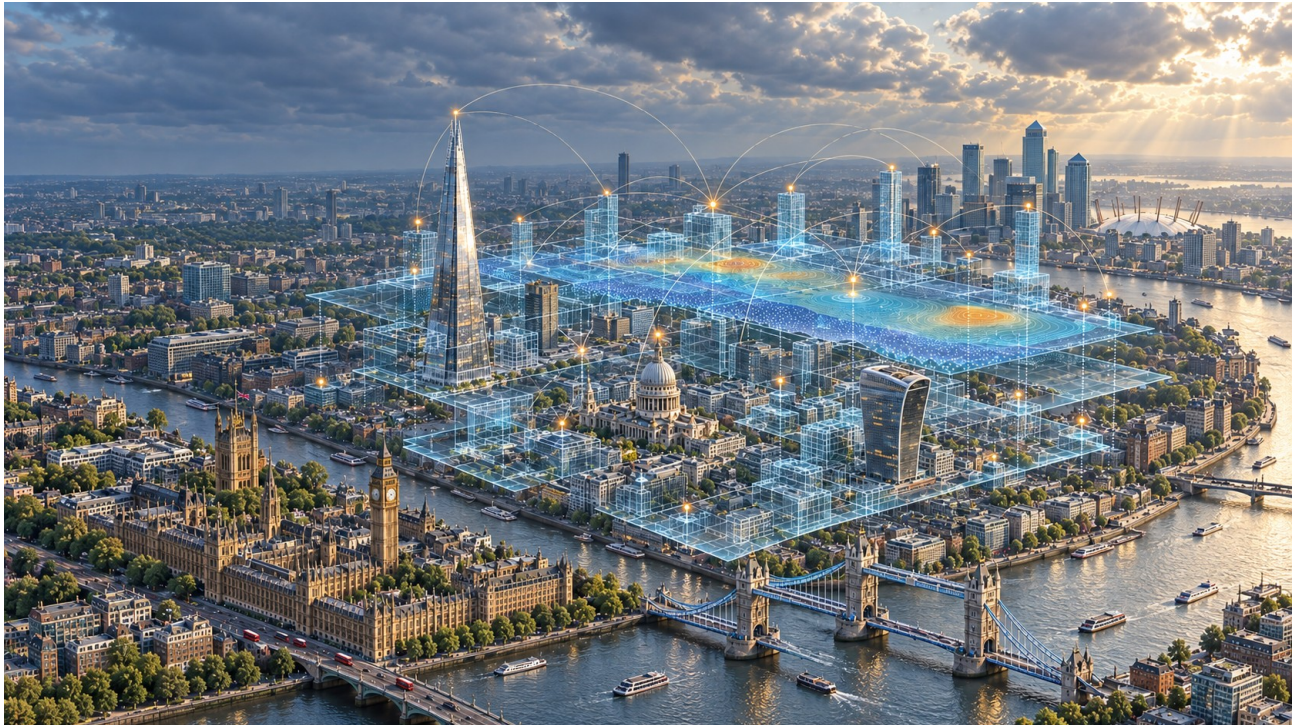


A Theoretical Method for Building a Radio Frequency Digital Twin of the Physical World

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Summary

A radio frequency digital twin could use transmissions already present in modern environments as sources of illumination. Distributed receivers could measure how these signals arrive after passing through, reflecting from and diffracting around physical objects. A computational system could compare those measurements with predictions derived from maps, terrain, buildings, atmospheric conditions and known transmitters, then update its model wherever prediction and observation differ.

Such a system would most efficiently use a hierarchical design. Most of the environment could remain represented at low resolution, while a small proportion—perhaps around one percent—could receive finer modelling and more frequent updates. Concentrating resources in this way could improve local accuracy, but it would not overcome the physical limits imposed by wavelength, bandwidth, receiver geometry, noise and incomplete observations.

The resulting digital twin would be a changing probability map of structure, material response and motion.

