

Backscatter-Aided Cooperative Relay Communications in Wireless-Powered Hybrid Radio Networks

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ABSTRACT

Wireless backscatter communications has been introduced as a promising technique for data transmissions without a conventional energy supply from a battery or power outlet. It shares some similarity with RF energy harvesting powered wireless transmissions. Many benefits can be achieved when both techniques are integrated. In this article, we introduce the concept of a hybrid radio that is an integrated design of wireless-powered active RF communications and backscatter communications. We then discuss a few use cases of hybrid radio networks to suggest potential applications and to improve network performance. Furthermore, we consider a specific case in which hybrid radios act as passive relays to assist active RF communications. The passive relays backscatter the RF signals from the source to the receiver which, by experiments, shows to improve the transmission rate due to the enhanced multi-path diversity gain. We also introduce an optimization to quantify the performance improvement achievable by the radios' cooperation in the hybrid radio network.

INTRODUCTION

RF energy harvesting has been proposed as a cost-effective solution to replenish energy for wireless networks. Nevertheless, RF-powered active communications are challenged by relatively high power consumption of active radios. This calls for an innovation to the design of self-sustainable wireless networks, which are featured with the capabilities of RF energy harvesting and extreme low power consumption. Recently, the development of *wireless backscatter* has emerged as a potential solution [1]. With wireless backscatter communications, the source node transmits data in a *passive mode* by reflecting the RF signals emitted from existing active devices. Information modulation is performed by varying the antenna's reflection coefficient. Without releasing any RF signals, the backscatter devices consume orders of magnitude less power than that of the active devices, making it sustainable by energy harvesting from ambient active devices such as cellular base stations and WiFi access points.

A few studies have shown that RF-powered active communications and wireless backscatter can complement each other. Due to their heterogeneities in power demand and transmission

capability, network performance can be improved by allowing the wireless devices to switch between two operating modes. In this article, we first overview these two techniques as the basis for self-sustainable wireless networks. We then introduce a hybrid radio design that integrates wireless backscatter and RF-powered active communications. A few use cases are also discussed for its applications. Following that, we study a specific hybrid radio network in which hybrid radios act as passive relays to backscatter the RF signals between a transceiver pair in active RF communications. Through experiments, we verify that the backscatter-aided relay communications can significantly improve transmission performance. In this regard, we further introduce an optimization of the operational parameters for the passive relays and the transmitter to maximize the overall transmission rate. Finally, some open research issues toward the integration are discussed in the final section.

SELF-SUSTAINABLE HYBRID RADIO NETWORKS

In this section, we present overviews of two major techniques for self-sustainable wireless networks, that is, RF-power active communications and wireless backscatter communications. We highlight their similarities and differences, and then demonstrate how they can complement each other in data transmission of a hybrid radio network.

ACTIVE AND PASSIVE COMMUNICATIONS

RF energy harvesting can support low-power wireless networks by allowing wireless devices to harvest energy from RF signals emitted from dedicated transmitters or ambient sources, for example, TV towers and cellular base stations [2]. It can leverage the same set of antenna front-ends used for data communications. Under a particular setting, the RF-powered wireless device supports data reception and energy harvesting at the same time, that is, simultaneous wireless information and power transfer, by using the energy harvested from RF signals for decoding data from the same RF signals. Specifically, the RF signals captured by the antenna are first converted into analog waves. After passing through the impedance matching network, the analog waves are then rectified and amplified into DC voltage, which can be stored in an energy storage and supplied to other components, for example, a micro-controller and the transceiver for *active RF communications*. Such a

Reference	Year	Carrier signal (modulation)	Data rate/range	Power consumption	Multiple access	Configuration
Ambient backscatter [1]	2013	TV signals (OOK)	1 kb/s/0.45–0.76 m	Tx: 0.25 μ W Rx: 0.54 μ W	CSMA/CA	Ambient
Turbocharging [5]	2015	TV signals (OOK)	1 kb/s/24 m 1 Mb/s/1.2–2.1 m	μ mo: 8.9 μ W μ code: 422 μ W	CSMA/CA	Ambient
WiFi backscatter [6]	2014	WiFi signals (OOK)	UL: 1 kb/s/2.1 m DL: 20 kb/s/2.2 m	Tx: 0.65 μ W Rx: 9 μ W	Reader driven	Ambient
BackFi [7]	2015	WiFi signals (16BPSK)	5 Mb/s/1 m 1 Mb/s/5 m	2–10 pJ/b	Not specified	Monostatic
Passive WiFi [8]	2016	Dedicated carrier (DQPSK)	1 Mb/s/30 m 11 Mb/s/9 m	14.5–59.2 μ W	WiFi compatible	Bistatic
BLE Backscatter [9]	2017	Dedicated carrier (FSK)	1 Mb/s/13 m	1.56 nJ/b (156 μ W)	BLE compatible	Bistatic
UWB backscatter [10]	2017	Wideband signals (OOK)	1 kb/s/50 m	1.3 μ W	Not specified	Ambient

TABLE 1. Comparison of wireless backscatter communications systems.

