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Harnessing Ambient RF Waves for Novel Applications

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Abstract—The wireless revolution has created a mobile information society. One key element in this revolution has been the use of RF waves for information transmission. RF waves can be used directly for transmission but it is also possible to harness RF waves that are already in use for other applications. These existing RF waves can be thought of as ambient RF waves or signals and can be harnessed for a wide variety of applications. Using sunlight as an analogy, for ambient RF waves, we can deduce that applications such as cameras, navigation, solar cells, heliostats and heliographs can be readily carried over to ambient RF waves in the form of imaging, device free location estimation, ambient RF energy harvesting, reconfigurable intelligent surface (RIS) and ambient backscatter communication (AmBC). In this paper we explore technologies and techniques that can harness ambient RF waves for our benefit, without adding further RF transmissions to the environment. In essence we treat the harnessing of ambient RF waves as a single research area rather than a collection of unrelated applications. This allows us to explore and develop new and novel applications. It also allows us to focus on the fundamental phenomena and applications of ambient RF waves.

Index Terms—Ambient RF waves, Reconfigurable Intelligent Surfaces, Radio Tomographic Imaging

I. INTRODUCTION

Ambient radio frequency (RF) energy harvesting is becoming an important source of energy for powering devices for the internet of things (IoT). The key to its success is its scavenging or harvesting of RF energy from RF sources already in the environment such as cellular, WiFi, broadcast radio and TV systems. However it is just one example of the possible applications for which existing ambient RF waves can be harnessed.

In this paper we explore technologies and techniques that can harness ambient RF waves for our benefit, without adding further RF transmissions to the environment. The applications include RF imaging [1]–[4], reconfigurable intelligent surfaces (RISs) [5]–[7], ambient backscatter communication (AmBC) [13], [14] and energy harvesting [15]–[17].

RISs for example are considered a critical element in future wireless communications such as 6G and falls within the scope of harnessing ambient RF waves as RISs do not add further RF transmissions to our environment [5]–[7]. The role of RISs is to control the radio environment to enhance wireless

communication without adding its own transmissions. Another example of harnessing ambient RF waves include AmBC for communication [13], [14] and radio tomographic imaging (RTI) for device free location and imaging [1]–[4].

The development of the applications that harness ambient RF waves are essential for future wireless communication. In the years ahead mobile traffic is expected to increase by 25% annually until 2025; IoT is predicted to have more than 24.6 billion devices connected to the Internet by 2025 (Ericsson Mobility Report, June 2020). To satisfy these demands new and novel techniques will need to be developed to meet the requirements of these future systems and harnessing ambient RF waves can form one approach for performing this.

To systematically analyze the harnessing of ambient RF waves we divide the area into three topics which we refer to as wave shaping, wave sensing and wave characterization. Wave shaping can be thought of as the process of manipulating ambient RF waves so that we can communicate or enhance an existing application. Examples include AmBC and RIS where ambient RF waves are either backscattered for communication or where they are scattered by an RIS to enhance communication performance. Wave sensing is the process of measuring or acquiring ambient RF waves to sense or image the environment (for example for security or safety) or harvest the RF energy it carries. The third aspect we need to consider is to understand the characteristics of ambient RF waves so that we can sense and shape them for useful applications.

In the remainder of this paper we will provide examples of wave shaping, sensing and characterization with applications.

II. HARNESSING AMBIENT RF WAVES

A. Wave Shaping

We define wave shaping as the control and manipulation of ambient RF waves. Wave shaping can be performed by controlling scattering, diffraction, absorption and reflection of waves using structures such as an array of loaded antennas or a metasurface as shown in Fig. 1. In this illustration ambient RF waves are shaped by the RIS so that wireless performance at the receiver can be enhanced [5]–[11].

