Digital Spectrum Twinning and the Role of RFID and Backscatter Communications in Spectral Sensing

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***Abstract*—In this work, we formalize a long-felt need in the spectrum sharing community using the concept of a *digital spectrum twin*, which is the maintenance of a virtual representation of spectrum properties with near- or quasi-real time updates using selected spectrum sensing. An immediate consequence of this formulation is the need for low-cost, widespread spectrum sensing technology. We illustrate how emerging technologies in RFID and backscatter communications can fill this void and allow next-generation spectrum management technology to flourish.**

I. Introduction

A *digital twin* is a digital replica of an object, place, or process in the physical world that is updated through sensor measurements. An important part of the digital twin concept is that algorithms are applied to the digital twin to produce *parallel intelligence*, from which useful information about the corresponding physical twin can be gleaned. A *digital spectral twin* (DST) is a digital twin that is used to represent the behavior of a frequency block of radio spectrum in a geographical region.

- An online digital representation of RF spectrum properties and activities
- Sensors and other measurements that are used to update this online representation
- Parallel intelligence that gleans useful information from this data

The DST concept maintains a sort of "living" database of RF spectrum activity that continually updates and provides useful information to spectrum shareholders to enable or enhance their activities.

There has been a long-felt need for digital spectrum twinning, even if the concept has not been so explicitly identified. Future spectrum management concepts have been built around the idea of dynamic observations and predictions of spectrum behavior. The Citizens Broadband Radio Spectrum (CBRS) spectrum allocation in the US at 3.5 GHz relies on dynamic reservation of spectrum through a Spectrum Access System (SAS) that accounts for current use amid a hierarchy of differently privileged users. The emerging National Dynamic Radio Zone (NRDZ) concept requires users within an otherwise unlimited use of spectrum block in a geographic zone to conduct radio communications in a way that minimizes impact to certain users outside of the zone [1]. Much of the cognitive radio and frequency agile radio research in the last two decades were pre-conditioned on real-time observation of the radio spectrum with intelligence built into transmitting radios and/or networks to adjust to other transmitters. Thus, the digital spectrum twinning concept is really just a formalization of ideas that have been circulating for quite some time.

Interestingly, though, once the idea of a DST is formalized, it immediately provides insight into how the technology can be integrated into a new paradigm of radio communications – as well as illuminating where next-generation spectrum research should focus. For example, consider the "three-point" diagram of Figure 1. In this conception, a digital twin of the radio spectrum is added to the operation of a wireless network. The twin is updated with radio spectrum sensing and coordinates operation with *parallel intelligence* to help with spectrum access decision making. This additional interaction allows a more integrated approach to spectrum management that can accommodate more users at higher data rates. It can also be used to provide more real-time monitoring and protection of passive spectrum users (radar, remote sensing, astronomy, etc.)

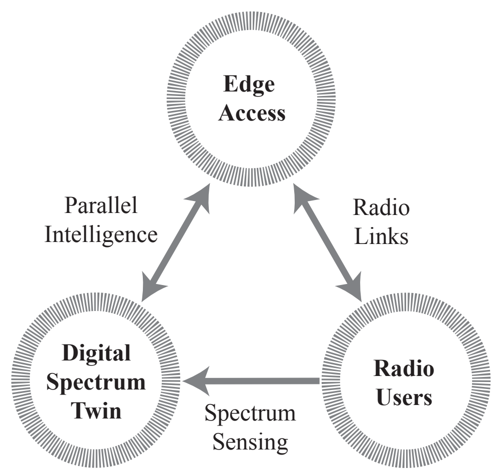

Fig. 1. Example of how a digital spectrum twin cooperates with an existing radio network to enhance communications. Spectrum sensing provides an additional mode of updating the digital spectral twin, while parallel intelligence gleans useful information for directing communications.

II. The Importance of Spectrum Sensing for Maintaining a Digital Twin

Real-time spectrum sensing has been a long-felt need in the field of radio. Without real-time spectrum sensing, one cannot properly optimize networks, share spectrum dynamically, estimate monetary value of frequency blocks, gage efficiency and occupancy of RF bands, provide accurate location-based services, protect passive users, monitor and enforce compliance with regulations, incorporate artificial and parallel intelligence into operations, design and simulate new radio technologies, or maintain an updated and useful digital spectral twin (DST) [2], [3], [4], [1], [5], [6], [7], [8], [9]. Past approaches to measure radio spectrum involved either time-consuming, expensive measurement campaigns that produced small data sets or large amounts of crowd-sourced data from user device with limited bandwidth, sampling, and quality [10].

Current methods for radio spectrum sensing can be classified into three categories: 1) measurement campaigns, 2) sensing infrastructure, and 3) crowd-sourced device measurement. There will always be a place for measurement campaigns that characterize radio wave propagation and usage, although these types of measurements are targeted, high-quality, labor-intensive, and very expensive per datum. Crowd-sourced device measurements from commercial radios on a wireless network have the opposite issues: they are highly varied, low-quality, inexpensive, high-volume, and ill-conditioned. The samples for such measurements are also biased toward existing radios in existing bands.

