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A Joint Scheduling and Beamforming Scheme for RoF-Aided MC-SSN

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ABSTRACT Applied to harsh scenarios, the mission critical sensors and sensor network (MC-SSN) is expected to be of high capacity, density, and low cost. Both the industry and research community have a consensus on the need for energy and spectrum saving. Radio over fiber (RoF) system is promising for low latency and flexible system of high efficiency. In this paper, we consider the RoF-aided MC-SSN system serving the sensors with massive multiple-input multiple-output (MIMO) equipped. Based on this model, the base stations, relays, and other network elements can set up connections with each other via optical fiber or wireless links. Aiming to maximize the energy efficiency, this paper proposes a scheme including two aspects: 1) scheduling of the sensors based on the direction of arrival sensing of interference an 2) massive MIMO beamforming matrices generation based on a codebook. The numerical results show that the proposed scheduling and resource allocation method can achieve sufficient throughput with reduced power consumption for the RoF-aided MC-SSN system.

INDEX TERMS Codebook, massive MIMO, MC-SSN, resource allocation, RoF.

I. INTRODUCTION

During the past decades, communication networks have been developed for mission-critical applications, providing end-to-end reliability guarantees and posing substantial challenges [1], [2]. The mission critical sensors and sensor network (MC-SSN) is becoming extensive worldwide, with the transmission of huge volume of data and large amount of sensors.

For the future communication system, there remain great challenges to support the requirements for larger data volume, higher data rate, higher density, lower latency and so on. To fulfill these demands, system throughput shall be increased with a relatively low power consumption to provide a sufficient quality of service (QoS) [3].

To support the upcoming communication system, there are several key contributors such as the network architecture, air-interface, spectral efficiency (SE), spectrum usage, and base station (BS) deployment [4]. As the network will be dense both for data traffic and users, the multi-layer heterogeneous network (HetNet) will provide a solution with seamless coverage, and the system is capable for technologies such as millimeter-wave (mmWave) and massive multiple-input multiple-output (MIMO). The high frequency and space-time multiplexing will lead to higher spectral and energy efficiency and resolve many technical challenges for the future system [5].

In recent years, considerable attention is focused on the convergence of wireless communication and optical fiber technologies, i.e., the field of radio over fiber (RoF) system. RoF system is capable for distributing mmWave signal and of low power consumption [6]–[9]. People notice there is a great potential of the RoF system for the secure and effective transmission for multiple categories of application scenarios, such as vehicular (high mobility), multimedia, and interactive services. In this paper, we consider an RoF-aided mission critical sensors and sensor network (MC-SSN) system.

As shown in Fig. 1, in this paper, we consider an RoF system including a central station (CS), optical distribution network (ODN) including fiber for long term transmission and BSs to amplify the optical signal. BSs and relays serve the sensors via wireless communication with massive MIMO

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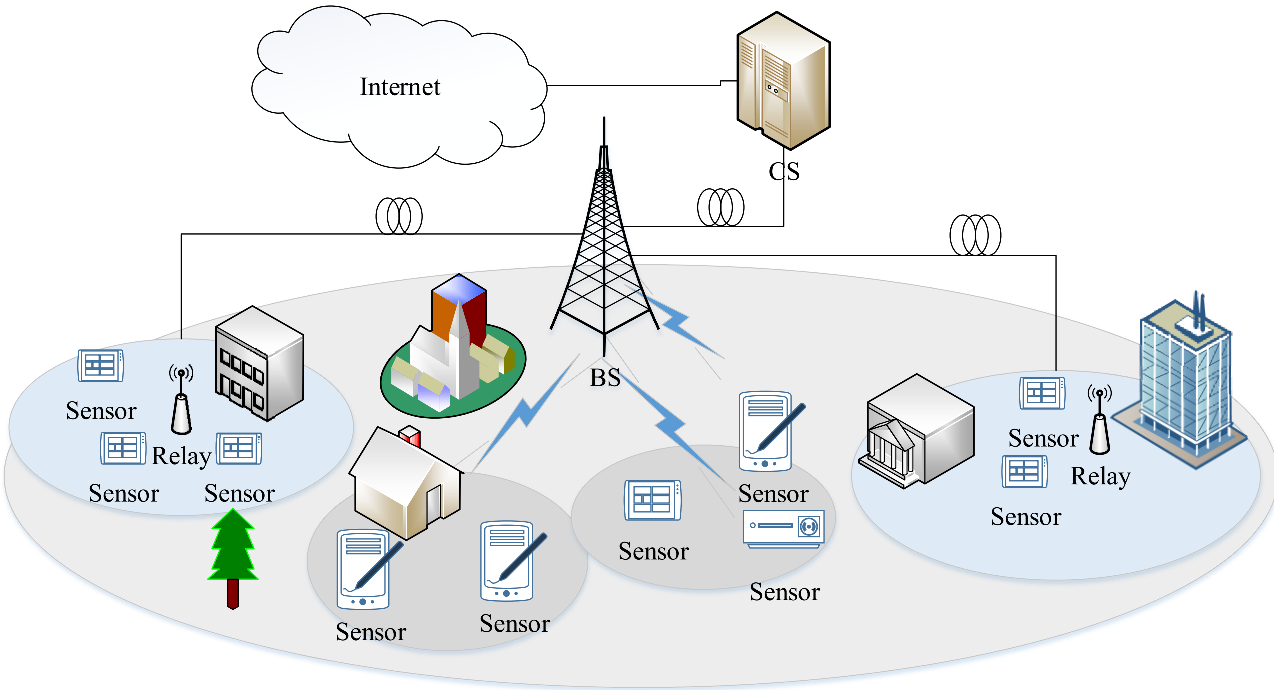

