Multi-Tag Selection for IRS-Assisted Ambient Backscatter Communication Networks

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***Abstract*—In this paper, we propose multi-tag selection and transmission protocol for intelligent reflecting surface (IRS)-assisted ambient backscatter communication (AmBC) networks with multiple tags. More specifically, we propose a frame structure, IRS phase control methods, and the best tag selection scheme for two different scenarios according to the number of IRSs. The performance of the proposed IRS-assisted AmBC network is evaluated in terms of bit error rate (BER) and achievable rate through simulations. With increasing the number of AmBC tags and the number of IRS elements, the performance is significantly improved since the received signal quality is enhanced by the gains from IRS beamforming and multi-tag selection diversity. Especially, when two IRSs exist, it is dramatically improved, and a few tags are enough to achieve the maximum performance.**

Keywords—ambient backscatter communication (AmBC); intelligent reflecting surface (IRS); Internet of things (IoT)

I. INTRODUCTION

As Internet of things (IoT) era is coming, many researchers have been studying on securing frequency bands and improving spectral efficiency. Ambient backscatter communication (AmBC) [1] is regarded as a promising technology to solve a serious spectrum shortage caused by explosively increasing number of wirelessly connected devices. The AmBC utilizes existing radio frequency (RF) signals, such as TV, radio, cellular, Wi-Fi, and so on, to enable a battery-free tag to communicate with a reader. In principle, the battery-free tag can transmit information bit '0' or '1' by adjusting its antenna impedance to switch between absorbing and reflecting states. In this manner, the AmBC tag is able to modulate its desired information bits and transmit them to the reader. Since the tag does not require RF transceiver, it is possible to operate as an ultra-low power level like a passive device. Since IoT networks consist of a number of connected devices, it is necessary to consider multi-tag environments. Recently, several multi-tag selection schemes were proposed in multi-tag AmBC networks [2-4].

On the other hand, intelligent reflecting surface (IRS) is one of next-generation communication technologies, which is aimed at improving signal quality. Each antenna array element on the IRS independently imposes a phase shift on the incoming signal to reconstruct the radio wave environment, thereby enhancing the spectrum of wireless system and energy efficiency [5]. Most recently, there are several studies on performance improvement of AmBC networks with a single tag by introducing IRS [6-8].

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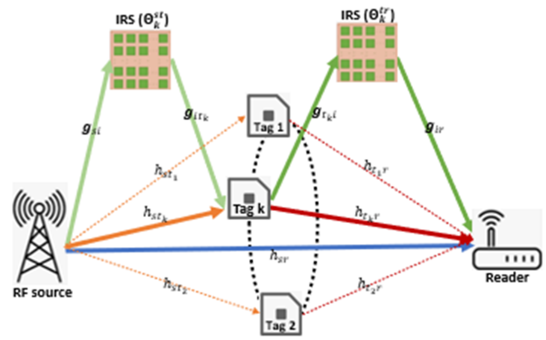


Fig. 1. IRS-assisted multi-tag AmBC network

In this paper, an IRS-assisted AmBC network with multiple tags is investigated. We propose a multi-tag selection scheme in order to improve the performance of the AmBC network in terms of bit error rate (BER) and achievable rate. More specifically, we propose a transmission protocol and an IRS phase control method taking multi-tag selection into consideration. Eventually, the performance of the proposed scheme is evaluated through extensive simulations.

The rest of this paper is organized as follows. In Section II, the system model is illustrated. The proposed multi-tag selection scheme and transmission protocol are presented in Section III, and numerical results are shown in Section IV. Finally, we conclude this paper in Section V.

II. SYSTEM MODEL

As shown in Fig. 1, we consider an AmBC network with a single RF source, a single reader, K tags, each of which has a single antenna, and two IRSs, each of which has N reflecting elements, assist a source-to-tag link and a tag-to-reader link, respectively. The channel gains for source-to-reader and source-to-k-th tag are denoted as h_{sr} and h_{st_k}, respectively. The channel gain between the source and the i-th element of the RIS for the source-to-tag link is denoted by $\boldsymbol{g}_{si} \in \mathbb{C}^{N\times 1}$, while the one between the i-th element and the k-th tag is denoted by $\boldsymbol{g}_{it_k} \in \mathbb{C}^{N\times 1}$. Similarly, the channel gains between the k-th tag and the i-th element of IRS for the tag-to-reader link is denoted by $\boldsymbol{g}_{t_ki} \in \mathbb{C}^{N\times 1}$, while the one between the i-th element and the reader is denoted by $\boldsymbol{g}_{ir} \in \mathbb{C}^{N\times 1}$. Throughout the paper, we assume that all the channels suffer from independent and identically distributed (i.i.d.) Rayleigh block fading and the reader knows all channel status information (CSI).

