# Symbiotic Radio:
# Towards Spectrum and Energy Efficient Transmission

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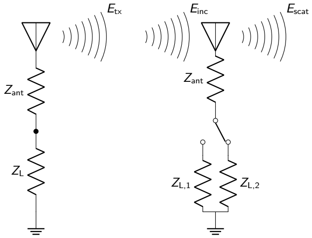
# Table of Contents

# Antennas: Transmitter vs Scatterer

**Green's decomposition:** the (back)scattered signal of an antenna can be decomposed into *structural mode* component and *antenna mode* component.




**(a)** Transmit antenna **(b)** Backscatter antenna

$$E_{scat}(Z_L) = \underbrace{E_{scat}(Z_{ant}^*)}_{\text{structural mode, fixed}} + \underbrace{\Gamma^* E_{ant} \frac{I_m^*}{I_{ant}}}_{\text{antenna mode, adjustable}} \tag{1}$$

# Non-Frequency Shifting Modulation

**Non-Frequency Shifting (FS) modulation** only changes the amplitude and phase of the incident signal. The backscattered signal can be controlled by varying the load at the reflector.

$$\Gamma^*(Z_\mathrm{L}) = \frac{Z_\mathrm{ant}^* - Z_\mathrm{L}}{Z_\mathrm{ant} + Z_\mathrm{L}} \tag{2}$$

Key issue: design a reflection coefficient set corresponding to the signal constellation set $\mathcal{C}$. For each constellation point $c_i \in \mathcal{C}$,

$$\Gamma_i = \alpha \frac{c_i}{\max_{c\in\mathcal{C}}|c|} \tag{3}$$

where the constant $\alpha < 1$ determines the tradeoff between *backscatter strength* and *harvestable power* at the reflector.

# Frequency Shifting Modulation

**Frequency shifting modulation** changes $\Gamma$ over time to approximate a sine wave $ce^{j2\pi\Delta ft} = c\,(\cos(j2\pi\Delta ft) + j\sin(j2\pi\Delta ft))^1$.

For a incoming signal $\cos(2\pi ft)$, the backscattered signal is

$$ce^{j2\pi\Delta ft}\cos(2\pi ft) = \frac{c}{2}(\underbrace{e^{j2\pi(f+\Delta f)t}}_{\text{desired}} + \underbrace{e^{j2\pi(-f+\Delta f)t}}_{\text{mirror}}) \tag{4}$$

Some modulation techniques (e.g. inter-technology backscatter [1], HitchHike [2]) can be used to suppress the mirror copy.

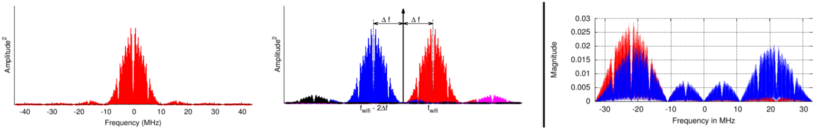



**Figure:** Incident and backscattered waveform [1, 3]

[1] In practice, the sin/cos terms can be approximated by a convenient square wave (large amplitude at $\Delta f$, small interference at harmonics)

# Ambient Backscatter Communication

**Ambient Backscatter Communication (AmBC)** utilizes the surrounding RF signals (e.g. TV, Wi-Fi) to enable communications between batteryless devices.

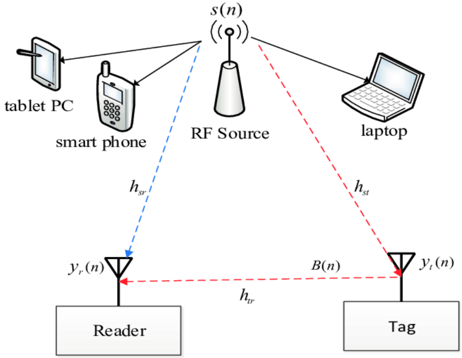
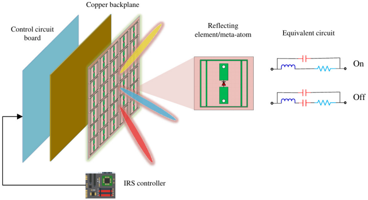



**Figure:** An ambient backscatter communication system [4]

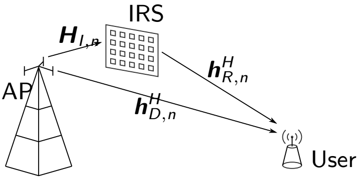
The passive tag harvests energy from and modulate over the ambient RF signal.