“harvest-store-use” protocol allows the wireless device to harvest energy, store it, and use it to transmit data on demand.

Wireless backscatter is the instrumental technology of radio frequency identification (RFID). A dedicated reader emits high power single-tone RF signals and excites the RFID tag to backscatter information bits, referred to as the *monostatic configuration* [3]. The benefits of wireless backscatter communications stem from the fact that, without self-generating carrier signals, it operates in the *passive communication mode* by reflecting the existing RF signals. Thus, it consumes very low power and can avoid requiring dedicated spectrum. Recently, it has been explored for data communications between peer devices by exploiting RF signals from ambient sources such as cellular and WiFi systems. It is implemented by adapting the antenna’s reflection coefficient via load modulation. As such, the incident RF signal is reflected differently. This adaptation is usually done by RF switches connected to a set of load impedances. By switching between the load impedances, the backscatter node can modulate information symbols on the reflected signals [3]. For example, the antenna can be switched between absorbing and reflecting states, which can be distinguished at the backscatter receiver by the received signal strength. The backscatter receiver interprets the absorbing and reflecting states as the transmissions of different information bits. Unlike RFID, newly developed wireless backscatter communications separates the RF emitter from the backscatter receiver. With a dedicated RF source emitting single-tone signal, the backscatter receiver can be configured with the knowledge of the RF signal, making data decoding at the receiver more efficient. This technique is referred to as the *bistatic backscatter configuration* [4]. In contrast, with ambient RF sources, the knowledge of the RF signals is limited. In such *ambient backscatter configuration*, the data decoding relies on an averaging mechanism [1]. The ambient RF signals are averaged to smooth out random variations in the signal envelope. Then the backscatter information carried by the signal envelope can be easily extracted by an energy detector at the backscatter receiver [4].

The ambient backscatter is vulnerable to the

change and unpredictability of ambient RF signals. As such, a large body of research focuses on the design of novel modulation and detection schemes to improve the data rate, reliability, and transmission range of wireless backscatter communications. A brief overview of the current research is presented in Table 1. The prototype in [1] uses ambient TV signals, and achieves 1 kb/s data rate in the distance around 0.5 meters. The turbocharged implementation with two antennas at the receiver improves both the data rate and range significantly [5]. The ultra-wideband ambient backscatter in [10] is capable of backscattering signals from 15 kHz to 2.5 GHz. The experiments show that a nearby cell-phone (e.g., in a distance of 1–3 meters) performing uplink transmission can be a strong RF source that supports ambient backscatter communications at 1 kb/s in a range of 50 meters. The ubiquitous WiFi signals also motivate the design of backscatter communications coexisting with the WiFi systems. The modulated variations in channel state information (CSI) over multiple sequential WiFi data packets can be averaged and extracted by WiFi receivers, enabling direct communications between the backscatter and WiFi devices [6]. The data rate of WiFi backscatter can be improved to 5 Mb/s if the WiFi receiver is capable of full-duplex signal processing [7]. Backscatter communications can also be designed as the stand-alone WiFi compatible system [8], in which the WiFi access point is bistatically configured to beamform single-tone carrier signal for the backscatter devices to synthesize WiFi data packets.

RF-POWERED HYBRID RADIO NETWORKS

RF-powered active communications and wireless backscatter communications share an important similarity, that is, they both rely on energy harvesting from dedicated or ambient RF sources. They also significantly differ in how information is transmitted. RF-powered active communications will inject self-generated RF signals to the spectrum environment, and thus have to be performed on an idle channel to avoid interference with co-channel transceivers. The backscatter radio embraces the interference in the spectrum