Introduction

Computed tomography creates an internal image by transmitting X-rays through a subject from multiple angles and reconstructing the resulting pattern of attenuation. The same general mathematical principle can be applied to radio waves: collect many observations of a scene, measure how the signals have changed and solve the inverse problem of determining which physical arrangement most likely produced those changes.

The similarity is conceptual rather than literal. X-rays have extremely short wavelengths and are used within a controlled scanner. Civil radio signals have longer wavelengths, originate from multiple transmitters and undergo complicated propagation. Wi-Fi, cellular, broadcast and satellite signals reflect from walls, vehicles and terrain, diffract around obstacles and interfere with delayed copies of themselves. This multipath behaviour complicates reconstruction, but it also encodes information about the surrounding environment.

A radio frequency digital twin can therefore be understood as a passive, multi-band synthetic-aperture sensing system connected to a persistent computational model.

“Passive” means that the system observes existing transmissions rather than generating signals specifically for imaging. “Multi-band” means that it combines measurements from several parts of the radio spectrum. “Synthetic aperture” means that observations made at different locations are combined to behave like measurements from a much larger antenna. The digital twin stores the current estimate of the physical scene together with the uncertainty associated with each inferred feature.

What the System Would Measure

A receiver could preserve much more information than signal strength alone. Depending on the hardware and transmitted waveform, measurements could include:

- Amplitude
- Phase
- Frequency
- Channel response
- Time of arrival
- Angle of arrival
- Doppler shift
- Polarisation

These quantities describe how a transmitted wave has been delayed, weakened, redirected or shifted by its interaction with the environment.

No individual frequency band would provide a complete reconstruction. Lower-frequency signals travel farther and can propagate through or around some obstacles, but their longer wavelengths and often narrower bandwidths limit spatial detail. Higher-frequency and wider-bandwidth signals can distinguish nearby surfaces more effectively, although they are more easily blocked and generally operate over shorter distances.

Combining several bands can reveal complementary properties of a scene. It cannot create spatial information that is absent from the measurements.

Signal source	Likely contribution	Main limitation
FM and DAB radio	Wide-area coverage and detection of large-scale changes	Long wavelengths and modest bandwidth limit fine detail
Digital television	Strong, structured signals suitable for regional passive sensing	Transmitter geometry and coverage vary by location
Cellular networks	Dense urban illumination, timing information and motion cues	Scheduling, waveform and configuration changes
Wi-Fi	Local presence, movement and room-scale channel changes	Short range, irregular placement and severe indoor multipath
Bluetooth and local devices	Additional nearby paths and short-range changes	Low power and intermittent transmission
GNSS and satellite signals	Illumination from high and changing directions	Weak signals and difficult reflected-signal recovery
Weather, aviation and maritime radar	Powerful pulses and useful motion or atmospheric information	Specialised waveforms and geographically uneven coverage
Millimetre-wave links	Finer surface sensitivity at short range	Blockage, weather sensitivity and limited coverage

Public Data Systems That Could Inform the Twin

A radio frequency digital twin would require several categories of prior information. No single organisation or database would supply a complete model. Terrain maps, building data, atmospheric models, transmitter records and orbital catalogues could instead be combined within a shared spatial and temporal reference system.

These sources would inform the digital twin rather than perform the reconstruction themselves. They could provide starting conditions, expected transmitter locations, environmental corrections and independent observations against which RF measurements could be compared.

Terrain Maps and Structures

Terrain and elevation datasets could define the ground surface, slopes and large obstacles that affect radio propagation. Building outlines, road networks and land-use maps could supply likely structural boundaries. Where available, three-dimensional surface models or lidar data could add building heights, vegetation and other surface features.

Possible examples include national mapping agencies, the United States Geological Survey's elevation products and openly licensed geographic databases such as OpenStreetMap. In the United Kingdom, appropriate open products from Ordnance Survey could provide additional geographic context. The selected information would need to be converted into a consistent coordinate system and simplified to the resolution supported by the RF observations.

