Mastering Digital Twins: Introducing ABoT for Cross-Disciplinary Simulation and Model-Based System Engineering

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ABSTRACT

Building digital twins is a cross-disciplinary endeavor, combining the efforts of modelers, system engineers, data analysts, UX designers and domain experts. For digital twins to be able to evolve with their paired, real-world system the artifacts associated with these various disciplines must remain synchronized and coherent throughout the digital twin lifecycle. We provide a paradigm for harmonizing this multi-disciplinary effort using what we call an Authoritative Broker of Truth (ABoT). We apply this paradigm to a real-world case study: Can I cut the cord on my cable provider?

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THE AUTHORITATIVE BROKER OF TRUTH

Definition of a Digital Twin

We adhere to the Digital Twin definition provided by the Digital Twin Consortium:

> *A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.*
>
> *Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in Information Technology/Operational Technology (IT/OT) systems.*

Decomposing this definition, we summarize the core properties of a digital twin:

- **Virtualization**: the twin digitally represents the real-world system
- **Synchronization**: operational data and parameters are regularly updated between the twin and the real-world system
- **Purpose**: there was a reason to build the twin: namely to better understand and control the real-world system

Restated, we define Digital Twins as:

> *Digital Twins are living companions to real systems whose primary purpose is to answer meaningful questions about the current and future functioning of their twinned, real-world system.*

In this paper we will present:

- The core processes needed to build and evolve a digital twin
- The relationship between these processes during the full life cycle of a digital twin
- A tangible, real-world example determining the necessary hardware for providing free over-the-air television to a house based on simulated radio-frequency coverage and in-house cabling options.

THE ABoT PARADIGM

We define the following processes:

- **Design**: the determination of the constraints and requirements for the digital twin
- **Simulation**: the construction of the execution logic and stakeholder-oriented manifestation of the digital twin

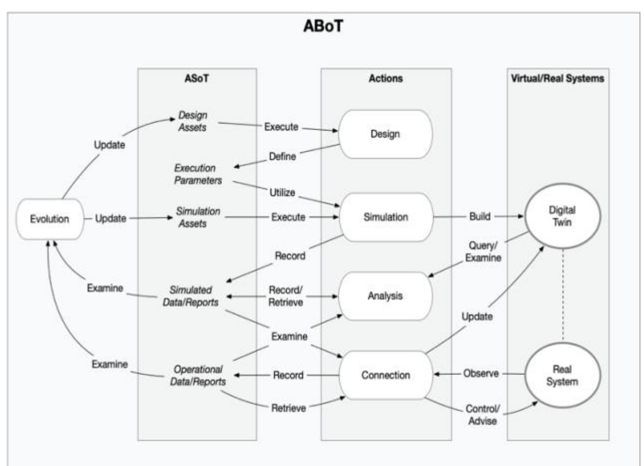

Figure 1. ABoT Overview Diagram

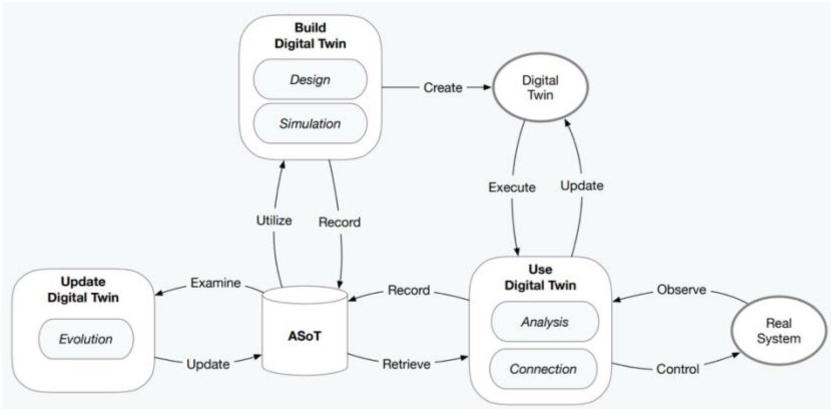

Figure 2. ABoT Usage

- **Analysis**: the use of the digital twin to provide insight into the past, current and future behavior of the real system
- **Connection**: the mechanisms by which data is retrieved from the real system and control is provided to the real system
- **Evolution**: the method by which the above processes are updated to improve and maintain the synchronization between the digital twin and the real system

The collection of these processes and their data relationships constitute the Authoritative Broker of Truth (ABoT) for building a digital twin.

