Digital Spectrum Twinning for Next-Generation Spectrum Management and Metering

Gregory D. Durgin[1], Michael A. Varner[1], Neal Patwari[2], Sneha K. Kasera[3], Jacobus Van der Merwe[3]
[1]Georgia Institute of Technology [2]Washington University in St. Louis [3]University of Utah

2022 IEEE 2nd International Conference on Digital Twins and Parallel Intelligence (DTPI) | 978-1-6654-9227-0/22/$31.00 ©2022 IEEE | DOI: 10.1109/DTPI55838.2022.9998981

***Abstract*—This paper further develops the concept of a *digital spectrum twin* (DST), which can be used to enhance dynamic radio access and spectrum management. Specifically, we define the three types of *parallel intelligence* at work in a DST. With this framework, we demonstrate with economic principles and an illustrative case study the importance of *spectrum metering* on a DST-enabled radioscape.**

I. Introduction

A *digital spectrum twin* (DST) is an online representation of radio spectrum that tracks current and historical radio usage across a geographic region. DSTs have been proposed as a means to manage spectrum with more savvy and automation than past methods, thereby increasing efficiency and the total number of radios that can use the scarce resource of radio spectrum [1], [2], [3], [4], [5]. This work presents a framework for incorporating a DST into the management of radio spectrum for either private networks or large-area regulatory frameworks. As a case study, we demonstrate how the concept of *spectrum metering* – enabled by the DST concept in Figure 1 – can be used to manage spectrum in a way that is less hierarchical and rigid than past concepts.

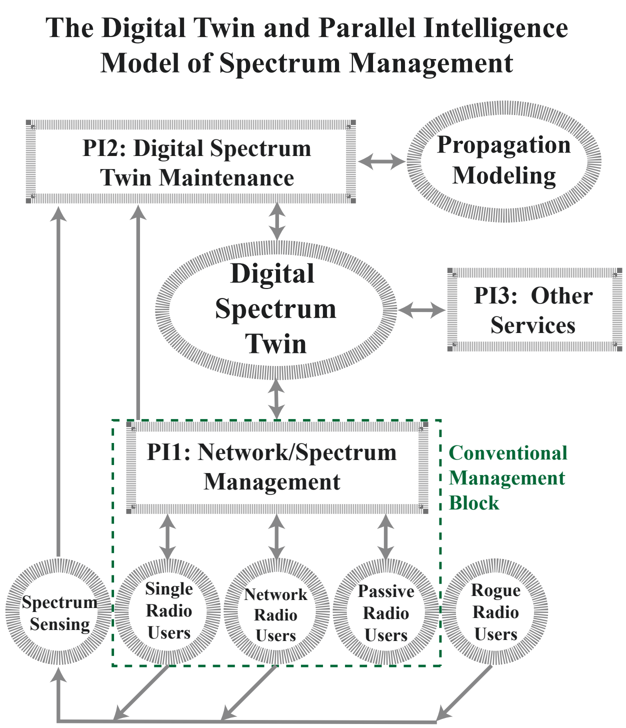

Fig. 1. Block diagram of a digital spectrum twin (DST) and its interfaces with other radios and operations in spectrum management.

Emerging spectrum management concepts are already demanding increased agility and dynamism from radio users. For example, the growing Citizens Broadband Radio Service (CBRS) spectrum between 3.550-3.700 GHz allows many different types of users to share spectrum under the direction of a spectrum access system (SAS)[6]. Another example is the new *radio dynamic zone* concept, where agile radios are allowed to transmit within a geographic frequency band, provided they can be excluded from interfering with sensitive users [7].

II. The Digital Spectrum Twinning Concept

The DST concept outlined in Figure 1 can be applied generically to any number of spectrum management scenarios, from small private radio networks to the full regulatory environment of a geographical region. Central to the concept is the DST – the online representation of current radio spectrum activity over a given bandwidth and area. The DST consists of information about radio transmitters along with propagation maps derived from measurements and modeling. Generally, these elements in the DST provide a "snapshot" of radio activity as well as a log of past activities that can inform more intelligent, automated decisions about use management. An example of a DST composed of a collection of propagation maps is shown in Figure 2.

