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 User Terminals (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 in 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 RF chain to the other.

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 (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. This implementation may be found at the **LEO User Link** repository.

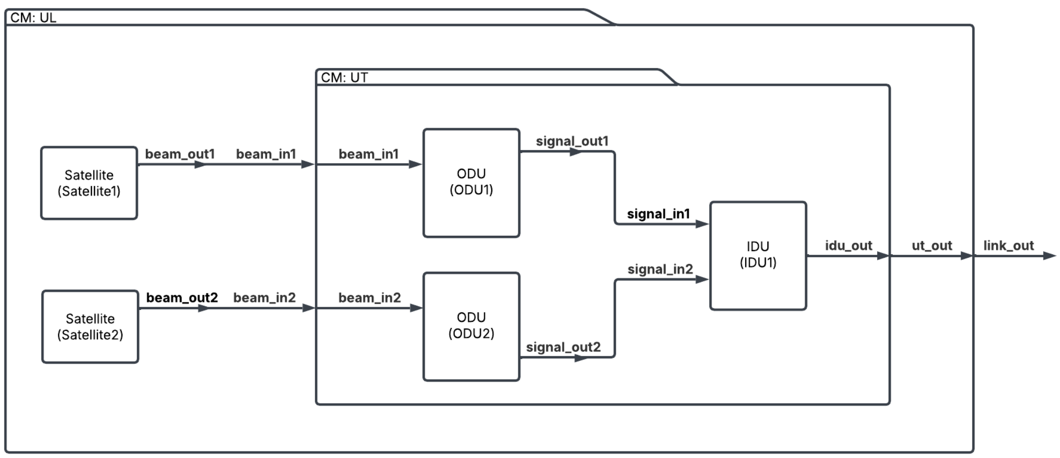

Figure 1: Conceptual Model of a LEO UL

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 ULs to satellites 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) and 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 formal definition [1]:

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

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

DEVS formal specifications for CM components are presented according to the following formal definition [1]:

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

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
- $\text{SELECT} : 2^M - \emptyset \rightarrow M$ = tie-breaking selector

1.1 AM: Satellite

The DEVS graph for the Satellite AM is as follows:

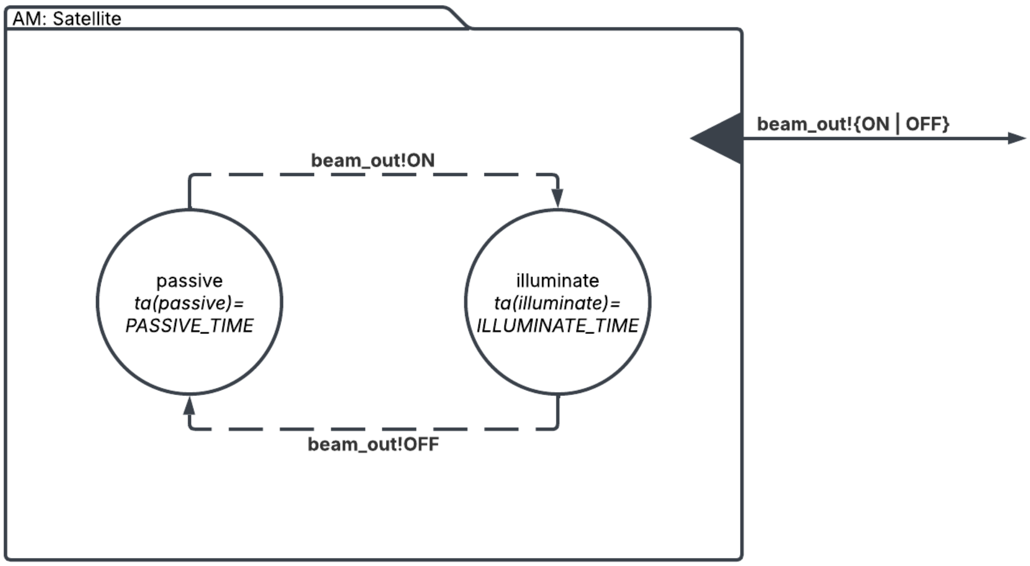

Figure 2: Atomic Model: Satellite

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

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

```
if (s == passive) {
    return illuminate;
}
return 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:

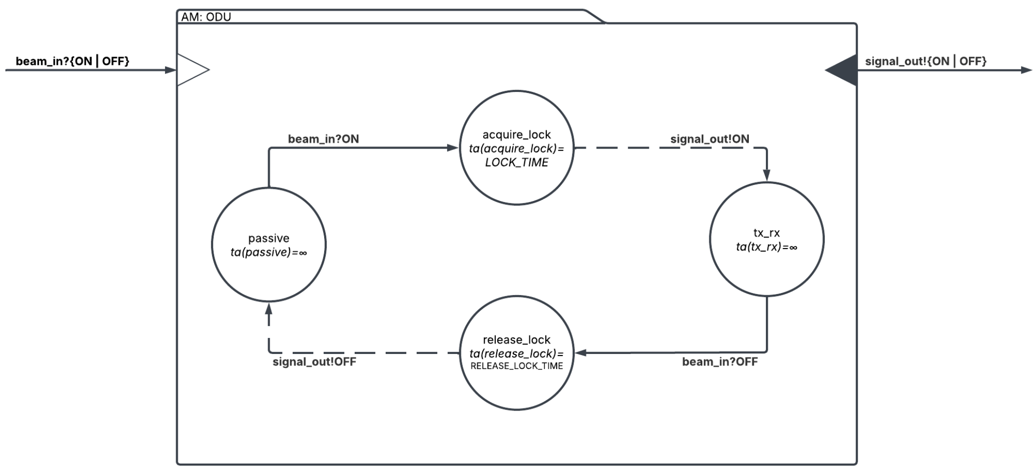

Figure 3: Atomic Model: ODU

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

- $S = \{\text{passive}, \text{acquire\_lock}, \text{release\_lock}, \text{tx\_rx}\}$
- $X = \{\text{beam\_in}\}$
- $Y = \{\text{signal\_out}\}$
- $\delta_{\text{int}}(s = \{\text{acquire\_lock, release\_lock }\})$ {

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

}

- 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 release_lock;
            }
            break;
        default:
            return s;
    }
```

}

- λ(s={acquire_lock, release_lock}) {

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

}

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

```
    switch(s) {
        case passive:
        case tx_rx:
            return INFINITY;
            break;
        case acquire_lock:
            return ACQUIRE_LOCK_TIME;
            break;
        case release_lock:
            return RELEASE_LOCK_TIME;
            break;
        default:
            break;
    }
```

}

1.3 AM: IDU

The DEVS graph for the IDU AM is as follows:

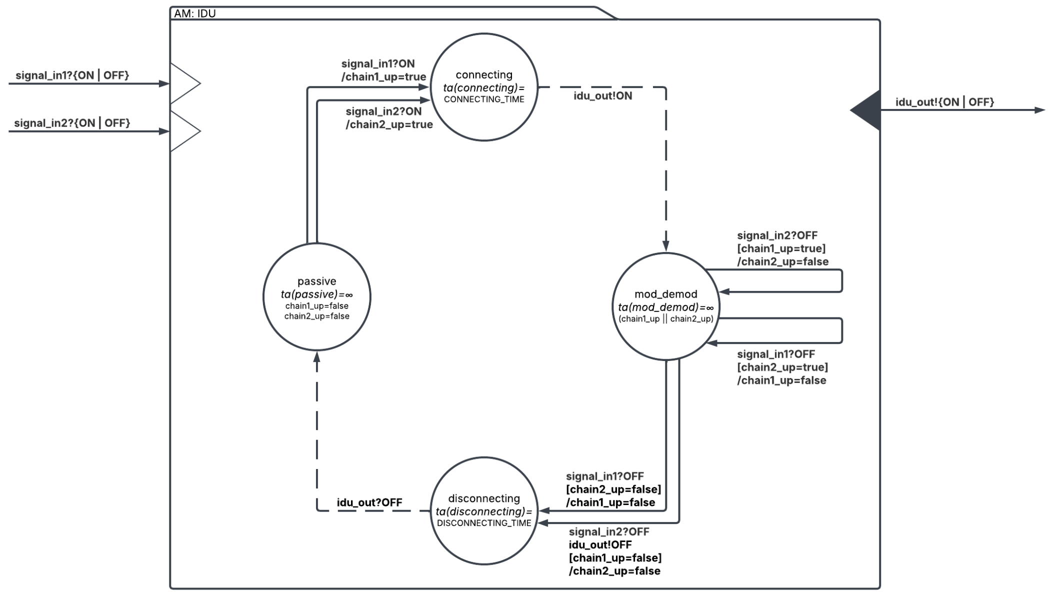

Figure 4: Atomic Model: IDU

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

- $S = \{\text{passive}, \text{connecting}, \text{disconnecting}, \text{mod\_demod}\}$
- $X = \{\text{signal\_in1, signal\_in2}\}$
- $Y = \{\text{idu\_out}\}$
- $\delta_{\text{int}}(s = \{\text{connecting, disconnecting}\})$ {

```
if (s == connecting) {
    return mod_demod;
}
return passive;
```