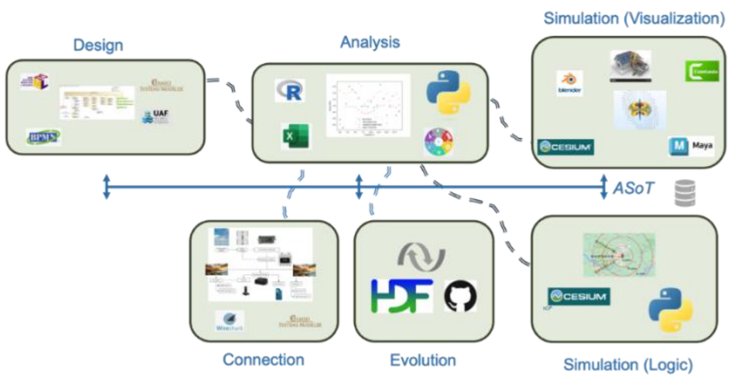

Figure 3. Example ABoT Process Tooling

The Authoritative Source of Truth (ASoT)

Core to the ABoT is the underlying data repository, the Authoritative Source of Truth (ASoT). The ASoT contains the artifacts necessary to construct the digital twin at any point in its life cycle; however, the ASoT itself is not the digital twin. The ASoT provides traceability as the system evolved, capturing historical knowledge and connecting selectable configuration-controlled versions of models and data for analysis and other capabilities. The ASoT is tasked with storing heterogenous types across different domains with widely diverging file sizes and formats.

The ASoT has three functions:

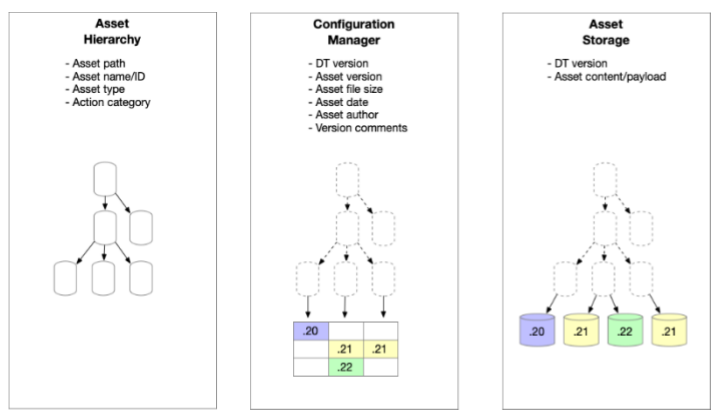

Figure 4. ASoT Substructure

1. **Structural**: defining the access and retrieval language of the ASoT assets
2. **Configuration**: providing versioning of individual assets and thus the ability to combine constellations of these versioned assets into different versions of Digital Twins
3. **Storage**: effecting the raw storage mechanism for the assets.

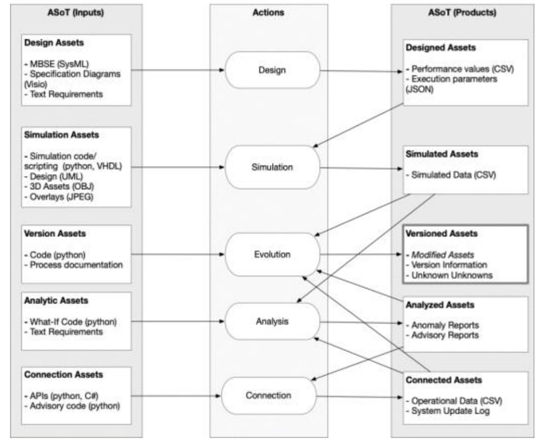

Figure 5. ASoT Assets

VALIDATION, VERIFICATION AND UNCERTAINTY QUANTIFICATION

In the National Academies of Sciences, Engineering, and Medicine 2024 study on Foundational Research Gaps and Future Directions for Digital Twins

Digital twins require Validation, Verification and Uncertainty Quantification (VVUQ) to be a continual process that must adapt to changes in the physical counterpart, digital twin virtual models, data, and the prediction/decision task at hand.

It is critical that VVUQ be deeply embedded in the design, creation, and deployment of digital twins.