The bottom tier of the diagram in Figure 1 shows the radio units present in the target environment. Examples include single radio users, networks of radios, and passive radio users. However, there is always a possibility of *rogue users* that operate outside of the outlined jurisdiction (rogue users do not necessarily need to be viewed as *unlawful* users of radio spectrum). There has also been shown the need for supplemental spectrum sensing radios to maintain a DST, to provide real-time visibility of radio transmissions where there are no such measurements among radio users that can report spectrum observations [2].

A key value of the DST formulation in Figure 1 is its ability to illuminate what types of parallel intelligence might interface with the DST. Figure 1 identifies three such classes of parallel intelligence, denoted PI1, PI2, and PI3:

- **PI1: Network/Spectrum Management:** This parallel intelligence consists of algorithms and operations that poll information from the DST in order to better manage users within a radio environment or network.
- **PI2: Digital Spectrum Twin Maintenance:** This parallel intelligence applies automation to maintain the DST. It

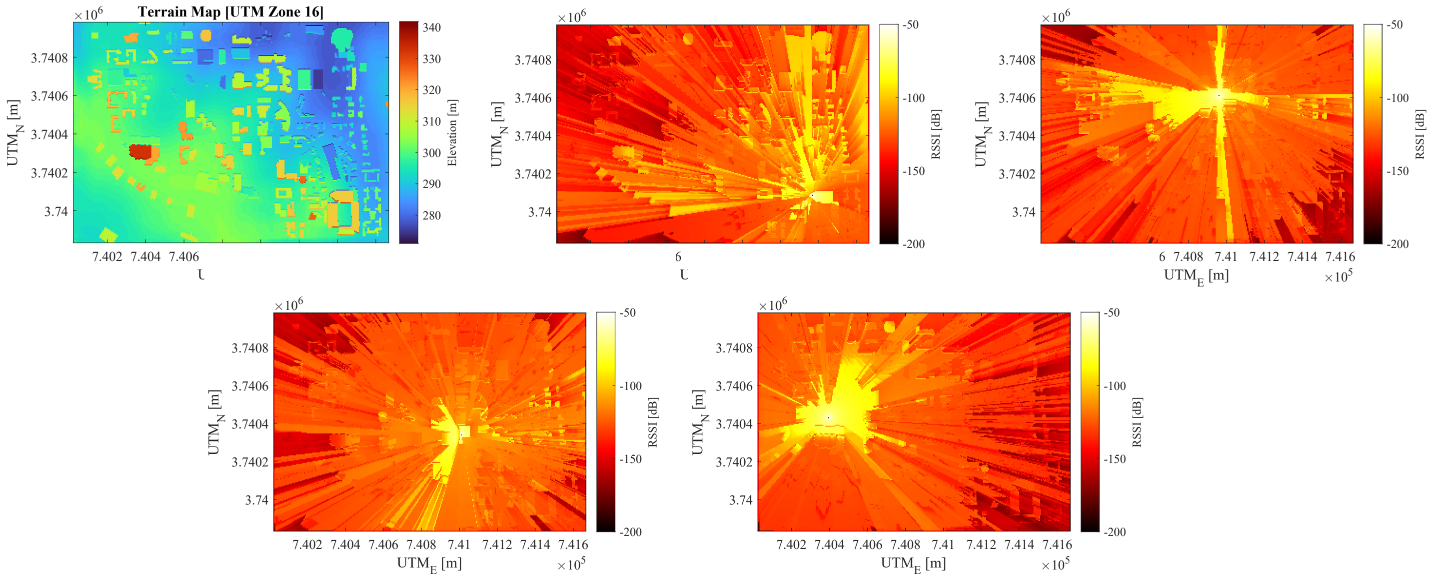

Fig. 2. One example of a region's possible digital spectrum twin (DST) contents, a collection of geo-referenced propagation maps derived from measurements and modeling of identifiable transmitters. Example taken from the campus of Georgia Tech, generated with modeling of 2.4 GHz transmitters at various locations and a digital elevation map based on terrain and building footprints/heights. Graphed RSSI is dB with respect to transmit power.

combines spectrum sensing measurements with propagation models to update a DST. The radios coordinated by PI1 may also be a source of measured spectrum activity for PI2 [2].

