A Communication Model to Decouple the Path-Planning and Connectivity-Optimization and Support Cooperative Sensing

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Abstract—When multiple mobile robots (e.g., robotic equipment and Unmanned Aerial Vehicles (UA Vs)) are deployed to work cooperatively, it is usually difficult to jointly optimize the algorithms involving the following two aspects: finding optimal paths and maintaining reliable network connectivity. This is due to the fact that both these objectives require the manipulation of sensors’ physical locations. We introduce a new relay-assisted communication model to decouple these two aspects so that each one can be optimized independently. However, using additional relay nodes is at the expense of an increased number of transmissions and reduced spectrum efficiency. Theoretical results based on mutual information and average data rate of the model reveal that such drawbacks can be compensated if the sensor nodes are arranged carefully into groups. Based on these results, we further propose a pairing strategy to maximize the spectrum efficiency gain. Simulation experiments have confirmed the performance of this strategy in terms of improved efficiency. We provide a simple example to demonstrate the application of this model in cooperative sensing scenarios where multiple UAVs are deployed to explore an unknown area.

Index Terms—Cooperative sensing, wireless communication, sensor networks, connectivity, UAV, path planning, optimization

I. INTRODUCTION

Sensing applications usually require efficient and timely data acquisition, thus the deployment of multiple mobile sensors, e.g., robots and Unmanned Aerial Vehicles (UAVs), working cooperatively is particularly important and useful. Cooperative sensing has attracted significant interest, especially with the advancement of agile platforms, integrated circuits and artificial intelligence [1]–[7]. Cooperative sensing can also increase the adaptivity and robustness of the whole sensor system if the deployed area has a large-size and represents a complicated geographical environment where one mobile sensor can neither cover the whole area nor ensure the data quality.

The key challenge in cooperative sensing is to handle the team-work so that the tasks can be optimized. For example, an autonomous UAV swarm should be able to achieve a global objective in an efficient and reliable manner. However, the practical deployment of multiple UAVs often encounters operational problems, such as they cannot be freely deployed without the limitation of network connection or the power budget of mobile sensors limits their coverage and deployment time. Of particular interests are (1) to efficiently arrange the sensing task with path planning so as to maximize the collective information gain and maintain the network connectivity and (2) to ensure fast and reliable communication of data and commands.

However, these two objectives are usually conflicting as they both require manipulation of physical locations of the mobile sensors and UAVs. For example, in some scenarios, the planned paths with the highest information gain have a significant risk of losing connectivity, while the safe paths do not provide the highest information gain. Furthermore, the complexity of such problems increases exponentially with the number of participants [1], [4]. Other factors such as coverage, data rate, safety management and connection outage can further constrain the optimization algorithms and make them even less likely to converge. Since this scenario can be divided into two parts - sensing path planning and communications, it is thus of particular importance to decouple them so that each part can be optimized independently.

In this paper, we propose to achieve this goal by introducing relays dedicated to communications thus liberating the mobile sensors so that they can focus on data acquisition. Furthermore, it is often the case that mobile sensors have limited battery capacities and the relays have easy access to power supplies. By shifting the majority of communication and signal processing work to relays, we can also extend the sensors’ working life, as well as the life of the whole network. Besides these benefits, the employment of relays can also extend the network coverage. It is known that the received signal strength drops exponentially with the increase of distance between a transmitter and receiver [8]. By introducing relays, if this distance is halved, in free space channels (where the path loss exponent $\alpha = 2$) a quadruple received power can be enjoyed compared with the case without relays. Relay channels and communications were firstly studied in [9] and have gained wide interest in Wireless Sensor Networks (WSNs), cellular networks etc. [10]–[12].
However, using additional relays is at the expense of an increased number of transmissions, therefore the spectrum efficiency might be reduced if the relay model is not well handled. In order to explicitly know whether such a model would impair the network performance, we use both theory and experiments to study it with the focus on mutual information, average data rate and outage performance. The results reveal that we can improve the average data rate by using network coding. The highest spectrum gain is obtained when the network has only two mobile sensor nodes and one relay in communication at the same time. When applying this result in cooperative sensing scenarios with multiple sensors and relays, we propose a scheduling strategy to pair and coordinate the participants effectively. Experiments confirm the achieved data rate gain. We further study the decoding algorithms and other issues involving this strategy.

In order to demonstrate the system model, this paper introduces the cooperative sensing scenario shown in Fig. 1 where multiple mobile sensors collaboratively work towards a common target, e.g. Simultaneous Localization And Mapping (SLAM), or cooperative searching and rescuing. As introduced before, there are two kinds of nodes in the network: 1) mobile sensors which are specialized in data collection (named as sensor nodes); 2) relays which connect the mobile sensors and are responsible for communication (named as relay nodes). The mobile sensor nodes frequently exchange their collected data via the relays. Since relays receive two or more signals from different sensor nodes at the same time, they can take the combination of all the signals together for transmission. This technique can be regarded as network coding [13], which has shown to be able to increase the capacity of multicast networks. This strategy was further exploited in wireless channels where signals from different transmitters are received simultaneously by the station.