VVUQ may be described from the viewpoint of the ABoT processes:

Verification determines if the formal requirements of the Digital Twin are met:
- Design: Determine system parameters and requirements
- Simulation: Provide simulated results for these parameters
- Connection: Obtain operational results for these parameters
- Analysis: Compare simulated and operational results

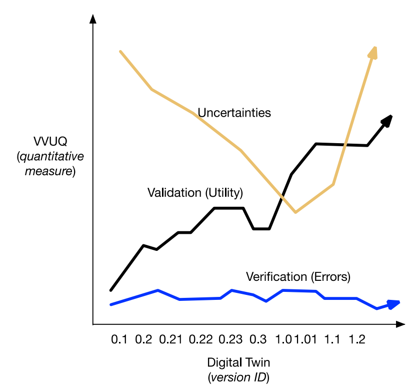

Figure 6. Conceptual VVUQ Metrics for an Evolving Digital Twin

Validation determines success of system from the viewpoint of the stakeholder:
- Design: Document user intention
- Simulation: Manifest simulation results to users in comprehensible ways
- Analysis: Assure that edge cases produce meaningful results
- Connection: Obtain direct user input regarding system behavior

Uncertainty assesses unknowns associated with digital twin execution:
- Design: Document limits of requirements
- Simulation: Detect parts of simulation which cannot be adequately stress-tested
- Analysis: Note inability to test subsystems of digital twin
- Connection: Anticipate future obsolescence scenarios

Within the ABoT context, the **Evolution** is the process where results of the VVUQ activities are realized, and a new version of the digital twin is generated. These version changes can impact any ABoT processes including the Evolution process itself.

THE PROBLEM (*DESIGN*)

Our purpose is to create the digital twin of an over-the-air television reception area for homeowners who are interested in replacing cable-television with free local channels. The design of the system took into consideration:

- The distance between the transmitter and the location of the receiver.
- The predicted RF energy at the face of the receiving antenna.
- The predicted RF energy after signal distribution within the structure (input at the television)
- Identification of components of the system to meet requirements based on RF performance prediction and cost.

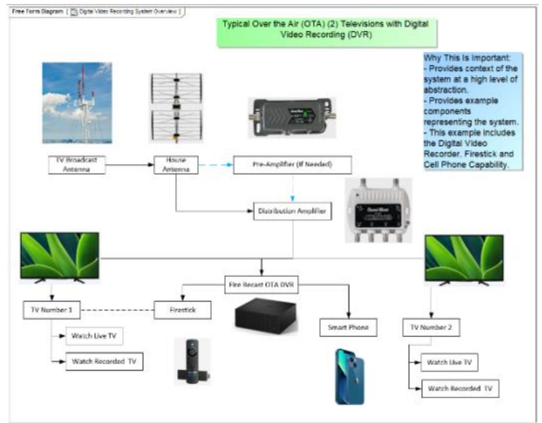

Figure 7. Over-the-Air TV Reception System

A Model Based System Engineering (MBSE) approach was used in the ABoT Design Process to generate requirements, technical performance measures (TPMs) for RF signal strength, the structure (system components) and behavior (how the system operates in the environment). The model contains over 120 types of diagrams and 30,000 elements creating a customizable design based on re-usable model elements. The RF signal level characteristics and predictions were used to create and drive the simulation for further RF analysis and predictions.

MBSE Model and Diagrams

The model contains all (9) types of diagrams found within the SysML modeling language. In this paper, we highlight (3) diagrams with graphical representations from the model for brevity (Requirement diagrams, Block Definition Diagrams, and Parametric Diagrams and tables. The remaining diagrams are described in paragraph form only.

- <u>Requirement Diagrams (REQ):</u> - The modeling process starts with requirement diagrams capturing stakeholder needs to understand why the customer is interested in an over-the-air TV antenna system. We refer to this process as asking the "20 Questions" as shown in Figure 8. The stakeholder needs are transformed into functional and non-functional requirements (shall statements) which are used later in the process for automated verification. Figure 9 shows an example of the automated verification of the requirements by the model (requirements passing verification are highlighted in green).

Criteria
Scope (optional): Stakeholder 20 Questions ... Filter: Context (optional): Drag elements from the Model Browser ...