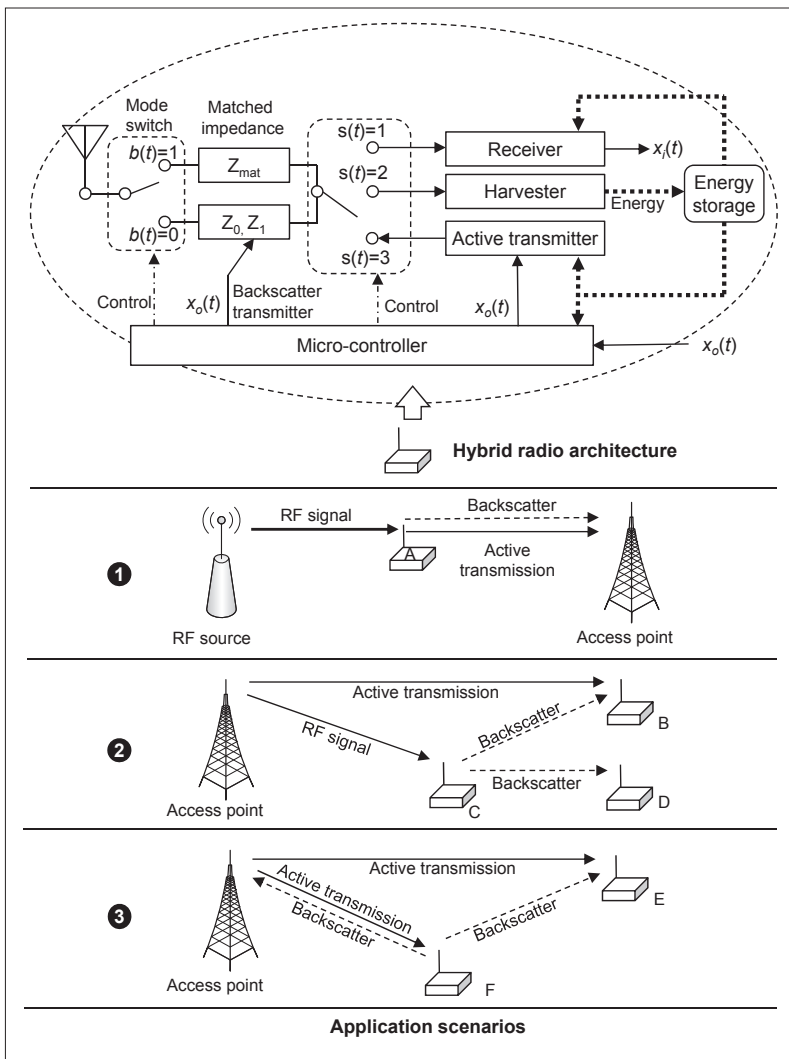


FIGURE 1. Hybrid radio network with a few application scenarios.

environment, that is, it performs passive communications by leveraging the ambient RF signals in the spectrum environment.

To capitalize on the complementary operation between active and backscatter communications, we introduce the RF-powered hybrid radio architecture that integrates the active and passive modes in one radio to take advantage of both, that is, the passive radio's low power consumption and the active radio's reliability in data transmission. When the radio has sufficient energy supply, it can transmit in the active mode with a higher data rate and enhanced reliability against channel variations. It can also switch to the power-saving passive mode and transmit via backscatter communications if power resources become more critical. We foresee that the flexibility in the radio's operating mode can improve overall network performance. The integrated prototype in [11] verifies that switching between Bluetooth Low Energy (BLE) and RFID can achieve a higher goodput than that of RFID and lower energy consumption than that of BLE. An integration of wireless backscatter and cognitive radios in [12] is shown to achieve significant performance improvement by optimizing transitions among energy harvesting, backscatter and active RF communications.

In the following section, we present the hybrid radio architecture and illustrate a few use cases in hybrid radio networks. As shown in Fig. 1, the major components of a hybrid radio include:

- *Antenna* for active and backscatter transmission, data reception, and energy harvesting.
- *Mode switch* $b(t)$ to choose between the active and passive backscatter modes.
- *Matched impedance* to bypass the incident RF signals from the antenna to other components.
- *Backscatter transmitter* to perform passive transmission by modulating the load impedance.
- *Three-throw switch* $s(t)$ to choose among reception, active mode, and energy harvesting.
- *Energy storage* to store the harvested energy and sustain other components.
- *Micro-controller* to control and optimize the overall operation of the system.

The notable benefit of the hybrid radio is its capability to operate in different modes by dynamically controlling mode switching according to its energy and channel conditions. In particular, it can perform the following functions.

Data Transmission: The hybrid radio uses switches $b(t)$ and $s(t)$ for data transmission. For active communications, the switches are set as $b(t) = 1$ and $s(t) = 3$. Then, the micro-controller feeds output $x_o(t)$ to the active transmitter and then the antenna with matched impedance Z_{mat} . In the passive mode, the switches are set as $b(t) = 0$ and $s(t) = 2$. Then the micro-controller adjusts the switches between Z_0 and Z_1 according to $x_o(t)$ [1].