In our previous work [14], Code Division Multiple Access (CDMA) coding was implemented in the system to achieve multiple access and orthogonality between transmitter and receivers. However, the implementation complexity and star-shape topology make it less desirable for scenarios where nodes work in an ad-hoc manner with limited wireless communication capabilities. In this paper, the system employs multiple relays which simply amplify the received signals (similar to Analog Network Coding (ANC) [15]), thus it has low implementation complexity. The key idea of signal processing is that, after one data-exchange session, each node decodes the data from the others by deleting its own data from the combinations and therefore recovers the signals from the other nodes using detection algorithms such as zero forcing [16].

Besides the advantage that the proposed scheme can decouple the optimization problems between sensing and communications, from the communication perspective, it has the following benefits: 1) The model achieves a better average data rate than the situation without a relay and this gain is achieved without the sacrifice of outage performance; 2) The coverage of sensing area is extended to be four times larger than the normal case in the ideal situation of path loss factor $\alpha = 2$; 3) With the same battery capacity, the sensing nodes can therefore work longer than the case without relays; 4) The relays can accommodate more powerful wireless components (e.g. antenna arrays) to improve the connectivity.

The major contributions and key features of this paper are: (1) We introduce a relay model to separate the cooperative sensing problems regarding path planning and communication connectivity, without the employment of more complicated coding strategies such as CDMA; (2) The mutual information and spectrum efficiency of the proposed model are studied in terms of average data rate and outage probability; (3) We propose a pairing strategy to compensate the spectrum efficiency loss when there are multiple sensor nodes; (4) The overall performance of the proposed model is verified using simulation experiments.

The rest of this paper continues as follows: Section II describes the background of this paper; Section III introduces the system model and network coding strategy; Section IV analyzes the performance of the communication model; Section V proposes the nodes pairing and scheduling strategy; Section VI provides an example of the model; Section VII discusses the implementation issues, the limitations of the model and future work; Section VIII concludes this paper.

Throughout this paper, $\tau$ and $\dagger$ denote the transpose and conjugate transpose respectively. $\text{tr}\{\cdot\}$, $\text{det}\{\cdot\}$ and $\text{E}\{\cdot\}$ are the trace, determinant and expectation of a matrix respectively. $\log$ denotes the logarithm function with base 2.
II. BACKGROUND

A. Deployment Scenario and Challenges

A swarm of robotic equipment are deployed in a wide area whose size renders it impossible to effectively cover the whole area with individual deployment. An example of such a scenario is shown in Fig. 1. The swarm works cooperatively to achieve a global goal. For example, in the SLAM scenario, the target is to finish the localization and mapping of the area; in the Wilderness Search and Rescue (WiSaR) scenario, the collective target is to locate the missing people as fast as possible. Each robotic machine has a camera to collect images on its route, such data with its position information are sent out using a wireless link. Each one fuses its local data with the received data from other members of the group and makes plan for next sensing path using algorithms such as Frontier Exploration (FE) [17].

Despite the advantages of direct control by human operators, such as better response and adaptivity, the complexity of some sensing tasks means that it is impossible for a human operator to make the best of the available resources on mobile robots in real time, especially when multiple robots are deployed to work cooperatively. The total information in this case is not just the sum of information collected by all nodes, rather it has redundancy from multiple sources which can be reduced by fusing data from uncorrelated sources.

In these scenarios, a highly effective sensing path for each mobile robot is not only useful but also necessary when efficiency and safety are concerned. A number of path planning algorithms were thus proposed to coordinate the actions of multiple robots for the purpose of optimized gains in terms of collective information or coverage [1], [18], [19]. In such cases, the optimization algorithm is targeted towards the end of maximizing the desired output. On the other hand, in order to increase the efficiency of cooperation, it is important for each individual to exchange data in a timely manner for the purpose of reducing redundancy and maximizing collective information gain which is defined below.

Denote the information collected by the sensor node \(j\) as \(I_j(T)\) and \(T\) as the exchange interval, the information gain is defined by

\[
I_g = \sum_{j=1}^{J} I_j(T) - I_r(T),
\]

where \(I_r(T)\) is the redundancy information because the sensor nodes may repeat visit the same area. In order to maximize \(I_g\), \(I_r(T)\) should be minimized, which can be achieved by dividing the information exchange interval \(T\) into smaller segments to reduce the probability of repetition.

For real world problems, it is often insufficient to consider the two issues described above, e.g. desirable sensing path and communication connectivity maintenance, as separate problems because they both involve the manipulation of physical positions. The joint optimization of these two issues could be very difficult and sometimes even impossible. For example, in the shadow of big buildings and hills/mountains, it is often the case that these areas have the highest information gain [17], e.g., a missing person, but also the biggest risk of degraded communication quality or even the loss of connectivity [20]. Thus the sensor nodes will face an optimization dilemma, for example, they may either stay away from that area for communication purposes, or enter the area to collect data and get lost eventually. Therefore, the decoupling of these two issues does not only lead to reduced optimization complexity, but also the improved cooperative efficiency.

A wide scope of practical applications require cooperation among a swarm of mobile robots, e.g., WiSaR [1], [4], [21] where a reliable and efficient communication network is essential to the success of the whole task [14], [22].

B. Cooperative Communications

The basic idea in cooperative communications is similar to cooperative sensing, which explores the collective benefits - network throughput, system robustness, coverage etc. - by coordinating multiple nodes in a network. The motivation behind the exploration of cooperation is that the sacrifice of some nodes in terms of energy and computation/communication abilities can lead to the saving of overall network resources and the enhancement of collective performance. In [11], [23], user cooperation was studied for communication which achieved higher diversity than traditional individual based communication. In [24], the user cooperation and relaying protocols were studied in detail for a three-node communication channel. With the help of relay, a diversity order of 2 can be achieved. In [25], the diversity-multiplexing trade-off of multiple access channel was discovered, which revealed the fundamental compromise between diversity order and spectrum efficiency.

