system with satisfying the communication performance.

Keywords: OFDM ranging · F-OFDM · Resource allocation · Data transmission rate · Equivalent Fisher information (EFI)

1 Introduction

Accurate localization of mobile devices is becoming increasingly important for many emerging scenarios, such as indoor navigation and IoT applications [1]. In recent years, with the development of communication technology, the idea of using communication facilities as positioning infrastructure to meet the dual needs of communication and positioning has attracted much attention [2,3]. In the current wireless communication system, the waveform technology is dominated by OFDM, so there is a lot of research on OFDM ranging technology [4,5]. In [6], a TOA (Time of Arrival) estimation method by using OFDM subcarrier phase difference is proposed. Literature [7–9] analyzes the accuracy and influence factors when OFDM signal is used as a ranging signal, and shows that

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ranging accuracy is one of the fundamental reasons affecting positioning performance. Improving ranging accuracy is an effective means to enhance positioning performance. Therefore, on the existing communication infrastructure, we can not only use OFDM signals for high-speed and high-capacity communication, but also achieve high-precision ranging. Since communication and ranging using OFDM technology are realized by processing the received and sent signals, the resource allocation in the system will affect the propagation quality of the signal, which in turn will affect the communication and ranging performance. However at the beginning, the resource allocation in the existing communication system [10,11] only serves to improve the communication performance, and the literature [12,13] only considers to optimize the positioning accuracy of the system. There are very few studies combining the two at present.

In view of the above problems, this paper studies the impact of joint resource allocation about communication and positioning. At the same time, in order to overcome the shortcoming of OFDM that can only be configured with fixed frequency band parameters, the F-OFDM technology that can adapt to communication and positioning services is adopted [14]. Therefore, we build an integrated communication and positioning network based on F-OFDM, realize the joint design of communication and positioning depend on independent sub-bands, and propose a JCP-OSOP (optimal sub-carrier optimal power under joint communication and positioning) allocation strategy.

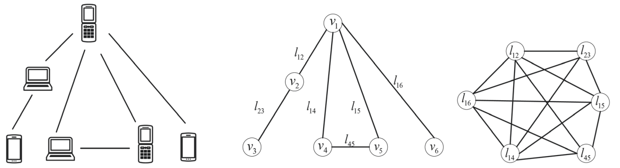
2 System Model

In this section, we introduce the wireless multi-hop communication and positioning integrated network system model. At the same time, we also make the analysis of the communication and ranging performance of the network.

2.1 Network Model

As shown in Fig. 1(a), we abstract it as the connected graph $G = (V, L)$ in Fig. 1(b), where $V = \{v_1, v_2, \cdots, v_n\}$ is the set of all vertices and $L = \{l_{12}, l_{13}, \cdots, l_{mn}\}$ is the set of all edges in the connected graph, representing the wireless access nodes and transmission links in the network of Fig. 1(a) respectively. In a multi-hop network, interference may occur between any two links due to the broadcast characteristics of the wireless channel. Interference determines whether multiple nodes in the network can work at the same time, and the interference is crucial to the study of data transmission in the network. Our system model adopts the protocol interference mentioned in [15], assuming that there is interference within two hops among the network node. Therefore, based on the connected graph, we use the edges in Fig. 1(b) as vertices, and connect the vertices corresponding to the two interference edges to obtain the conflict graph shown in Fig. 1(c).

When grouping the vertices of the graph, it can be realized by the vertex coloring algorithm of the graph. We can group the links of the conflict graph to get the link group set $LG = \{(l_{12}), (l_{23}, l_{45}), (l_{14}), (l_{15}), (l_{16})\}$, which means that only the link group (l_{23}, l_{45}) does not have interference and can reuse resources, and other links cannot share resources with each other.



(a) (b) (c)

Fig. 1. Wireless multi-hop network model and interference conflict graph.

2.2 Communication and Ranging Performance Analysis

In communication and positioning integrated network, we use the data transmission rate on the link as the communication performance, at the same time, the number of sub-carriers is set to N, the channel bandwidth it set to B, and the data transmission rate is expressed as follows:

$$r_{ij} = \frac{B}{N} \log_2 \left(1 + \frac{P_{ij} h_{ij}}{\varphi_0^2 + I_{ij}} \right) \tag{1}$$

where h_{ij} and P_{ij} are respectively the channel gain and allocated power of the $j - th$ sub-carrier on the $i - th$ link, I_{ij} is the sum of interference caused by the remaining links sharing $j - th$ sub-carrier on the $i - th$ link. It can be seen that the reasonable allocation of sub-carriers and power to each link can promote a significant increase in the SNR, and thus increase the data transmission rate on each link.

