Carleton University

Department of Systems and Computer Engineering

Assignment 1:

DEVS: Model and Simulation of a LEO User Link

SYSC 4906 G

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Part I: Conceptual Model and Components

Presently, Low Earth Orbit (LEO) satellite constellations are revolutionizing the satcom industry (eg. SpaceX's Starlink, Amazon's Kuiper, Telesat's Lightspeed), providing exceptional global coverage with high throughput and low latency.

Terrestrial UTs (UT), the network elements that facilitate end-user connectivity to the satellite constellation, face a technically challenging task in maintaining network connectivity from fixed or mobile points on Earth. A UT generally consists of two types of components: one or more Outdoor Units (ODU), each containing an antenna and necessary control units; and a single Indoor Unit (IDU), which contains a modem for signal processing, and a means for data transmission to an external gateway (eg. network router or switch) which may then manage traffic to end-user devices on the network.

To enter the network, a UT must establish a link to at least one satellite in the constellation, which is referred to as a User Link (UL). A UL may be established along a Radio Frequency (RF) chain that connects the IDU and the satellite through one ODU; thus, in a system with multiple ODUs, there are multiple RF chains that may form the UL. For example, in a common UT configuration, two ODUs are present to allow multiple RF chains to be established, either concurrently or in quick succession, to optimize the time that a UL may be in a connected or "up" state, and minimize the time it is in a disconnected or "down" state.

In a LEO constellation, satellites move rapidly around the Earth, and do not maintain geosynchronous orbit. As such, stationary UTs on Earth are only able to establish a UL with satellites that are in their current field of view (FOV). The duration of time when a LEO satellite is within the FOV of a UT is known as a "pass". During a pass, the satellite is said to "illuminate" a UT with its beam, and the UT may establish a UL by bringing up an RF chain from the satellite through an ODU to its IDU, allowing the transmission (Tx) and reception (Rx) of network traffic via a carrier signal.

Due to the low orbit and high speeds of LEO satellites, these passes are relatively brief (generally on the order of minutes). In order to maintain a UL to the network, a UT must be able to switch between satellites as they come into and out of its FOV. A UT does this by transitioning its UL from one satellite in its FOV to another in a process called a "handover". As the currently held satellite approaches the end of its pass (temporarily termed the "falling" satellite, as it is falling out of view), the UT must switch its UL to use an RF chain with another satellite preferably near the beginning of its pass (temporarily termed the "rising" satellite, as it is rising into view). Ideally, this handover process will occur seamlessly, incurring no discontinuity of service as the UL is handed over from one satellite to another.

Constellations and UTs are both designed towards the goal of seamless transition in handover scenarios in order to maximize up time and minimize down time for nodes in the network. To increase the likelihood of a seamless handover, the constellation should ensure that coordinates in all of its serviced areas on Earth can be illuminated by at least two satellites during handover periods. Similarly, UTs are often designed with multiple ODUs so that both a rising and falling satellite can be tracked by separate antennae concurrently as their passes overlap in time. With such a design, it is therefore possible to perform a handover with very little, or even no down time at all.

Extensive modeling and simulation of satellite handovers are essential to informing LEO system design for both space and terrestrial components. Fig. 1 below shows a conceptual model of a LEO UL with two satellites and two ODUs available to it. This model will be used as the basis of simulation for two different experimental frames, each exercising a different type of handover (defined in Part II below). The models and simulation will be constructed according to the Discrete Event System Specification (DEVS) formalism, and will be implemented using Cadmium to aid in the testing of LEO ULs during different handover scenarios.