#	Owner	Name	Text	Rationale
1	Stakeholder 20 Questions	Ques-1 Cut the Cable	What is the primary reason you are considering cutting the cord (dropping paid for cable television and converting to Over-The-Air (OTA) free local channels?	Ensure we understand the reason why the customer is cutting the cord. Is it to save money? Poor performance over Dish TV, etc.
2	Stakeholder 20 Questions	Ques-2 Budget	What is your budget that you want to spend to be able to cut the cord?	To ensure the customer understand the value of switching from cable to over the air. Switching can be expensive - customer may not realize a quality installation will provide a nice return on investment in the future.
3	Stakeholder 20 Questions	Ques-3 Friends with OTA	Do you know any friends or relatives using OTA television? Are they happy with the reception of local channels?	Probing question to see if the customer has any experience of OTA channels in their local area and what to expect. Picture quality, number of channels, good or bad reviews, fading of channels during storms, etc.
4	Stakeholder 20 Questions	Ques-4 Major Local Channels	Are you only interested in receiving the major local channels (ABC, CBS, NBC, Fox)?	Sets the expectation of the customer, most as a minimum want to get the major networks. Other channels are bonus.
5	Stakeholder 20 Questions	Ques-5 Number of TVs	How many TVs are in your home? What areas are you planning to watch TV?	The number of TVs is a design constraint that drives equipment selection. More TV = more amplification and additional wiring if needed.
6	Stakeholder 20 Questions	Ques-6 OTA TV Expansion	Are you interested in expanding your OTA TV system to <u>more than 2</u> TVs?	If the homeowner wants to expand the OTA system to other TVs in the future, the distribution amp came be upgraded during the initial installation.
7	Stakeholder 20 Questions	Ques-7 Brand of TVs	What brand of televisions are going to be connected to the OTA antenna system?	Probing question - if there are any non-digital TVs being used - they should be identified and a cable box converter will need to be used.
8	Stakeholder 20 Questions	Ques-8 Smart TVs	Are any of the television 'smart' TVs?	Probing question, if the TVs are Smart TVs and Fire TVs, it makes the installation less expensive. Try to keep it in the same product line for integration.
9	Stakeholder 20 Questions	Ques-9 Record TV	Do you record shows using your paid cable TV?	This is a probing question concerning recording live TV. Most cable companies offer this as a paid service. Does the customer want to continue to record live TV. If the answer is yes, there are additional costs involved.

Figure 8 Requirements Diagram - The Customer "20 Questions"

-

Requirement Verification: Pass Fail ...

#	Name	Text	Bounds	Value	Margin
1	50 Record multiple shows at the same time	The OTA TV system shall record up to 4 TV shows concurrently.	<=4	4	0
2	43 Save Money On Cable TV	The OTA TV system shall be less than or equal to 1200 dollars.	<=1200	1120.68	79.32
3	49 Store atleast 40 hours of live TV shows	The OTA TV system shall store greater than or equal to 150 hours of live HDTV broadcast.	>=150	150	0
4	45 ABC TV Signal Performance	The OTA TV system shall provide ABC TV signal strength of greater than or equal to -65 dBm at the TV tuner.	>=-65	-50.89	14.11
5	53 CBS TV Signal Performance	The OTA TV system shall provide CBS TV signal strength of greater than or equal to -65 dBm at the TV tuner.	>=-65	-54.673	10.327
6	51 NBC TV Signal Performance	The OTA TV system shall provide NBC TV signal strength of greater than or equal to -65 dBm at the TV tuner.	>=-65	-32.729	32.271
7	41 FOX TV Signal Performance	The OTA TV system shall provide FOX TV signal strength greater than or equal to -65 dBm at the TV tuner.	>=-65	-49.616	15.384

Figure 9 Requirements Verification Table

- Block Definition Diagrams (BDD): The BDD shown in Figure 10, is used to identify the components of the reconfigurable system (antennas, pre-amplifiers, distribution amplifiers, cabling, and connectors). This diagram also conveys which component within the system design is satisfying what requirement in the design. Another example of a BDD of the ABC Channel Cost and Performance Analysis is shown in Figure 11. The values shown in the Madison ABC Cost and Performance Analysis block are used in the parametric equations for the RF link budget analysis, cost data, and other information needed for trade study analysis, simulation, and optimization.