FIGURE 1. Structure of the RoF-Aided MC-SSN system.

equipped. This paper focuses on the scheduling and resource allocation based on codebook and direction of arrival (DoA) for massive MIMO equipped in the RoF-aided MC-SSN system.

This paper makes the following contributions:

1) We take advantage of the model of MC-SSN system by introducing RoF. RoF is potential to provide a solution to the flexible and high communication demands, with optical fiber technologies enlarge the bandwidth and wireless domain enables the flexibility. It is a system with the following advantages [8]: Low attenuation, simplicity and cost-effectiveness, low cost expandability, high capacity, flexibility and dynamic resource allocation. RoF system is also capable for supporting MIMO transmission with the deployment of multi-mode fiber [10], [11].

2) Allocate the resource to minimize the consumption and avoid the interference, and schedule the multiple users. Taking advantages of the extremely short wavelength of mmWave, the antenna elements of massive MIMO can be packed within a small area, which make the hardware implementation possible for both BS and sensor sides. So it is effective to make better use of the resource blocks (RBs) within the area.

3) Perform beamforming based on codebook. As the growing demand of serving more users with lower latency, the system requires better strategy of serving multiple users. Massive MIMO with scheduling and beamforming scheme properly designed can meet this requirement and provide sufficient throughput. We design a codebook based on the.

The paper is organized as follows: In Sec.II, we address the up-to-date related works as well as our motivation. Then the system model is described in Sec.III. Following by Sec.IV, the interference description and scheduling scheme is proposed. The detailed codebook design and beamforming scheme is discussed in Sec.V. Followed by the simulation results in Sec.VI. Finally, Sec.VII concludes the paper.

II. RELATED WORKS AND MOTIVATION

In this section, we present some outstanding works recently proposed for efficient sensor communication systems, then address the upcoming challenges and the motivation of our work.

To fulfill the growing demand of the MC-SSN communication system and further improve the system efficiency, researchers and engineers of academia and industry have been making continuous efforts and result in plenty of achievements. Here we summarize the related works by the following 3 aspects:

A. ARCHITECTURE AND FRAMEWORK

Among the existing technologies, RoF is very suitable for MC-SSN applications, since they have the advantages of wide coverage, low deployment cost, and high technical maturity [6], [9], [12]–[15]. MIMO and mmWave technologies are capable for such system, achieving high capacity gain and limited resource assumption [8], [11], [16]. Moreover, some adaptive and intelligent frameworks are introduced, such as cloud/edge [10], [17], [18] or fog/edge computing, software defined network (SDN), multihop/multilayer network [19]–[22], integrated wireless sensor network (WSN) and hybrid LiFi/WiFi [23], etc.

B. RADIO RESOURCE MANAGEMENT

Radio resource management (RRM) mainly focuses on PHY layer, which is also the key point of this paper. Since the advantage of time and space multiplexing, MIMO technology is promising for high demand networks [3], [5], [11]. DoF of the circular multirelay MIMO interference channel is analyzed, while full duplex MIMO is deployed in [24]. To reduce the intercell interference and limit the energy consumption, power is allocated due to the scheduling scheme [20], [25]–[27]. Codebook is utilized to limit the system computing complexity [28]. Beamforming is effective for making advantage of the directivity of mmWave and reduce the interference [29]. Some smart scheme are developed to improve the system adaptivity, such as blockchain-based access control [17]. The characters of intelligence and flexibility make the sensor system adaptive to the dynamics of the practical system.