Map data would not normally contain the electromagnetic properties required by a propagation model. The twin would therefore associate mapped surfaces with approximate material classes such as soil, water, vegetation, concrete, glass or metal. These estimates could be revised when measured propagation repeatedly disagreed with prediction.

NOAA Environmental and Computational Models

The United States National Oceanic and Atmospheric Administration, or NOAA, illustrates several kinds of environmental information that could contribute to a radio frequency digital twin.

NOAA's National Centers for Environmental Prediction distribute outputs from computational systems including the Global Forecast System. The NOAA Operational Model Archive and Distribution System provides access to model analyses and forecasts. These products can contain estimates of temperature, pressure, humidity, precipitation and atmospheric structure.

Such variables influence radio attenuation and refractivity. Incorporating them into the propagation model could reduce the chance that a change in the atmosphere would be misinterpreted as a change in a physical object.

NOAA also archives data from the Next Generation Weather Radar system, known as NEXRAD. NEXRAD is a network of 160 high-resolution S-band Doppler weather radars jointly operated by the US National Weather Service, Federal Aviation Administration and US Air Force. Its measurements include reflectivity, radial velocity, spectrum width and dual-polarisation quantities.

Within a theoretical digital twin, NEXRAD products could contribute mapped precipitation and wind information or provide comparison data for atmospheric and large-scale motion estimates. NEXRAD should not, however, be treated as a general-purpose urban imaging network. Its principal function is atmospheric observation.

Other NOAA systems—including environmental satellites, surface stations, radiosondes, ocean buoys and weather-model archives—could provide further boundary conditions. Their main value would be environmental correction and independent context rather than detailed reconstruction of buildings or people.

NORAD Space Track and CelesTrak

NORAD maintains awareness of objects in Earth orbit as part of its aerospace-warning mission. However, the public source relevant to this method is more accurately described as Space-Track.org rather than NORAD itself.

Space-Track distributes public satellite-catalogue and general-perturbation records. Objects are indexed using catalogue numbers commonly called NORAD catalogue numbers. CelesTrak provides another widely used public distribution and documentation service for general-perturbation orbital data and the SGP4 propagator used to calculate approximate satellite positions from orbital elements.

These records could allow the digital twin to estimate the position and motion of a satellite at the time of an RF observation. This information could support the modelling of GNSS, communications-satellite or other space-to-ground signal paths.

Orbital elements are estimates rather than exact trajectories. Their uncertainty and age would therefore need to be included in the predicted observation.

The phrase “NORAD orbital data” is understandable shorthand, but “public orbital data from Space-Track or CelesTrak, indexed by NORAD catalogue number” is more precise.

Spectrum and Transmitter Information

National spectrum databases could indicate which radio services operate in particular frequency ranges. In the United Kingdom, Ofcom’s Spectrum Information System provides information about spectrum allocations and types of radio licences. Comparable information is published by communications regulators in other countries, including the United States Federal Communications Commission.

Broadcast-transmitter records could help locate FM, DAB and television sources. Other databases might indicate the approximate locations or operating bands of fixed links, satellite gateways, maritime stations or other licensed services.

These records would be treated as prior information. A database entry would not guarantee that a transmitter was active, that its waveform was suitable for passive sensing or that its exact timing, antenna pattern and power were known.

Examples Across the Radio Spectrum

Frequency region	Educational examples	Possible contribution
HF, VHF and lower UHF	FM, DAB and communications services	Wide-area illumination and detection of large environmental changes
VHF and UHF television bands	Digital terrestrial television transmitters	Strong structured signals suitable for passive coherent processing
UHF and microwave cellular bands	Cellular base stations, informed by spectrum and transmitter records	Dense urban illumination, delay measurements and Doppler