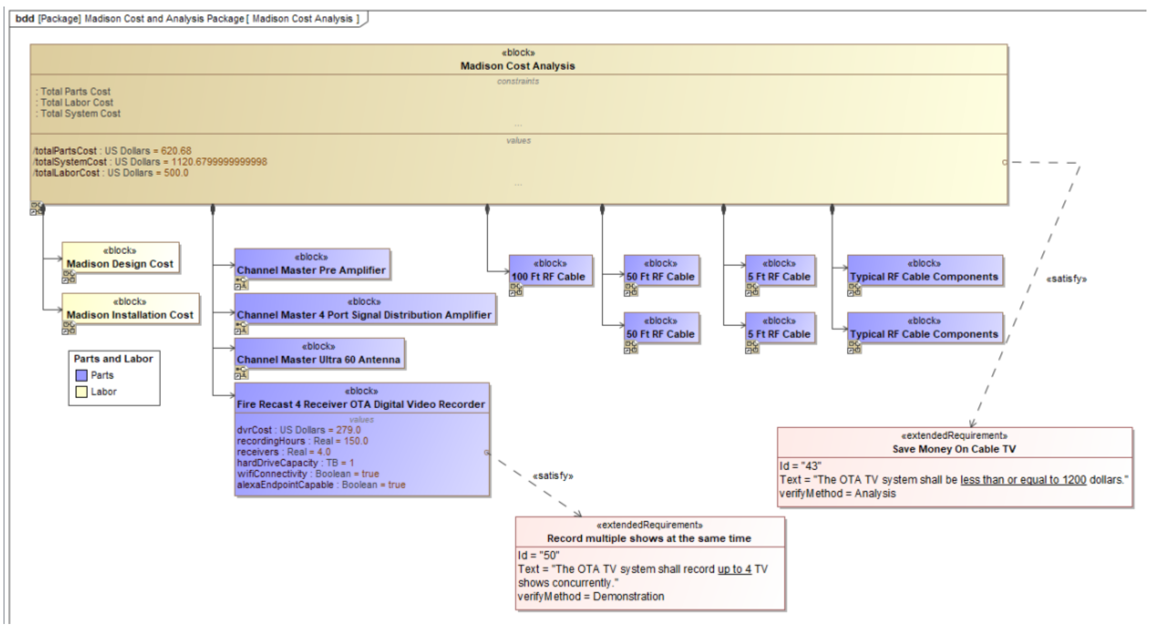

Figure 10 Block Definition Diagram (BDD) of Customer's Configuration and Cost Estimate

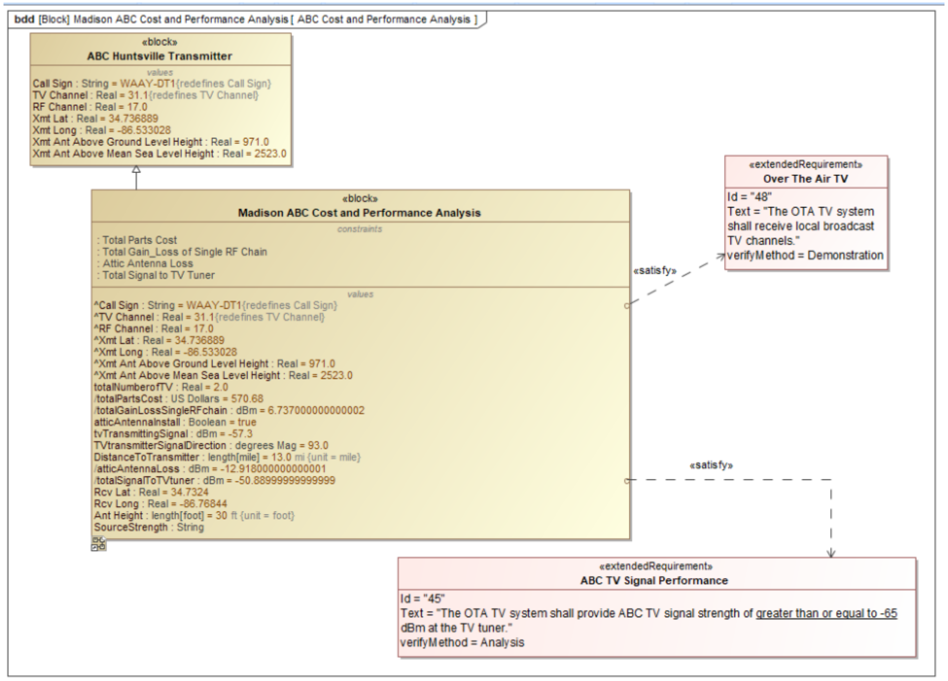

Figure 11 ABC Broadcast Channel with Attributes and Requirements

- <u>Parametric Diagrams (PAR)</u>: The parametric diagrams express how one or more constraints (equations and inequalities) are bound to the properties of the system. The parametric diagram shown in Figure 12 calculates the total signal level to the TV tuner. The Instance table shown in Figure 13 shows the performance characteristics of the broadcast channel ABC, at various geographical locations within the viewing area. Of note is the cell, colored red, which indicates the RF energy at that location does not meet the minimum signal strength specified in the requirement. These diagrams were used extensively to predict the RF energy levels at multiple geographical locations within the TV viewing area and shared with the simulation.