C. HIGHER LEVEL CONTROL

Because of the low cost and low energy consumption, sleep schedules is suitable for MC-SSN system [30], in which some of the nodes would be turned off for low cost. In addition to the transmission protocols, communication protocols, and messaging protocols, other protocols play important roles in MC-SSN as well [31]–[33]. For example, service management can effectively discover the devices and applications, and schedule efficient and reliable services to meet requests. A service, such as security consideration [34], can be considered as a behavior, including collection, exchanging, and storage of data, or an association of these behaviors to achieve a special objective. In MC-SSN, according to the mission, some requirements can be met by only one service, while other requirements have to be met by the integration of multiple services.

Although there are many standards defined to reduce the power consumption, many details are openly discussed and most of which are still challenging. For example, the power-saving details of sleeping strategy includes the following factors [30], [35]: the target to be turned off, the proper time to start and end the power-saving mode, how to keep the balance between the energy efficiency and the network performance, and so on. The variety of parameters further enhances the complexity of the system.

To the best knowledge of the authors, related works have not been working on similar schemes by now. Reference [28] proposed a combined horizontal and vertical codebook-based scheduling scheme for 3D multi-user MIMO system. Dowhuszko *et al.* [29] have been working on randomly beamforming as well as the opportunistic scheduling for machine-to-machine (M2M) scenario. References [10] and [18] focused on the resource allocation optimization for multimedia heterogeneous cloud radio access networks (H-CRANs) and achieved a higher energy efficiency (EE). Reference [10] proposed a joint mode division multiplexing (MDM) and frequency division multiplexing (FDM) based fronthauling scheme allowing cost-effective and bandwidth efficient connections in RoF system. But the work was designed for the single layer centralized radio access network (C-RAN) and implemented for one served user and limited antenna elements.

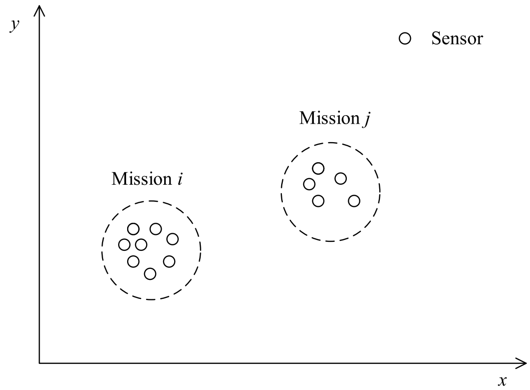

FIGURE 2. Sensors clustered due to the requirement of missions.

In this paper, we focus on the MC-SSN system, and apply RoF technology to enable the flexibility. Then control the interference by sensing and identifying the surrounding sensor nodes clusters. To simplify the computation process, we design a codebook to help with the massive MIMO beamforming process.

III. SYSTEM MODEL

As is shown in Fig. 2, the sensors of specific mission are clustered within an area. The sensors of the same mission are served by the same relay. Therefore, we define $\mathbf{v}$ as the identifier of the priority of the missions. And the mission priority affects the communication strategy of the relays.

Consider a fiber and wireless combined link shown in Fig. 3. For simplicity, we assume there is a direct optical link between the CS and the BS. There are fiber links between the BS and relays. The BS and relays are equipped with multiple antenna elements numbered N_{TB} and N_{TR}, respectively. Hybrid beamforming is performed and the detailed procedure is shown in Fig. 4. At the receiver side, the sensors are equipped with multiple antenna elements numbered N_{RS}. We consider a single macro cell system including one BS and K relays, serving U_0 and $U_k (k = 1, 2, \dots, K)$ sensors respectively. Let $\mathcal{U}_i = \{1, 2, \dots, U_i\} (i = 0, 1, \dots, K)$ be the set of users within the coverage.

For the wireless link, we focus on the half-duplex time division duplex (TDD) air interface because of the channel reciprocity. It is also possible to make an extension to frequency division duplex (FDD) if utilizing advanced channel parameterization techniques, to make a reliable channel estimation in the uplink based on the downlink feedback channel state information (CSI).