The open and easy access feature of wireless propagation channel provides an enormous space for cooperative strategies to be implemented. Specifically, two types of network coding schemes emerged for wireless systems, e.g., Physical Network Coding (PNC) [26] and Analog Network Coding (ANC) [15]. Similar to the amplify-forward protocol [24], ANC amplifies the received data and forwards them to the destination; PNC performs decoding and encoding rather than amplification before forwarding. ANC is simple and works ideally in higher Signal-to-Noise (SNR) scenarios while PNC can use decoding to deal with noises and outperforms ANC in lower SNR scenarios. For both the schemes, cooperation provides the benefit of increased spectrum efficiency compared to the case without cooperation.

III. SYSTEM MODEL

In this section, we propose the system model and the basic signal processing procedure. The system model includes \(M\) sensor nodes (denoted as \(u_j, j = 1, \ldots, M\)) and \(M - 1\) relays (denoted as \(r_i, i = 1, \ldots, M - 1\)). The wireless channel between \(u_j\) and \(r_i\) is denoted as \(h_{u_j r_i}\). In the theoretical
analysis, we assume all the nodes use the same transmitting power. The channels are modelled as flat block independently and identically distributed (i.i.d.) Rayleigh fading because the introduction of relays overcomes the shadowing effects [27], otherwise the Rayleigh Lognormal distribution should be used. The Rayleigh Probability Distribution Function (PDF) is given by $P_X(x) = \frac{2}{\mu^2} x e^{-x^2/\mu^2}$, $x \geq 0$, where $\mu$ is the corresponding Gaussian component. The noise is modelled as additive white Gaussian with mean 0 and variance $N_0$.

The scheduling of the model is as follows. At the first time slot, all $M$ sensor nodes broadcast their data, which will be received by all the relays, as follows

$$y_R = \sqrt{P_T}H_{UR}x_U + w_R,$$

where $P_T$ is the transmitting power for each symbol, $y_R = \{y_{r1}, y_{r2}, \ldots, y_{rM-1}\}^T$ are the received signals at relays, $x_U = \{x_{u1}, x_{u2}, \ldots, x_{u_M}\}^T$ are the transmitted signals from the $M$ sources, $H_{UR}$ is the sensor-to-relay channel matrix as follows

$$H_{UR} = \begin{bmatrix} h_{u1r1} & h_{u2r1} & \cdots & h_{uMr1} \\ h_{u1r2} & h_{u2r2} & \cdots & h_{uMr2} \\ \vdots & \vdots & \ddots & \vdots \\ h_{u1rM} & h_{u2rM} & \cdots & h_{uMrM} \end{bmatrix},$$

and $w_R = \{w_{r1}, w_{r2}, \ldots, w_{rM-1}\}^T$ is the corresponding noise. During the next $M-1$ time slots, the relays broadcast the encoded signals from all users using wireless network coding. The encoding strategy in relays is similar to the Amplify-Forward (AF) method used in [10]. A relay simply amplifies its received data and then forwards them to the destinations. The amplifying factor is given by

$$\lambda_{ri} = \sqrt{\frac{1}{\sum_{j=1}^{M} |h_{ur,j}|^2 + 1/\rho}}, \quad i = 1, \ldots, M-1$$

where the SNR $P_T/N_0$ is denoted as $\rho$. The transmitted data from relay $r_i$ can be denoted as

$$x_{r_i} = \lambda_{ri}H_{UR}x_U + \lambda_{ri}w_R.$$  

After one relay session - each relay finishes its forwarding operation, the received data at $u_j$ can be denoted as

$$y_{u_j} = \sqrt{P_T}H_{Ru_j}\Lambda H_{UR}x_U + H_{Ru_j}\Lambda w_R + w_{u_j},$$

where $y_{u_j} = \{y_{u_{j1}}, y_{u_{j2}}, \ldots, y_{u_{jM-1}}\}^T$, $H_{Ru_j} = \text{diag}(h_{ru_{j1}}, h_{ru_{j2}}, \ldots, h_{ru_{jM-1}})$ is the channel matrix between relays and $u_j$, $\Lambda = \text{diag}(\lambda_{r1}, \lambda_{r2}, \ldots, \lambda_{rM-1})$ and $w_{u_j} = \{w_{u_{j1}}, w_{u_{j2}}, \ldots, w_{u_{jM-1}}\}^T$ is the noise at $u_j$.

### IV. Performance Analysis

#### A. Mutual Information

The mutual information of a channel with input $x$, output $y$ and channel coefficient $H = C$ can be denoted as $I(x; y|H = H)$. Given the system model (4), we have

$$I_{u_j} = \frac{1}{M} \log \det \{I + \rho HH^H C^{-1}\}$$

where $I_{M-1}$ is the identity matrix with dimensions $(M - 1) \times (M - 1)$, $H = H_{Ru} \Lambda H_{UR}$ is the equivalent channel gain and $C$ is the equivalent noise variance matrix with only diagonal entries $|h_{ru_{m+1}}| \lambda_{r_{m+1}}$, $m = 1, \ldots, M - 1$. Because of the $M$ phase transmission, the mutual information of the system is scaled by a factor $M$ in (6).