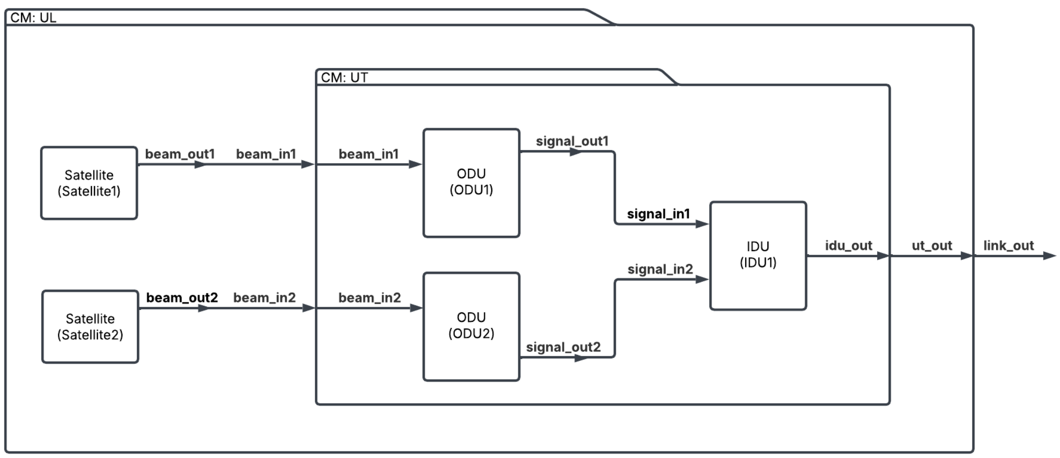

Figure 1: Conceptual Model of a LEO UL

The components within Fig. 1 are as follows:

1. **User Link (UL):** The top-level model which describes the link established between a LEO satellite and a terrestrial UT.
2. **Satellite:** A satellite in a LEO constellation that will serve to transmit and receive data across established links. In this model, each satellite may be temporarily designated as the rising or falling satellite in a handover scenario.
3. **User Terminal (UT):** The end-user terrestrial device that will establish a UL to a satellite in the LEO constellation. It is comprised of two ODUs connected to a single IDU.
4. **Outdoor Unit (ODU):** Contains the antenna responsible for facilitating RF connectivity with constellation satellites.
5. **Indoor Unit (IDU):** Contains the modem responsible for RF signal processing (modulate/demodulate), and an output port that may carry data out of the UT to an external gateway component.

Part II: DEVS Formal Specifications and Experimental Frames

This section introduces DEVS formal specifications for the atomic models (AM) coupled models (CM) of the system under study, corresponding to the conceptual model of Fig. 1. It additionally defines the experimental frames (EF) that will be exercised under simulation using the Cadmium tool.

1 DEVS Formal Specifications

DEVS formal specifications for AM components are presented according to the following definition:

$$\langle S, X, Y, \delta_{\text{int}}, \delta_{\text{ext}}, \lambda, ta \rangle$$

where:

- S = input event set
- X = output event set
- δ_{int} = internal transition function
- δ_{ext} = external transition function
- λ = output function
- ta = time advance function

The DEVS formal specification for a CM is:

$$DN = \langle X, Y, D, \{M_d | d \in D\}, EIC, EOC, IC, \text{SELECT} \rangle$$

where:

- X = external input event set
- Y = external output event set
- D = set of all component names for each $d \in D$
- M_d = is a DEVS basic component (AM or CM) for each $d \in D$
- $EIC \subseteq DN.\text{IN} \times M.\text{IN}$ = external input coupling relation
- $EOC \subseteq M.\text{OUT} \times DN.\text{OUT}$ = external output coupling relation
- $IC \subseteq M.\text{OUT} \times M.\text{IN}$ = internal coupling relation
- SELECT : $2^M - \emptyset \rightarrow M$ = tie-breaking selector

1.1 AM: Satellite

The DEVS graph for the Satellite AM is as follows:

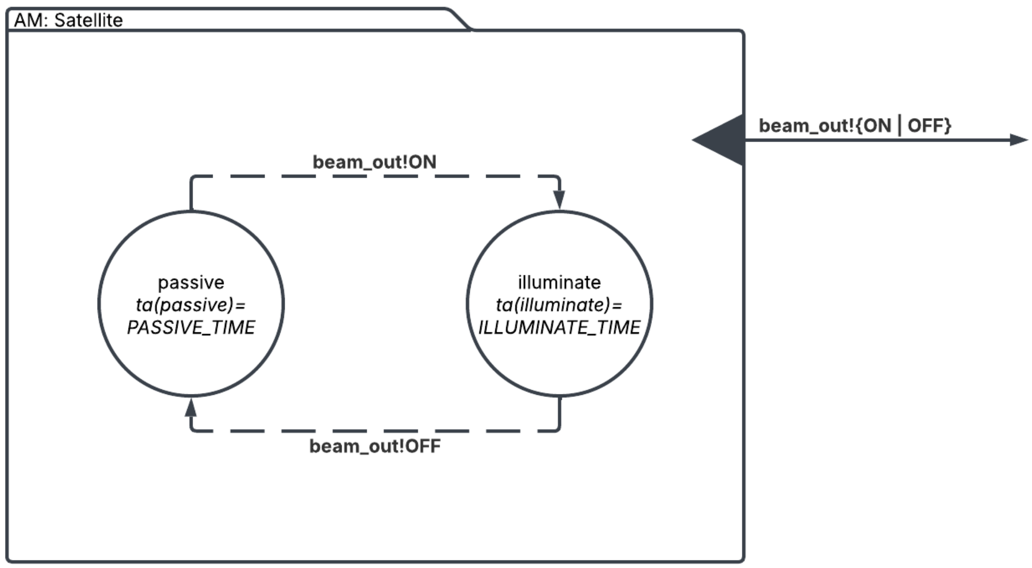

Figure 2: Atomic Model: Satellite

The DEVS formal specification for the Satellite AM is as follows:

- $S = \{\text{passive}, \text{illuminate}\}$
- $X = \emptyset$
- $Y = \{\text{beam\_out}\}$
- $\delta_{\text{int}}(\text{passive}) = \text{illuminate}$
- $\delta_{\text{int}}(\text{illuminate}) = \text{passive}$
- λ(s={passive, illuminate}) {

```
if (s == passive) {
    return beam_out!ON;
}
return beam_out!OFF;
```

  }
- t_a(s={passive, illuminate}) {

```
    if (s == passive) {
        return PASSIVE_TIME;
    }
    return ILLUMINATE_TIME;

}
```

1.2 AM: ODU

The DEVS graph for the ODU AM is as follows:

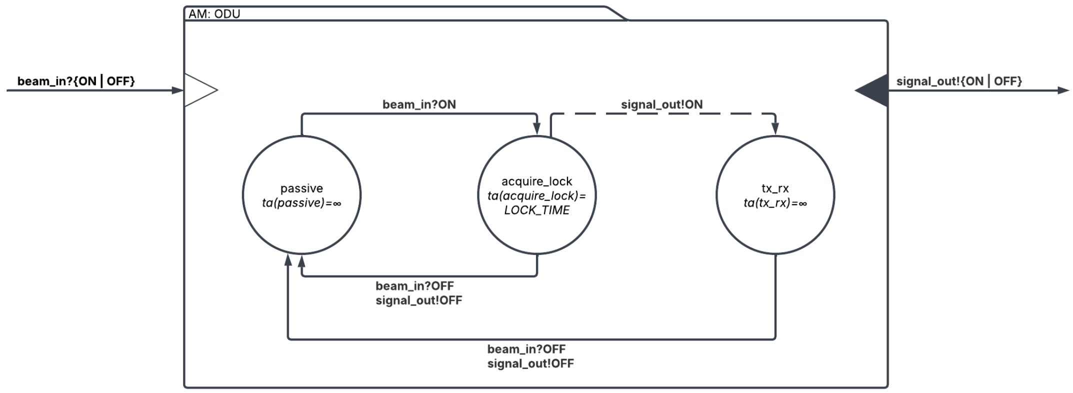

Figure 3: Atomic Model: ODU

The DEVS formal specification for the ODU AM is as follows:

- $S = \{\text{passive}, \text{acquire\_lock}, \text{tx\_rx}\}$
- $X = \{\text{beam\_in}\}$
- $Y = \{\text{signal\_out}\}$
- $\delta_{\text{int}}(\text{acquire\_lock}) = \text{tx\_rx}$
- δ_{ext}(s={passive, tx_rx}, e, x={beam_in?ON, beam_in?OFF}) {

```
switch(s) {
    case passive:
        if (beam_in?ON) {
            return acquire_lock;
        }
        break;
    case tx_rx:
        if (beam_in?OFF) {
            return passive;
        }
        break;
    default:
        return s;
}
return s;
```

}

- λ(s={acquire_lock, tx_rx}) {

  ```
  if (s == acquire_lock) {
      return signal_out!ON;
  }
  return signal_out!OFF;
  ```

  }

- t_a(s={passive, acquire_lock, tx_rx}) {

  ```
  if (s == passive) {
      return INFINITY;
  }
  if (s == acquire_lock) {
      return LOCK_TIME
  }
  return INFINITY;
  ```

  }

1.3 AM: IDU

The DEVS graph for the IDU AM is as follows:

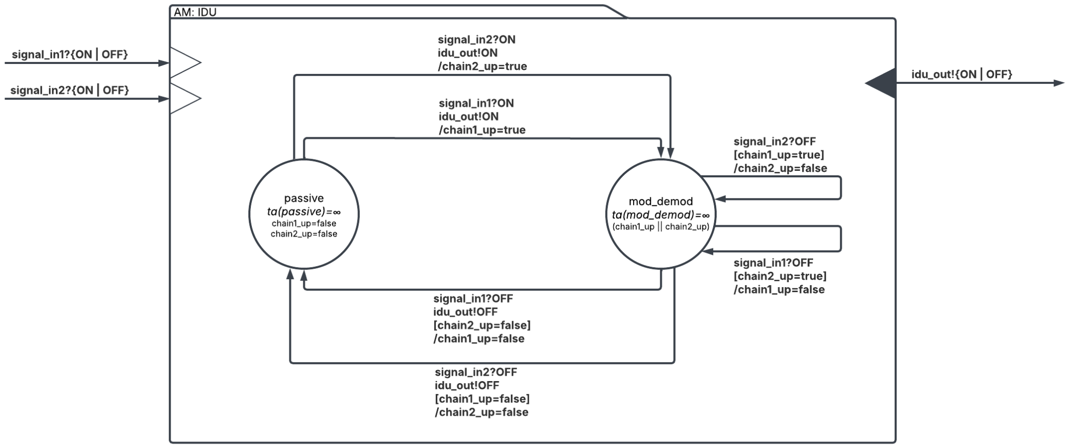

Figure 4: Atomic Model: IDU

The DEVS formal specification for the IDU AM is as follows:

- $S = \{\text{passive}, \text{mod\_demod}\}$
- $X = \{\text{signal\_in1, signal\_in2}\}$
- $Y = \{\text{idu\_out}\}$
- δ_{ext}(s={passive, mod_demod}, e, x={signal_in1?ON, signal_in1?OFF, signal_in2?ON, signal_in2?OFF}) {

```
// bool chain1_up: indicator for up/down state of RF chain 1
// bool chain2_up: indicator for up/down state of RF chain 2

switch(s) {
    case passive:
        if (x == signal_in1?ON) {
            chain1_up = true;
            return mod_demod;
        }
        if (x == signal_in2?ON) {
            chain2_up = true;
            return mod_demod;
        }
        return passive;
        break;
    case mod_demod:
```

```
            if (x == signal_in1?OFF) {
                chain1_up = false;
                if (chain2_up == true) {
                    // Other chain still up, remain in mod_demod with one chain up
                    return mod_demod;
                }
                // All chains down, cannot remain in mod_demod
                return passive;
            }
            if (x == signal_in2?OFF) {
                chain2_up = false;
                if (chain1_up == true) {
                    // Other chain still up, remain in mod_demod with one chain up
                    return mod_demod;
                }
                // All chains down, cannot remain in mod_demod
                return passive;
            }
            if (x == signal_in1?ON) {
                chain1_up = true;
                return mod_demod;
            }
            if (x == signal_in2?ON) {
                chain2_up = true;
                return mod_demod;
            }
            break;
        default:
            return s;
    }
```

}

- λ(s={passive, mod_demod}) {

```
    // bool chain1_up: indicator for up/down state of RF chain 1
    // bool chain2_up: indicator for up/down state of RF chain 2

    if (s == passive) {
        // All outgoing transitions will complete a chain and bring link up
        return idu_out!ON;
    }
    if (s == mod_demod) {
        // At least one chain is up, so link is up
        if (chain1_up || chain2_up) {
            return idu_out!ON;
        }
        // All chains down, so link is down
        else {
            return idu_out!OFF;
        }
```

```
    }
```

}

- t_a(s={passive, mod_demod}) $= \infty$

1.4 CM: UT

The DEVS graph for the UT CM is as follows:

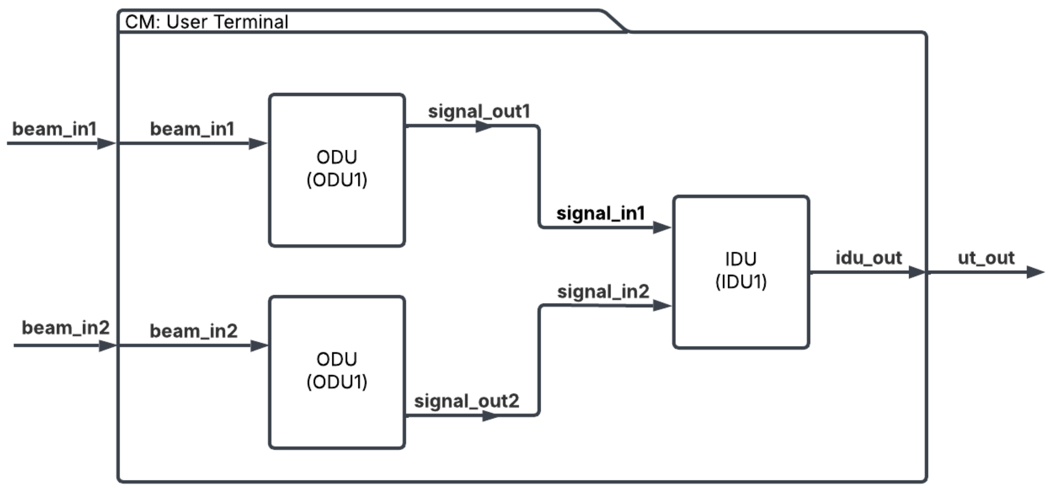

Figure 5: Coupled Model: UT

The DEVS formal specification for the UT CM is as follows:

- X = {beam_in1, beam_in2}
- Y = {ut_out}
- D = {ODU1, ODU2, IDU1}
- $M_d = \{M_{ODU1}, M_{ODU2}, M_{IDU1}\}$
- $EIC \subseteq$ {(UT.beam_in1, ODU1.beam_in1), (UT.beam_in2, ODU2.beam_in2) }
- $EOC \subseteq$ {(UT.ut_out1, IDU1.idu_out) }
- $IC \subseteq$ {(ODU1.signal_out1, IDU1.signal_in1), (ODU2.signal_out2, IDU1.signal_in2)}
- SELECT : = { ({ODU1, ODU2, IDU1} = IDU1}), ({ODU1, ODU2} = ODU1) }

1.5 CM: UL

The DEVS graph for the UL CM is as follows:

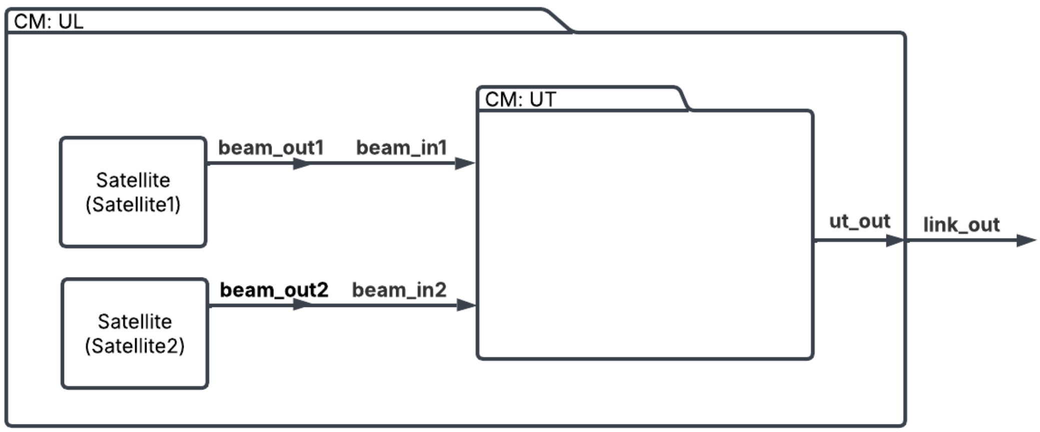

Figure 6: Coupled Model: UL

The DEVS formal specification for the UL CM is as follows:

- $X = \emptyset$
- $Y = \{\text{link\_out}\}$
- $D = \{\text{Satellite1, Satellite2, UT}\}$
- $M_d = \{M_{Satellite1}, M_{Satellite2}, M_{UT}\}$
- $EIC \subseteq \{\emptyset\}$
- $EOC \subseteq \{$(UT.ut_out, UL.link_out) $\}$
- $IC \subseteq \{$(Satellite1.beam_out1, UT.beam_in1), (Satellite2.beam_out2, UT.beam_in2) $\}$
- SELECT : = { ({Satellite1, Satellite2, UT} = UT}), ({Satellite1, Satellite2} = Satellite1) }