We apply the following expressions for the channels within different links. $\mathbf{H}_{opt0}$ corresponds to the channel matrix for the optical link between the CS and the BS and $\mathbf{H}_{opti} (i = 1, 2, \dots, K)$ is the optical link between the BS and the i-th relay. Similarly, $\mathbf{H}_{wl0}$ and $\mathbf{H}_{opti} (i = 1, 2, \dots, K)$ denote

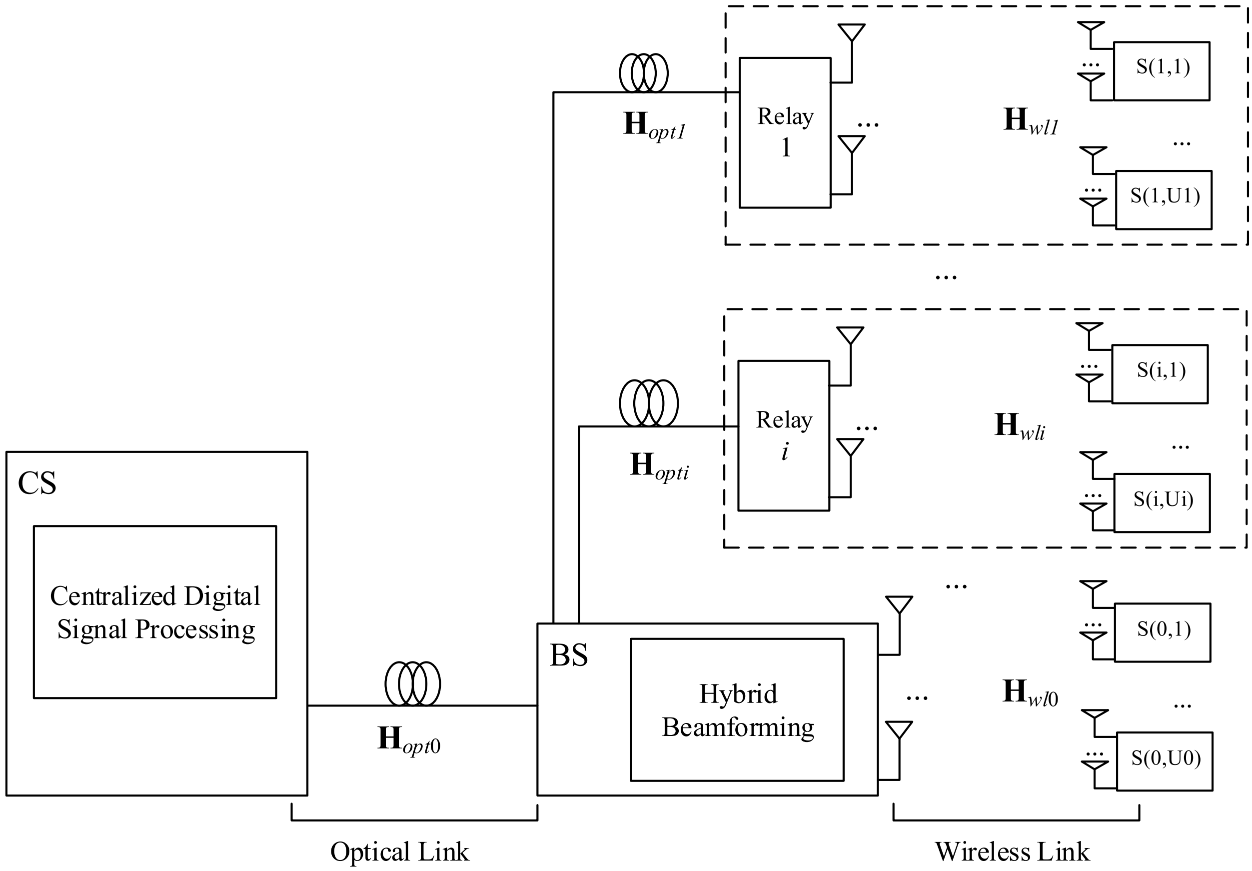

FIGURE 3. System model of the RoF-Aided MC-SSN.

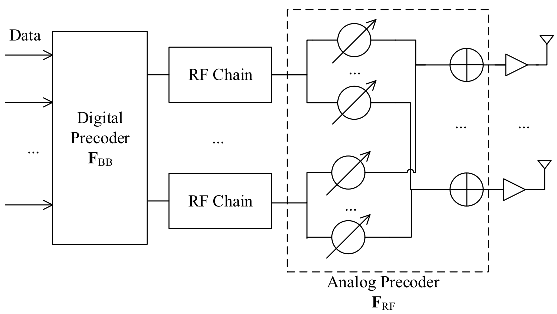

FIGURE 4. Hybrid beamforming procedure.

the wireless links between the BS and its served sensors, and between the i-th relay and its served sensors. For the u-th sensor within the coverage of the power node j, the corresponding channel vector between it and power node i is $\mathbf{h}_{wli,j,u}(i,j = 0, 1, 2, \ldots, K,$ and $u = 1, 2, \ldots, U_i)$. We include UL and DL in the superscripts to stand for the uplink or downlink channel, for example, $\mathbf{H}_{wl0}^{(DL)}$ stands for the downlink wireless channel of the BS.