  }

- 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 connecting;
            }
            if (x == signal_in2?ON) {
                chain2_up = true;
                return connecting;
            }
            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 disconnecting;
            }
            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 disconnecting;
            }
            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;
            break;
    }
```

}

- λ(s={connecting, disconnecting}) {

```
    if (s == connecting) {
        return idu_out!ON;
```

```
    }
    return idu_out!OFF;

}
```

- t_a(s={passive, connecting, disconnecting, mod_demod}) {

```
    switch(s) {
        case passive:
        case mode_demod:
            return INFINITY;
            break;
        case connecting:
            return CONNECTING_TIME;
            break;
        case release_lock:
            return DISCONNECTING_TIME;
            break;
        default:
            break;
    }
```

}

1.4 CM: UT

The DEVS graph for the UT CM is as follows:

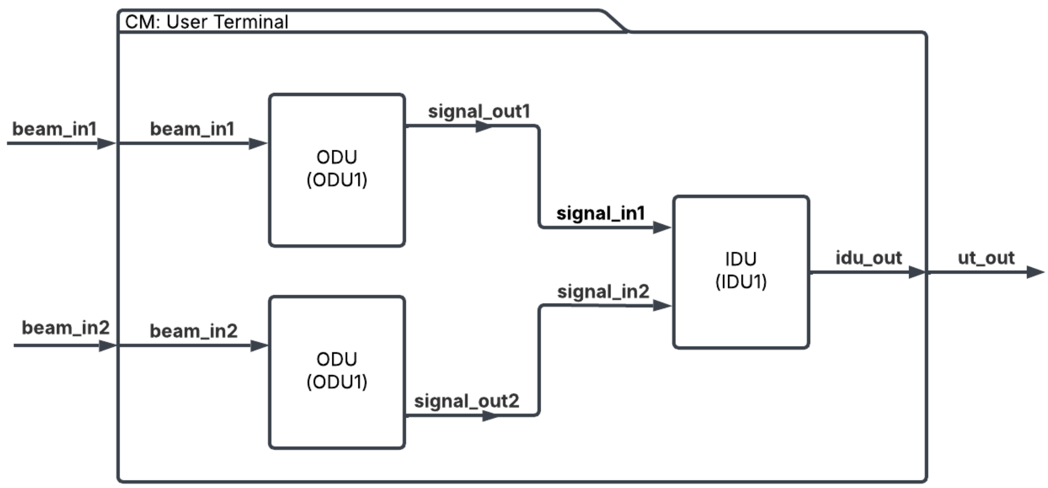

Figure 5: Coupled Model: UT

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:

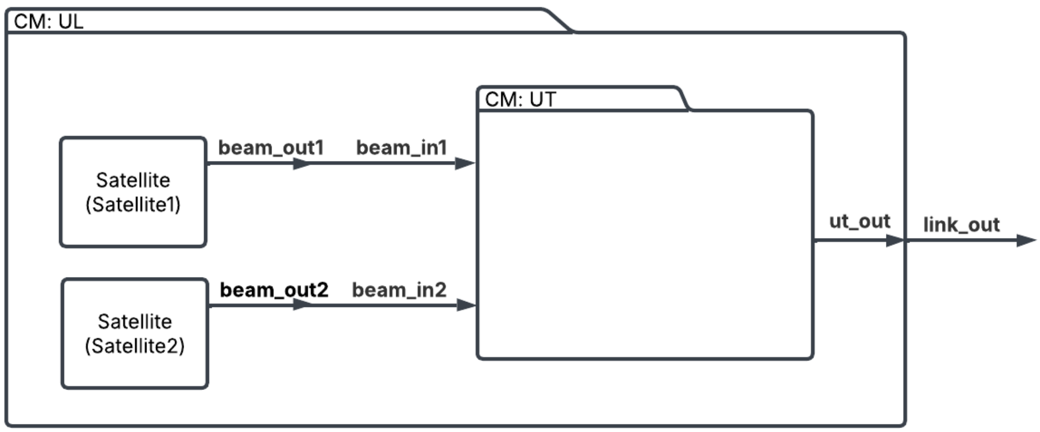

Figure 6: Coupled Model: UL

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 Experimentation

The models defined above were implemented in Cadmium, and each model was independently tested. In the case that a model component required external inputs to drive simulation, a simulation driver was connected to the model in order to provide necessary stimulus (IDU, ODU, UT, UL). In the case that a model component was generative, no driver was required (Satellite). In all cases, simulation outputs were logged to a file for analysis. The results of these simulations are analyzed in Part III below.

2.1 Experimentation Goal: Handover Analysis

Experiments were conducted in order to assess the performance of a UL during handover scenarios, considering recorded up time and down time of the link, and the quality of service during these handovers. In order to understand the analysis of the experimental results, some brief context is given on the two types of handover scenarios tested and analyzed.

2.2 Make-Before-Break (MBB) Handover

In the Make-Before-Break (MBB) handover scenario, 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 UT is not interrupted.

2.3 Break-Before-Make (BBM) Handover

In the Break-Before-Make (BBM) handover scenario, 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 UT during the handover.

2.4 Experimental Frames