# Intelligent Reflecting Surface

**Intelligent Reflecting Surface (IRS)** consists of multiple individual passive reflecting elements that adjust the amplitude and phase of the incident signal.




**(a)** IRS architecture [5]




**(b)** Application scenario

- outer layer: redistribute incident signals
- middle layer: avoid signal energy leakage
- inner layer: adjust reflection amplitude and phase shift

- enhance primary transmission by constructive reflection
- null interference by destructive reflection
- enable LoS Racian fading for less outage

# Performance of Conventional Backscatter Systems

| | | Maximum Bit Rate | | Range | | Deployment | |
|---|---|---|---|---|---|---|---|
| Name | Minimum Power | Bit Rate | Distance | Transmitter to Tag | Tag to Receiver | Transmitter | Receiver |
| BackFi [6] | N/A | 5 megabit/s | 1 m | 7 m | 7 m | Ambient Wi-Fi | Software-defined radio |
| Ambient backscatter [7] | 0.79 $\mu$W | 10 kilobit/s | 0.4 m | N/A | 2.5 m | Ambient TV | Customized hardware |
| Wi-Fi backscatter [8] | 9.65 $\mu$W | 1 kilobit/s | N/A | N/A | 2.1 m | Commodity Wi-Fi | Commodity Wi-Fi |
| Passive Wi-Fi [9] | 14.5 $\mu$W (IC) | 11 megabit/s | N/A | 3.7 m | 16.8 m | Customized hardware | Commodity Wi-Fi |
| HitchHike [10] | 33 $\mu$W (IC) | 300 kilobit/s | 34 m | 1 m | 54 m | Commodity Wi-Fi | Commodity Wi-Fi |
| LoRea [11] | 70 $\mu$W | 197 kilobit/s | 175 m | 1 m | 3.4 km | Patched commodity | Customized hardware |
| Interscatter [12] | 28 $\mu$W (IC) | 11 megabit/s | N/A | 0.9 m | 27.4 m | Commodity BLE | Commodity Wi-Fi/Zigbee |
| Battery-free cell phone [13] | 3.48 $\mu$W | N/A | N/A | 15.2 m | 15.2 m | Customized hardware | Customized hardware |
| LoRa backscatter [14] | 9.25 $\mu$W (IC) | 37.5 kilobit/s | N/A | 5 m | 2.8 km | Customized hardware | Commodity LoRa |
| FM backscatter [15] | 11.07 $\mu$W (IC) | 3.2 kilobit/s | 4.9 m | N/A | 18.3 m | Ambient FM | Commodity FM |

**Figure:** A performance comparison of promising backscatter systems [6]

Conventional backscatter systems cannot be spectrum and energy efficient at the same time:

- Non-FS modulation creates and is subject to interference
- FS modulation needs extra bandwidth

# Symbiotic Radio

In a **Symbiotic Radio (SR)** system, the non-FS backscatter device

- enables a secondary transmission over the primary transmission (like AmBC)
- can be used to assist the primary transmission (like IRS)

**Table:** Backscatter Technologies

| Technology | RFID | IRS | AmBC | SR |
|---|---|---|---|---|
| Coexist links | 1 | 1 | $\geq 2$ | $\geq 2$ |
| Role/relationship | Dedicated | Auxiliary | Interf | Interf or collab |
| Spectrum sharing | — | — | Yes | Yes |
| Energy sharing | — | — | Yes | Yes |
| Joint transceiver design | Yes | Yes | No | Yes |
| Relative range | Short | Long | Short | Short |

With fully passive backscatter devices, SR is spectrum efficient (non-FS) and energy efficient (reuse existing signals).

# Table of Contents

# System Architecture

Consider a $M$-antenna transmitter, a single antenna backscatter device and a single antenna receiver. Denote the primary message as $s(n)$.