Firstly, we will try to normalize the noise variance. From (4), the equivalent noise power received at $u_j$ can be given by $E[|r_{uj}|^2] = \frac{\gamma_{ri}^2}{\lambda_{ri}^2}N_0$ where $\gamma_{ri} = \sqrt{E[|r_{ur_j}|^2]}$. By stacking $\gamma_{ri}$ over the $M - 1$ dimensions, we have $\Gamma = \text{diag}(\gamma_{r1}, \gamma_{r2}, \ldots, \gamma_{rM-1})$. The normalized noise is thus obtained as $w_{u_j} = \Gamma^{-1}(H_{Ru_j}\Lambda w_R + w_{u_j})$ and $w_{u_j} \sim C(0, N_0)$ since $w_R$ and $w_{u_j}$ are i.i.d. Gaussian distributions and they are independent from the other parameters of $w_{u_j}$.

In order to keep Signal-to-Noise Ratio (SNR) unchanged, the useful signal is also multiplied by the corresponding
factor in $\Gamma$, and we have $\hat{x}_{u_j} = \Gamma^{-1} \Lambda H_{UR}' M_{x_{u_j}}$. Thereby the system model (4) is transformed as follows

$$\hat{y}_{u_j} = \sqrt{P_T} H_{R_{u_j}} \hat{x}_{u_j} + w_{u_j}. \quad (7)$$

We can further obtain the matrix of signal power as $P = P_T \cdot E\{[H_{R_{u_j}}\Gamma^{-1}\Lambda H_{UR}']^2\}$ and noise power matrix as $W = \text{diag}\{N_0, \ldots, N_0\}$. Therefore the mutual information can be obtained similar to [29], given the channel model (7):

$$I_{u_j} = \frac{1}{M} \log \det \left\{ I_{M-1} + P W^{-1} \right\}$$

$$= \frac{1}{M} \log \det \left\{ I_{M-1} + \rho H_{R_{u_j}} \Gamma^{-1} \Lambda H_{UR}' \cdot (H_{R_{u_j}} \Gamma^{-1} \Lambda H_{UR}')' \right\}, \quad (8)$$

By introducing $G = H_{R_{u_j}} \Gamma^{-1} A = \text{diag}\{\sqrt{1+E[|h_{r,u_j}\lambda_1|^2]}, \ldots, \sqrt{1+E[|h_{r,u_j}\lambda_{M-1}|^2]}\}$, the above equation can be simplified as

$$I_{u_j} = \frac{1}{M} \log \det \left\{ I_{M-1} + \rho G H_{UR}(G H_{UR}')' \right\}$$

$$= \frac{1}{M} \log \det \left\{ I_{M-1} + \rho G^{H} G H_{UR}(H_{UR}')^H \right\}, \quad (9)$$

where

$$G^{H} G = \text{diag}\{E[|h_{r,u_j}\lambda_1|^2]/(1+E[|h_{r,u_j}\lambda_1|^2]), \ldots, E[|h_{r,u_j}\lambda_{M-1}|^2]/(1+E[|h_{r,u_j}\lambda_{M-1}|^2])\}.$$  

Because i.i.d. distributions are assumed in the model, $E[|h_{r,u_j}\lambda_i|^2]$ is the same for every sensor node, $G^{H} G$ is a $(M-1) \times (M-1)$ dimension constant matrix with diagonal entries as $r_m = E[|h_{r,u_j}\lambda_1|^2]/(1+E[|h_{r,u_j}\lambda_1|^2])$.

In (9), since $H_{UR}'$ is a Gaussian matrix, the equivalent SNR on the $k$th stream from $u_i$ to $u_j$ is a Chi-squared variable distribution [16, Theorem] given by

$$p(\rho_k) = \frac{\sigma_k^2 e^{-\rho_k \sigma_k^2 / \rho}}{\rho (M_t - M_r)!} (\frac{\rho_k \sigma_k^2}{\rho})^{M_t - M_r}, \quad (10)$$

where $M_t$ and $M_r$ are the number of transmitting and receiving antennas, in this case, $M_r = M_t$, and $\sigma_k^2 = 1/r_m$. Thus the PDF of the equivalent stream SNR can be obtained as

$$p(\rho_k) = e^{-\rho_k / \rho r_m} (\frac{\rho_k}{\rho r_m})^{0} = e^{-\rho_k / \rho r_m}. \quad (11)$$

The average data rate is defined as follows

$$\bar{R} = E[I] = \int_0^{+\infty} I \cdot p_I(x)dx, \quad (12)$$

where $p_I(x)$ is the PDF of mutual information $I$.

By introducing the equivalent SNR and its distribution (11), the mutual information of the stream between $u_i$ and $u_j$ can be denoted as $I_{i,j} = \log(1+\rho_{i,j})$. Thus the average data rate can be obtained as

$$\bar{R}_{i,j} = \int_0^{+\infty} \log(1+\rho_k) e^{-\rho_k / \rho r_m} d\rho_k$$

$$= -e^{-\rho r_m} \log(e) Ei(-\frac{1}{\rho r_m})$$

$$= -e^{-\rho r_m} \log(e) \left[ C + \ln\frac{1}{\rho r_m} + \sum_{j=1}^{\infty} \frac{(-\rho r_m)^{-j}}{j \cdot j!} \right], \quad (13)$$

where $C$ is the Euler constant $C = 0.577215$. $Ei(x)$ is the exponential integral function [30].