Frequency region	Educational examples	Possible contribution
		information
2.4, 5 and 6 GHz	Wi-Fi access points and other local transmitters	Room- or building-scale channel response, occupancy and motion changes
L-band satellite services	GNSS and communications satellites, supported by orbital records	Signals arriving from known and changing directions
S-band	NOAA NEXRAD and other weather or surveillance radars	Atmospheric context, precipitation mapping and strong pulsed signals
C-, X- and Ku-band	Weather, marine, aviation, fixed-link and satellite systems	Additional propagation paths, motion cues and environmental measurements
Ka-band and millimetre wave	Satellite links, fixed wireless links and high-frequency cellular systems	Finer surface sensitivity over shorter, frequently line-of-sight paths

The existence of a transmission would not automatically make it useful. A practical measurement would also depend on received signal strength, waveform structure, bandwidth, timing stability, observation geometry and the receiver's ability to isolate the direct and reflected components.

How the Prior Information Would Enter the Model

The information supplied by public systems could enter the twin in four main forms.

Spatial priors. Terrain, roads, building outlines, elevation data and surface models would establish the initial geometry.

Environmental priors. NOAA and comparable meteorological systems would provide atmospheric conditions used to predict attenuation, delay and refraction.

Transmitter priors. Spectrum, licensing and broadcast records would indicate likely frequency bands, signal classes, transmitter locations and operating characteristics.

Orbital priors. Space-Track and CelesTrak would provide estimated satellite trajectories for predicting space-to-ground signal paths.

The twin would compare all these priors with measurements made by its receivers. A database record would be treated as an initial hypothesis rather than unquestioned truth. Maps can be outdated, transmitters can change configuration, orbital predictions accumulate error and weather models have limited spatial and temporal resolution.

Persistent disagreement between prediction and observation would therefore reduce confidence in the relevant prior and could cause the model to revise it.

The Reconstruction Cycle

The digital twin could operate through a repeating forecast-and-correction cycle similar to data assimilation in numerical weather prediction. Instead of primarily estimating pressure, temperature and wind, its state would describe geometry, material response, transmitters, propagation conditions and dynamic objects.

1 Construct the baseline

Terrain, buildings, infrastructure, weather, transmitter data and orbital information are combined into an initial model. The environment is divided into spatial cells or learned regions. Each region contains estimated geometry, electromagnetic properties and a confidence value.

2 Calibrate the receivers

The system estimates the position, clock offset, frequency error, antenna response and local interference environment of each receiver. Time and phase errors must be tracked continuously because calibration drift can resemble physical movement or a change in range.

3 Capture reference and surveillance channels

Where the signal structure permits, one receiver channel records a relatively clean copy of the transmitted waveform while other channels record versions that have propagated through the scene. Correlating the reference and surveillance signals helps distinguish transmitter behaviour from effects introduced by the environment.

4 Predict the measurements

The current digital twin is used to calculate what each receiver should observe. Different propagation models can be used at different scales. Ray tracing, diffraction models, statistical channel models and learned approximations can cover large regions. Full-wave electromagnetic simulation can be applied selectively to small areas where simpler models fail to reproduce the measurements.

5 Calculate the residual

The predicted measurement is compared with the actual measurement. Their difference is the residual: the part of the observation that the current model does not explain. A residual may result from a moving object, a changed surface, atmospheric variation, interference, altered transmitter behaviour, calibration error or an incomplete propagation model. A single residual therefore does not uniquely determine its cause.

6 Solve the inverse problem

The system estimates the smallest physically plausible change that explains the residual across multiple receivers, paths, times and frequencies. Possible techniques include Bayesian inference, sequential filtering, numerical optimisation, sparse reconstruction and physics-informed machine learning. Combining independent observations reduces ambiguity. An explanation supported by several frequencies and viewing directions would normally receive greater confidence than one supported by a single propagation path.

7 Update the twin

Changes are incorporated into the digital twin according to the strength and consistency of the evidence. When several explanations remain plausible, the system can retain multiple hypotheses rather than selecting one prematurely. Static structures would normally update slowly. Dynamic objects and propagation conditions would update more rapidly. Every state estimate would retain information about its confidence, spatial resolution and age.