A. UPLINK

The received signal of power node i is

$$\mathbf{y}_i^{(UL)} = \mathbf{H}_{wli}^{(UL)}\mathbf{s}_i^{(UL)} + \sum_{j,j\neq i}\mathbf{H}_{wli,j}^{(UL)}\mathbf{s}_j^{(UL)} + \mathbf{n}, \quad (1)$$

where $\mathbf{s}_i$ is the signal transmitted by the users covered by power node i and assumed to be Gaussian distributed, i.e., $\mathbf{s}^{(UL)} \sim \mathcal{CN}(0, \sigma_{UL}^2\mathbf{I})$, where σ_{UL}^2 is the uplink signal power. Here $\mathbf{H}_{wli,j}^{(UL)}$ denotes the channel between the node i and the users of interfering neighboring node j, and noise $\mathbf{n} \sim \mathcal{CN}(0, \sigma^2\mathbf{I})$.

Therefore, the received signal to interference plus noise ratio (SINR) is

$$SINR_i^{(UL)} = \frac{||\mathbf{H}_{wli}^{(UL)}||^2\sigma_{UL}^2}{\sum_{j,j\neq i}||\mathbf{H}_{wli,j}^{(UL)}||^2\sigma_{UL}^2 + \sigma^2}. \quad (2)$$

The signal received by the CS is

$$\hat{\mathbf{s}}_i^{(UL)} = \begin{cases} \mathbf{W}\mathbf{H}_{opt0}^{(UL)}\mathbf{y}_i^{(UL)}, & i = 0 \\ \mathbf{W}\mathbf{H}_{opt0}^{(UL)}\mathbf{H}_{opti}^{(UL)}\mathbf{y}_i^{(UL)}, & i \neq 0 \end{cases} \quad (3)$$

where $\mathbf{W}$ is the beamformer for the optical signal.

B. DOWNLINK

The received signal at sensor u covered by power node i is

$$\hat{\mathbf{s}}_{i,u}^{(DL)} = \sqrt{P_i\rho_{i,u}}\mathbf{H}_{wli}^{(DL)}\mathbf{x}_{i,u} + \sum_{v\in\mathcal{U}_i,v\neq u}\sqrt{P_i\rho_{i,v}}\mathbf{H}_{wli}^{(DL)}\mathbf{x}_{i,v} + \sum_{j,j\neq i}\sqrt{P_j}\mathbf{H}_{wli,j}^{(DL)}\mathbf{x}_j + \mathbf{n}, \quad (4)$$

where $\mathbf{x}_{i,u}$ is the signal transmitted by power node i for sensor u, $\mathbf{x}_j$ is the signal transmitted by power node j, and $\mathbf{x} \sim \mathcal{CN}(0, \sigma_x^2\mathbf{I})$. P_i is the power consumption for the i-th power node, $\rho_{i,u}$ is the power allocation fraction of power node i for sensor u.

And the SINR can be expressed as

$$SINR_{i,u}^{(DL)} = \frac{P_i\rho_{i,u}\|\mathbf{H}_{wli}^{(DL)}\|^2\sigma_x^2}{\sum\limits_{v\in\mathcal{U}_i, v\neq u} P_i\rho_{i,v}\|\mathbf{H}_{wli}^{(DL)}\|^2\sigma_x^2 + \sum\limits_{j,j\neq i} P_j\|\mathbf{H}_{wli,j}^{(DL)}\|^2\sigma_x^2 + \sigma^2}. \quad (5)$$

The signal at the power node i is

$$\mathbf{x}_i = \begin{cases} \mathbf{F}\mathbf{H}_{opt0}^{(DL)}\mathbf{s}_i^{(DL)}, & i = 0 \\ \mathbf{F}\mathbf{H}_{opt0}^{(DL)}\mathbf{H}_{opti}^{(DL)}\mathbf{s}_i^{(DL)}, & i \neq 0 \end{cases} \quad (6)$$

where $\mathbf{F} = \mathbf{F}_{BB}\mathbf{F}_{RF}$ is the beamformer for the wireless signal.

IV. INTERFERENCE SENSING AND JOINT SCHEDULING SCHEME

Appropriate interference control scheme helps to improve the QoS by making specific users higher priority as well as considering fairness [20]. In this section, we propose a flexible interference control scheme based on the mission priority of the node, then perform beamforming with codebook deployed to lower the cost.

