

## I. SYSTEM MODEL

Consider an IRS-aided multiuser MISO SWIPT system where the IRS not only assists the primal transmission but also retrieves channel state information (CSI) and harvests energy for its own operation. The  $M$ -antenna transmitter delivers information and power simultaneously, through the  $U$ -reflector IRS, to  $K$  single-antenna users over  $N$  orthogonal subbands. It is assumed that the IRS performs channel estimation in the first subframe and supports information and power transfer in the second subframe [1]. Due to the passive characteristics of IRS, we consider a time-division duplexing (TDD) protocol where the CSI can be obtained by exploiting channel reciprocity. Perfect CSI is assumed at the AP and IRS to investigate the analytical upper-bound of the proposed system. The signals reflected by IRS for two and more times are assumed negligible and thus not considered. The channel is assumed to be unchanged within each transmission frame and the quasi-static frequency-selective model is used for both the AP-user and AP-IRS-user links. A superposition of multicarrier modulated and unmodulated waveforms, both transmitted on the same frequency bands, are designed adaptively to maximize the rate-energy tradeoff [2]. Note that although frequency selective surface (FSS) has received much attention for wideband communications, active FSS requires RF-chains thus becomes prohibitive while passive FSS is not reconfigurable with fixed physical characteristics [3], [4], [5]. Therefore, we assume a frequency-flat IRS with same reflection coefficients for all subbands.

### A. Transmitted Signal

1) *Modulated Information Waveform*: Assume the carrier are evenly spaced with equal bandwidth  $B_s$  such that the frequency of the  $n$ -th subband is  $f_n = f_0 + (n - 1)\Delta f$  ( $n = 1, \dots, N$ ). The information symbol  $\tilde{x}_{I,n}$  on subband  $n$  is a capacity-achieving i.i.d. Circular Symmetric Complex Gaussian (CSCG) variable with zero mean and unit variance (i.e.  $\tilde{x}_{I,n} \sim \mathcal{CN}(0, 1)$ ). Denote  $w_{I,n,m} = s_{I,n,m}e^{j\phi_{I,n,m}}$  as the information weight on the  $n$ -th subcarrier of the  $m$ -th ( $m = 1, \dots, M$ ) transmit antenna with magnitude  $s_{I,n,m}$  and phase  $\phi_{I,n,m}$ , the corresponding modulated symbol can be expressed as  $x_{I,n,m} = \tilde{s}_{I,n,m}e^{j\tilde{\phi}_{I,n,m}}$ , with  $\tilde{s}_{I,n,m} = s_{I,n,m}|\tilde{x}_{I,n}|$  and  $\tilde{\phi}_{I,n,m} = \phi_{I,n,m} + \angle\tilde{x}_{I,n}$ , which also follows zero-mean CSCG distribution with variance equal to the subcarrier power (i.e.  $x_{I,n,m} \sim \mathcal{CN}(0, s_{I,n,m}^2)$ ). Therefore, the transmit information waveform on the antenna  $m$  at time  $t$  writes as

$$\begin{aligned} x_{I,m}(t) &= \sum_{n=1}^N \tilde{s}_{I,n,m}(t) \cos(2\pi f_n t + \tilde{\phi}_{I,n,m}(t)) \\ &= \Re \left\{ \sum_{n=1}^N x_{I,n,m}(t) e^{j2\pi f_n t} \right\} \\ &= \Re \left\{ \sum_{n=1}^N w_{I,n,m} \tilde{x}_{I,n}(t) e^{j2\pi f_n t} \right\} \end{aligned} \quad (1)$$

On top of this, the information waveform vector is spread over  $M$  antennas

$$\mathbf{x}_I(t) = \Re \left\{ \sum_{n=1}^N \mathbf{w}_{I,n} \tilde{x}_n(t) e^{j2\pi f_n t} \right\} \quad (2)$$

where  $\mathbf{w}_{I,n} = [w_{I,n,1}, \dots, w_{I,n,M}]^T$ .

2) *Unmodulated Power Waveform*: As suggested in [2], [6], we use deterministic multisine waveform to boost the harvested energy. It has no randomness over time and the equivalent input power symbol  $\tilde{x}_{P,n}$  is a constant on subband  $n$  (i.e.  $\tilde{x}_{P,n} = 1$ ). Therefore, on the  $n$ -th subcarrier of the  $m$ -th transmit antenna, the power weight  $w_{P,n,m} = s_{P,n,m}e^{j\phi_{P,n,m}}$  represents the complex-valued sinewave (i.e.  $x_{P,n,m}(t) = w_{P,n,m}$ ) in the baseband. The transmit power waveform on the antenna  $m$  at time  $t$  is given by

$$\begin{aligned} x_{P,m}(t) &= \sum_{n=1}^N s_{P,n,m}(t) \cos(2\pi f_n t + \phi_{P,n,m}(t)) \\ &= \Re \left\{ \sum_{n=1}^N x_{P,n,m}(t) e^{j2\pi f_n t} \right\} \\ &= \Re \left\{ \sum_{n=1}^N w_{P,n,m} e^{j2\pi f_n t} \right\} \end{aligned} \quad (3)$$

The corresponding power waveform vector is stacked across  $M$  transmit antennas as

$$\mathbf{x}_P(t) = \Re \left\{ \sum_{n=1}^N \mathbf{w}_{P,n} e^{j2\pi f_n t} \right\} \quad (4)$$

where  $\mathbf{w}_{P,n} = [w_{P,n,1}, \dots, w_{P,n,M}]^T$ .