- **PI3: Other Services:** This class of parallel intelligence includes new, additional services that were not possible or practical without the DST. Examples might be mining the DST for long-term traffic trends or providing new location-based services for radios [8].

These three items are, in a way, the spectrum-centric forms of parallel intelligence that interface *any* digital twin that is freshly applied to a complicated system (there is parallel intelligence to (1) improve existing operations, (2) maintain the digital twin, and (3) provide new potential services using the twin-enhanced capabilities). These classifications of parallel intelligence help clarify what information is useful to put in the DST as well as how and where artificial intelligence, machine learning, and other forms of parallel intelligence might be applied to the problem of radio spectrum management.

III. Who Could Use a Digital Spectrum Twin?

Spectrum management takes a number of different forms, all of which could benefit from the DST paradigm. Examples range from private/cellular radio networks to the regulatory agency of an entire region or nation. These examples are discussed in detail below.

A. Private Radio Networks

In a private radio network, a single owner/operator of spectrum manages radio usage without concern from unwanted/unlawful transmissions (in principle). An example of a private network that could employ the DST concept is a single cellular provider and their radio users operating within their spectrum allocation. The base stations and mobile users are radios that inhabit the dotted "conventional management block" box of Figure 1, with a combination of automated and manual decisions governing the operation of each. Figure 1 provides a roadmap for incorporating a DST for such a network.

In many ways, the cellular network already *manually* performs functions analagous to the parallel intelligence and DST blocks in Figure 1. For example, a cellular provider periodically *drive-tests* its network, sending engineers out to measure RF signal strength in its network in order to make seasonal or growth-based adjustments to its frequency plan. Although this is not a fully automated operation, it nonetheless is a form of spectrum sensing, intelligent comparison with historical measurements and predictions (typically involving a software planning tool), and some intelligent engineering adjustments made to the operation of the base stations that provide service.

The DST-concept can be used to automate many of the functions of this private network by adding spectrum sensing capability, modeling, and a digital twin of spectrum activity. The primary goal for doing this would be *increasing efficiency* of the existing network and allowing more (paying) subscribers onto the same, limited radio spectrum. As a side benefit, the DST could be mined for "other services" not currently possible with the conventional means of network operation, including localization, traffic analysis, and customer data.

B. Heterogeneous Radio Networks

A heterogeneous radio network is one in which multiple types of users coordinate transmission within the same geographic region and frequency block. An example of this network type would be CBRS, which allows incumbent military users, commercial cellular networks, unlicensed users, and on-demand users to all communicate within a frequency allocation at 3.5 GHz. These transmissions are coordinated through a spectrum access system (SAS).

In many ways, the CBRS SAS already performs some of the functions of the DST-enabled network in Figure 1. Requests from various users are made to the SAS, which uses propagation maps and planning tools to manually authorize users of the CBRS spectrum within a geographic area. A DST-enabled network would allow much more of this operation to be automated.

The primary goal for a DST-enabled heterogeneous network would be for *coexistence* of more and varied radio users within the allocation.

C. Regulatory Authority

A regulatory authority, such as the Federal Communications Commission (FCC) in the United States, could also be viewed as a candidate for DST operation in Figure 1. A regulatory authority sets policy for *all* radio spectrum usage in a geographic region.

Again, regulatory agencies already perform manually some of the functions outlined in Figure 1. The FCC, for example, collects reports of spectrum usage from across the nation, often judging compliance through these reports and supplementing them with manual, customized RF measurements, when necessary. And although most of the FCC's records are computerized, there was a time when the "spectrum twin" was an array of filing cabinets filled with maps and paper licenses.