A. INTERFERENCE DESCRIPTION

For a typical scenario, the relay located in a coverage hole can effectively enhance the QoS for the surrounding sensors. As a result, the relay itself may also produce or suffer from interference of the nearby BSs or relays with missions of higher or lower priority. To solve this problem, the relay first senses the frequency usage and corresponding power distribution of its different directions. The spectrum sensing matrix is extended to synthetic the interference. Fig.5 shows an integrated cell formed by three sectors with the interferences of other relays are considered. As is presented in Fig.5, it is easy to figure out the interference-free area radius r, the distance l between relays. Then the interference angle area is at the range of $[\theta_{i,j} - \arcsin(r/l), \theta_{i,j} + \arcsin(r/l)]$. Here $\theta_{i,j}$ is the angle of relay i to j.

Then we have an angle sensing matrix $\mathbf{A}_{p\times q}$, where p and q represents the index of angle divisions and frequency bands, respectively. Let $\mathbf{A}$ be the synthetic interference matrix to collect the state of the surrounding multi-inference. It takes into account all the interference vectors $\mathbf{a}_i (i = 0, 1, 2, \cdots, K)$, where $\mathbf{a}_i$ represents the i-th column of matrix $\mathbf{A}$.

$$\mathbf{a}_i(\phi) = \begin{cases} q_j, & \phi \in [\theta_{i,j} - \arcsin(r/l), \theta_{i,j} + \arcsin(r/l)] \\ 0, & else \end{cases} \quad (7)$$

Then, matrix $\mathbf{A}$ is obtained by the superposition of all $\mathbf{a}_i$.

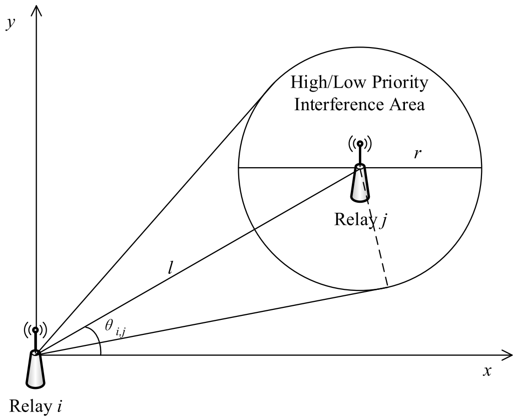

FIGURE 5. Interference sensing by the specific relay.

B. JOINT SCHEDULING PROCESS

Since the BS and relays are connected to the CS, joint scheduling can be performed. In Alg. 1 we present the proposed joint scheduling scheme in details.

V. CODEBOOK-BASED BEAMFORMING

With the results of the previous interference sensing and joint scheduling, the codebook-based beamforming scheme is required to provide sufficient beam gain and avoid interferences.

A. CODEBOOK DESIGN

The codeword $\mathbf{w}_c$ has the structure as

$$\mathbf{w}_c = \mathbf{F}_{RF}\mathbf{F}_{BB} = \sum_{j=1}^{M_{RF}} [\mathbf{f}_{BB}]_j [\mathbf{F}_{RF}]_{:,j}, \quad (9)$$

where $\mathbf{f}_{BB}$ denotes the i-th column of $\mathbf{F}_{BB}$.

The codeword should be able to cover the target angle range $[\theta_{i,T}, \theta_{i,T} + B]$, and avoid the interference range $[\theta_{i,j} - \arcsin(r/l), \theta_{i,j} + \arcsin(r/l)]$. The beam gain of the codeword along angle Θ is expressed as

$$A(\mathbf{w}_c, \Theta) = \sqrt{N}\mathbf{a}(N, \Theta)^H \mathbf{w}_c = \sum_{n=1}^{N} [\mathbf{w}_c]_n e^{-j\pi(n-1)\Theta}. \quad (10)$$

Proofed by Xiao *et al.* [37], the codebook can be generated as follows.

1) Split each RF chain into $M_S = \lceil\sqrt{B_k N/(2M_{RF})}\rceil$ subarrays with equal number of antenna elements, where $B_k = 1/M_{RF}^k$.

2) Compute $\mathbf{w}_c = \mathbf{F}_{RF(k,1)} = \{\mathbf{v}_i\}_{i=1,2,\ldots,M_{RF}}$, where $[\mathbf{v}_i]_{(m-1)N_S+1:mN_S} = \sqrt{N_S/N}e^{j\theta_i}\mathbf{a}(N_S, \omega_{i,m})$.