In order to exercise the experiments above, EFs were defined to tests both AMs and CMs. EFs for the CMs of the UT and UL are provided below, with the results of experimentation analyzed in Part III below.

EF1: This EF is used to test the UT component, and to ensure that inputs into the UT (from generative drivers) trigger the correct behaviour (outputs) during the simulation. Primarily, this EF is evaluated to ensure that:

- if no ODUs have acquired a lock on a Satellite, then the IDU's RF chains are both down, and no signal is output from the IDU.
- if one or both IDUs have acquired a lock on a Satellite, then at least one of the IDU's RF chains are up, and modulated/demodulated signal is output from the IDU.

EF1 for testing the UT CM, showing simulation inputs and outputs, is as follows:

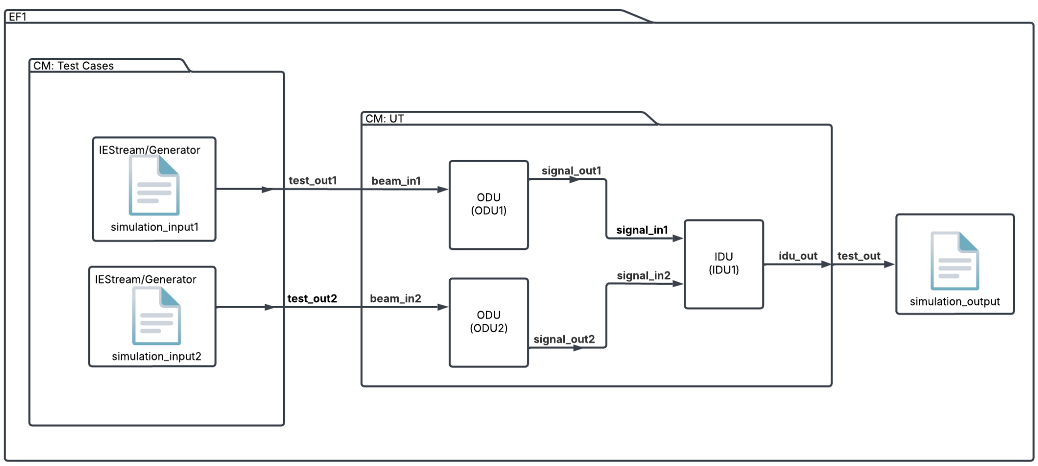

Figure 7: EF1: User Terminal

EF2: This EF is used to test the UL component (including constellation Satellite components and a single UT), and to ensure that the generative inputs from the Satellites are handled by the UT to correctly perform MBB and BBM handover scenarios during simulation, as discernible in the simulation outputs. Primarily, this EF is evaluated to ensure that:

- if a BBM scenario occurs as per the states of the rising and falling Satellites and their generative output, the UT: temporarily has no active RF chains; the UL is temporarily dropped; and there is a discontinuity in network connectivity for a measurable duration.
- if a MBB scenario occurs as per the states of the rising and falling Satellites and their generative output, the UT: temporarily maintains both RF chains before the chain attached to the falling Satellite is dropped; the UL is maintained throughout the handover; and there is no discontinuity in network connectivity.

EF2 for testing the UL CM, showing simulation outputs (inputs are generative), is as follows:

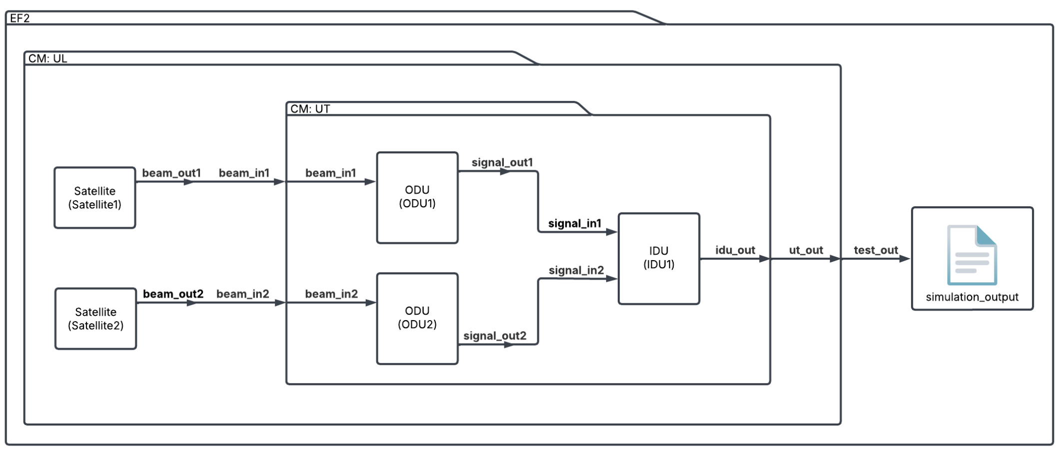

Figure 8: EF2: User Link

Part III: DEVS Simulation and Experimental Results

Results from the exercise of the above EFs, as implemented and simulated in Cadmium, are presented and discussed below.

1 EF1: CM UT

In order to simulate the required inputs to the CM of the UT, two test driver AMs were defined, with their output ports coupled to the input ports of the UT. These drivers generate outputs at random intervals (within a defined range), and send them to the coupled input ports. A top model was defined to contain the EF (as per Fig. 7 above), and the simulation was executed. Selections from the simulation output file (cf. LEO User Link: *sample-output/ut_driver_test*) corresponding to one execution of the simulation are shown below.