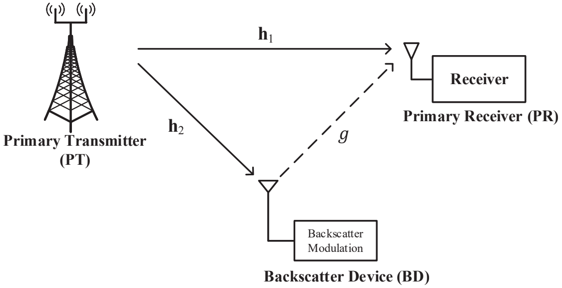



**Figure:** Architecture of an symbiotic radio network [7]

Assume a block-fading channel model, denote

- PT-PR channel: $\boldsymbol{h}_1^H \in \mathbb{C}^{1\times M}$
- PT-BD channel: $\boldsymbol{h}_2^H \in \mathbb{C}^{1\times M}$
- BD-PR channel: $g \in \mathbb{C}$

# Categories of Symbiotic Radio

Denote $T_s$ and $T_c$ as the the symbol duration of primary and secondary transmission. Let $T_c = NT_s, N \in \mathbb{R}_{++}$. Two types of SR depending on $N$:

- **Parasitic SR (PSR)** ($N = 1$): treat backscattered signal as interference.
- **Commensal SR (CSR)** ($N \gg 1$): treat backscattered signal as multipath component.

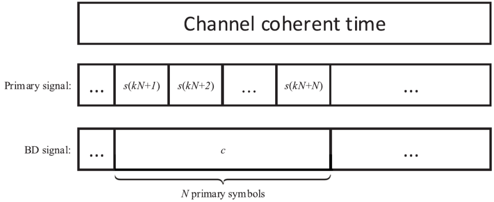



**Figure:** CSR transmission frame ($N \gg 1$) [7]

# System Model: Parasitic Symbiotic Radio

**PSR treats the backscattered signal as interference and use SIC to decode.** In PSR, $T_C = T_S$ and the backscatter message is $c(n)$.

Received signal:

$$y(n) = \underbrace{\boldsymbol{h}_1^H \boldsymbol{w} s(n)}_{\text{direct signal}} + \underbrace{\sqrt{\alpha} g \boldsymbol{h}_2^H \boldsymbol{w} s(n) c(n)}_{\text{backscattered signal}} + z(n) \tag{5}$$

Intermediate signal (assume perfect cancellation):

$$y_b(n) = \underbrace{\sqrt{\alpha} g \boldsymbol{h}_2^H \boldsymbol{w} s(n)}_{\text{equivalent channel } h_c} c(n) + z(n) \tag{6}$$

# System Model: Parasitic Symbiotic Radio

Primary achievable rate:

$$R_s^{\mathrm{PSR}} = \log_2 \left(1 + \frac{|\boldsymbol{h}_1^H \boldsymbol{w}|^2}{\alpha |g|^2 |\boldsymbol{h}_2^H \boldsymbol{w}|^2 + \sigma^2}\right) \tag{7}$$

Secondary achievable rate:

$$R_c^{\mathrm{PSR}} = \mathbb{E}_s \left[\log_2 \left(1 + \frac{\alpha |g|^2 |\boldsymbol{h}_2^H \boldsymbol{w}|^2 |s(n)|^2}{\sigma^2}\right)\right] = -e^{1/\gamma_c^{\mathrm{PSR}}} \mathrm{Ei}(-\frac{1}{\gamma_c^{\mathrm{PSR}}}) \log_2 e \tag{8}$$

where $\gamma_c^{\mathrm{PSR}} = \alpha |g|^2 |\boldsymbol{h}_2^H \boldsymbol{w}|^2 / \sigma^2$ and $\mathrm{Ei}(x) \triangleq \int_{-\infty}^{x} (1/u) e^u \, \mathrm{d}x$.

PSR characteristics:

- enables high-rate low-SNR secondary transmission
- creates interference to primary transmission
- need to synchronize the primary and backscatter messages

# System Model: Commensal Symbiotic Radio

**CSR treats the backscattered signal as a multipath component and use SIC to decode.** In CSR, $N \gg 1$ and the backscatter message is $c$ within a channel block.