3) Compute $\mathbf{w}_c(k, n) = \mathbf{F}_{RF(k,1)}, \sqrt{N}\mathbf{a}(N, 2(n-1)/M_{RF}^k), (n = 2, 3, \ldots, M_{RF}^k)$.

B. OPTIMAL BEAMFORMING SOLUTION

Beamforming is performed at the CS side and do not act directly on the relay signal. Here we analyze the two aspects of uplink and downlink.

Algorithm 1 Joint Scheduling Algorithm

Initialization:

Interference matrix, **A**; The priority vector **v**.

Main loop:

- For power node $i (i = 0, 1, \ldots, K)$, apply proportional fair scheduling (PFS). At time t, we have
$$\frac{R_{i,u}^{(DL)}(t)}{T_{i,u}^{(DL)}} = \frac{\log_e\left(1+\gamma_{i,u}^{(DL)}(t)\right)}{\mathbf{E}\left\{\log_e\left(1+\gamma_{i,u}^{(DL)}(t)\right)\right\}}. \tag{8}$$
Here $R_{i,u}^{(DL)}(t)$ and $T_{i,u}^{(DL)}$ are the requested and average data rates, and $\gamma_{i,u}^{(DL)}(t)$ represents the SINR at time t.
- Check the matrix A and confirm if the scheduled sensors are located at the direction of interference. If so, assume the interference is generated by relay j, then confirm the priority of relay i and j.
- If $v_i > v_j$, let relay j perform the beamforming considering interference of relay i based on codebook.
- If $v_i < v_j$, let relay i perform the beamforming considering interference of relay j based on codebook.
- If $v_i = v_j$, let a random relay perform the beamforming considering interference from the other relay based on codebook.
- If the system have met the constraints of all sensors, stop the process and break out of the loop. On the other hand, if the system do not meet the constraints of some users with higher priority in every cell, eliminate the user with worst SINR.
- If the system cannot fulfill the constraints of some sensors with higher SINR (higher priority) only in cell i, identify whether the constraints of all sensors in cell i can be fulfilled by controlling the transmit power of power node $j, j \neq i$.

1) UPLINK

As discussed, the signal received after the optical channel can be expressed as Eq. 7. Then we have
$$\mathbf{w} = \frac{\mathbf{R}_y^{-1}\mathbf{a}(\theta_{MD})}{\mathbf{a}^H(\theta_{MD})\mathbf{R}_y^{-1}\mathbf{a}(\theta_{MD})}, \tag{11}$$
where matrix $\mathbf{R}_y$ stands for the covariance matrix of $\mathbf{y}^{(UL)}$, and $\mathbf{a}(\theta_{MD}) = \left[1, e^{j\pi\sin\theta_{MD}}, \ldots, e^{j\pi(N_t-1)\sin\theta_{MD}}\right]^T$ is the steering vector for the MD of interest with N_t denotes the number of antenna elements.

2) DOWNLINK

As the phase-only control is performed at the radio frequency (RF) domain, we extract the phases of the conjugate transpose of the aggregate downlink channel matrix from the relay to multiple users. This is to harvest the large array gain by aligning the phases of channel elements. The elements of the

TABLE 1. Main parameters in the numerical evaluation.

Parameters	Values
Simulation scenario	ITU-UMa/UMi
Carrier frequency	28GHz
System bandwidth	100Mhz
BS max power	46dBm
Relay max power	21dBm
TX antenna elements of BS and relays	64
Number of RF chains	8
RX antenna elements of sensors	16
Thermal noise level	-174 dBm/Hz

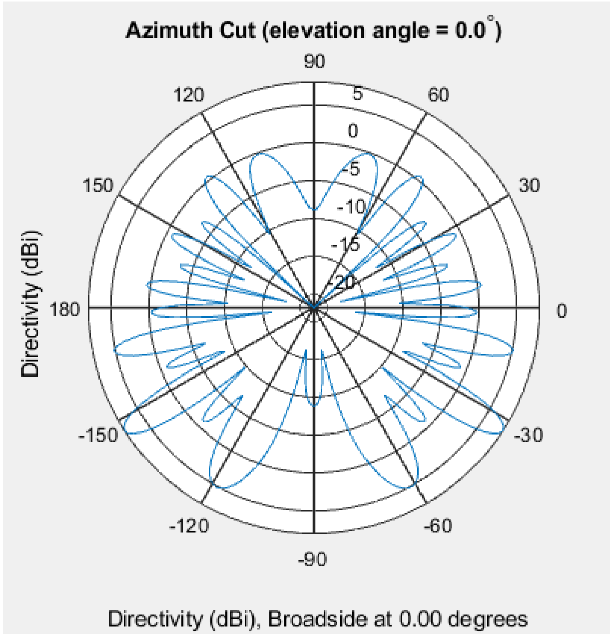

FIGURE 6. The azimuth array pattern after beamforming.