Data Reception: The hybrid radio uses the common receiver for data reception from both active and backscatter communications. The switches are set as $b(t) = 1$ and $s(t) = 1$ to ensure maximum antenna efficiency in data reception. Moreover, full-duplex communications can be realized if we set $b(t) = 0$ and keep $s(t) = 1$ unchanged [13], that is, the hybrid radio can receive and simultaneously transmit information via backscattering.

Energy Harvesting: By setting $b(t) = 1$ and $s(t) = 2$, the hybrid radio maximizes the efficiency of RF energy harvesting. Different functions can be performed by combining different parameter settings. By setting $b(t) = 1$ and switching between $s(t) = 1$ and $s(t) = 2$, we can implement the time-switching protocol for simultaneous wireless information and power transfer [2].

APPLICATION SCENARIOS

Hybrid radio networks are able to support versatile applications. Some example scenarios are described as follows and also illustrated in Fig. 1.

Cognitive Backscatter Communications: The RF source provides energy for node A to communicate with the access point in the active mode. Alternatively, node A can backscatter data by reflecting the incident RF signals. The decision to adapt or switch the radio mode depends on the spectrum conditions. It can operate in the passive mode if the channel is occupied and switch to the active mode if the channel is idle. It can also turn into the energy harvesting mode if the channel condition is not preferable for data transmission.

By scheduling the mode transitions, this scenario is shown to achieve a higher transmission rate than that achievable by backscatter or active communications alone [12].

Underlay Backscatter Communications:

The access point communicates with node B by active transmission. Simultaneously underlay backscatter transmission is used between nodes C and D. The backscatter signal from node C can be also decoded at node B, enabling information exchange between different nodes [14]. This scenario allows one or more passive radios to reuse the spectrum of the active radio. The bit rates of passive radios can be specially design to ensure interference-free transmissions.

Backscatter-Aided Relay Communications:

Nodes E and F can harvest energy from the access point, which transmits data to node E by active communications. Meanwhile, node F in close proximity to the access point can help to relay the RF signals to node E via backscatter communications. Node F can also utilize part of the incident RF signals (e.g., by setting $b(t) = 0$ and keep $s(t) = 1$) and thus decode information from the access point. The other part is modulated and reflected back to the access point, enabling two-way communications between the access point and node F [13].

With the proposed hybrid radios, we expect to improve network flexibility and overall performance as each node in the hybrid radio network can optimize their operating modes dynamically. To demonstrate this, we envision a wireless powered network with a few hybrid radios randomly distributed around the access point, similar to scenario 2 in Fig. 1. The access point provides RF energy for the active radios and carrier signals for the passive radios. It can adjust the beam-forming strategy to optimize its power transfer to different nodes. The access point also coordinates the radios' data transmissions in a time division multiple access protocol. To maximize the sum throughput, we formulate a convex optimization for the access point's beamforming and the radios' time allocation strategies. Figure 2 compares the throughput performance in three different cases. It is obvious that the throughput in all cases is increasing in the power budget of the access point. When we allow radio switching between two radio modes, the throughput can be increased significantly compared to the cases with only one radio mode. The performance gain can be viewed as the radio diversity gain in the hybrid radio network.

BACKSCATTER-AIDED RELAY COMMUNICATIONS

In this section, we present a novel application scenario to improve transmission performance based on the concept of backscatter-aided relay communications. Hybrid radios can collaborate to improve network performance. Figure 3 illustrates the scenario where a multi-antenna hybrid access point (HAP) delivers information to one of the user equipments (UEs) by using active transmission. The nearby UEs can act as the wireless relays for the HAP's active transmission. However, these UEs may be insufficient in energy supply or sensitive to energy consumptions. Hence, the conventional relay strategies using active communications will not be applicable in this case. With