A goal of a DST-enabled regulatory authority is, in addition to accommodating more and efficient radio usage, to increase *fairness* of spectrum usage.

IV. The Role of Digital Spectrum Twinning in Future Spectrum Management

In this section, we provide some economic theory context for managing experiment, motivating DST use for *spectrum metering*.

A. Economic Theory for Managing Shared, Public Resources

In economic theory, individual consumers of a public resource that act only in their own self-interest run the risk of over-use and ruin of the resource. This effect is called the *tragedy of the commons* in economic science, named so by British economist William Forster Lloyd in his study of public lands ("commons") that were ruined by the visiting livestock of so many farmers looking for free grazing. Much of spectrum regulatory effort is meant to avoid the tragedy of the commons, allowing spectrum to accommodate vastly different applications (cellular users, low-powered unlicensed devices, astronomers, radar, television and radio broadcasters, etc.).

To solve the tragedy of the commons, regulatory rules for radio transmission are enforced by local (national) authorities. A rigid, top-down regulatory effort can work to avoid the tragedy of the commons with respect to spectrum, which was the prevailing principle for much of the early days of spectrum regulatory agencies [9]. This mindset began to change in 1959 when Coase highlighted inefficiencies in the classical rigid government-controlled spectrum allocations and questioned whether this top-down method of allocation was effective [10]; the work would eventually lead to paid-licensing schemes for spectrum [9]. Since then, economists have recognized that all resources are, to some degree, public and scarce (in the way defined by economists) and often have more efficient, less-hierarchical solutions for avoiding the tragedy of the commons. Recent work by economists have explored these non-hierarchical solutions, which includes some Nobel prize-winning work [11].

One way to arrive at an efficient solutions to a public resource management problem is to *meter* usage, attaching a quantifiable metric to the actions of users that invokes a fair cost. In general, efficient solutions to avoid the tragedy of the commons can be achieved by classifying users as *registered* and *unregistered*. *Registered* users are ones that identify themselves to the local authorities and faithfully report each usage of the public resource. *Unregistered* users do not report usage, either by choice or inability [11].

Registered usage can be charged per metered use, with the rate of the usage being adjusted to encourage or discourage additional consumption. Unregistered users can then be charged a flat fee for their usage, based on the value of the remaining public resource left divided up by the number of users. If unregistered use is made more expensive, there will be an additional incentive for a user to register. In this simple scheme, users of a public resource can be regulated and still be given a great deal of freedom and autonomy to operate.

B. Spectrum Metering

Of course, it is no simple task to meter radio spectrum usage. To arrive at even a crude estimate of spectrum activity and occupancy, a system would need to automatically collect RF measurements over space, time, and frequency. Even with direct RF measurement, it is difficult to arrive at a quantifiable metric for radio spectrum usage. Estimation is even more challenging when usage is inferred from alternative metrics.

Cellular carriers often use the number of *transmitted data bytes* as a proxy for metering spectrum usage among their users. However, this is fraught with difficulty even in a relatively homogeneous wireless network. What type of bits are used – transmitted, detected, coded, or unencoded data? Modulation type, bandwidth, transmitted power, antenna pattern, duty cycle, and location all complicate the metering operation further.

Consider the simple case of a transmission of a mobile handset to a cellular base station. Regardless of the other physical parameters, that handset will be transmitting for part of the time at certain frequencies and at a certain power level, all of which affect the "use" of radio spectrum. Where the radio transmits also changes the calculus of use and value; a high-powered transmission in a remote area may *effectively* use less spectrum resources than an identical, lower-powered transmission in a dense urban area.

Passive radio spectrum users, such as radar, remote-sensing, and radio astronomists, are also difficult to incorporate into a metering scheme. These users are consuming radio spectrum, but indirectly through enforced *absence* of users within an area. However, the DST concept is particularly valuable for metering RF spectrum, as the example in the next section illustrates.