2 Experimental Frames

2.1 EF1: Make-Before-Break (MBB) Handover

This experimental frame is designed to test the Make-Before-Break (MBB) handover scenario. In this handover type, the rising satellite establishes a UL RF chain with with the secondary ODU *prior* to the dissolution of the UL RF chain between the falling satellite and the primary ODU; that is, a secondary UL RF chain is established before the first is broken. With two UL RF chains up at the same time, the ODU may then transition to the secondary link without a loss of service. Once the transition has been made, the primary link can safely be dropped without interruption of service, as the secondary link has already been established and switched to. An MBB handover scenario is one characterized as a seamless handover, as no service interruption is incurred during the handover due to the *make* of a secondary link *before* the *break* of the primary. From the perspective of the end user, this type of handover is invisible and unnoticed, as the data stream leaving the UL is not interrupted.

To test the MBB handover scenario, inputs are structured from the rising and falling satellites in such a way that both are connected to an ODU concurrently for some duration, wherein the IDU may then perform the seamless transition from one UL RF chain to the other. The inputs defining the MBB experimental frame and the resulting outputs are presented in Part III below.

2.2 EF2: Break-Before-Make (BBM) Handover

This experimental frame is designed to test the Break-Before-Make (BBM) handover scenario. In this handover type, the UL RF chain with the rising satellite is established only *after* the UL RF chain with the falling satellite is dissolved; that is, the primary UL RF chain is broken before the second is established. With only one UL RF chain up at a given time, the transition between links incurs a loss of service during handover. A BBM handover scenario is *not* a seamless handover, as a service interruption is incurred during the handover due to the *break* of the primary link *before* the *make* of the secondary. From the perspective of the end user, this type of handover is visible and noticed, as is represented by the discontinuity of the signal from the ODU during the handover.

To test the BBM handover scenario, inputs are structured from the rising and falling satellites in such a way that only one can be connected to an ODU concurrently at any point in the simulation, precluding the possibility of a seamless transition from one UL RF chain to the other. From the perspective of the end user, this type of handover is visible and may be noticed, as the data stream leaving the UL is temporarily interrupted.

2.3 EF: Testing Configuration

In order to exercise the EFs defined above, a CM is defined to allow input event test files to be given as inputs to the UL model. This test CM is as follows:

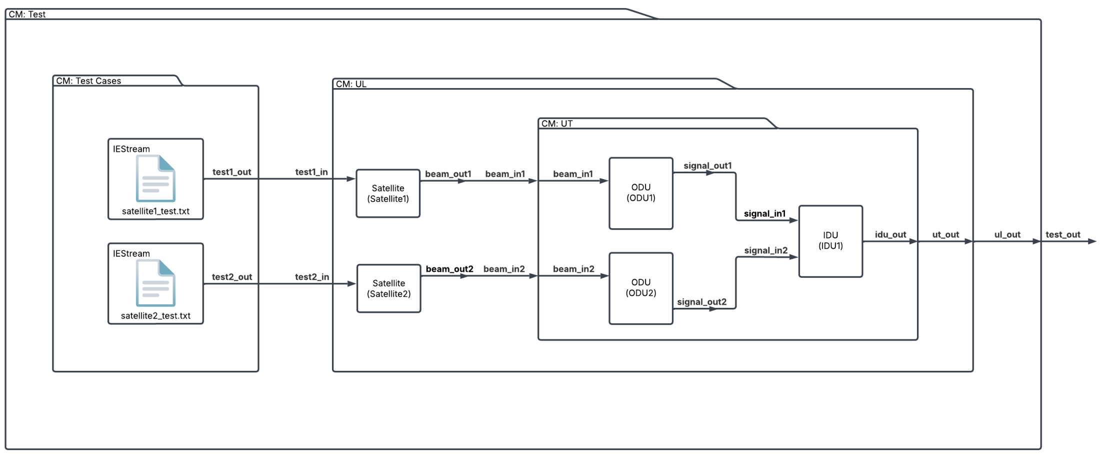

Figure 7: Coupled Model: Test

Part III: DEVS Simulation and Experimental Results

1 EF1: Make-Before-Break (MBB) Handover

The Cadmium input files designed to exercise the experimental frame for the MBB handover are presented below for the atomic, coupled, and top models used in the simulation. Lines corresponding to notable events are denoted with a comment identifier so that they may be referenced in the corresponding analysis and discussion.

