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RIScatter: Unifying Backscatter Communication and Reconfigurable Intelligent Surface

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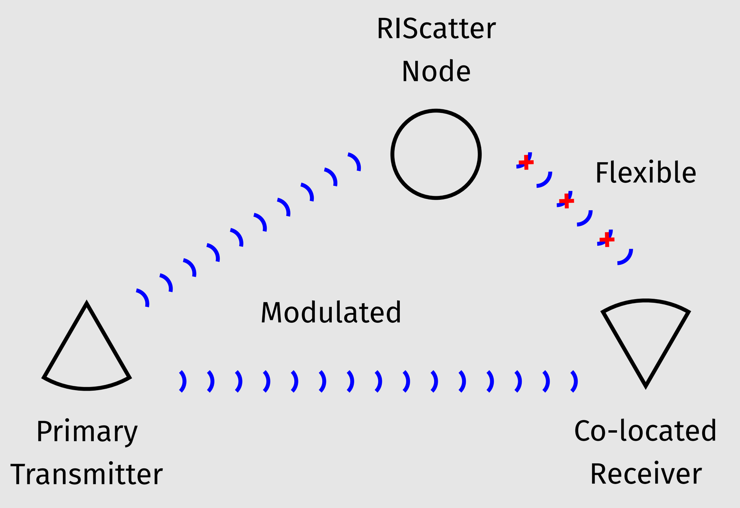
Overview

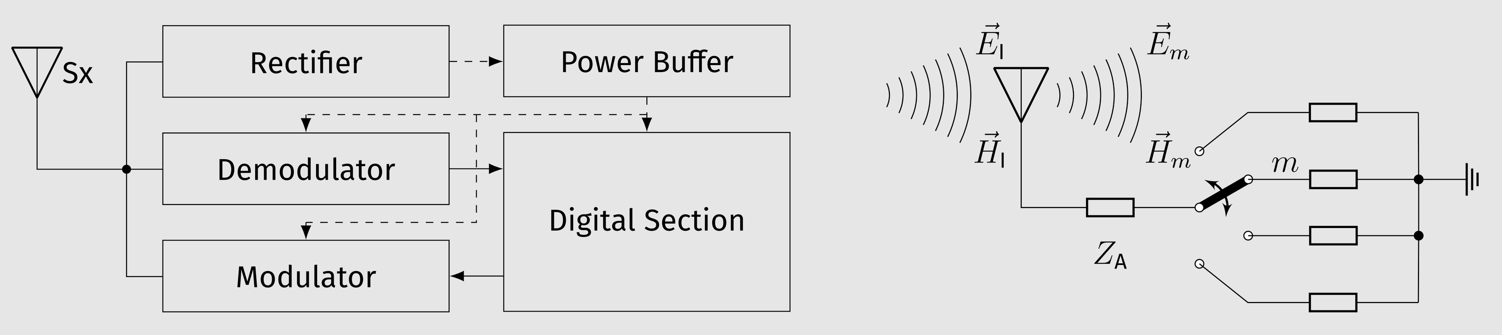
- **What does this paper propose?**
  RIScatter – a batteryless cognitive radio that recycles ambient signal in an adaptive and customizable manner.
- **How does it differ from previous work?**
  Backscatter modulation and passive beamforming are seamlessly integrated from the perspective of probability distribution.
- **What are the benefits?**
  It supports cooperative and distributed deployment, avoids complex architecture and signal processing, and can be built over legacy systems.

RIScatter system



- Primary link: active ambient transmission from an RF source
- Backscatter link: passive free-ride transmission from IoT nodes

Node architecture



(a) Block Diagram (b) Scatter Model

- Wave scattering or reflection are manipulated by antenna or metamaterial
- Incoming signals are used for powering, modulation, and beamforming
- The node changes reflection state by switching load impedance