Received signal:

$$y(n) = \underbrace{\boldsymbol{h}_1^H \boldsymbol{w} s(n)}_{\text{direct signal}} + \underbrace{\sqrt{\alpha} g \boldsymbol{h}_2^H \boldsymbol{w} s(n) c}_{\text{backscattered signal}} + z(n) \tag{9}$$

$$= \underbrace{\left(\boldsymbol{h}_1^H + \sqrt{\alpha} g \boldsymbol{h}_2^H c\right)}_{\text{equivalent channel } \boldsymbol{h}_s^H(c)} \boldsymbol{w} s(n) + z(n) \tag{10}$$

Intermediate signal (assume perfect cancellation):

$$y_b(n) = \sqrt{\alpha} g \boldsymbol{h}_2^H \boldsymbol{w} \underbrace{s(n)}_{\text{spreading code}} c + z(n) \tag{11}$$

# System Model: Commensal Symbiotic Radio

Primary achievable rate ($c$ is unknown, noncoherent, $N$ sufficiently large):

$$R_s^{\mathrm{CSR}} = \mathbb{E}_c\left[\log_2\left(1+\gamma_s^{\mathrm{CSR}}(c)\right)\right] \overset{\gamma_s^{\mathrm{CSR}}(c)\to+\infty}{\approx} \underbrace{\log_2 \lambda}_{\text{without SR}} \underbrace{-\mathrm{Ei}\left(-\frac{\lambda}{2\Sigma}\right)\log_2 e}_{\geq 0,\ \text{primary rate gain by multipath}} \tag{12}$$

where $\gamma_s^{\mathrm{CSR}}(c) = |\boldsymbol{h}_s^H(c)\boldsymbol{w}|^2/\sigma^2$, $\lambda = |\boldsymbol{h}_1\boldsymbol{w}|^2/\sigma^2$, $\Sigma = \alpha|g|^2|\boldsymbol{h}_2\boldsymbol{w}|^2/2\sigma^2$.

Secondary achievable rate (assume perfect cancellation):

$$R_c^{\mathrm{CSR}} = \frac{1}{N}\log_2\left(1+\frac{N\alpha|g|^2|\boldsymbol{h}_2^H\boldsymbol{w}|^2}{\sigma^2}\right) \tag{13}$$

CSR characteristics:

- compared with PSR, symbol rate decreased by $1/N$ but SNR increased by $N$
- enhances the primary link by additional multipath component
- synchronization is much relaxed (every $N$ symbols)
- suitable for slow-fading channels (large coherence time)

# Transmit Beamforming: WSRM and TPM

Weighted Sum-Rate Maximization (WSRM) through transmit beamforming:

$$\max_{\boldsymbol{w}} \quad \rho R_s^{\text{PSR/CSR}} + (1-\rho) R_c^{\text{PSR/CSR}} \tag{14a}$$

$$\text{s.t.} \quad \|\boldsymbol{w}\|^2 \leq P, \tag{14b}$$

$$0 \leq \rho \leq 1 \tag{14c}$$

Transmit Power Minimization (TPM) through transmit beamforming:

$$\min_{\boldsymbol{w}, P} \quad P \tag{15a}$$

$$\text{s.t.} \quad R_s^{\text{PSR/CSR}} \geq \epsilon_s, \tag{15b}$$

$$R_c^{\text{PSR/CSR}} \geq \epsilon_c, \tag{15c}$$

$$\|\boldsymbol{w}\|^2 \leq P \tag{15d}$$

Problem 14 can be solved by the Semidefinite Relaxation (SDR) technique together with a 1-D exhaustive search. Problem 15 can be solved by SDR.

# Low-Complexity Solution

The optimal beamformer of WSRM or TPM is a *linear combination* of scaled channel vectors:

$$\boldsymbol{w}^{\star} = \alpha_1 \tilde{\boldsymbol{h}}_1 + \alpha_2 \tilde{\boldsymbol{h}}_2 = \boldsymbol{H}\boldsymbol{\alpha} \tag{16}$$

where $|\alpha_1|^2 + |\alpha_2|^2 = 1$, $\boldsymbol{H} = [\tilde{\boldsymbol{h}}_1, \tilde{\boldsymbol{h}}_2] \in \mathbb{C}^{M \times 2}$, $\boldsymbol{\alpha} = [\alpha_1, \alpha_2]^T \in \mathbb{C}^{2 \times 1}$. The SDR problems are now related to $\boldsymbol{A} = \boldsymbol{\alpha}\boldsymbol{\alpha}^H \in \mathbb{C}^{2 \times 2}$ only.