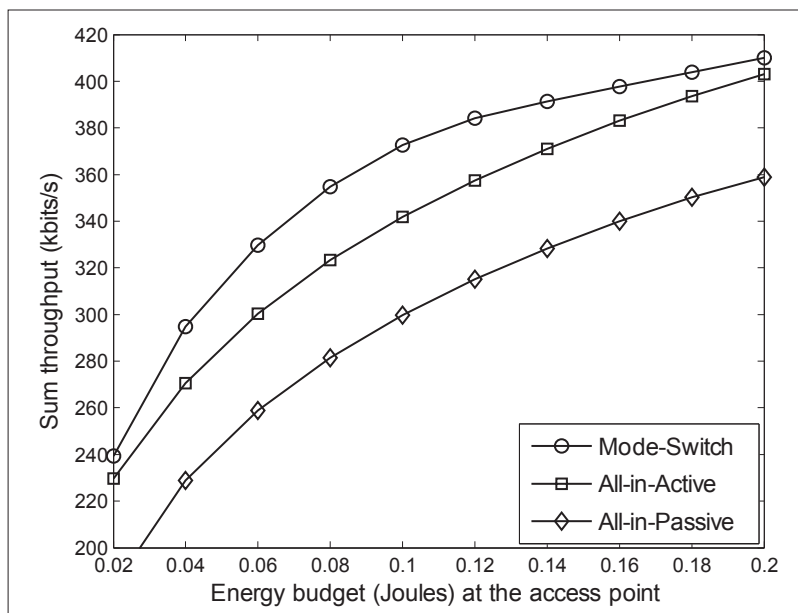


FIGURE 2. Throughput improvement in hybrid radio networks.

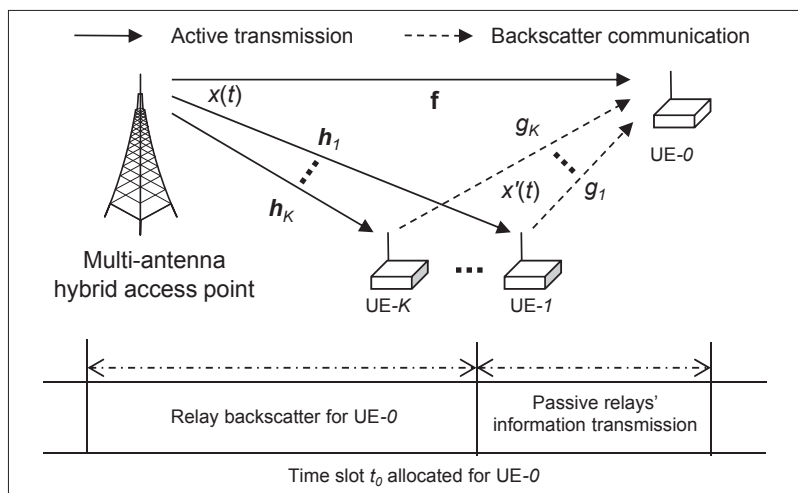


FIGURE 3. Backscatter-aided relay communications from the hybrid access point to UE-0 assisted by multiple passive relays.

the capability of mode switching, the UEs can opt to perform power-saving backscatter transmission, that is, passive relaying, for the active transmission from the HAP to the receiver. This is called backscatter-aided relay communications, corresponding to $b(t) = 0$ and $s(t) = 2$ as shown in Fig. 1. Such a passive relay scheme is very economical as it does not consume much power or require extra spectrum. By optimizing reflection coefficients at passive relays, we can change the signal propagation characteristics and thus control the multi-path effect to enhance the signal-to-noise ratio (SNR) at the receiver. In practice, we can implement an adaptive procedure similar to the work in [15] that tunes the reflection coefficients based on one-bit feedback from the receiver.

EXPERIMENT VERIFICATION

In this section, we verify the performance enhancement of backscatter-aided relay communications as shown in Fig. 3. We fix the role of each device to simplify the implementation. Specifically, the HAP and UE-0 are convention-