Infrastructure-based radio sensing — use of dedicated RF sensing networks to collect spectrum data — is a middle ground between measurement campaigns and crowd-sourced RF data that has the most room to grow and contribute to future spectrum needs. There are six areas of improvement over the state-of-the-art spectrum infrastructure-based sensing practices, each requiring significant innovation to achieve:

a. Real Time Sensing: Not only is the goal to minimize latency in spectrum sensing, but also to involve simultaneity – the ability to take "snapshots" of certain spectrum data at a precise point in time.
b. Bandwidth: The ability to make dynamic RF measurements across broader bandwidths is crucial for emerging broadband applications.
c. Carrier Frequencies: Spectrum sensing hardware of the future will need to measure the upper-microwave, mm-wave, and THz bands rather than conventional sub-6 GHz bands.
d Sensitivity: It is not enough to simply estimate signal strength on decoded packets of radio communications. Some of the most valuable information about spectrum usage is in reception of signals within several dB of the noise floor, requiring modes of sensing with greater sensitivity.
e Locations: Infrastructure-based sensing often suffers from limited locations of gathering nodes. A key goal is to enhance the locations over which data is collected without similarly growing the complexity of the network.
f Cost: All of these goals must be achieved at minimal hardware and deployment costs.

In particular, cost is of paramount importance. It is here where the low-cost power of RFID and backscatter communications can significantly contribute a new paradigm for RF sensing.

III. Need for Enhanced Spectrum Sensing

Current research focuses on adding spectrum sensing infrastructure, augmenting classical nodes with low-powered sensors, wide-area readers, and even airborn/satellite radiometry to measure and extrapolate spectrum behavior [2], [11], [12]. A key challenge is the development of very low-cost sensing nodes and measurement techniques that allow proliferation of data collection *without excessive cost*. Another key challenge is innovating new hardware capable of spectrum data measurement at very wide bandwidths and in the mm-wave/THz bands of the future. The economic impact of this thrust is extraordinary; not only does it enhance operation and value of current radio spectrum usage, but it will enable the development of new, complicated radio systems for commercial wireless, navigation, environmental sensing, surveillance, and transportation.

In this work, we propose backscatter motes to arrive at a ubiquitous "smart-dust" paradigm for measuring the spectrum. In a low-powered RF sensing mote architecture, the variety and quantity of spectrum sensing multiplies without incurring significant costs. Pictured in Figure 2 on the right, a low-power, broadband spectrum sensing device is connected to a low-power backscatter link that employs ultra low-power quantum tunnel reflectors (QTRs) to relay digital information back to a reader/collector [13]. In this scheme, inexpensive RF tags use of small-cell batteries, RF energy-harvesting, and hybrid power scavenging techniques to power the low-cost sensor nodes. Some read ranges for semi-active QTRs have been demonstrated in excess of 1 kilometer at extraordinarily low power consumption, enabling long battery life or operation with exclusively energy-harvesting sources [14].

Another aspect of this type of infrastructure-based sensing could be array-based polling of low-powered sensors [15], [16], [17], [18], [19], [20], [21], [22], [23], [23]. Rather than design a single broadband sensor, a distribution of low-cost sensors that operate at targeted sub-bands can be distributed throughout an environment of interest and polled by a broadband wireless reader. The inclusion of arrays at the reader could further enhance range and read rate of the spectrum sensors [24], [25].

Ultimately, there are two modes of spectrum sensing that could be exploited in a backscatter communications network. First, the sensor mote can gather measured data, digitize the results, and relay this information to a reader over potential long distances. This sensing mode could be made long-range ($>$1 km) if semi-active tags are used. Alternatively, the backscatter mote could simply mix a unique signature onto all impinging RF sources that could then be processed for spectrum information back at the reader. Although this mode would likely benefit from the linear mixing of passive or semi-passive backscatter modes, the maximum range might be closer to 100m of tag-reader and tag-source separation distance.

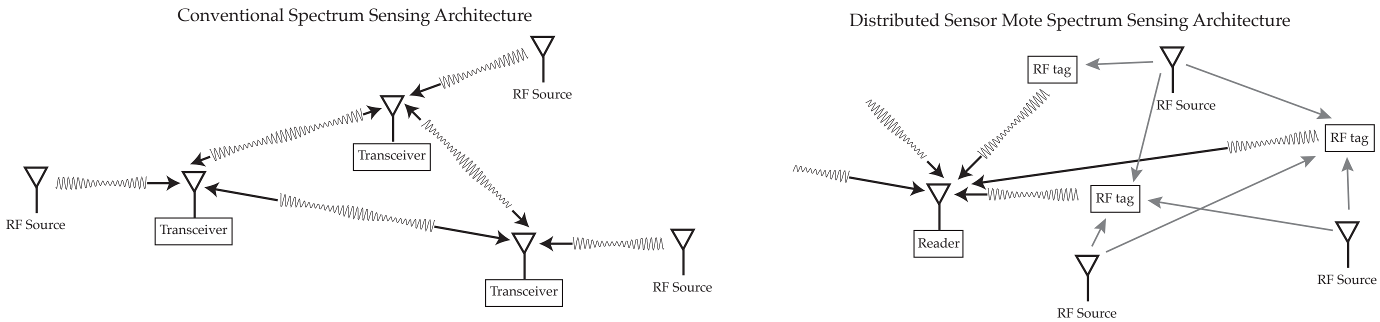

Fig. 2. Two modes of spectrum sensing. Conventional sensing (left) involves a network of broadband receivers that listens to nearby radio transmissions, contrasted to the backscatter network (right) that either directly or indirectly scatters spectrum sensing information from low-cost tags to a network of RF readers.

IV. Conclusions

The concept of a *digital spectrum twin* illuminates the need for greatly enhanced, low-cost spectrum measurement. RFID and backscatter communications are well-suited to fill this need, offering different modes of gathering a lot of low-cost, high-quality measurements across a network. Next steps include building out test setups that demonstrate broadband sensing capabilities using backscatter systems.

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