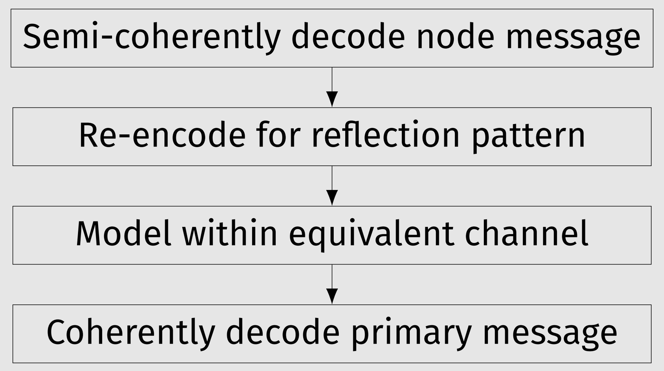
Properties

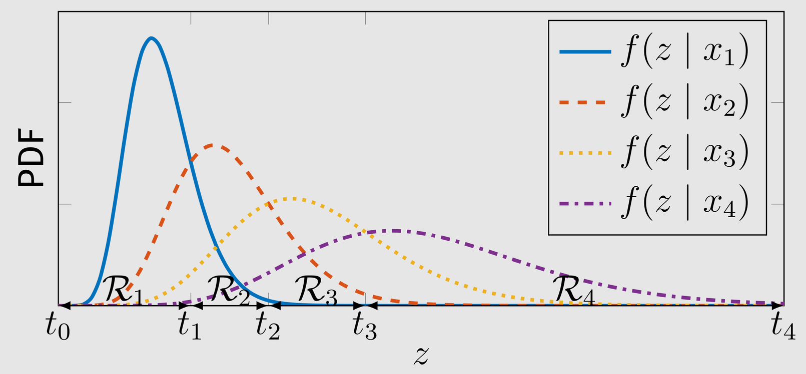
1. Primary and backscatter symbols are superimposed by *double modulation*
2. Backscatter signal is much weaker due to *double fading*
3. The spreading factor (symbol period ratio) is usually large
4. Each *state* is simultaneously part of information and beamforming *codeword*
5. Reflection pattern over time is semi-random and guided by input probability assigned to each state

Applications comparison

	Backscatter	Ambient backscatter	Symbiotic radio	Reconfigurable intelligent surface	RIScatter
Information link(s)	Backscatter	Coexisting	Coexisting	Primary	Coexisting
Primary on backscatter	Carrier	Multiplicative interference	Spreading code	—	Energy uncertainty
Backscatter on primary	—	Multiplicative interference	Channel uncertainty	Passive beamforming	Dynamic passive beamforming
Cooperative devices	—	No	Transmitter and receiver	—	Transmitter, nodes, and receiver
Sequential decoding	—	No	Primary-to-backscatter	—	Backscatter-to-primary
Reflection pattern by	Information source	Information source	Information source	Channel	Information source, channel, and relative priority
Input distribution	Equiprobable	Equiprobable	Equiprobable or Gaussian	Degenerate	Flexible
Load-switching speed	Fast	Slow	Slow	Quasi-static	Arbitrary

Low-complexity receiver





- Accumulated receive energy follows conditional Gamma distribution
- Node detection under primary uncertainty becomes part of channel training
- Requires one additional energy comparison and re-encoding per backscatter symbol

Problem formulation

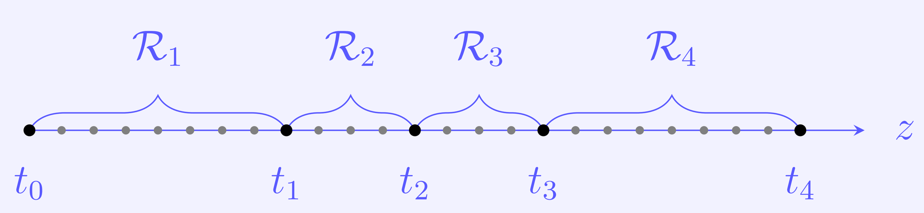
$$\begin{aligned} \max_{\{\boldsymbol{p}_k\},\boldsymbol{w},\boldsymbol{t}} \quad & \rho R_{\mathsf{P}} + (1-\rho)\sum_k R_{\mathsf{B},k} \\ \text{s.t.} \quad & \mathbf{1}^{\mathsf{T}}\boldsymbol{p}_k = 1, \quad \boldsymbol{p}_k \geq \mathbf{0}, \quad \forall k, \\ & t_{l-1} \leq t_l, \quad t_l \geq 0, \quad \forall l, \\ & \|\boldsymbol{w}\|^2 \leq P \end{aligned}$$

- $\boldsymbol{p}_k$ is the input distribution of node k
- $\boldsymbol{w}$ is the active beamforming vector
- $\boldsymbol{t}$ is the decision threshold vector

Block 1: Input distribution

$$p^{(r+1)}(x_{m_k}) \leftarrow \frac{p^{(r)}(x_{m_k}) \exp\left(\frac{\rho}{1-\rho} I_k^{(r)}(x_{m_k})\right)}{\sum_{m'_k} p^{(r)}(x_{m'_k}) \exp\left(\frac{\rho}{1-\rho} I_k^{(r)}(x_{m'_k})\right)}$$