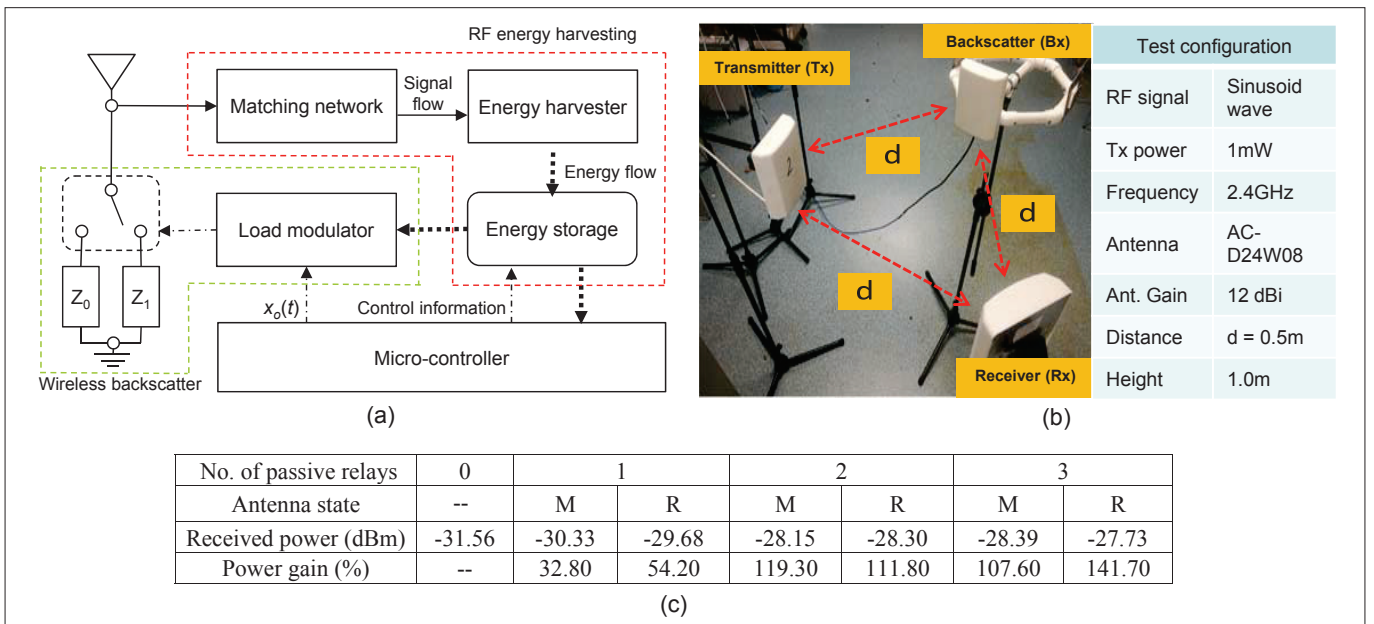


FIGURE 4. Experiment on backscatter-aided relay communications. The states “M” and “R” refer to “Matching” and “Reflecting,” respectively: a) RF-powered backscatter radio; b) experiment configuration; c) measurements of RF power at the receiver antenna.

al active radios. We implement a prototype for passive relays that can switch between two load impedances, denoted by “Matching” and “Reflecting,” as shown in Fig. 4a. The HAP’s active transmission is emulated by a signal generator operating at 2.4 GHz with the output power at 0 dBm, connected with the directional AC-D24W08 antenna. The passive relays are also connected to an AC-D24W08 antenna and set with one of the two load impedances. The received signal at the receiver is a mixture of the direct transmission from the active transmitter and the backscatter signals from the passive relays. The signal strength at the receiver is measured by the same antenna and fed to a spectrum analyzer. The distances between antenna pairs are all set to 0.5 meters, as shown in Fig. 4b. The measurements of RF power at the receiver are shown in Fig. 4c.

Without passive relays, the received signal is measured at -31.56 dBm, which is increased by 54.2 percent when one passive relay is deployed in the “Reflecting” state. This observation implies that we can achieve a significant increase in the signal strength at the receiver without increasing the transmit power. We also observe that the passive relay in the “Matching” state still reflects part of the incident RF power. This amounts to a 32.8 percent increase in the received signal strength. When there are multiple passive relays in the “Reflecting” state, we further observe a significant increase in the received signal strength, that is, 111.8 percent and 141.7 percent with two and three passive relays, respectively. This result clearly shows that the passive relays can improve the data rate of active transmission by controlling the relays’ reflection coefficients.

One major challenge for implementing backscatter-aided relay communications lies in that the dynamic channel conditions between the passive relays and the receiver require online tuning of the relays’ reflection coefficients. The control of reflection coefficients can be implemented by a multi-throw RF switch connected to a collection of

load impedances. Then, the passive relay’s reflection coefficient is chosen to best match the channel conditions. This can be implemented by an adaptive beamforming algorithm similar to [15]. Any mismatch will cause a random phase offset at the receiver, and thus compromise the multipath diversity gain. Besides, for each passive relay, the reflection coefficient has to balance between energy harvesting and backscatter transmission, as the energy required to power backscatter circuitry is actually harvested from the same RF signals for backscatter communications.

PASSIVE RELAY SCHEME

In this section, we present a joint optimization of the passive relays’ reflection coefficients and the RF emitter’s energy beamforming strategies, to maximize the throughput performance of backscatter-aided relay communications. We focus on the active transmission from the HAP to UE-0 assisted by K passive relays. The passive relays harvest energy from the HAP while simultaneously reflecting part of the RF signals from the HAP to UE-0 by setting appropriate reflection coefficients $\mathbf{x}$ in the complex domain. The received signal at UE-0 is a mixture of the signal beamforming from the HAP and the reflections from the passive relays. The SNR at UE-0, defined as the ratio between the signal power and the noise power, depends on the HAP’s beamforming strategy $\mathbf{w}$ and the equivalent channel $\mathbf{f}_x$ from the HAP to UE-0, which consists of the direct channel $\mathbf{f}$ from the HAP to UE-0 and the backscatter channels via each of the passive relays. The beamformer $\mathbf{w}$ and the reflection coefficients $\mathbf{x}$ can be jointly optimized so that the equivalent channel $\mathbf{f}_x$ results in higher throughput than that of the direct channel $\mathbf{f}$ alone. For each passive relay, there is a *power budget constraint* which requires that the energy harvested from the HAP is sufficient to power the backscatter device and its data transmission. This constraint actually imposes a requirement on the relay’s reflection coefficient, similar to the pow-