For the positioning performance, it will be directly affected by the ranging error. According to the literature [16], the CRB (Cramé-Rao Bound) for estimating the ranging delay is equivalent to estimate the inverse of the EFI (Equivalent Fisher Information). We use the following equation represents the ranging error on the link:

$$J_{ei}(N_i, \mathbf{P}_i) = \sum_{j=1}^{N_i} P_{ij} w_{ck}^2 - \left(\sum_{j=1}^{N_i} P_{ij} \mathbf{W}_j \mathbf{b}_j \right)^{\mathbf{T}} \left(\sum_{j=1}^{N_i} P_{ij} \mathbf{W}_j \mathbf{C}_j \mathbf{W}_j \right)^{-1} \left(\sum_{j=1}^{N_i} P_{ij} \mathbf{W}_j \mathbf{b}_j \right) \tag{2}$$

where N_i represents the set of sub-carriers allocated on the $i - th$ link, and $\mathbf{P}_i = [P_{i1}, P_{i2}, \cdots, P_{iN_i}]$ represents the power allocated for each sub-carrier on the $i - th$ link. It can be seen that the number of sub-carriers and power allocation will directly affect the CRB of the ranging accuracy.

Therefore, let the data transmission rate on each link as the primary optimization goal, and let the overall ranging accuracy of the system as the secondary optimization goal, the resource allocation model for joint communication and positioning services can be established as follows:

$$\begin{aligned}
&\arg\max_{\delta}\{\min\{J_{ei}(N_i,\mathbf{P}_i), i=l_1,l_2,\dots,l_n\}\}\\
&s.t.\\
&\quad \text{AC1}: \quad R_i \geq t_i \qquad\qquad \forall i \in L\\
&\quad \text{AC2}: \quad N_i \cap N_j = \varnothing \qquad\quad j \notin l(i)\\
&\quad \text{AC3}: \quad \sum_{i=l_1}^{l_n}\sum_{j=1}^{N_i} P_{ij} \leq P_{total}\\
&\quad \text{AC4}: \quad P_{ij} \geq 0 \qquad\qquad \forall i \in l, j \in N_i
\end{aligned} \tag{3}$$

where the objective function adopts the maximization criterion of minimization, that is, take the EFI of the ranging delay on the link with the worst ranging performance in the system as the evaluation of ranging performance, δ is the best resource allocation strategy. AC1 indicates that the primary optimization goal is to meet the data transmission rate on the $i-th$ link. AC2 means that the links in different link groups cannot use the same resources, otherwise interference will occur. AC3 and AC4 limit the power.

3 JCP-OSOP Resource Allocation Strategy

Since the F-OFDM technology is used in the integrated communication and positioning network, the system frequency band can be divided into multiple sub-bands according to the link grouping situation, so that the sub-band resources can be flexibly configured for communication and positioning. Therefore, the optimal sub-carrier allocation strategy in (3) can be converted to the optimal communication sub-band and ranging sub-band division strategy, and the power allocation strategy on each sub-carrier can be converted to the optimal power allocation strategy on sub-band. Due to the high complexity of solving (3), we can decompose it into sub-carrier allocation model and power allocation model.

3.1 The Sub-carrier Allocation Model

Assuming that the power allocated on each sub-carrier is equal, the communication sub-band is divided to meet the data transmission rate of each link firstly. For one single link, the communication sub-band division model is as follows:

$$\begin{aligned}
&\arg\min N_{l(i)_c}\\
&s.t.\\
&\quad \text{AC1}: \quad R_i \geq t_i \qquad\qquad \forall i \in l(i)\\
&\quad \text{AC2}: \quad N_{i_c} \cap N_{j_c} = \varnothing \quad j \notin l(i)\\
&\quad \text{AC3}: \quad P_{ij} = \frac{P_{total}}{N} \qquad \forall i \in l(i), j \in N_{l(i)}
\end{aligned} \tag{4}$$

where N_{i_c} represents the set of sub-carriers used for communication on the $i-th$ link.