V. Case Study for Digital Spectrum Twinning

This section describes the operation of spectrum management for a metropolitan region using the illustrated case study in Figure 3.

A. Example Scenario

Consider the case study of how a DST-enabled radio network might work Figure 3. The spectrogram in Figure 3 shows a single measurement node within a geographic region where spectrum usage is measured over time and frequency. This region experiences heterogeneous activity from a number of users (air traffic control radar, cellular, public safety, weather radar, and unlicensed users).

Transmission of signals in this region is governed by a *spectrum authority* of SAS that inhabits PI1. This authority has little actual role other than to inform or mark certain spectrum in space, time, and frequency as "reserved".

This heterogeneous RF environment employs the concept of registered and unregistered users, but must also accommodate other user types.

- **Registered Users:** These users register with an authority and faithfully report their transmissions. These users also respond to a spectrum authority's requests to avoid transmission in certain bands at specified times and locations.
- **Unregistered Users:** These users also respond to authority requests, but have not registered their use, Low-powered, simple radios and wireless sensors might fall in this category as it may not be practical to report their transmissions.
- **Rogue Users:** Users that neither register their usage nor heed network commands are *rogue users*.
- **Passive Users:** These users require "blackouts" of transmissions in specified regions at certain bands or times.

Each of these user types can be metered through the spectrum twin in Figure 3. A DST is maintained by collecting data across a geographic region and tracking both current and historical spectrum usage. A play-by-play example of this is described in the next section.

B. Example Operations

Now we will move from left to right on the RF spectrogram in Figure 3 to describe what is happening and how the DST is engaged in network operation.

General users fill up most areas of the spectrogram, finding available spectrum and transmitting their signals wherever possible, thereby filling up the spectrum. This is very much in line with a national radio dynamic zone conception of spectrum usage [6], [8].

Radar users are shown to occupy a fixed bandwidth at the top and bottom of the spectrogram. The top band is a weather radar signal that is fixed in bandwidth and periodic; the spectrum authority must request other users to evacuate this spectrum during the periodic transmissions. In between transmissions, however, the spectrum may be filled with activity by other users. The airport radar is continuously reserved for its operation. In both instances, the spectrum usage is metered based on the distributed measurement and modeling of the DST over space, time, and frequency, weighted with the historic demand of radio spectrum in that region.

Passive users can request blackouts in certain space-time-frequency blocks, as illustrated by the stretch of time and frequency that transmission has ceased in Figure 3. The spectrum authority will command all registered and unregistered transmitters to cease transmission in this block. Again, the DST can be employed to *meter* the usage of the radio astronomers' experiment by calculating the size of the space-time-frequency block and weighting it with typical usage in the area.

Special events can also be accommodated, such as the public safety event illustrated in the Figure 3 spectrogram. In this time-frequency block, registered and unregistered users have been commanded to cease transmission so that unfettered communications can occur between law enforcement, medical workers, firefighters, etc. – presumably in response to a local and unusual emergency. While these emergency radio users may proceed without registration or cost (they could be viewed as a form of rogue user), their impact on the overall spectrum can be measured and accounted by the DST.

Enforcement operations in which overall compliance to the spectrum authority. For example, how does one estimate rogue use of the spectrum if those users neither register nor report to the spectrum authority? One solution is to quiet all compliant transmitters and make a spectrum measurement of the remaining transmission activity. In Figure 3, the enforcement operation opens up a block in time and frequency so that the remaining rogue transmissions can be measured.

In the end, all of these operations enabled by the DST allow a spectrum authority to meter the usage of the radio spectrum. Even without an absolute gauge of total spectrum resources, the DST would at least quantify the relative proportion of spectrum usage among the various users – registered, unregistered, rogue, and passive.

C. Observations

The thought experiment run by the previous example in dynamic spectrum allocation by a DST-enabled spectrum authority leads to a number of interesting observations.