1.1 EF1: Atomic Model - Satellite1

The **input** file, `input.txt`, for `Satellite1` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `Satellite1` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

1.2 EF1: Atomic Model - Satellite2

The **input** file, `input.txt`, for `Satellite2` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `Satellite2` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

1.3 EF1: Atomic Model - ODU1

The **input** file, `input.txt`, for `ODU1` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `ODU1` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

1.4 EF1: Atomic Model - ODU2

The **input** file, `input.txt`, for `ODU2` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `ODU2` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

1.5 EF1: Atomic Model - IDU

The **input** file, `input.txt`, for `IDU` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `IDU` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

1.6 EF1: Coupled Model - UserTerminal

The **input** file, `input.txt`, for `UserTerminal` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `UserTerminal` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

1.7 EF1: Top Model - UserLink

The **input** file, `input.txt`, for `UserLink` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `UserLink` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

2 EF2: Break-Before-Make (BBM) Handover

The Cadmium input files designed to exercise the experimental frame for the BBM handover are presented below for the atomic, coupled, and top models used in the simulation. Lines corresponding to notable events are denoted with a comment identifier so that they may be referenced in the corresponding analysis and discussion.

2.1 EF2: Atomic Model - Satellite1

The **input** file, `input.txt`, for `Satellite1` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `Satellite1` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

2.2 EF2: Atomic Model - Satellite2

The **input** file, `input.txt`, for `Satellite2` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `Satellite2` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

2.3 EF2: Atomic Model - ODU1

The **input** file, `input.txt`, for `ODU1` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `ODU1` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

2.4 EF2: Atomic Model - ODU2

The **input** file, `input.txt`, for `ODU2` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `ODU2` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

2.5 EF2: Atomic Model - IDU

The **input** file, `input.txt`, for `IDU` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `IDU` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

2.6 EF2: Coupled Model - UserTerminal

The **input** file, `input.txt`, for `UserTerminal` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `UserTerminal` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

2.7 EF2: Top Model - UserLink

The **input** file, `input.txt`, for `UserLink` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

The **output** file, `output.txt`, for `UserLink` is as follows:

```
00:00:10:00 in 11 // Event A
01:00:10:00 in 11
02:00:10:00 in 11 // Event B
```

Event A denotes...

As per the above record of inputs and outputs, it can be concluded that...

2.8 Conclusion

In comparing the simulations for the MBB and BBM handovers exercised under Cadmium in the experimental frames defined above, useful conclusions can be drawn regarding the impacts to quality of service for each handover scenario. In observing the results from the simulation of the MBB handover in EF1, there is no quantifiable downtime for the UL; transitions between UL RF chains is consistently seamless, and if all handover scenarios for a UT are MMB, then no quality of service loss will result. In contrast, from the simulation of the BBM handover in EF2, each and every handover incurs some quantifiable downtime for the UL, necessarily diminishing the the quality of service for a UT. For the highest level of service within a LEO constellation, the constellation should be designed to maximize MBB handover scenarios over BBM. Although BBM scenarios will still occur due to external and not necessarily predictable events (eg. weather events, unexpected blockages), the constellation should, in the absence of these events, be able to perform MBB handovers whenever possible. Further work could be done to extend the DEVS models and simulations provided here to encapsulate an entire LEO constellation, multiple UTs, or UTs of different configurations (eg. "N+1" arrays). Experimental frames for such a complex system would provide valuable insight to the design of a LEO constellation, and how the optimization of handover scenarios may improve quality of service to UTs in the network.

References

1. Wainer, Gabriel A. *Discrete-Event Modeling and Simulation: A Practitioner's Approach.* Boca Raton: CRC Press, 2009. Print.

Appendix A: DEVS Model Data Form

Title: LEO User Link

Type: DEVS Model

Acronym/Short name: LEO_User_Link

Purpose for which Developed:

To model and simulate a Low Earth Orbit (LEO) User Link (UL) between a satellite and a terrestrial User Terminal (UT) in order to exercise experimental frames for handover scenarios.

Other Applications for which it is Suitable:

This model and simulation may serve as a basis for other satcom constellation applications.

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URL: TODO

Description:

Links to Related Documents: None

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