In the high SNR region, $Ei(-\frac{1}{\rho r_m}) \approx C + \ln\frac{1}{\rho r_m}$ given $\lim_{\rho \to 0} Ei(x) \approx C + \ln(-x)$. The average data can be approximated as

$$\bar{R}_{i,j} \approx e^{\frac{1}{\rho r_m}} \left[ \log(\rho r_m) - C \log e \right]. \quad (14)$$

For the whole system, the average data rate is the combination of the data rate of all independent streams, divided by the total time slots, given by

$$\bar{R}_p = \frac{1}{M} \sum_{i=1,j=1,i\neq j}^{M,M} \bar{R}_{i,j} = (M-1) \bar{R}_{i,j}. \quad (15)$$

Specifically, if there are only two sensor nodes, $M = 2$, the equivalent sum data rate is the same as the case with only one stream. The explanation is, if $M = 2$, to finish the exchange of one frame per user ($u_i$ to $u_j$ and $u_j$ to $u_i$) needs two time slots. Thus two units of information are received for two time slots. This is equivalent to the scenario where one user sends two units of information within two time slots.

The average data rate of the individual model where there is no relay is given below,

$$\bar{R}_O \approx \log(\rho) - \alpha \log(\tau) - C \log e, \quad (16)$$

where $\tau$ is the distance normalization factor between transmitter and receiver.

C. Outage Probability

Over fading channels, the outage event can be expressed as the instantaneous mutual information falling below the target data rate $\bar{R}$ [25]. The frequency of the occurrence of such events is described as the outage probability. Low outage probability is usually desired for a communication system. In this subsection, the outage probability of the proposed model is studied.

Based on the same definition in [25], we can write the outage event for one user as

$$\mathbb{O} \triangleq \{I(x,y|H) < \bar{R} : H\}$$

The average data rate is defined as follows

$$\bar{R} = E[I] = \int_0^{+\infty} I \cdot p_I(x)dx, \quad (12)$$

where $p_I(x)$ is the PDF of mutual information $I$.

By introducing the equivalent SNR and its distribution (11), the mutual information of the stream between $u_i$ and $u_j$ can be denoted as $I_{i,j} = \log(1+\rho_{i,j})$. Thus the average data rate can be obtained as

$$\bar{R}_{i,j} = \int_0^{+\infty} \log(1+\rho_k) e^{-\rho_k / \rho r_m} d\rho_k$$

$$= -e^{-\rho r_m} \log(e) Ei(-\frac{1}{\rho r_m})$$

$$= -e^{-\rho r_m} \log(e) \left[ C + \ln\frac{1}{\rho r_m} + \sum_{j=1}^{\infty} \frac{(-\rho r_m)^{-j}}{j \cdot j!} \right], \quad (13)$$

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The average data rate of the individual model where there is no relay is given below,

$$\bar{R}_O \approx \log(\rho) - \alpha \log(\tau) - C \log e, \quad (16)$$

where $\tau$ is the distance normalization factor between transmitter and receiver.
The outage probability of this model can be obtained by directly applying its definition \[25\] where \(\varepsilon = \log(1 + \rho_k)\). Given \(\mathcal{R}\) and the distribution of stream SNR \((11)\), the outage probability of this model can be obtained as

\[
P(I < \mathcal{R}) = P(\rho_k < 2^\mathcal{R} - 1) = \int_0^\infty e^{-\rho_k/\rho_m} d\rho_k = 1 - e^{-\frac{\mathcal{R}}{\rho_m}}, \tag{17}\]

where \(\varepsilon = 2^\mathcal{R} - 1\). Finally, diversity order can be obtained by directly applying its definition \[25\]

\[
\lim_{\rho \to \infty} \frac{-\log P(I < \mathcal{R})}{\log \rho} = \lim_{\rho \to \infty} \frac{-\log(1 - e^{-\frac{\mathcal{R}}{\rho_m}})}{\log \rho} = 1. \tag{19}\]

The diversity result is the same as the case where there is no relay (direct transmission) \[31\]. Thus the proposed model does not reduce the diversity order, which is verified in Fig. 4.

### D. Numerical Test

This subsection uses numerical tests to study the communication performance of the model. These two cases are compared: the proposed model (denoted as Cooperation) and the case without cooperation (denoted as Individual).

In order to highlight the communication capability in the physical layer, we use the same parameters as before. The channels are modelled by i.i.d. Rayleigh distributions and the parameter \(\mu = d^\alpha\) where \(d\) is calculated from the distance between transmitter and receiver. We tested the normal SNR range from 10dB to 40dB. The number of sensor nodes \(M\) is set to 2, 3 and 4, respectively.

Fig. 2 shows the average data rates per channel used in the proposed model and the original model. From the spectrum efficiency point of view, the proposed cooperation model has the highest data rate when there are only two cooperative sensor nodes. The more users join in the network, the smaller the average data rate and the lower the spectrum efficiency. The gap between \(M = 2\) and \(M = 4\) is about 0.8 bit/s/Hz. This difference comes from the co-channel interference at simultaneous transmission. For the individual case, since the transmissions of all users are orthogonal, there is no co-channel interference, thus the data rate remains the same with the increase of sensor nodes. The cooperative model with \(M = 2\) achieves the highest average data rate and has a lower average data rate than the individual model when \(M > 2\).