An intuition is that the optimal beamformer of PT-PR (traditional MISO) and PT-BD-PR (traditional BackCom) are the MRT of the corresponding links. SR is basically a combination of both.

# WSRM: Rate Region

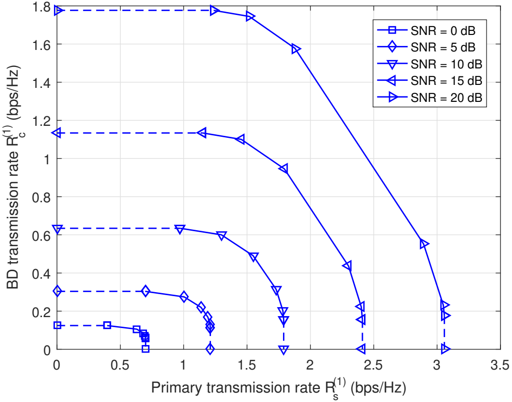
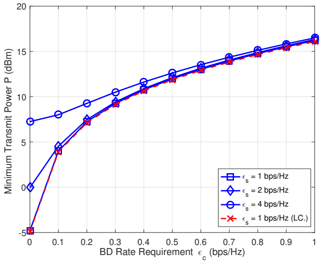
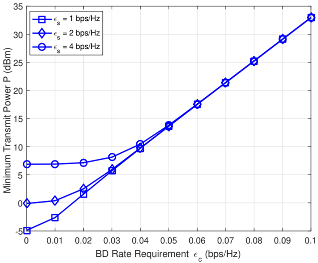



**Figure:** Rate region of PSR [7]

# TPM: Transmit Power



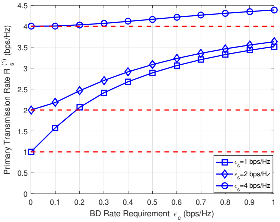

**(a)** PSR ($N = 1$)



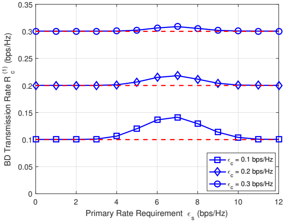

**(b)** CSR ($N = 128$)

**Figure:** Minimum transmit power $P$ vs backscatter rate constraint $\epsilon_c$

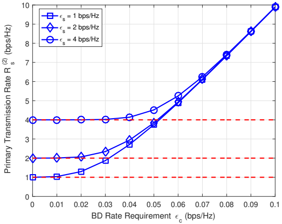
# TPM: Rate Tradeoff



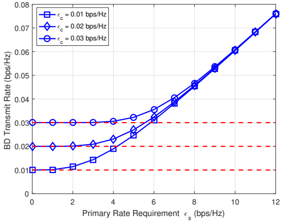

**(a)** PSR: primary rate $R_s^{PSR}$ vs backscatter rate constraint $\epsilon_c$




**(b)** PSR: secondary rate $R_c^{PSR}$ vs primary rate constraint $\epsilon_s$




**(c)** CSR: primary rate $R_s^{CSR}$ vs backscatter rate




**(d)** CSR: secondary rate $R_c^{CSR}$ vs primary rate

# Limitations and Opportunities

Limitations:

- **Channel model:** double fading may not cover backscatter channel properties as rank deficiency and channel correlation.
- **Channel estimation:** need carefully designed pilots and low complexity algorithms.
- **Synchronization:** traditional solution requires power-consuming oscillators at the backscatter device.
- **Security:** the secondary transmission relies heavily on the primary transmission.

Opportunities:

- Integrate the IRS reflection coefficient $\phi$ and the backscatter message $c$ for multi-antenna backscatter?
- Design SR in broadcasting and multiple access systems?
- Suppress the backscatter signal at other frequencies?

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