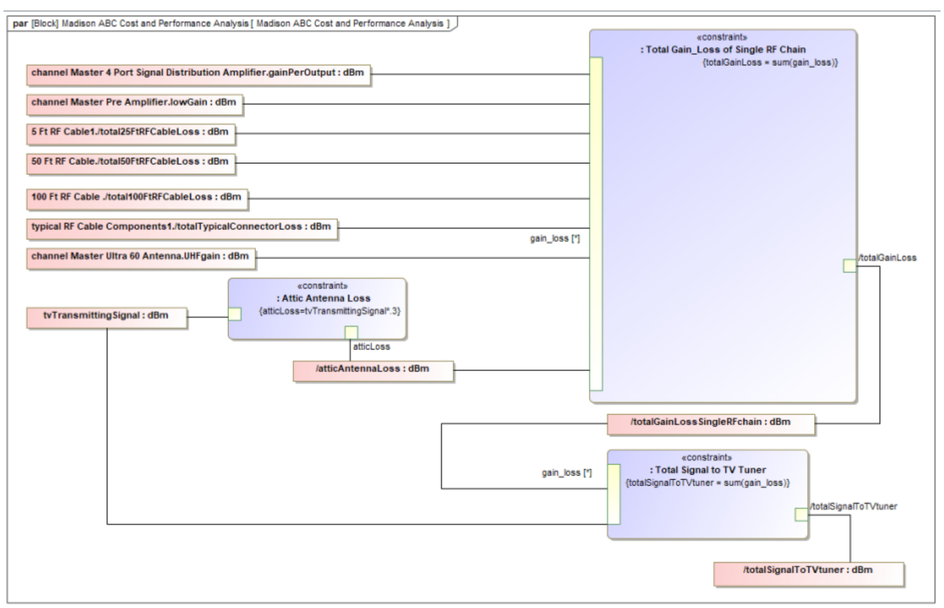

Figure 12 Parametric Diagram - ABC Television Signal Performance Analysis

Criteria
Classifier: lison ABC Cost and Performance Analysis ... Scope (optional): Channel Master ABC Instance Table ... Filter:

#	Name	DistanceToTransmitter : length[mile]	TVtransmitterSignalDirection : degrees Mag	Rcv Lat : Real	Rcv Long : Real	totalSignalToTVtuner : dBm	Call Sign : String	TV Channel : Real	RF Channel : Real	SourceStrengt : String
1	(240) 15 Lake Forest Blvd SW, Huntsville, AL 35824	13 mi	60	34.6435	-86.7323	-31.494	WAAY-DT1	31.1	17	Channel Master
2	(240) 4147-4237 SW Bilow Rd, Madison, AL 35756	18 mi	60	34.6076	-86.8092	-34.601	WAAY-DT1	31.1	17	Channel Master
3	(240) 26647 Henderson Rd, Madison, AL 35756	21 mi	60	34.5861	-86.8546	-36.876	WAAY-DT1	31.1	17	Channel Master
4	(240) 65 Duncansby Dr SW, Decatur, AL 35603	24 mi	60	34.5646	-86.9009	-40.36	WAAY-DT1	31.1	17	Channel Master
5	(240) 3418 Hooper Ln SE, Decatur, AL 35603	27 mi	60	34.5426	-86.9469	-40.295	WAAY-DT1	31.1	17	Channel Master
6	(240) 4413 Dogwood Dr SW, Decatur, AL 35603	30 mi	60	34.5211	-86.9918	-106.387	WAAY-DT1	31.1	17	Channel Master
7	(270) 111 Kelvingrove Dr, Madison, AL 35758	13 mi	90	34.7379	-86.7627	-51.371	WAAY-DT1	31.1	17	Channel Master
8	(270) 26328 Beech Grv Ln NW, Madison, AL 35756	18 mi	90	34.738	-86.8506	-29.167	WAAY-DT1	31.1	17	Channel Master
9	(270) 12623 Cambridge Ln, Athens, AL 35613	21 mi	90	34.738	-86.9038	-32.768	WAAY-DT1	31.1	17	Channel Master

Figure 13 Instance Table of ABC Broadcasting Channel in Various Locations within the Viewing Area of Interest

The remaining (6) types of SysML diagrams and their descriptions:

- Activity Diagrams (ACT): describe the flow of RF energy through the system and to express the behavior (how the system works). The activity diagrams are used to visualize the RF energy, signal distribution, function of each component, and how the user interacts with the system.
- Sequence Diagrams (SEQ): are used to create test cases for system verification. This includes how the test engineer interacts with the system, taking test readings of RF signals, and the results of these measurements are linked back to the system requirements for verification.
- State Machine Diagrams (STM): describe the operational modes the system can operate. Examples include power on/off, live TV or recorded TV, external antenna, or video streaming).
- Internal Block Diagrams (IBD): are used to identify interface connection points between components, signals within the system design, and visualization of the RF chain through the system.
- Use Case Diagrams (UC): describe what functions the system must perform (receive, distribute, and record TV signals) and how homeowners (actors) will collaborate with the system.
- Package Diagrams (PKG): display how the model is organized and used as a roadmap for users to understand were elements and diagrams are located and the relationship between them supporting system analysis.

The SysML and all predictions from the MBSE model were stored in the ASoT (Figure 4).