III. Proposed Multi-Tag Selection

In this section, we present our proposed multi-tag selection scheme and transmission protocol for IRS-assisted multi-tag AmBC networks.

Let us denote the transmitted signal from the RF source as $s(n) = \tilde{s}(n)e^{j2\pi f_s n}$, where f_s represents the carrier frequency and $\tilde{s}(n)$ denotes a complex baseband equivalent signal. First of all, the received signal at the k-th tag is given by $(\boldsymbol{g}_{si}\boldsymbol{\Theta}_k^{st}\boldsymbol{g}_{it_k} + h_{st_k})s(n)$ where a phase shift vector of the source-to-tag IRS is represented as $[\theta_{k,1}^{st}, \cdots, \theta_{k,N}^{st}]^T, \theta_{k,m}^{st} \in [0, 2\pi], m = 1, \cdots, N$ and the phase shift matrix of the IRS is given by $\boldsymbol{\Theta}_k^{st} = diag\ (e^{j\theta_{k,1}^{st}}, \cdots, e^{j\theta_{k,N}^{st}})$. The tag will backscatter the signals from the source and the source-to-tag IRS to transmit its own binary information bit, $B(n)$. When both the source-to-tag IRS and the tag-to-reader IRS exist, the received signal at the reader for the k-th tag and the n-th frame can be written by

$$y_k(n) = h_{sr}s(n) + [\eta(\boldsymbol{g}_{si}^T\boldsymbol{\Theta}_k^{st}\boldsymbol{g}_{it_k} + h_{st_k})(\boldsymbol{g}_{t_k i}^T\boldsymbol{\Theta}_k^{tr}\boldsymbol{g}_{ir} + h_{t_k r})s(n)]B(n) + w(n)$$
$$= \begin{cases} h_{sr}s(n) + w(n), & f\ B(n) = 0, \\ h_{sr}s(n) + [\eta(\boldsymbol{g}_{si}^T\boldsymbol{\Theta}_k^{st}\boldsymbol{g}_{it_k} + h_{st_k})(\boldsymbol{g}_{ti}^T\boldsymbol{\Theta}_k^{tr}\boldsymbol{g}_{ir} + h_{t_k r})s(n)] + w(n), & f\ B(n) = 1, \end{cases} \quad (1)$$

where η and $w(n)$ denote the antenna efficiency factor and the additive white Gaussian noise (AWGN). Fig. 2 shows the frame structure according to our proposed transmission protocol.

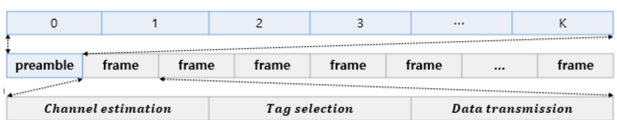


Fig. 2. Frame structure

A. Transmission Protocol with a Single IRS

For a single source-to-tag IRS, the protocol is as follows:

1) Preamble: To determine the decoding threshold at the reader, only the k-th tag will transmit N_0 bits of zeros and ones to the reader, while the other $(K-1)$ tags remain in an absorbing state [2]. The average powers for "0" and "1" bits are given, respectively, by

$$\Phi_0 = \frac{1}{N_0}\sum_{n=k*N_0+1}^{(k+1)N_0} |h_{sr}s(n) + w(n)|^2,$$
$$\Phi_1 = \frac{1}{N_0}\sum_{n=k*N_0+1}^{(k+1)N_0} |(h_{sr} + \eta(\boldsymbol{g}_{si}^T\boldsymbol{\Theta}_k^{st}\boldsymbol{g}_{it_k} + h_{st_k})h_{t_k r})s(n) + w(n)|^2.$$

2) Frame: Each frame consists of the following three steps.

(i) Step 1. Channel estimation

In this step, the optimal phase shift for the IRS is determined based on the estimated CSI. The goal is to maximize the effective channel gain from the source to the k-th tag. By equalizing the phase shifts of the IRS with the channel phases from the source to the k-th tag, it is determined by

$$\theta_{k,n}^{st*} = \angle h_{st_k} - (\angle \boldsymbol{g}_{si,n} + \angle \boldsymbol{g}_{it_k n}), \quad (2)$$

where $\boldsymbol{\Theta}_k^{st*} = diag\ (e^{j\theta_{k,1}^{st*}}, \cdots, e^{j\theta_{k,N}^{st*}})$.