Then, we establish the ranging sub-band division model as follows:

$$\begin{array}{ll} & \arg\max_{\delta_N} \left\{ \min \left\{ J_{e_{l(i)}}(N_{{l(i)}_R}, \mathbf{P}), i = l_1, l_2, \ldots, l_n \right\} \right\} \\ s.t. & \\ & \text{AC1 :} N_{i_R} \cap N_{j_R} = \varnothing \qquad j \notin l(i) \\ & \text{AC2 :} N_{i_C} \cup N_{i_R} {=} N_i \qquad i \in l(i) \\ & \text{AC3 :} P_{ij} {=} \frac{P_{total}}{N} \qquad \forall i \in l(i), j \in N_{l(i)} \end{array} \tag{5}$$

where N_{i_R} represents the sub-carriers set used for ranging on the $i-th$ link. AC2 means that the sub-carriers used for communication and ranging on the link cannot exceed the allocated sub-carriers. The minimum sub-carrier set $N_{{l(i)}_R}$, which is allocated to the ranging sub-band $l(i)_R$ can be obtained by solving the above model.

Due to the sub-band division, the sub-carriers contained in each sub-band must be continuous. Therefore, we use the sub-carrier block composed of multiple consecutive sub-carriers as the minimum allocation unit. In order to reduce the complexity of the allocation, we propose an allocation algorithm based on sub-carrier splitting, which allocates the complete sub-carrier block grouping set to the link group. We assume that there are N sub-carriers in the system, and each sub-carrier block contains n sub-carriers, so the number of sub-carrier blocks is $N_{rb} = \frac{N}{n}$, and we use the set $Sub = \{sub_1, sub_2, \ldots, sub_{N_{rb}}\}$ to represent sub-carrier blocks. Then according to coloring the conflict graph, we get the link group set $LG = \{l(1), l(2), \ldots, l(m)\}$. The specific algorithm flow is as follows:

Algorithm 1. Complete Sub-carrier Block Grouping Set Generation Algorithm.

Step 1:

Define $G = \{2^0, 2^1, \cdots, 2^{N_{rb}-2}\}$, add $m-1$ combination of the elements in G to get the set of decimal numbers $Q_D = \{(q_D)_1, (q_D)_2, \cdots, (q_D)_{C^{m-1}_{N_{rb}-1}}\}$;

Step 2:

Convert each element in Q_D into the binary number and fill in other bits with 0 to make the length C to get the set of binary number numbers $Q_B = \{(q_B)_1, (q_B)_1, \cdots, (q_B)_{C^{m-1}_{N_r-1}}\}$;

Step 3:

Let $i = 1$, insert the binary sequence of the $i-th$ element in Q_B into Sub in order, so that a grouping situation can be obtained, which can be stored in the grouping set T^N as the $i-th$ element;

Step 4:

If $i \leq C^{m-1}_{N_r-1}$ is true, let $i = i + 1$ and jump to Step 2; Otherwise, the final grouping set T^N can be obtained, and the algorithm ends.

We can solve (4) directly to get the minimum sub-carrier block grouping set allocated to the communication sub-band $l(i)_C$ when the communication needs are met, and then get the specific sub-carrier set $N_{{l(i)}_C}$. Since (5) is a 0–1 integer programming problem, we use an iterative solution algorithm based on Hungary to solve it. The specific steps are as follows:

Algorithm 2. Optimal Ranging Sub-band Division Algorithm Based on Hungary Iterative Algorithm.

```
Step 1:
    Initialize: $j = 1$;
Step 2:
    Traverse each element in the link group set $LG$, and record the each link group in the number set $G^L$;
Step 3:
    Traverse each element in $T_j^N$, according to the grouping of sub-carriers, record the sub-carriers number of each sub-carrier block in set $G_j^N$;
Step 4:
    Traverse each element in $G^L$ and $G_j^N$, and calculate the metric matrix $\mathbf{TP}$ according to equation (2);
Step 5:
    Take $\mathbf{TP}$ as the coefficient matrix, find the optimal sub-carrier grouping and optimal matching strategy by the Hungarian algorithm, then store it in $\mathbf{Je}$ ;
Step 6:
    If $j > \left|T^N\right|$, skip and execute Step 7; otherwise, $j = j + 1$, skip and execute Step 2;
Step 7:
    Find the global maximum value in $\mathbf{Je}$, according to the column index to get the best sub-carrier grouping and the best sub-carrier block and link matching.
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3.2 The Power Allocation Model

After the sub-carrier allocation, we first allocate power resources for the sub-carriers on the communication sub-band to meet the data transmission rate on the link. The power allocation optimization model on one communication sub-band is as follows:

$$\begin{array}{ll} & \arg\min P_{l(i)_C} = \sum_{j=1}^{N_{l(i)_C}} P_{l(i)_C j} \\ s.t. & \\ & \begin{array}{lll} \mathrm{AC1}: & R_i \geq t_i & \forall i \in l(i) \\ \mathrm{AC2}: & P_{l(i)_C j} \geq 0 & \forall i \in L, j \in N_{l(i)_C} \end{array} \end{array} \tag{6}$$

the minimum transmit power required on the communication sub-band can be obtained by solving it.

Then, taking the two-path channel as an example, (2) can be converted to:

$$J_{e_{l(i)}}(\mathbf{P}_{l(i)_R}) = \frac{2\alpha_1^2 T}{N_0}\left(-\frac{\omega_{\mathrm{c}}^2 T}{2E_{\mathrm{T}}}\mathbf{P}_{l(i)_R}{}^{\mathrm{T}}\mathbf{H}^{\mathrm{T}}\mathbf{H}\mathbf{P}_{l(i)_R} + \mathbf{w}^{\mathrm{T}}\mathbf{P}_{l(i)_R}\right) \tag{7}$$

We establish the sub-carrier power allocation optimization model on the ranging sub-band as follows:

$$
\begin{aligned}
& \arg\max_{\delta_P} \left\{ \min \left\{ J_{e_{l(i)}}(\mathbf{P}_{l(i)_R}), i = l_1, l_2, \ldots, l_n \right\} \right\} \\
s.t. & \\
& \text{AC1}: \sum_{i=l_1}^{l_n} P_{l(i)_R} \le P_{total} - \sum_{i=l_1}^{l_n} P_{l(i)_C} \\
& \text{AC2}: P_{l(i)_R j} \ge 0 \qquad \forall i \in L, j \in N_{l(i)_R}
\end{aligned}
\tag{8}
$$

where AC1 indicates that the power consumed on all ranging sub-bands and communication sub-bands cannot exceed the total power in the system. By solving the above model, we can get the power on the ranging sub-band, and then get the best power allocation strategy. (6) is a typical nonlinear constrained optimization model, which can be solved by Lagrangian multiplier method. (8) is a quadratic programming problem. Since $\mathbf{H}^{\mathbf{T}}\mathbf{H}$ is a positive semi-definite matrix, and the constraints are all linear, (8) as a quadratic programming problem can be converted to a standard convex optimization model and then solved using the interior point method.

4 Performance Evaluation

4.1 Simulation Setup

The simulation parameter settings are shown in Table 1. In order to study the optimality of the JCP-OSOP resource allocation strategy, the ASAP (Average Sub-carrier Allocation and Average Power Allocation) resource allocation strategy in the literature, ASOP (Average Sub-carrier Allocation and Optimized Power Allocation) resource allocation strategy, and the OSAP (Optimized Sub-carrier Allocation and Average Power Allocation) resource allocation strategy in [17] have been simulated and compared.

Table 1. Simulation Parameters

5G band number	n78	Number of sub-carrier blocks	64
Center frequency (MHz)	3450	Number of sub-carriers in sub-carrier block	24
Bandwidth (MHz)	100	Total transmit power W	10