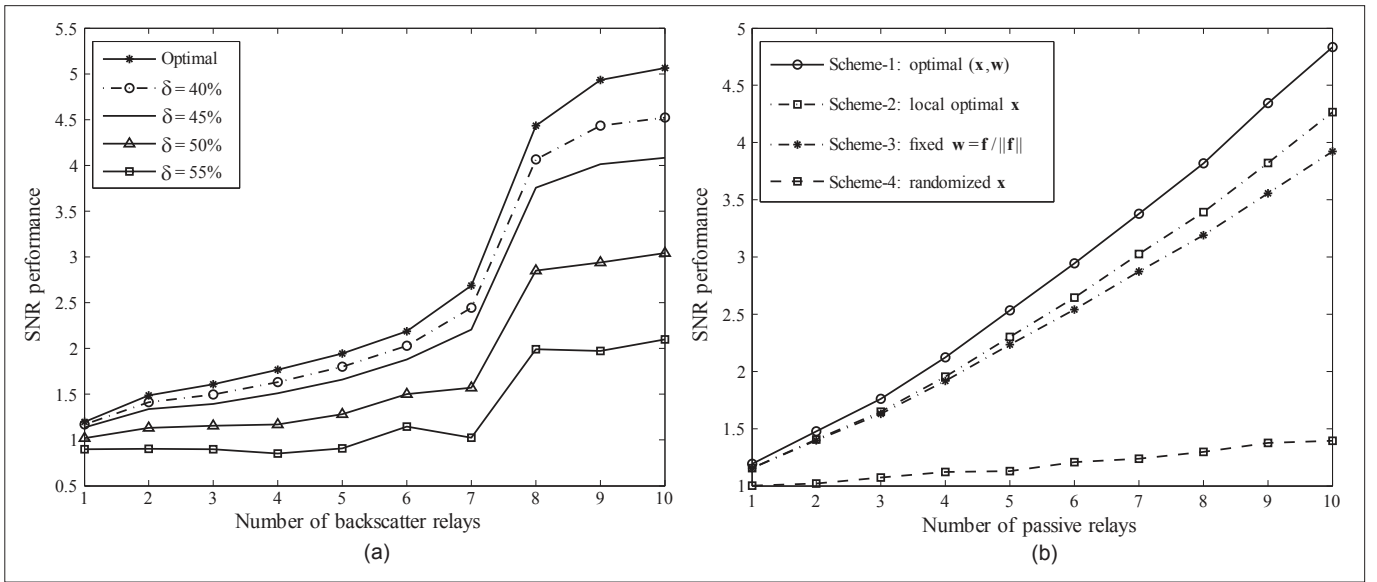


FIGURE 5. Performance gain with different number of backscatter relays: a) SNR achieved with different quantization errors; b) performance comparison with different schemes.

er-splitting scheme for RF-powered active communications, in which a part of the incident RF power is harvested as energy and the other part is used for signal detection [2].

Our objective is to maximize SNR performance such that the power demand of each passive relay is met by adjusting the HAP's beamformer $\mathbf{w}$ and the relay's reflection coefficients $\mathbf{x}$. The optimal beamformer $\mathbf{w}$ can be obtained by aligning it with the equivalent channel $\mathbf{f}_x$ if the set of passive relays is known and fixed. However, the availability of each passive relay also depends on $\mathbf{w}$ through the power budget constraints. If the direct path from the HAP to UE-0 becomes worse-off or blocked, the HAP needs to adjust its beamformer to enhance RF power transfer toward the relays, activating more passive relays to detour the RF signals. Another challenge lies in the design of the relays' reflection coefficients to jointly enhance the signal strength at UE-0. In an ideal case with complete channel information and perfect control, we can find the optimal reflection coefficients $\mathbf{x}^*$ by maximizing the power gain of the equivalent channel $\mathbf{f}_x$. We expect that the maximum channel gain is non-decreasing when we add more passive relays. In fact, the feasible set of $\mathbf{x}$ is a finite discrete set corresponding to the combinations of different load impedances. The reflection coefficient $\bar{\mathbf{x}}_k^*$ actually chosen for the k -th relay is a projection of the optimum $\mathbf{x}_k^*$ onto the finite feasible set by minimizing their difference, which can be viewed as the quantization error and result in a random phase offset on the backscatter signals.

