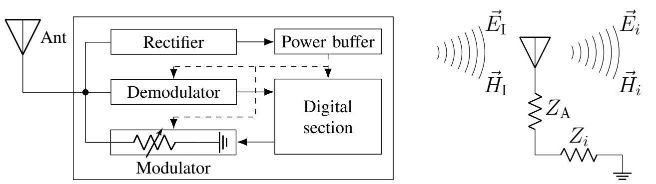
Backscatter Modulation Design for Symbiotic Radio Networks



(a) Block diagram (b) One-port network model

Fig. 1. For a passive tag, the rectifier and demodulator rely on the incident electromagnetic wave for energy harvesting and downlink information decoding, while the load-switcher manipulate the reradiated signal for backscatter modulation.

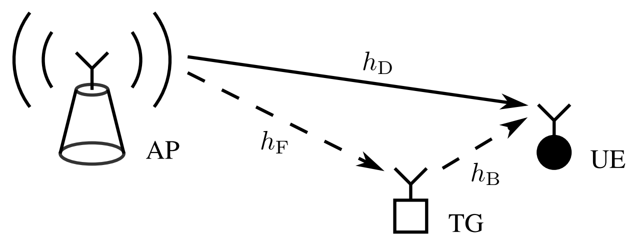


Fig. 2. A single-user single-tag symbiotic radio system.

I. Backscatter Model

A. Backscatter Principles

Consider a bistatic backscatter system that consists of an excitation source, a dedicated reader, and a passive tag. The excitation source generates a carrier wave signal, the dedicated reader decodes the tag message, and the tag simultaneously harvests energy, backscatters its own message, and demodulates the downlink information if necessary. As shown in Fig. 1(a), a typical passive tag consists of a scattering antenna, an energy harvester, a integrated receiver[1], a load-switching modulator, and on-chip components (e.g., micro-controller, memory, and sensors). A portion of the impinging signal is absorbed by the tag while the remaining is backscattered to the space, as illustrated in Fig. 1(b). According to Green's decomposition [2], the backscattered signal can be decomposed into the *structural mode* component and the *antenna mode* component. The former is fixed and depends on the antenna geometry and material properties[2], while the latter is adjustable and depends on the mismatch of the antenna and load impedance. Hence, the equivalent reflection coefficient at tag state i is defined as[3]

$$\Gamma_i = \frac{Z_i - Z_{\mathrm{A}}^*}{Z_i + Z_{\mathrm{A}}}, \tag{1}$$

where Z_i is the designable antenna load impedance at state i and Z_{A} is the antenna input impedance.

Remark 1. *The reflection coefficient plays an important role in various network designs. For example, $\Gamma_i = 0$ (perfect matching) achieves maximum power transfer that is optimal for Wireless Power Transfer (WPT), $|\Gamma_i| = 1$ (perfect mismatching) achieves fully signal reflection that is optimal for Intelligent Reflecting Surface (IRS), and $\Gamma_i \neq \Gamma_j$ (adjustable matching) enables backscatter modulation.*

[1]For example, [1] prototyped a compact-size pulse position demodulator based on an envelope detector, which brings great potential to coordination, synchronization, and reflection pattern control.

[2]We assume the structural mode reflection can be modeled as part of the environment multipath and covered by channel estimation [3].

[3]We assume the linear backscatter model where Γ_i is irrelevant to the incident electromagnetic field at the tag [4].

B. Backscatter Modulation

Tags perform backscatter modulation by switching the load impedance between different states. For M-ary Phase Shift Keying (PSK), the reflection coefficient Γ_i maps to the desired signal constellation point c_i as [5]

$$\Gamma_i = \alpha c_i = \alpha e^{\jmath\left(\frac{2\pi i}{M} + \phi\right)}, \tag{2}$$

where $\alpha \in [0, 1]$ is the reflection efficiency at a given direction, and ϕ is a fixed phase offset.

Remark 2. *For passive tags, the reflection efficiency α controls the tradeoff between the backscatter strength and harvestable power. Interestingly, when $\alpha = 1$, the reflection coefficient set $\{\Gamma_i\}$ of the M-PSK backscatter coincides with that of an ideal discrete M-state uniform IRS. The optimal strategy for the IRS is to choose one reflection state with probability 1 to boost the equivalent channel, while the optimal strategy for the modulator is to utilize all constellation points with equal probability. It inspires one to adaptively design the p.m.f. of tag symbols to jointly benefit the backscatter modulation and passive beamforming.*

II. System Model

As shown in Fig. 2, we propose a single-user (UE) single-tag (TG) symbiotic radio network where the RF signal generated by the single-antenna Access Point (AP) is shared by two coexisting systems. In the primary AP-UE downlink system, the AP transmits to the single-antenna user. In the secondary AP-TG-UE backscatter system, the AP acts as the carrier emitter, the user serves as the backscatter reader, and the single-antenna tag modulates its information over the reradiated RF signal by varying the reflection coefficient. Denote the AP-UE direct channel as h_{D}, the AP-TG forward channel as h_{F}, and the TG-UE backward channel as h_{B}. We consider the quasi-static block fading model and assume the CSI of the direct channel and the cascaded forward-backward channel

$h_{\mathrm{C}} \triangleq h_{\mathrm{B}} h_{\mathrm{F}}$ are known at the AP.[4] It is assumed that the primary symbol s follows standard CSCG distribution $\mathcal{CN}(0,1)$ and the secondary symbol c employs M-PSK modulation by (2). Let P be the average transmit power of the AP. The user simultaneously captures the signal from both primary and secondary links as[5]

$$y = \sqrt{P} h_{\mathrm{D}} s + \sqrt{\alpha P} h_{\mathrm{C}} s c + n, \tag{3}$$

where $n \sim \mathcal{CN}(0,1)$ is the additive white Gaussian noise.

Remark 3. *The symbiotic radio network can be regarded as as a special case of Multiple Access Channel (MAC) because the AP and the tag transmit to the user simultaneously. It is known that SC-SIC with different decoding orders can achieve different vertices of the MAC capacity region [12]. Therefore, most relevant papers proposed to decode the primary message first (by treating the tag interference as noise), cancel out the primary contribution from the received signal, then decode the secondary message. Since the direct channel is typically much stronger than the cascaded channel [13], the primary decoding should enjoy a high Signal-to-Interference-and-Noise Ratio (SINR) and the secondary decoding should be interference-free in the ideal case.*

Remark 4. *To investigate how backscatter modulation potentially benefits the primary transmission, we instead decode the secondary link before the primary link. Once the tag message is successfully decoded, the uncertainty of the AP-TG-UE path can be perfectly removed (by combining the backscattered symbol and the cascaded channel), and its contribution can be modeled within the equivalent AP-UE channel. This is reminiscent of IRS-aided point-to-point transmission with CSI uncertainty (by backscatter modulation instead of channel estimation), where the passive tag simultaneously embeds its own message (embodied in secondary decoding) and assists the legacy transmission (embodied in primary decoding).*

[Channel over channel, randomness over randomness]

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[4] Due to the lack of RF chains at the passive tag, accurate and efficient CSI acquisition at the AP can be challenging. One possible approach is that the AP sends known pilots, the tag responds in a pre-defined manner, and the user performs least-square estimation then feeds back to the AP [6]–[8].

[5] We assume the time difference of arrival from the AP-UE path and the AP-TG-UE path are negligible compared to the symbol period [9]–[11].