(ii) Step 2. Tag selection

Based on the phase shifts in the previous step, we select the best tag offering the highest power gain at the reader as follows:

$$k_1^* = \arg \max_{1\le k\le K} |\eta(\boldsymbol{g}_{si}^T\boldsymbol{\Theta}_k^{st*}\boldsymbol{g}_{it_k} + h_{st_k})h_{t_k r}|. \quad (3)$$

(iii) Step 3. Data transmission

In this step, the selected tag transmits its data as follows:

$$y_{k_1^*}(n) = (h_{sr} + \eta(\boldsymbol{g}_{si}^T\boldsymbol{\Theta}_{k_1^*}^{st*}\boldsymbol{g}_{it_{k_1^*}} + h_{st_{k_1^*}})h_{t_{k_1^*}r})s(n) + w(n). \quad (4)$$

B. Transmission Protocol with Two IRSs

When both IRSs exist in between the source and the reader – one between the source and a tag, and the other between a tag and the reader, the protocol follows the next procedures.

1) Preamble: Similarly in Section III-A, each tag among K tags transmits N_0 bits to the reader sequentially, and the reader finds average powers Φ_b when $B(n) = 0$ and $B(n) = 1$ as

$$\Phi_0 = \frac{1}{N_0}\sum_{n=k*N_0+1}^{(k+1)N_0} |h_{sr}s(n) + w(n)|^2,$$
$$\Phi_1 = \frac{1}{N_0}\sum_{n=k*N_0+1}^{(k+1)N_0} |(h_{sr} + \eta(\boldsymbol{g}_{si}^T\boldsymbol{\Theta}_k^{st}\boldsymbol{g}_{it_k} + h_{st})(\boldsymbol{g}_{t_k i}^T\boldsymbol{\Theta}_k^{tr}\boldsymbol{g}_{ir} + h_{t_k r}))s(n) + w(n)|^2.$$

2) Frame: Each frame consists of the following three steps.

(i) Step 1. Channel estimation

Here, it is required to determine two different phase shift matrices for IRSs: one is $\boldsymbol{\Theta}_k^{st}$ for the source-to-tag IRS and the other is $\boldsymbol{\Theta}_k^{tr}$ for the tag-to-reader IRS. The received signal at the reader is written by

$$y_{k,2}(n) = (h_{sr} + \eta(\boldsymbol{g}_{si}^T\boldsymbol{\Theta}_k^{st}\boldsymbol{g}_{it_k} + h_{st_k})(\boldsymbol{g}_{t_k i}^T\boldsymbol{\Theta}_k^{tr}\boldsymbol{g}_{ir} + h_{t_k r}))s(n) + w(n), \quad (5)$$

Similar in (2), the phase shift matrix for the tag-to-reader IRS is determined by

$$\theta_{k,n}^{tr*} = \angle h_{t_k r} - (\angle \boldsymbol{g}_{t_k i,n} + \angle \boldsymbol{g}_{ir,n}), \quad (6)$$

where $\boldsymbol{\Theta}_k^{tr*} = diag\ (e^{j\theta_{k,1}^{tr*}}, \cdots, e^{j\theta_{k,N}^{tr*}})$.

(ii) Step 2. Tag selection

By applying (2) and (6) for the IRS phase shifts, the tag with the highest power gain is selected as follows:

$$k_2^* = \arg \max_{1\le k\le K} |\eta(\boldsymbol{g}_{si}^T\boldsymbol{\Theta}_k^{st*}\boldsymbol{g}_{it_k} + h_{st_k})(\boldsymbol{g}_{t_k i}^T\boldsymbol{\Theta}_k^{tr*}\boldsymbol{g}_{ir} + h_{t_k r})|. \quad (7)$$

(iii) Step 3. Data transmission

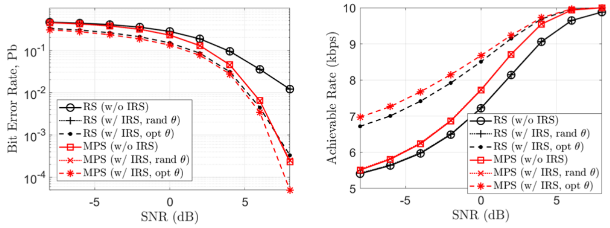
Finally, the selected tag transmits its data as follows:

$$y_{k_2^*}(n) = (h_{sr} + \eta(\boldsymbol{g}_{si}^T\boldsymbol{\Theta}_{k_2^*}^{st*}\boldsymbol{g}_{it_{k_2^*}} + h_{st_{k_2^*}})(\boldsymbol{g}_{t_{k_2^*}i}^T\boldsymbol{\Theta}_{k_2^*}^{tr*}\boldsymbol{g}_{ir} + h_{t_{k_2^*}r}))s(n) + w(n). \quad (8)$$