Hierarchical Processing and the One Percent Principle

A city-scale digital twin would not need to process every location at maximum resolution. Most of the environment changes slowly and could remain represented by large spatial cells and approximate propagation models.

A small proportion of the model—perhaps around one percent of its cells, locations or objects—could be selected for higher-resolution processing. This is a form of adaptive refinement rather than a separate sensing mechanism.

A refined region could receive:

- Measurements from more receivers and frequency bands
- Longer coherent observation intervals
- A smaller spatial grid
- More detailed multipath modelling
- More frequent state updates
- Greater computational resources
- Selective full-wave simulation

If the underlying measurements contain sufficient information, refinement could improve localisation, motion continuity, separation of weak changes from background clutter and the rate at which the local model is updated.

The improvement would remain bounded by signal physics. Range resolution depends strongly on usable bandwidth. Angular resolution depends on wavelength and effective aperture. Reconstruction quality also depends on signal-to-noise ratio, transmitter knowledge and diversity of viewing geometry.

Allocating substantially more computation cannot recover an angle that was never observed or spatial detail that the waveform cannot resolve.

Layer	Most of the environment	Refined portion
Spatial model	Large cells and stable surfaces	Smaller cells where measurements justify them

Layer	Most of the environment	Refined portion
Update rate	Slow updates for static structures	Faster updates for local change and motion
Propagation model	Approximate rays and learned regional responses	Detailed multipath and selective full-wave modelling
Measurements	A subset of receivers and bands	Additional paths, bands and observation history
Output	Coarse occupancy and change probability	Improved local geometry, motion and confidence estimates

Physical Reconstruction and Identity

Radio sensing naturally measures physical effects. It can indicate that a reflective object moved, that a propagation path became blocked or that energy began arriving from a new direction.

These measurements do not inherently provide identity. Associating a reconstructed object with a named person would require a separate source of identity information and a continuity model connecting that identity to the observed RF track. Such an association could fail when objects cross paths, leave the receiver network or enter dense environments.

Physical reconstruction and identity association should therefore be treated as different technical problems. The RF twin itself would describe estimated structure, occupancy and motion. Any identity layer would be external to the radio-frequency reconstruction.

Computing Architecture

The required computation could range from a single GPU-equipped server for a room-scale model to a data-centre or supercomputer-scale system for continuous metropolitan coverage.

The central efficiency principle is to avoid solving the complete electromagnetic field for every cubic centimetre at every moment. Most of the physical environment is static or changes slowly. The system could therefore store a persistent baseline and devote most real-time processing to residuals and dynamic regions.

Processing could be divided into three levels:

Edge processing: Receivers perform filtering, interference suppression, waveform detection, compression and initial timestamping.

Regional processing: Nearby observations are synchronised and combined to estimate channels, arrival directions, delays and coherent changes.

Central modelling: A broader computational system maintains the digital twin, selects regions for refinement and merges local updates into the persistent model.

Graphics processors are well suited to correlation, beamforming, Fourier transforms, matrix operations, optimisation and learned-model inference. Full-wave solvers would be reserved for regions in which simpler models repeatedly produce unexplained residuals.

A learned electromagnetic world model could further reduce repeated computation by approximating how a familiar environment scatters radio waves. Such a model would act as a fast propagation surrogate. Its predictions would still need to be constrained by measured data, known physics and explicit uncertainty.

Possible Outputs

A mature radio frequency digital twin could contain several linked layers:

- Terrain and buildings
- Estimated electromagnetic material properties
- Weather and atmospheric refractivity
- Known radio-frequency infrastructure
- Orbital signal sources and reflectors
- Dynamic objects
- Confidence, resolution and observation age

The output would be a time-varying field of estimated properties and probabilities rather than a photographic image.

At wide-area scale, the twin might represent large structural changes, traffic flow, major moving objects and regions where current propagation no longer matches the baseline.

At building or room scale, suitable signals and receiver geometry might support estimates of occupancy, position and movement. In favourable conditions, coarse pose or shape might also be recoverable.