First, there is clearly a need for independent spectrum sensing in this environment. While self-reported usage and RF measurement by registered radios can certainly be used by the DST to maintain a current twin of the spectrum environment,

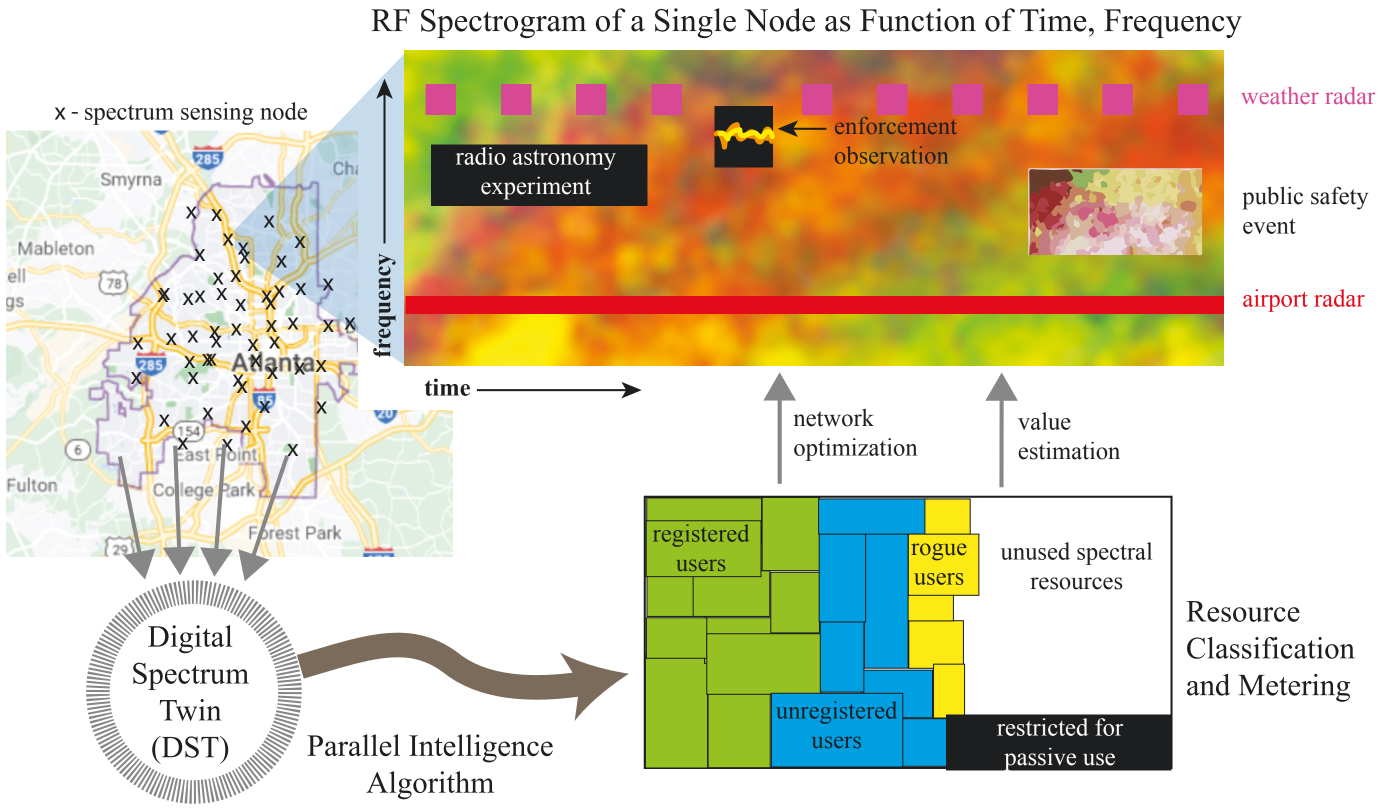

Fig. 3. Example usage scenario of a DST with spectrum metering to manage a dynamic environment with many types of radios. Most radios dynamically find space for their (colored) transmission over frequency and time. Measurements from some of these radios and supplemental spectrum sensing nodes, along with modeling, are used to maintain a DST. Information from the DST is used to meter the relative spectral usage by the different classes of radio users, which can then be used for billing purposes.

measurements from self-reporting radios alone are insufficient. The DST must also update itself where user radios *do not* measure and report in order to grasp the true state of a region's spectrum usage. Thus, a low-cost, independent network of spectrum-sensing radios across a region is critical for operating this type of dynamic spectrum environment.