```
sep=;
time;model_id;model_name;port_name;data

0;2;IDU;;{state=PASSIVE, sigma=inf, chain1_up=0, chain2_up=0}
0;3;ODU2;;{state=PASSIVE, sigma=inf, lock=0}
0;4;ODU1;;{state=PASSIVE, sigma=inf, lock=0}
0;5;DriverSatellite2;;{state=SENDING, sigma=1}
0;6;DriverSatellite1;;{state=SENDING, sigma=1}

1;3;ODU2;;{state=PASSIVE, sigma=inf, lock=0}
1;4;ODU1;;{state=PASSIVE, sigma=inf, lock=0}
1;5;DriverSatellite2;test_out;0
1;5;DriverSatellite2;;{state=SENDING, sigma=3.02914}
1;6;DriverSatellite1;test_out;0
1;6;DriverSatellite1;;{state=SENDING, sigma=1.43755}

2.43755;4;ODU1;;{state=ACQUIRE_LOCK, sigma=inf, lock=1}
2.43755;6;DriverSatellite1;test_out;1
2.43755;6;DriverSatellite1;;{state=SENDING, sigma=5.76942}

4.02914;3;ODU2;;{state=ACQUIRE_LOCK, sigma=inf, lock=1}
4.02914;5;DriverSatellite2;test_out;1
4.02914;5;DriverSatellite2;;{state=SENDING, sigma=3.71491}

4.43755;2;IDU;;{state=CONNECTING, sigma=inf, chain1_up=1, chain2_up=0}
4.43755;4;ODU1;signal_out;1
4.43755;4;ODU1;;{state=TX_RX, sigma=inf, lock=1}

5.43755;2;IDU;idu_out;1
5.43755;2;IDU;;{state=MOD_DEMOD, sigma=inf, chain1_up=1, chain2_up=0}

6.02914;2;IDU;;{state=MOD_DEMOD, sigma=inf, chain1_up=1, chain2_up=1}
6.02914;3;ODU2;signal_out;1
```

```
6.02914;3;ODU2;;{state=TX_RX, sigma=inf, lock=1}

7.74406;3;ODU2;;{state=RELEASE_LOCK, sigma=inf, lock=0}
7.74406;5;DriverSatellite2;test_out;0
7.74406;5;DriverSatellite2;;{state=SENDING, sigma=5.87375}

8.20697;4;ODU1;;{state=RELEASE_LOCK, sigma=inf, lock=0}
8.20697;6;DriverSatellite1;test_out;0
8.20697;6;DriverSatellite1;;{state=SENDING, sigma=1.02841}

8.74406;2;IDU;;{state=MOD_DEMOD, sigma=inf, chain1_up=1, chain2_up=0}
8.74406;3;ODU2;signal_out;0
8.74406;3;ODU2;;{state=PASSIVE, sigma=inf, lock=0}

9.20697;2;IDU;;{state=DISCONNECTING, sigma=inf, chain1_up=0, chain2_up=0}
9.20697;4;ODU1;signal_out;0
9.20697;4;ODU1;;{state=PASSIVE, sigma=inf, lock=0}