Such observation inspires a strategy to arrange the sensor nodes into pairs to achieve higher average data rate, which will be studied in Section V.

The second test is to explore the sensing scenario where the relay stations have higher transmitting power than sensor nodes. This is due to the fact that relays are only responsible for data transmission and have ground power supply; they can therefore be equipped with more powerful transceivers on-board. In this test, we set the transmitting power of the relays to be twice the sensor nodes power. Fig.3 shows the average data rate per channel. With more powerful relays, this rate is improved significantly. For example, the data rate per sensor node within four robot cooperating network is even higher than that of the individual model (about 0.5 bit/s/Hz at SNR = 25dB).

The third example is to show the diversity order of the cooperative model. The outage is tested at the SNR range from 0dB to 40dB and the target data rate is set to 2bit/s/Hz. Fig.4 shows the results. From the figure, we can see that the outage of the cooperative model is similar to that of direct transmission which is well known to have one diversity order. This numerical experiment confirms the theoretical result \(19\).
V. Nodes Pairing and Scheduling

As shown in Fig. 2, the cooperation model with two sensor nodes and one relay is superior to the others in terms of average data rate. Therefore we propose a scheme to arrange the M sensor nodes into pairs and the corresponding detection strategy. In this case, only one relay is required which should also serve as the administrator for nodes pairing and scheduling. The strategy is as follows:

- Sensor nodes inform the relay of the volume of data they need to exchange with a training sequence in the header;
- Relay estimates all the channel state information using these sequences and match the pairs which consume a similar segments of bandwidth denoted by the occupancy time which approximates to the data volume divided by the corresponding instant mutual information;
- Relay pairs the sensor nodes who have similar bandwidth requirements and broadcasts the schedule (more complicated criteria can be explored);
- Each pair transmits data successively to the relay at the odd numbered time slot given the schedule. The encoded version of these data will be broadcast immediately by the relay at the next time slot after receiving;
- Other sensor nodes overhear both the signals from the pair and relay and detect the signals as follows. Suppose \( u_i \) and \( u_j \) are the transmitting pair, \( u_k (k \neq \{i,j\}) \) is the overhearing node, \( r \) is the relay. Then \( u_k \) receives

\[
y_{u_k} = \sqrt{P_T} H x_{u_k} + w_{u_k},
\]

where

\[
H = \begin{pmatrix}
    h_{u_i, u_k} & h_{u_j, u_k} \\
    h_{u_i, r \lambda}, h_{r, u_k} & h_{u_j, r \lambda}, h_{r, u_k}
\end{pmatrix}
\]

We can subsequently apply the maximum likelihood criterion to detect the symbols from the pair:

\[
\hat{x}_{u_k} = \arg\min_{x_{u_k} \in A_{u_k}} ||y_{u_k} - \sqrt{P_T} H x_{u_k}||^2,
\]

where \( A_{u_k} \) is the modulation symbol set common to all users.

- The pair detects each other’s messages using the same algorithm introduced before, e.g. (4).

If there are multiple relays, one relay will play the role of administrator to coordinate the others. The communication between relays is supported by administration packets. Depending on the implementation schemes: centralized scheme and distributed scheme, there exist two different ways. For the first one, the administrator emerges from the candidates by a predefined rule, e.g. a hierarchy system, which will inform others to remain silent by a predefined message. The second scheme takes the distributive methods such as time slot competition [32] or opportunistic relaying. The one holds the flag broadcasts the administration messages to inform other relays and pair the sensor nodes. How to find the best relay and the corresponding searching algorithms are beyond the scope of this paper and will be left for further study in the next step.

Using this strategy, we calculated the achieved gain of average data rate per channel over the previous network coding strategy which is without nodes pairing and scheduling, for the case of \( M = 2, 4, 6, 8, 10 \). The conditions are the same as the first test in Section IV-D. The results are shown in Fig. 5 and demonstrates that the achieved gain increases with the rise of SNR and sensor node numbers and becomes stable at 40dB and beyond, which suggests that the interference from co-channel users plays the major role when the noise levels are low. Overall, the nodes pairing scheme significantly decreases the co-channel interference and improves the average data rate if the number of sensor nodes is large.

The disadvantage of this pairing strategy is that it increases the overheads to coordinate the sensor nodes and signals for every pair of sensor nodes and thus decreases
Algorithm 1 Frontier Exploration of $u_j$

**Input:** Map of $u_j$ ($M_j$), position of $u_j$($P_j$), data from other UAVs.

**Output:** The next position of $u_j$

1: Integrate the data from other UAVs into $M_j$
2: Mark the positions of other UAVs on $M_j$
3: Set the search radius $R = 1$
4: **while** $R \leq R_{\text{Max}}$ **do**
5:  **if** Find cell $C_i$ within ($M_j$, $R$) with probability 0.5
6:      **then**
7:          **if** $C_i$ is not marked **then**
8:              Output coordinates of $C_i$
9:          **end if**
10:      **end if**
11:  **end if**
12:  **end while**
13: Output (0,0) $\triangleright$ The whole map has been explored.
14: **return**