NUMERICAL EVALUATION

In the simulation, we sequentially generate UEs distributed randomly in a square area (10×10 meters) centered at the origin. The HAP is at $(-5, 0)$ and UE-0 is fixed at $(5, 0)$. The path loss exponent is set to 2 and the path loss measured at unit distance is -30 dB. The bandwidth is assumed to be 1 MHz and the noise power density is -100 dBm. The HAP's maximum transmit power is $p_{\max} = 10$ mW. The energy conversion efficiency of RF power is 0.5 [2].

Figure 5a shows the SNR performance that is achievable with a different number of passive relays. At each point k on the x-axis, UE- k is included to perform passive relaying. Without quantization errors, we observe that the optimal SNR gradually increases when we add more UEs. However, the rate of change varies on the SNR curve due to the relays' different channel conditions. In particular, when UE-7 and UE-8 are sequentially included as the passive relays, we observe a fast increase in the SNR performance as shown in Fig. 5a. This implies that these two UEs have favorable channel conditions to improve the overall SNR performance significantly. When quantization errors are considered, it is intuitive that the SNR decreases with the increase of error bound δ . For a large error bound, the SNR may even decrease when the number of passive relays increases, for example, the SNR decreases when UE-7 is included as one of the passive relays for $\delta = 55$ percent in Fig. 5a. This verifies that the multi-path diversity gain can be adversely affected by random phase offsets with large quantization errors. Hence, relay selection becomes a non-trivial design problem in practice with quantization errors.

In Fig. 5b, we compare the optimal passive relay scheme with other baseline schemes. Note that the optimization of $(\mathbf{x}, \mathbf{w})$ can be performed at the HAP. However, it is challenging for the HAP to disseminate $\mathbf{x}$ to individual passive relays which incurs some communication overhead. In Scheme-2, we overcome this difficulty by allowing each passive relay to decide its own reflection coefficient locally while the HAP optimizes its beamformer. Note that the direct channel is generally much stronger than the backscatter channel. This motivates us to find individual relay's reflection coefficient by simply maximizing the projection of the complex backscatter channel onto the direct channel. In Scheme-3, without knowing the existence of passive relays, the HAP simply sets its beamformer to align with the direct channel. Meanwhile, the passive relays locally set their reflection coefficients by the rules adopted in Scheme-2 to reduce communication overhead.

Multi-antenna has been shown to improve the data rate for both RFID and ambient backscatter. Millimeter wave technology can also facilitate high speed data communications. Its use in backscatter communications has not been well explored and exploited yet.

In Scheme-4, the passive relays are also unaware of active transmissions from the HAP to UE-0, and thus set their reflection coefficients randomly. The performance comparison in Fig. 5b reveals that the lightweight sub-optimal Scheme-2 and Scheme-3 perform relatively well and are suitable for distributed implementation. Compared with the optimal scheme, the performance gap is small with a few passive relays. Another observation is that the relay performance is very sensitive to the passive relays' reflection coefficients. That is, the SNR with randomized reflection coefficients in Scheme-4 is hardly improved with a different number of passive relays.

OPEN RESEARCH ISSUES

Relay Selection Scheme: Having more passive relays does not necessarily improve the overall performance, especially with quantization errors. Beamforming design has to meet the power budget constraint of each passive relay. In fact, some passive relays do not contribute much to the transmission rate. Hence, the set of passive relays can be optimized to assist the active transmissions.

Incentive Mechanisms: The passive relays can be rational and may participate in the relay scheme only if they receive a good incentive, for example, wireless energy harvesting from the HAP or some monetary rewards. Hence, an incentive mechanism or game theoretic models can be developed to address the conflict between different UEs.

Advanced Physical Layer Techniques: Multiple-antenna and millimeter wave communications can be employed at the hybrid radio and used for backscatter communications. Multi-antenna has been shown to improve the data rate for both RFID and ambient backscatter [5]. Millimeter wave technology can also facilitate high speed data communications. Its use in backscatter communications has not been well explored and exploited yet.

CONCLUSIONS

In this article, we have reviewed two techniques for self-sustainable wireless networks and introduced the hybrid radio to support their integration. Then, we focused on the passive relay scheme in a hybrid radio network that allows passive relays to backscatter signals for a pair of active radios. Our experiment has verified the performance improvement by exploiting the multi-path diversity gain. We have introduced an optimization to jointly optimize the transmitter's beamformer and the passive relays' reflection coefficients. Finally, some open research issues have been outlined.

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BIOGRAPHIES

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