9.23538;4;ODU1;;{state=ACQUIRE_LOCK, sigma=inf, lock=1}
9.23538;6;DriverSatellite1;test_out;1
9.23538;6;DriverSatellite1;;{state=SENDING, sigma=7.50414}

9.70697;2;IDU;idu_out;0
9.70697;2;IDU;;{state=PASSIVE, sigma=inf, chain1_up=0, chain2_up=0}
```

Analysis

At $t = 0$, the ODU1, ODU2, and IDU components are all in a $PASSIVE$ state; therefore, the UL is down as the UT has no chains active.

At $t = 2.43755$, DriverSatellite1 outputs a high signal on port $test\_out1$. Correspondingly, ODU1 reacts to this event by transitioning to the $ACQUIRE\_LOCK$ state and updating its *lock* state variable.

At $t = 4.02914$, DriverSatellite2 outputs a high signal on port $test\_out2$. Correspondingly, ODU2 reacts to this event by transitioning to the $ACQUIRE\_LOCK$ state and updating its *lock* state variable.

At $t = 4.43755$, after the elapse of $ta(ACQUIRE\_LOCK)$, ODU1 performs the internal transition to the TX_RX state, outputting a high signal on port $signal\_out1$. Correspondingly, the IDU then performs the external transition to the $CONNECTING$ state, updating its $chain1\_up$ state variable to indicate it is bringing up RF chain 1.

At $t = 5.43755$, after the elapse of $ta(CONNECTING)$, the IDU performs the internal transition to the MOD_DEMOD state, outputting a high signal on port *idu_out*. Hence, the UL is now up along RF chain 1, and the signal is continuous along the UL from DriverSatellite1, through ODU1, and out from the IDU, as expected.

At $t = 6.02914$, after the elapse of $ta(ACQUIRE\_LOCK)$, ODU2 performs the internal transition to the TX_RX state, outputting a high signal on port $signal\_out2$. Since the IDU is already in the MOD_DEMOD state, it remains there (ie. self-transition), updating its $chain2\_up$ state variable to indicate it is bringing up RF chain 2. At this point, both RF chains are active, and the IDU continues to output a high signal on port idu_out, as expected.

At $t = 7.74406$, DriverSatellite2 outputs a low signal on port $test\_out2$. Correspondingly, ODU2 reacts to this event by transitioning to the $RELEASE\_LOCK$ state and updating its $lock$ state variable.

At $t = 8.20697$, DriverSatellite1 outputs a low signal on port $test\_out1$. Correspondingly, ODU1 reacts to this event by transitioning to the $RELEASE\_LOCK$ state and updating its $lock$ state variable.

At $t = 8.74406$, after the elapse of $ta(RELEASE\_LOCK)$, ODU2 performs the internal transition to the $PASSIVE$ state, outputting a low signal on port $signal\_out2$. Correspondingly, the IDU updates its $chain2\_up$ state variable to indicate it is bringing down RF chain 2; however, even with this chain down, the UT remains in the MOD_DEMOD state since $chain21\_up$ is still true, and the UL is maintained along RF chain 1. Therefore, the UT continues to output a high signal on port idu_out, as expected.

At $t = 9.20697$, after the elapse of $ta(RELEASE\_LOCK)$, ODU1 performs the internal transition to the $PASSIVE$ state, outputting a low signal on port $signal\_out1$. Correspondingly, the IDU updates its $chain1\_up$ state variable to indicate it is bringing down RF chain 1; this time, since both chains are now down, the IDU performs the external transition to the $DISCONNECTING$ state.

At $t = 9.70697$, after the elapse of $ta(DISCONNECTING)$, the IDU performs the internal transition to the $PASSIVE$ state. With both RF chains down, the UL is dropped, and the UT outputs a low signal on port idu_out.

As per the above results, the behaviour of EF1 is as expected. When at least one RF chain is up, the UT outputs a high signal; only when both RF chains are down does the UT output a low signal, indicating that service is disrupted and the network connection is lost.

2 EF2: CM UL

In order to exercise EF2, the simulation requires no external inputs, as the Satellite AMs are generative and stimulate the system. A top model was defined to contain the EF (as per Fig. 8 above), and the simulation was executed. Selections from the simulation output file (cf. LEO USER LINK: *sample-output/leo_user_link*) corresponding to one execution of the simulation is shown below. The first selection is used to demonstrate the MBB handover scenario, and the second to demonstrate the BBM handover scenario.

2.1 MBB Handover Scenario

A selection of output demonstrating the MBB handover scenario in this simulation is as follows:

```
sep=;
time;model_id;model_name;port_name;data

...