Algorithm 2 Relay position calculation

**Input:** Position of UAVs ($P_j$, $j = 1, ... , J$), Global map ($M$)

**Output:** The next position of relays $R_i$, $i = 1, ... , J - 1$

1: Calculate the distance between each UAV $D_j', j''$, $j' \neq j''$
2: **for** $i = 1$ to $J - 1$ **do**
3:  Search the maximum $D_{1,2}$ and the two corresponding UAVs: $P_1$, $P_2$
4:  **if** $P_1$ or $P_2$ is located at poor connection area **then**
5:      Set the way point of relay on the edge between $P_1$ and $P_2$.
6:  **else**
7:      The way point of relay is $0.5 * (P_1 + P_2)$
8:  **end if**
9: **end for**
10: **return**

Simulation conditions of the program are set as follows. Four sensing UAVs and three Relays are sent out to draw the map of a $50 \times 50$ unknown wildness area. We set the probability for each unknown cell as 0.5, opened cell as a random value less than 0.5 and occupied cell as 1. All the UAVs set off from the same cell, but each one’s trajectory is adaptively modified by the FE algorithm in order to achieve better cooperative efficiency.

The channels between UAVs and relays are modelled as Rayleigh fading. Symbols are modulated by Differential Quadrature Phase-Shift Keying (DQPSK) and SNR is set as 20dB. All transmitted data are encoded by convolutional codes and decoded at the receiver by Viterbi algorithm. The other implementation details are neglected for conciseness.

Fig. 6 shows the full map where the white areas have been visited by UAVs and the dark areas are still unexplored. The current positions of UAVs and relays are marked on the map when half the map is explored. The numbers on the map denote the corresponding UAVs and Rs denotes the positions of relays.

Of particular interest is to see the increase of information exchange rate towards the sensing efficiency. In the experiment, we compared 5 levels of exchange frequencies, which are $F = 1, 1/2, 1/5, 1/10, 1/20$, where $F = 1/T$ and $T$ denotes the interval between two communication sessions. The bigger the $F$, the faster the data exchange frequency. Fig.7 shows the results. It is clearly seen that the setup with the most frequent exchange rate ($F = 1$) finishes the exploration of the whole map using the least time. The total time used to draw the whole map in this setting is only about 60% of the time used in the worst case ($F = 1/20$) which is heavily affected by redundancies.

In the next set of experiments, we set $F = 1$ and change the number of cooperative UAVs. Fig.8 shows the percentage of explored area against the used time. From the results, we can see the time consumed by a group of four UAVs is about 1/4 of the time used by one UAV.
Fig. 6. The explored map and the positions of UAVs and relays when 50% of the area has been visited. (The red 'U1 - U4' and Green 'R' denote UAVs' and relays' positions respectively.)

Fig. 7. The percentage of finished area vs the time consumed (4 UAVs). F denotes the communication frequency. E.g. F = 1/20 means UAVs exchange data at the frequency of 1/20.

Fig. 8. The percentage of visited area vs the number of UAVs (F = 1).

Fig. 9 compares the efficiency of two models: a cooperative communication model and an individual communication model, which are studied in Section III. Four UAVs are employed in both the models and the data exchange frequency is fixed to be F = 1/4. In the individual case, UAVs exchange data in an opportunistic manner where the probability is drawn from a uniform distribution. From the figure, we can see the time used by the cooperative model is about 150 time units less than the individual model.

Fig. 10 shows the total time used to finish exploring the whole map when one or more UAVs are deployed. In cooperative sensing scenarios, if the UAVs keep good communications and update their maps promptly, they can optimize their searching paths efficiently, therefore, the increase of UAVs can significantly decrease the time used to finish the task. From the figure, with the increase of communication frequency from F = 1/20 to F = 1, about 430 time units are saved at the scenario of four UAVs, which is a considerable saving given the total sensing time of 1100 units (approx.). And in the case of F = 1, the time used by four UAVs to finish sensing is about 670 time units which approximately equals to one fourth of the time
in wireless networks [33], [34]. By placing the sensor nodes on the Voronoi edges, the connectivity of the network is generally guaranteed and the complexity of path planning is simplified. However, the edges of Voronoi diagram do not often have the desired information for collection. So one possible solution is to increase the split within the Voronoi diagram in the attempt to increase the information gain on its edges. The problem is that this method may need an overwhelming number of sensors. Furthermore, the complexity of this solution cannot be guaranteed. Thus it is important to decouple the joint optimizations into separate objective functions in order to reduce the optimizing complexity. In this case, the paths of sensing robots can be optimized by the max-sum algorithm for the information target, while the deployment of relays is optimized to maintain connectivity using Voronoi diagrams.

2) Cooperative Efficiency: Cooperative sensing requires real time coordination of the mobile sensors, e.g., UAVs. Thus for one node, its working efficiency is not only affected by its own acquired data and decision, but also the collective data and decision of its partners who are working simultaneously. The information acquired by one member not only has its local utility but also global utility. However, global utility is not merely the sum of each one’s local utility, rather it is smaller because of redundancy. In a mobile network with varied channel conditions, redundancy rises because some sensor nodes have the inability to maintain connectivity or lack adequate bandwidth for data exchange. Therefore communication network plays a backbone role in the cooperative sensing applications. In order to achieve the greatest global utility and increase sensing efficiency, it is important to optimize both sensing and communication so that efficient information exchange can be reliably supported.