IV. Numerical Results

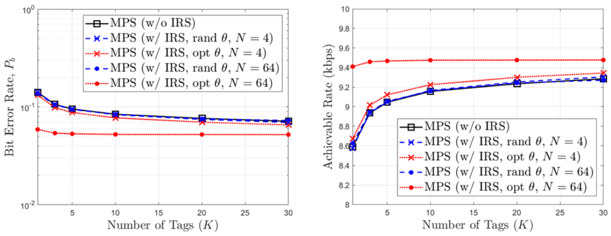
In this section, we evaluate the performance of the proposed multi-tag selection and transmission protocol in terms of BER and achievable data rate through simulations. Throughout the results, average channel gains for all links are set to 0.01 considering relatively low backscatter channel conditions. In addition, we set the antenna efficiency (η) to 0.5, the source rate to 1 Mbps, and the number of IRS elements (N) to 64. For performance comparison, we consider six different methods: the proposed max power selection (MPS) with optimal phase shifted IRS, MPS with random phase shifted IRS, MPS without IRS, random tag selection (RS) with optimal phase shifted IRS, RS with random phase shifted IRS, and RS without IRS.

Fig. 3 shows the performance of the AmBC network with a single source-to-tag IRS for varying signal-to-noise ratio (SNR). It is shown that the proposed MPS with optimal phase shifted IRS outperforms the other methods in both performance metrics.



(a) (b)

Fig. 3. Performance for varying SNR. (a) BER (b) data rate ($K = 5$ and $N = 64$)



(a) (b)

Fig. 4. Effect of number of tags. (a) BER (b) data rate (SNR = 3dB)

As shown in the figures, the RS schemes with and without the IRS achieve the same worst performance. Additionally, random phase shift methods for the IRS cannot provide a beamforming gain of the IRS, while the optimal phase shift method proposed in (2) effectively gives IRS beamforming gains. Therefore, it is more important to control phase shifts for the IRS in this case.

A. Effect of the number of tags

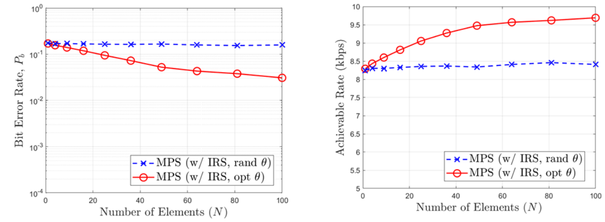
Fig. 4 shows the performance of the AmBC network with a single source-to-tag IRS for varying the number of tags (K). Basically, it is shown that a selection diversity gain increases as the number of tags increases. That is, the BER and the achievable rate are improved with increasing number of tags. However, for the proposed MPS with optimal phase shifted IRS, when N is sufficiently large, the performance is converged to the optimal value more quickly. After all, a small number of tags are enough to achieve the maximum performance.

B. Effect of the number of IRS elements

Fig. 5 shows the performance of the AmBC network with a single source-to-tag IRS for varying the number of IRS elements (N). It is shown that the performance of the MPS with optimal phase shifted IRS outperforms the MPS with random phase shifted IRS. As N increases, both BER and achievable rate of the proposed MPS with optimal phase shifted IRS are improved, while the one with random phase shifted IRS is not affected by the number of IRS elements.

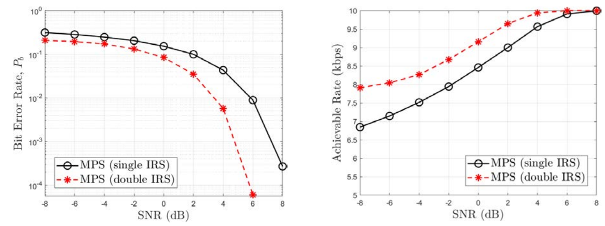
C. Effect of the number of IRSs

Fig. 6 shows the effect of the number of IRSs. As shown in the figures, the MPS with two IRSs, source-to-tag IRS and tag-to-reader IRS, achieves much better performance than the one with a single source-to-tag IRS in whole range of SNRs.



(a) (b)

Fig. 5. Effect of number of IRS elements. (a) BER (b) data rate (SNR = 3 dB and $K = 5$)



(a) (b)

Fig. 6. Effect of number of IRSs. (a) BER (b) data rate ($K = 5$)

V. Conclusions

In this paper, we proposed multi-tag selection and IRS phase control methods for IRS-assisted AmBC networks with multiple tags. It is shown that with increasing number of IRS elements and number of tags, the performance is improved due to IRS beamforming and selection diversity gains. Especially, when it is assisted by two IRSs for both links in between the source and the reader, the performance is dramatically improved. For future work, we plan to study on multi-tag IRS-assisted AmBC networks under limited or partial CSI conditions.

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