At higher frequencies, with wide bandwidth and diverse observation angles, finer surface features could be reconstructed over limited distances.

Ordinary ambient Wi-Fi and cellular signals would not produce medical-quality CT images, reliable internal anatomy, thoughts, speech or inherent personal identity.

Accuracy and Failure Modes

Every reconstructed feature should include confidence, spatial resolution and the time since it was last supported by observation. A visually precise display can conceal an uncertain inference, so the model should distinguish among direct measurements, predicted states and inferred changes.

Important failure modes include:

- Clock or phase drift producing false range or motion
- Transmitter power changes resembling environmental changes
- Network scheduling changes altering the observed waveform
- Rain, vegetation movement or atmospheric refraction creating persistent residuals
- Sparse receiver geometry leaving blind directions and ghost objects
- Frequency-dependent material behaviour causing disagreement between bands
- Incorrect or outdated map data biasing the baseline model
- Orbital-position errors affecting predicted satellite paths
- Machine-learning models producing confident predictions outside their training distribution
- Multiple physical scenes producing similar measurements

Calibration targets, controlled experiments and held-out measurements can be used to quantify these errors. Accuracy should be reported separately for presence, position, velocity, surface geometry and any external identity association because these are distinct reconstruction problems.

Illustrative Construction Sequence

A theoretical implementation can be understood through increasingly large sensing environments.

A room-scale system would begin with a measured floor plan, known Wi-Fi transmitters and several synchronised receivers. Its state could be limited to static geometry, occupancy and movement. Comparing its reconstruction with independent measurements would reveal the effects of receiver placement, calibration error and indoor multipath.

A building-scale system could add multiple frequency bands, material estimates and environmental corrections. Regional processing would combine observations between rooms and floors while the hierarchical model kept stable structures at lower update rates.

An outdoor test environment could incorporate cellular, broadcast and satellite signals. Public terrain data, weather-model outputs, spectrum records and orbital elements could inform the initial model. Known moving objects and surveyed structures would provide reference data for evaluating localisation, change detection and propagation modelling.

The same architecture could then be extended to larger areas by adding receiver regions rather than replacing the underlying reconstruction cycle. As scale increases, hierarchical processing, model compression and selective refinement become essential because complete full-wave simulation becomes computationally impractical.

Conclusion

A radio frequency digital twin is theoretically plausible as a limited, probabilistic sensing and modelling system. It would combine ambient radio illumination, distributed synchronised receivers, public maps and databases, electromagnetic prediction, inverse reconstruction and repeated data assimilation.

NOAA weather and radar products illustrate how environmental observations and computational models could supply atmospheric context. Public orbital records from SpaceTrack and CelesTrak, indexed by NORAD catalogue numbers, illustrate how moving satellite sources could be incorporated. National mapping and spectrum systems could provide terrain, structural and transmitter priors.

These systems would contribute supporting information rather than a ready-made RF reconstruction. Their records would be treated as uncertain starting conditions and continuously compared with receiver observations.

The practical architecture would keep stable parts of the environment relatively coarse while assigning more detailed computation to changing or selected regions. Concentrating resources on approximately one percent of the model could improve local accuracy and update frequency when the measurements provide sufficient information.

This concentration would not remove the fundamental limits of wavelength, bandwidth, noise and observation geometry. Nor would physical reconstruction inherently provide personal identity. The most credible output would be a layered model reporting what is estimated, the evidence supporting it, its achievable resolution and the associated uncertainty.

Source Note

This article presents a theoretical construction method based on established concepts from radio tomography, passive radar, synthetic-aperture sensing, electromagnetic propagation, data assimilation and digital twins. It does not assert that a single existing system provides the complete capability described.

The named organisations and databases are educational examples of publicly documented information sources. Their inclusion does not imply participation in such a system or access to non-public data. Performance would depend on the available signals, receiver density, synchronisation, bandwidth, geometry, calibration, prior information and physical environment.

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