Second, the ability of a spectrum authority to perform an enforcement operation – an observation of space, time, and frequency where compliant radios have been silenced – is one of the only ways to gauge the number and impact of rogue radio users on the network. Although there is little that a spectrum authority can do in real time to silence rogue users, areas where certain types of rogue users become problematic can be followed up with active localization and removal by authorities. Without the ability to perform an enforcement observation, rogue radios will always be problematic for dynamic spectrum management.

VI. Conclusions

DST-enabled spectrum management promises to greatly enhance the quantity, efficiency, and fairness of radio users – whether we are talking private networks, larger heterogeneous radio environments, or even regulatory agencies. The DST concept also helps to organize and break down the difficult problem of dynamic spectrum management.

As our example of a large, heterogeneous spectrum environment illustrates, there is value in supplemental spectrum sensing, (PI2) an up-to-date database for informing and measuring spectral usage (DST), and a DST-informed spectrum authority (PI1) to maximize spectrum usage. Collectively these components allow spectrum *metering* – even in a complicated radioscape with rogue transmitters. The example suggests a rich future research field of DST-enabled radio environments and networks.

VII. Acknowledgements

This work was supported, in part, under NSF grant #1827940 and the Georgia Tech foundation.

References

[1] G. D. Durgin, Ed., *BESTNEST Workshop on Intelligent Radio*, https://bestnest.wpi.edu/index.php/synapsis-2/, 2020.

[2] G. D. Durgin, M. A. Varner, M. A. Weitnauer, J. Cressler, M. M. Tentzeris, A. Zajic, S. Zeinolabedinzadeh, R. Zekavat, K. Pahlavan, U. Guler, and K. Van der Merwe, "Digital spectrum twinning and the role of RFID and backscatter communications in spectral sensing," in *2021 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, 2021, pp. 89–92.

[3] G. Lohsen, Ed., *5G/FutureG and the Merger of Sensors to Enable Dynamic Spectrum Access*, IEEE RFID 2022 Workshop on Digital Spectrum Twinning, 2022.
[4] S. Zekavat, Ed., *Intelligent Radio: A Gateway to a Comprehensive Spectrum Twinning*, IEEE RFID 2022 Workshop on Digital Spectrum Twinning, 2022.
[5] A. Drobot, Ed., *The Digital Spectrum Twin: The Path to Achieving Realtime Efficient Spectrum Sharing.*, IEEE RFID 2022 Workshop on Digital Spectrum Twinning, 2022.
[6] M. M. Sohul, M. Yao, T. Yang, and J. H. Reed, "Spectrum access system for the citizen broadband radio service," *IEEE Communications Magazine*, vol. 53, no. 7, pp. 18–25, 2015.
[7] C. R. Anderson, Ed., *Using NRDZ's to Shatter Spectrum Silos*, Keynote at IEEE RFID 2022 Workshop on Digital Spectrum Twinning, 2022.
[8] M. G. Weldegebriel, J. Wang, N. Zhang, and N. Patwari, "Pseudonymetry: Precise, private closed loop control for spectrum reuse with passive receivers," in *2022 IEEE International Conference on RFID (RFID)*, 2022, pp. 91–96.
[9] J. Brito, "The spectrum commons in theory and practice," *Stanford Technology Legal Review*, vol. 1, 2007.
[10] R. H. Coase, "The federal communications commission," *The Journal of Law and Economics*, vol. 1, 1959.
[11] E. Ostrom, *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge University Press, 1990.