44.0328;3;IDU;idu_out;1
44.0328;3;IDU;;{state=MOD_DEMOD, sigma=inf, chain1_up=0, chain2_up=1}

48.6654;5;ODU1;;{state=ACQUIRE_LOCK, sigma=inf, lock=1}
48.6654;7;Satellite1;beam_out;1
48.6654;7;Satellite1;;{state=ILLUMINATE, sigma=12.9001}

50.6654;3;IDU;;{state=MOD_DEMOD, sigma=inf, chain1_up=1, chain2_up=1}
50.6654;5;ODU1;signal_out;1
50.6654;5;ODU1;;{state=TX_RX, sigma=inf, lock=1}

55.4723;4;ODU2;;{state=RELEASE_LOCK, sigma=inf, lock=0}
55.4723;6;Satellite2;beam_out;0
55.4723;6;Satellite2;;{state=PASSIVE, sigma=7.8884}

56.4723;3;IDU;;{state=MOD_DEMOD, sigma=inf, chain1_up=1, chain2_up=0}
56.4723;4;ODU2;signal_out;0
56.4723;4;ODU2;;{state=PASSIVE, sigma=inf, lock=0}

...
```

Analysis

At $t = 44.0328$, the IDU is in the MOD_DEMOD state, with the RF chain up along ODU2, as indicated by the IDU's $chain2\_up$ state variable. As such, the IDU outputs a high signal on its output port *idu_out*, indicating that the UL is up along the RF chain connected to Satellite2 (the falling Satellite, in this handover scenario).

At $t = 48.6654$, Satellite1 performs the internal transition to the $ILLUMINATE$ state, indicating it has entered the FOV of the UT, and thus outputs a high signal to its output port *beam_out*. Correspondingly, ODU1 performs the external transition to the $ACQUIRE\_LOCK$ state.

At $t = 50.6654$, after the elapse of $ta(ACQUIRE\_LOCK)$, ODU1 performs the internal transition to the TX_RX state, outputting a high signal on its output port *signal_out*. Correspondingly, the IDU updates it $chain1\_up$ state variable, and remains in the MOD_DEMOD state where high values for both $chain1\_up$ and $chain2\_up$ indicate that both RF chains are up within the UT. This is the "Make" of the MBB scenario.

At $t = 55.4723$, Satellite2 performs the internal transition to the $PASSIVE$ state, indicating it has left the FOV of the UT, and thus outputs a low signal to its output port *beam_out*. Correspondingly, ODU2 performs the external transition to the $RELEASE\_LOCK$ state, updating its $chain2\_up$ state variable to show that it is bringing down the RF chain.

At $t = 56.4723$, after the elapse of $ta(RELEASE\_LOCK)$, ODU2 performs the internal transition to the $PASSIVE$ state, outputting a low signal on its output port *signal_out*. Correspondingly, the IDU updates its $chain2\_up$ state variable; however, it remains in the MOD_DEMOD state because the UT has maintained the RF chain with rising Satellite1, as indicated by its $chain1\_up$ state variable. This is the "Break" of the MBB scenario. The UT has thus performed a handover from the falling Satellite (Satellite2) to the rising Satellite (Satellite1) without dropping the UL into a down state. The seamlessness of this handover is demonstrated by the fact that the *idu_out* port remains with a high signal throughout the handover, therefore incurring no down time.

As per the above results, the behaviour of EF2 is as expected for the MBB handover scenario. When the UT makes an RF chain to the rising Satellite before breaking the chain with the falling Satellite, the UL maintains its high signal, indicating that service is continuous and the network connection remains. The outputs of the simulation support this, as there is verifiably no down time accrued in the handover scenario.

2.2 BBM Handover Scenario

A selection of output demonstrating the BBM handover scenario in this simulation is as follows:

```
sep=;
time;model_id;model_name;port_name;data

...

83.5719;3;IDU;idu_out;1
83.5719;3;IDU;;{state=MOD_DEMOD, sigma=inf, chain1_up=0, chain2_up=1}

87.9888;4;ODU2;;{state=RELEASE_LOCK, sigma=inf, lock=0}
87.9888;6;Satellite2;beam_out;0
87.9888;6;Satellite2;;{state=PASSIVE, sigma=10.5958}
```

```
88.9888;3;IDU;;{state=DISCONNECTING, sigma=inf, chain1_up=0, chain2_up=0}
88.9888;4;ODU2;signal_out;0
88.9888;4;ODU2;;{state=PASSIVE, sigma=inf, lock=0}