Number of nodes	6	Transmission rate threshold (increasing)	$t_1 - t_8$
Sub-carrier spacing (KHz)	60	Protocol interference model	Two hops

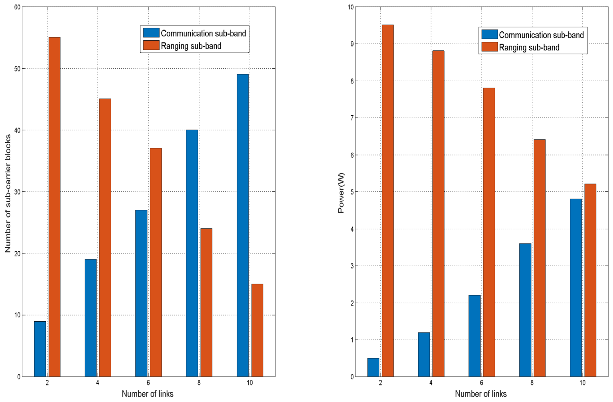

Fig. 2. Sub-carrier block and power allocation changes with network scale (SNR = 10 dB)

4.2 Results and Discussions

As can be seen in Fig. 2, when the resources in the system and the transmission rate threshold are constant, as the network scale becomes larger, the number of links in the system increases. In order to meet the data transmission rate on the links, the number of sub-carriers and power resources occupied by the communication sub-band will gradually increase, while the ranging sub-band will be the opposite.

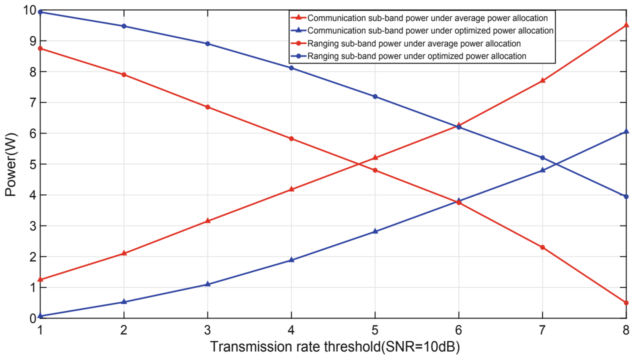

Fig. 3. Comparison results of average power distribution and optimal power distribution on the communication sub-band and the ranging sub-band

It can be seen from Fig. 3 that with the increase of the link transmission rate threshold in the system, since meeting the transmission rate of each link is our primary goal and the total power is constant, the power allocated to the communication sub-band continues to increase, the power of the ranging sub-band continues to decrease. At the same time, under the power optimization allocation strategy, the actual power required by the communication sub-band is much smaller than the pre-allocated power in the average power allocation strategy, and the actual power allocated to the ranging sub-band is much greater than the pre-allocated power in the average power allocation strategy, which will greatly improve the ranging performance of the system.

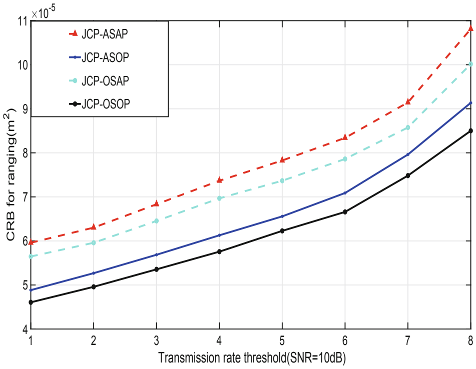

Fig. 4. The system ranging performance of four resource allocation strategies varies with the transmission rate

As shown in Fig. 4, due to the increase of the transmission rate threshold on each link, the resources occupied by the communication sub-bands increase, and the resources occupied by the ranging sub-band decrease, resulting in the ranging performance of the four resource allocation strategies deteriorates. Comparing JCP-ASAP and JCP-ASOP, JCP-OSAP and JCP-OSOP resource allocation strategies, we can see that the latter's ranging performance is greatly improved, which is consistent with the conclusion in Fig. 3. In a comprehensive comparison, the JCP-OSOP resource allocation strategy proposed in this paper has the best ranging performance, which can increase by 20% on average compared to the JCP-ASAP allocation strategy.

In addition, as the SNR in Fig. 5 increases, the resources required for the communication sub-bands are reduced when the data transmission rate on the link are met, and the resources used for the ranging sub-bands in the system increase, and noise has a smaller impact on ranging performance. Therefore, regardless of the resource allocation strategies, the ranging performance is gradually improved. Further, the JCP-OSOP resource allocation strategy proposed in this paper has the best system ranging performance.

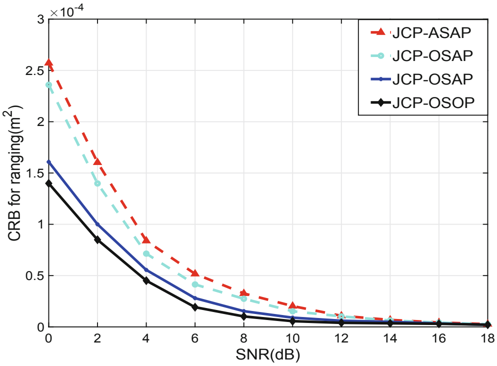

Fig. 5. The system ranging performance of four resource allocation strategies varies with SNR

5 Conclusion

This paper first builds an integrated communication and positioning network based on F-OFDM technology with the considerations of the protocol interference, and models the joint resource allocation of communication and positioning. Next, an iterative Hungary algorithm based on sub-carrier splitting is proposed to solve the sub-carrier allocation problem under the F-OFDM sub-band, then the power allocation problem is solved mathematically, the JCP-OSOP allocation strategy is obtained finally. Through simulation and analysis, the resource allocation strategy proposed in this paper can provide communication and ranging services at the same time, and has better ranging performance than JCP-ASAP, JCP-ASOP and JCP-OSAP resource allocation strategies.

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