RF precoding matrix **F** can be expressed as
$$\mathbf{F}_{a,b} = \frac{1}{\sqrt{N_t}} e_k^{j\beta_{a,b}}, \tag{12}$$
where $\beta_{a,b}$ represents the phase of the (a, b)th element of the conjugate transpose of the composite downlink channel.
$$\beta_{a,b} = \pm 2q\pi - ka\sin\theta_{max}\cos\left(\phi_j - 2\pi n/N_t\right), \quad n = 1, 2, \ldots, N_t, \tag{13}$$
here q is chosen to ensure $\beta_{a,b} \in [0, 2\pi)$. Assign $\theta_{max} = \frac{\pi}{2}$ and ϕ_b as follows
$$\phi_b = \frac{2\pi j}{N_t} + \alpha, \quad b = 0, 1, 2, \ldots N_t - 1. \tag{14}$$
Then determine the excitation phase $\beta_{i,j}$ of each element.

VI. SIMULATION RESULTS

In this section, numerical results are presented and the performance of the scheme is discussed. The main parameters for the simulation are given in Table 1.

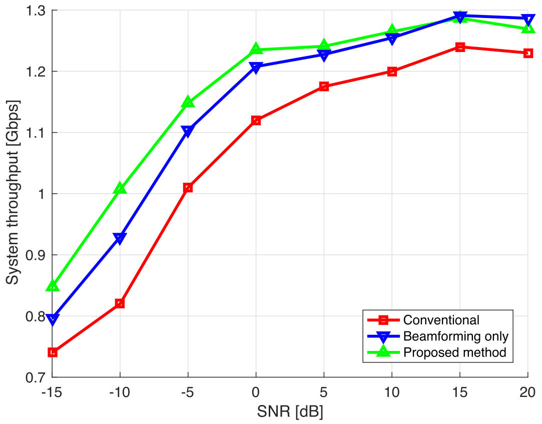

FIGURE 7. System throughput v.s. SNR.

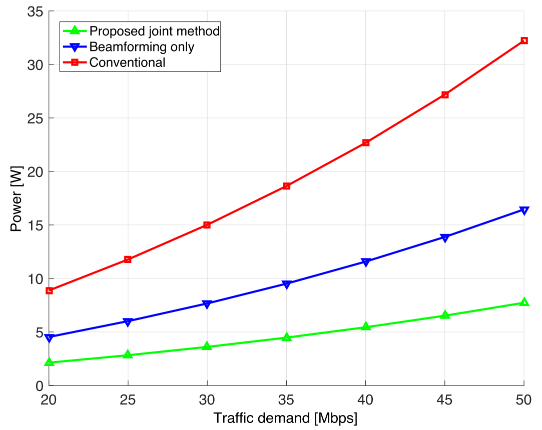

FIGURE 8. Power v.s. Traffic demand.

We setup the network layout with the relays and ordinary sensors of Poisson distribution, and the mission sensors within the coverage of relays obey a normal, or Gaussian, distribution.

Fig. 6 shows an example of beamforming results of array pattern. We can observe that the pattern of the direction at 90 degree is limited and some other direction such as -30 degree is amplified.

Then we present the results including system throughput and power consumption with the following three schemes considered: i) the conventional method without considering adaptive beamforming; ii) beamforming without considering joint scheduling; iii) the proposed method.

The system throughput of the three schemes are compared in Fig. 7. The increment of the SNR enhances the system throughput. It can be seen that the proposed scheme is effective to improve the overall system throughput.

Fig. 8 shows the relationship between the power consumption and traffic demand of the sensors. It is clear that the power consumption arises as the traffic demand increases. When deploying the proposed scheme, the total power consumption of the system decreases.

VII. CONCLUSION

This paper focused on the RoF-aided MC-SSN system supporting BSs and relays equipped with massive MIMO. We first presented the related works, analyzed the basics of the system model, then proposed a scheduling scheme considering interference, after which we proposed a beamforming scheme based on codebook. Finally we setup the simulation, with numerical results showing that the proposed scheduling and beamforming scheme leaded to sufficient system throughput as well as a high efficiency.

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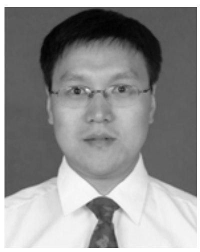

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