3) Communications: The proposed model improves communications for cooperative sensing. In free space, the Friis equation [35] is often used to describe the relationship between the received power strength and the distance from receiver to transmitter

\[
\frac{P_r}{P_t} = \frac{1}{d^2},
\]

where \(P_r\) and \(P_t\) are the corresponding received and transmitted power and \(\beta = G_tG_r \left(\frac{\lambda}{4\pi d}\right)^2\) is a parameter defined by the antennas characteristics and wave length. \(d\) is the distance from transmitter to receiver. The employment of relays can halve the original distance \(d\) in the ideal case. From the Friis equation, it is easy to see that if \(d\) is halved, to maintain the same level of received power \(P_r\) only needs one fourth of the original transmitted power \(P_t\). This provides considerable benefit since small transmitting power is usually desirable in the wireless systems. On the other hand, if transmitters use the same transmitting power, receivers can now enjoy much higher received power, thus leading to a better communication quality. As mentioned before, the increased power budget can also be used to extend the sensing coverage.

VII. DISCUSSION

A. Discussion of the Model

1) Optimization Complexity: Current research in cooperative sensing either considers the maximization of information gain in path planning or maintaining the connectivity in communications. There has been less work on incorporating both of these factors into the optimization. For example, in [1], the authors propose to use the Max-Sum algorithm to maximize the information gain. However, when communication costs are taken into account, the fundamental objective functions for optimization would have to search solutions involving two or more constraints, thus leading to increased complexity or exhaustive search without positive outcomes. On the other hand, some researchers propose to use the Voronoi diagram to tackle the connectivity problems needed by one UAV - 2500 time units. Such model provides strong support to the deployment of multiple UAVs in the scenarios requiring fast data collection.
B. Implementation Issues

Essentially the proposed model and node pairing scheme only require one relay, however, there are several benefits to have multiple relays. Firstly multiple relay candidates can be utilized to improve the system throughput. This is due to the fact that such a setup can avoid potentially poor channel conditions between the single relay and sensor nodes. Secondly high robustness can be achieved in the case of relay malfunctioning where the spare relays can take over without loss of connections or data.

Our previously studied multi-source multi-destination (MSMD) model [14] also uses one relay for data exchange. However, it has different system implementation than this paper. In detail, this paper introduces a pairing strategy while [14] employs CDMA coding. The advantage of the pairing strategy is achieved with a cost to coordinate sensor nodes; while MSMD model with CDMA in [14] has the advantage of increased diversity order but with the cost of implementation complexity.

Another issue is about the odd number of sensor nodes. In this case, the proposed pairing scheme should treat the last single sensor node independently. This slightly decreases the spectrum efficiency; however, it can be compensated with advanced pairing algorithms since it is usually not the case that every sensor node has the exact same amount of data. In this unbalanced scenario, we can arrange a new sensor node to take over the position of the old one which has finished transmitting before its paired partner. Thus a successive pairing strategy can be created.

C. Limitations and Future Work

This paper proposes a framework to employ relays in cooperative sensing scenarios for the following two purposes: to separate the optimization problems and to support communications. The advantages of using dedicated relays have been verified by theoretical studies and simulation experiments. However, there are still a few research and implementation topics which need to be addressed.

For example, efficient protocols for the cooperative sensing networks need to be designed. Even though the ad-hoc network structure can be used, future sensing and monitoring work may need to exchange a large amount of data in real-time, e.g., 3D image and video. The employment of relays can build a two-path cooperative system [36] to continuously transmit data. Thus it is worth to explore some hybrid relay protocols.

In the proposed general model, \( M = 1 \) relays are coordinated to help \( M \) sensor nodes because the channel matrix \( \mathbf{H} \) must have full row rank to ensure the symbols of \( \mathbf{X} \) to be successfully detected. Based on this observation, novel system configurations and protocols may be proposed to overcome the obstacle and develop cooperative networks. For example, in order to save the number of relays, we can have only one relay equipped with multiple antennas to achieve the required dimension. In this case, the received signals can be separated by spatial orthogonality provided by the antenna arrays. However, in this paper, in order to standardize the scenario, we only consider the general case that there is only one antenna on each mobile platform and all the sensor nodes have the same amount of data to transmit.

The existence of multiple relay candidates provides the possibility to explore opportunistic relaying techniques for enhanced diversity order and/or spectral efficiency. It is an interesting topic to study the implementation and complexity of opportunistic relaying schemes. Furthermore, to propose novel relaying strategies which can improve the UAVs/robots cooperative sensing network is also of great interest.

With the advancement of position technologies, e.g. Global Positioning System and indoor localization techniques, the sensor nodes and relays can have more accurate localization information. If this information is shared within the whole cooperative network, relays can plan their routes more reliably and efficiently, especially if the deployed map includes obstacles and restrictions. Even the path planning of sensing robots can benefit from efficient information sharing. The optimization of localization under such conditions is also an interesting topic for future study.

VIII. Conclusion

In this paper, we propose to use relays to decouple joint optimization problems and support communications in sensor nodes cooperative networks. In the proposed model, we separate the two major aspects of optimization: sensing and communication. By applying this model, the path planning of sensor nodes and the communication aspects were optimised separately. Mutual information and average data rate of the model confirm its potential to support a higher data rate than the individual model. Experimental results show that dedicated relays and a pairing strategy, not only the average data rate is increased, but the overall cooperation between robots is also improved. Such a model describes a useful deployment strategy for the scenarios requiring significant cooperative efficiency and reliable network connectivity, i.e., remote sensing, disaster monitoring, newscasting from battlefields etc..

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References


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