CREATING THE DIGITAL TWIN LOGIC AND MANIFESTATION (*SIMULATION*)

Within the ABoT context (Figure 1), the simulator contains the logical execution of the digital twin. For our use case, the simulator will determine the signal strength based on map coordinates and signal source.

The Design process placed 86 MBSE predictions into the ASoT (Figure 5). These predictions were then extracted by the Simulation Process and used to generate a signal source mesh. We developed our signal predictions using a finite element method (Larson & Bengzon, 2013) treating latitude, longitude, and signal strength as points in R^3. To discretize the surface, we used surface Delaunay triangulation (Berg, Cheong, Kreveld, & Overmars, 2008).

The manifestation of the simulation was an interactive Cesium application (Figure 14). A drop-down menu is used to switch between different datasets and signal sources. The green areas of the RF heatmap correspond to good signal strength, the red areas to poor. As we implemented our simulator within Cesium, we can zoom into locations to obtain further 3D geographic details. The generating code for the application is stored within the ASoT.

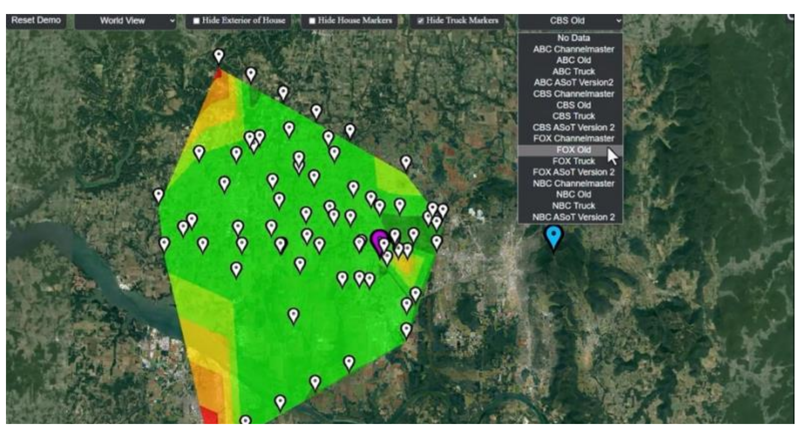

Figure 14. Interface to Digital Twin (Huntsville, AL)

What is Happening at My House? (*Analysis*)

A stakeholder in Huntsville, AL wants to determine if they can replace their cable television with radio transmission. From the ABoT perspective they wish to use the digital twin (Figure 2) by performing Analysis. Entering their home coordinates, they find that the signal strength of at their house is borderline (Figure 15). Exploring the geographic area with the tool they discover that Rainbow Mountain intersects the line of sight between the transmitter and house.

Figure 15. (NW) RF heat map and LOS between transmitter and house (NE) transmitter location (SW) Rainbow Mountain blocking line-of-sight between the transmitter and house (SE) the house

Collecting Operational Data - Enter the Truck (*Connection, Evolution*)

Although the location of Rainbow Mountain is a compelling explanation for the borderline signal, the stakeholder would like additional data points to refine the prediction before buying the necessary hardware (an amplifier). Note that refining the prediction of the simulation is part of the ABoT Evolution Process.

To collect more data, a portable test antenna test rig (Figure 16) is used to measure RF signals (within ABoT, data collection is part of the Connection Process). The test rig includes:

- An antenna meeting the requirements captured in the MBSE model.
- A mobile antenna platform a pickup truck, to relocate an antenna to within the area of interest.
- A hand-held GPS used to point the antenna and measure distance from the transmitter.
- An antenna signal strength meter to measure and display RF signal level and signal to noise ratio (SNR) for each channel. The signal strength was recorded in dBm (decibel-milliwatts).

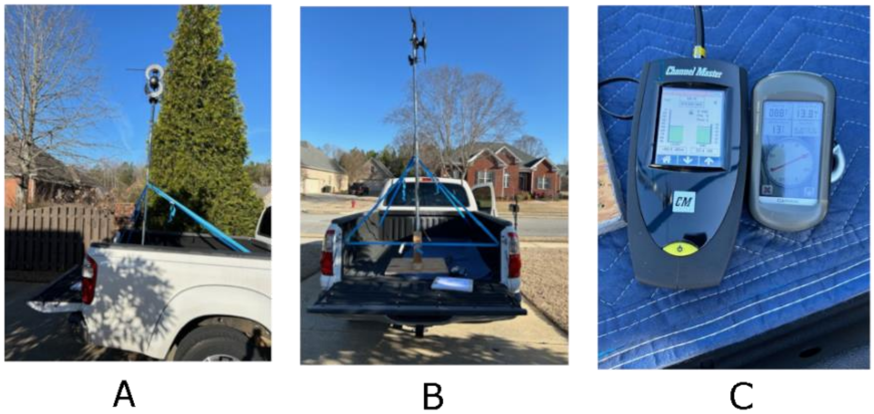

Figure 16. (A, B) Mobile antenna platform (C) Antenna signal strength meter and handheld GPS

The test rig was driven to different points in our area-of-interest; RF signal strength measurements and position data were recorded. We examined the signal strengths collected from the mobile rig in contrast to the predicted signal strength from our digital twin (Figure 17). The physical RF measurement at our house was lower than predicted, thus confirming the need for an amplifier.