An associated issue in RIS, is pathloss [7], [8] as it exhibits a “cascaded channel” pathloss proportional to $1/d \times 1/r$ where d and r are the distances between the RIS and the transmitter and receiver, respectively. This makes signals weaker than the

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Fig. 1. The RIS is configured by the system controller to enhance the link between the transmitter and the receiver.

direct propagation path and therefore, large RIS are needed. The RIS should therefore be lightweight and thin for ease of use.

Thin RIS can be constructed from RF metasurfaces [11] or an array of loaded antennas [12]. Incorporating reconfiguration into metasurfaces is critical to produce RIS and binary reconfiguration, termed digital/coding metamaterials, has been developed. RIS research is still in its infancy and many challenges remain in both systems and electromagnetics to make them useful in wireless communication applications.

Communication using wave shaping can also be performed. The concept is shown in Fig. 2 where an ambient source is backscattered by a Tag to communicate with a reader [13], [14]. One big advantage of AmBC is that no illuminating source is required and that no specific frequency allocations are required. The challenges that remain include the very low signal strengths due to the cascaded channel, the low bit rates due to the ambient RF source being unknown and not controllable, and integration with RIS.

Fig. 2. Example of AmBC where an AmBC Tag modulates the backscattering of ambient RF waves in order to send information to a WiFi reader.

B. Wave Sensing

An essential part of harnessing ambient RF waves is wave sensing and can be considered the complement of wave shaping. Changes in ambient RF waves can be used to sense or image the environment and used in applications such as navigation, security, imaging [1]–[4], [20] or energy harvesting.

An example of imaging ambient RF waves is shown in Fig. 3 and Fig. 4. In this configuration received signal strength

indicator (RSSI) at WiFi stations and access points are logged and used to create an image of the locations of people inside the area of interest as shown in Fig. 3 and Fig. 4 [4]. While in this example we use 20 WiFi nodes for demonstration of the concept, in principle it will be possible to reduce number of WiFi nodes to only a few using sparsity constraints and prior knowledge [4]. Wave sensing for detection of environmental parameters that extend well beyond imaging and many challenges remain such as development of appropriate inverse scattering formulations for the ambient RF waves [4].

Fig. 3. WiFi measurement system for acquiring RSSI and when two people are located within the imaging area of interest.

Fig. 4. RIS reconstruction using the RSSI measurement results from Fig. 3. The location of two people are clearly identified.

Associated with wave sensing is wave acquisition and the well known concept of ambient RF energy harvesting [15]–[17]. This is a well explored area and a key challenge is the development of efficient rectifiers and antennas that maximizes the output dc power at a low power density. In Fig. 5 we provide an example of a dual band 16-port antenna for ambient RF energy harvesting [16]. A novelty of the design is that at the lower band 4 ports are utilized while at the higher

frequency band 12 ports are utilized in order to keep the overall aperture of the antenna constant.

Fig. 5. Example of an energy harvesting antenna where the number of antennas ports is related to the operate frequency [16].

C. Wave Characterization

Wave characterization provides models for ambient RF waves so that we can learn how to shape and sense them. Without this we do not know what to shape or sense [17]–[19]. Particular challenges are understanding the stationarity of the ambient RF wave process across large surfaces such as RIS.

D. Integration

The integration of the three elements, wave shaping, sensing and characterization into systems has the potential to provide many applications including the enhancement of wireless communication, imaging, navigation, sensing, energy harvesting and future applications.

III. CONCLUSION

Treating the harnessing of ambient RF waves as a unified research area, instead of a collection of unrelated applications such as energy harvesting and RIS, provides a broad view of the potential of ambient RF waves. While research on individual applications can be fruitful, research on the underlying principles of ambient RF waves that are common to these applications can be much more impactful and can create many more applications. Considering ambient RF waves holistically brings three distinct benefits: 1) enables us to consider all the basic components of wave harnessing 2) establishes a platform for developing new and enhanced applications and 3) provides an integrated approach that allows ambient RF waves to be thoroughly exploited. Using this approach applications well beyond, straightforward RIS, energy harvesting and sensing can be developed.

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