Block 2: Decision threshold

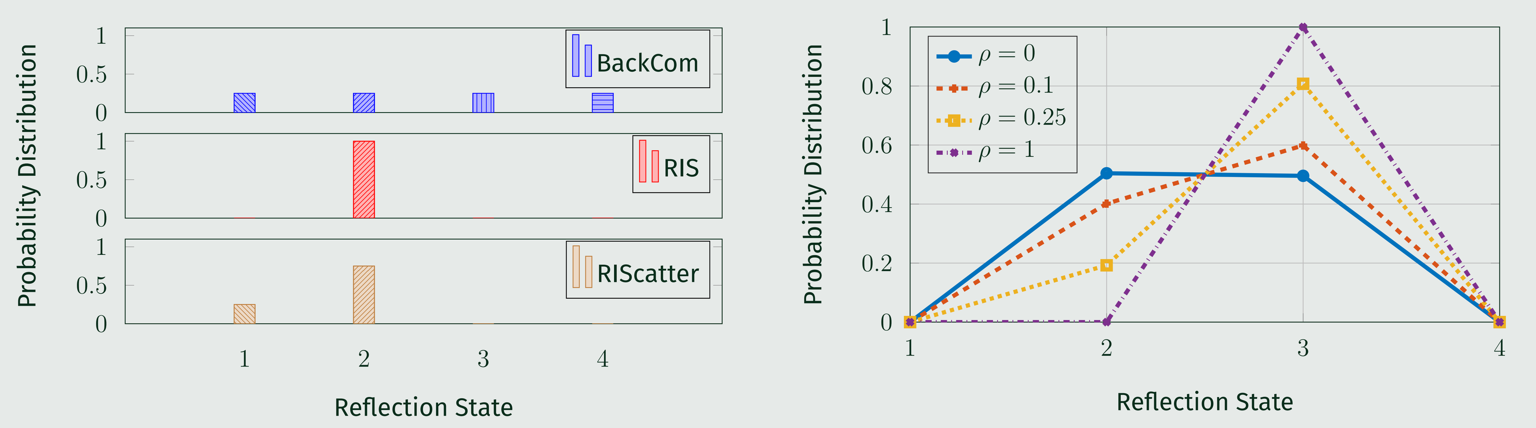


- Obtain the rate-optimal quantization by dynamic programming or bisection

Block 3: Active beamformer

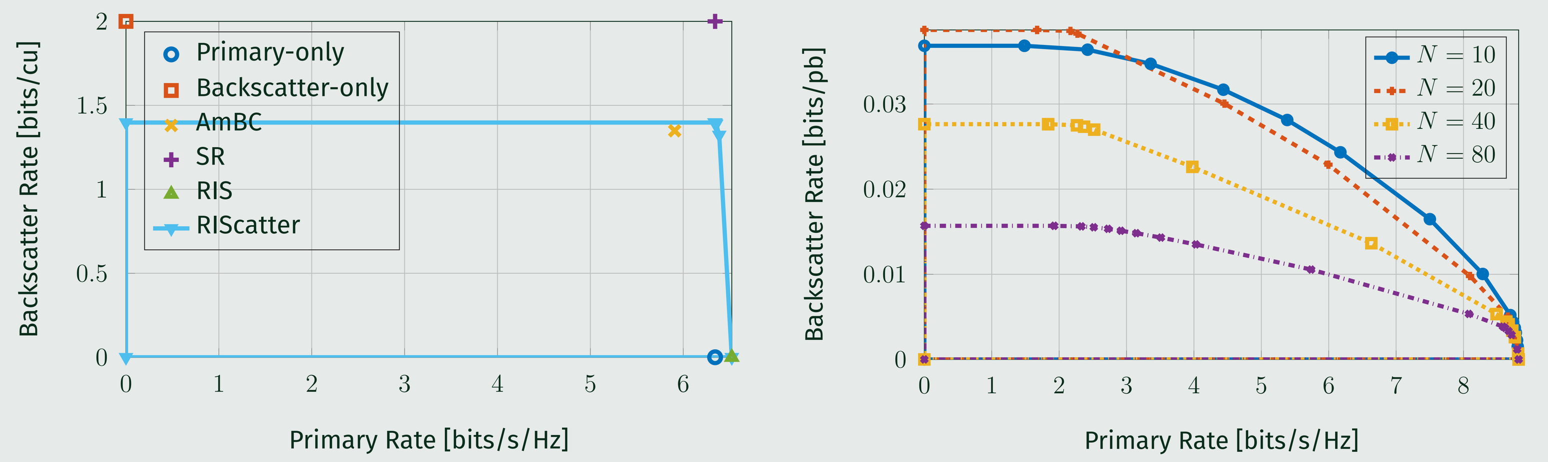
$$\boldsymbol{w}^{(r+1)} \leftarrow \mathrm{proj}_{\|\boldsymbol{w}\|^2 \leq P}\left(\boldsymbol{w}^{(r)} + \gamma \nabla_{\boldsymbol{w}^*} R^{(r)}\right),$$

Input distribution



Backscatter communication and reconfigurable intelligent surface are special cases of RIScatter with uniform and degenerate input distribution. Increasing ρ from 0 to 1 creates a smooth transition from backscatter modulation to passive beamforming.

Rate region



RIScatter backscatter rate is lower than symbiotic radio (due to energy detection) but higher than ambient backscatter (due to adaptive encoding). For backscatter link, a large spreading factor improves the bit error rate but reduces the gross data rate.

Conclusion

- Cognitive active and passive transmission can benefit each other
- RIScatter nodes recycle ambient signal for modulation and beamforming
- No interference cancellation is required at the co-located receiver
- The key is to render the input distribution as a joint function of the information source, channel state information, and priority of coexisting links

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