These new physical measurements were then added to the ASoT and incorporated as the basis for the simulation, thus Evolving the next version of the digital twin (Figure 18).

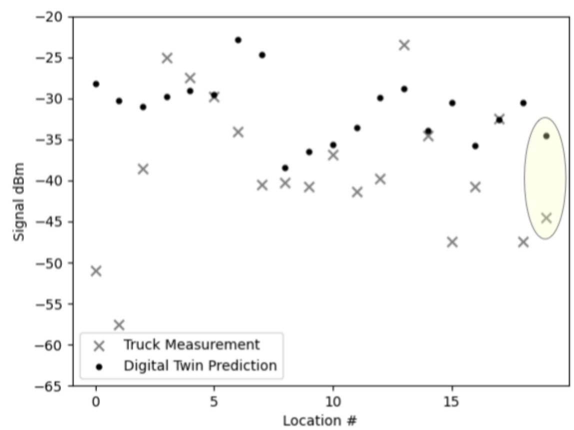

Figure 17. Comparison of Original Digital Twin and Collected Data

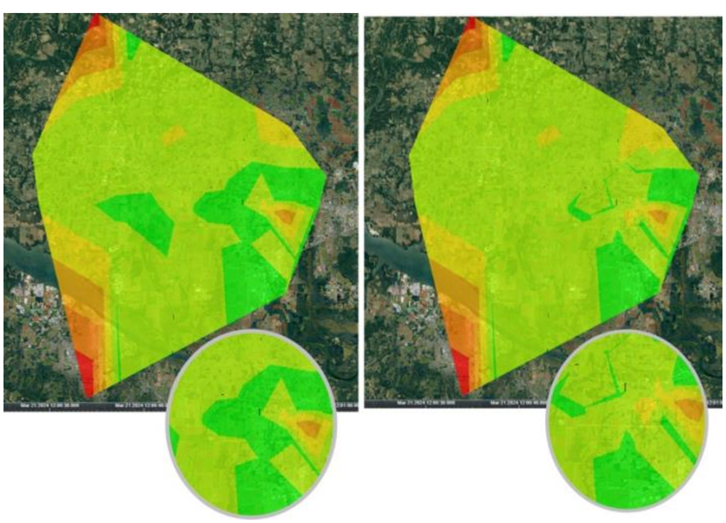

Figure 18. (Left) Original Digital Twin RF Heat Map (Right) Next Version of Digital Twin

CONCLUSION

We provided a paradigm for constructing a Digital Twin: Authoritative Broker of Truth (ABoT). ABoT provides the data organization and processes needed to build, utilize and evolve a digital twin. Our approach is vendor-neutral and allows the integration of disparate artifact types from different domains.

We applied this paradigm to a use case for determining requirements for TV reception from RF reception maps and component requirements. Digital design analysis and trade studies in the MBSE model coupled with the simulations drove the component selection including the type of antenna, pre-amplifier, distribution amplifier, and the digital video recorder (DVR). Once the system was built, RF signal strength and signal quality were captured real-time providing the operational data feedback loop to both the MBSE model and the simulation. The digital verification showed the evidence that the system, elements, simulation, and work products met the specified requirements captured in the model were satisfied. Ultimately, we validated the digital twin: a satisfied customer enjoying free TV.

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ACRONYMNS

3D	Three-dimensional
ABoT	Authoritative Broker of Truth
ASoT	Authoritative Source of Truth
BOM	Bill-of-Material
BPMN	Business Process Model Notation
dBm	decibel-milliwatts
DVR	Digital Video Recorder
IT	Information Technology
MBSE	Model Based System Engineering
OT	Operational Technology
OTA	Over the Air
RF	Radio Frequency
SNR	Signal-to-Noise Ratio
SysML	System Modeling Language
TPM	Technical Performance Measure
TV	Television
UAF	Unified Architecture Framework
UHF	Ultra-High Frequency
UX	User Experience
VHF	Very High Frequency
VVUQ	Verification, Validation and Uncertainty Quantification
XR	Extended Reality