3) *Superposed Waveform*: At time  $t$ , a superposition of the information and power waveform on antenna  $m$  over subband  $n$  writes as

$$\begin{aligned} x_{n,m}(t) &= x_{I,n,m}(t) + x_{P,n,m}(t) \\ &= w_{I,n,m} \tilde{x}_{I,n}(t) + w_{P,n,m} \end{aligned} \quad (5)$$

The transmitted signal on antenna  $m$  at time  $t$  is a summation over all subbands

$$\begin{aligned} x_m(t) &= x_{I,m}(t) + x_{P,m}(t) \\ &= \Re \left\{ \sum_{n=1}^N (w_{I,n,m} \tilde{x}_{I,n}(t) + w_{P,n,m}) e^{j2\pi f_n t} \right\} \end{aligned} \quad (6)$$

Hence, the composite transmit signal vector is

$$\begin{aligned} \mathbf{x}(t) &= \mathbf{x}_I(t) + \mathbf{x}_P(t) \\ &= \Re \left\{ \sum_{n=1}^N (\mathbf{w}_{I,n} \tilde{x}_n(t) + \mathbf{w}_{P,n}) e^{j2\pi f_n t} \right\} \end{aligned} \quad (7)$$

### B. Composite Channel Model

Denote the baseband equivalent channels from the AP to user  $k$ , from the AP to the IRS, and from the IRS to user  $k$  as  $\mathbf{h}_{D,k} \in \mathbb{C}^{1 \times MN}$ ,  $\mathbf{H}_I \in \mathbb{C}^{U \times MN}$ , and  $\mathbf{h}_{R,k} \in \mathbb{C}^{1 \times UN}$  respectively. At subband  $n$ , we collect the frequency response of both direct and reflective links from  $M$  and  $U$  transmit antennas to user  $k$  as  $\mathbf{h}_{D,k,n} = [h_{D,k,n,1}, \dots, h_{D,k,n,M}] \in$

$\mathbb{C}^{1 \times M}$  and  $\mathbf{h}_{R,k,n} = [h_{R,k,n,1}, \dots, h_{D,k,n,U}] \in \mathbb{C}^{1 \times U}$ . Similarly, the  $n$ -th incident channel gain matrix from  $M$  transmit antennas to  $U$  receive antennas is expressed as  $\mathbf{H}_{I,n} = [\mathbf{h}_{I,1,n}^T, \dots, \mathbf{h}_{I,U,n}^T]^T \in \mathbb{C}^{U \times M}$  with  $\mathbf{h}_{I,u,n} = [h_{I,u,n,1}, \dots, h_{I,u,n,M}] \in \mathbb{C}^{1 \times M}$ . Element  $u$  of the IRS receives a superposed waveform transmitted by  $M$  antennas after the multipath channel, then redistribute it by adjusting the reflection coefficient  $r_u = \beta_u e^{j\theta_u}$ , where  $\beta_u \in [0, 1]$  and  $\theta_u \in [0, 2\pi)$  are the amplitude reflection coefficient and phase shift respectively. Each passive reflector harvests a small portion  $(1 - \beta_u)$  of the signal to support CSI decoding and impedance matching. Construct a diagonal subband-wise IRS matrix by collecting the reflection coefficients of all reflectors onto the diagonal entries such that  $\mathbf{R}_0 = \text{diag}(r_1, \dots, r_U) \in \mathbb{C}^{U \times U}$ . With the assumption of frequency-flat reflection, the IRS matrix is obtained by stacking  $\mathbf{R}_0$  over  $N$  subbands such that  $\mathbf{R} = [\mathbf{R}_0^T, \dots, \mathbf{R}_0^T]^T \in \mathbb{C}^{UN \times U}$ . The IRS-aided extra links can be modeled as a concatenation of the AP-IRS channel to the IRS reflection matrix and the IRS-user channel. Both the direct link and the IRS-aided link contributes to the corresponding composite channel  $\mathbf{h}_k \in \mathbb{C}^{1 \times MN}$  which writes as

$$\mathbf{h}_k = (\mathbf{h}_{D,k} + \mathbf{h}_{R,k} \mathbf{R} \mathbf{H}_I) \quad (8)$$

On top of this, we select and combine every  $N$  entries to form the subchannel as  $\mathbf{h}_{k,n} = [h_{k,n,m}, \dots, h_{k,n,M}] \in \mathbb{C}^{1 \times M}$  to describe the frequency response at subband  $n$  for user  $k$ , with  $h_{k,n,m} = h_{D,k,n,m} + \mathbf{h}_{R,k,n} \mathbf{R}_0 \mathbf{H}_{I,n}$

### C. Received Signal

In the signal received by user  $k$ , the component from transmit antenna  $m$  captures the contribution of information and power waveforms through both direct and reflective links as

$$y_{m,k}(t) = \Re \left\{ \sum_{n=1}^N (w_{I,n,m} \tilde{x}_{I,n}(t) + w_{P,n,m}) h_{k,n,m} \right\} \quad (9)$$

Therefore, the RF input signal to the antenna of user  $k$  writes as

### REFERENCES

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