89.4888;3;IDU;idu_out;0
89.4888;3;IDU;;{state=PASSIVE, sigma=inf, chain1_up=0, chain2_up=0}

92.2124;5;ODU1;;{state=ACQUIRE_LOCK, sigma=inf, lock=1}
92.2124;7;Satellite1;beam_out;1
92.2124;7;Satellite1;;{state=ILLUMINATE, sigma=9.40438}

94.2124;3;IDU;;{state=CONNECTING, sigma=inf, chain1_up=1, chain2_up=0}
94.2124;5;ODU1;signal_out;1
94.2124;5;ODU1;;{state=TX_RX, sigma=inf, lock=1}

95.2124;3;IDU;idu_out;1
95.2124;3;IDU;;{state=MOD_DEMOD, sigma=inf, chain1_up=1, chain2_up=0}

...
```

Analysis

At $t = 83.5719$, the IDU is in the MOD_DEMOD state, with the RF chain up along ODU2, as indicated by the IDU's $chain2\_up$ state variable. As such, the IDU outputs a high signal on its output port *idu_out*, indicating that the UL is up along the RF chain connected to Satellite2 (the falling Satellite, in this handover scenario).

At $t = 87.9888$, Satellite2 performs the internal transition to the $PASSIVE$ state, indicating it has fallen out of the FOV of the UT, and thus outputs a low signal to its output port *beam_out*. Correspondingly, ODU2 performs the external transition to the $RELEASE\_LOCK$ state.

At $t = 88.9888$, after the elapse of $ta(RELEASE\_LOCK)$, ODU2 performs the internal transition to the $PASSIVE$ state, outputting a low signal on its output port *signal_out*. Correspondingly, the IDU performs the external transition to the $DISCONNECTING$ state.

At $t = 89.4888$, after the elapse of $ta(DISCONNECTING)$, the IDU performs the internal transition to the $PASSIVE$ state, outputting a low signal on its output port *idu_out*. Here, no RF chains are active, and the UL is down, carrying no signal. This is the "Break" of the BBM handover scenario, and represents disconnection from the network and a discontinuity of service. At this point, down time begins accruing.

At $t = 92.2124$, Satellite1 (the rising Satellite, in this handover scenario) comes into the FOV of the UT, and transitions to the $ILLUMINATE$ state, outputting a high signal on its output port *beam_out*. Correspondingly, ODU1 performs the external transition to the $ACQUIRE\_LOCK$ state.

At $t = 94.2124$, after the elapse of $ta(ACQUIRE\_LOCK)$, ODU1 performs the internal transition to the TX_RX state, outputting a high signal on its output port *signal_out*. Correspondingly, the

IDU performs the external transition to the $CONNECTING$ state.

At $t = 95.2124$, after the elapse of $ta(CONNECTING)$, the IDU performs the internal transition to the MOD_DEMOD state. As such, the IDU outputs a high signal on its output port idu_out, indicating that the UL is up along the RF chain connected to Satellite1, as affirmed by its $chain1\_up$ state variable. This is the "Make" of the BBM handover scenario, and represents reconnection to the network and the resumption of service. At this point, down time stops accruing, resulting in a total of 5.7236s of downtime for this simulated BBM handover.

As per the above results, the behaviour of EF2 is as expected for the BBM handover scenario. When the UT breaks its sole RF chain to the falling Satellite before making a chain with the rising Satellite, the UL outputs a low signal, indicating that service is disrupted and the network connection is temporarily lost. When the UT then brings up the other RF chain of the rising Satellite, the UL outputs a high signal, indicating that service has resumed and the network connection is re-established, but only after a measurable down time of 5.7236s.

2.3 Conclusion

In analyzing the simulations for EF1 and EF2, it was determined that the models behaved as expected under simulation. From EF1, the behaviour of the UT CM was verified, with the UT correctly bringing up and down RF chains according to the states and interactions of its internal AM components of the ODUs and the IDU. From EF2, the behaviour of the UL CM was verified, with the UL correctly representing its up and down state according to the states and interactions of its internal CM component of the IDU, and its internal AM components of two Satellites. Additionally, the exercise of EF2 also permitted the analysis of both MBB and BBM handover scenarios, with the simulation results proving a seamless handover with no quantifiable down time in the MBB scenario, whilst demonstrating quantifiable down time in the BBM scenario

For the highest level of service within a LEO network, the constellation and UTs should therefore be designed to maximize MBB handover scenarios over BBM scenarios. Although BBM scenarios may 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 with a variable number of ODUs enabling additional handover scenarios). 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 along ULs in a LEO 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.

Date Developed/Implemented: March 3, 2025.

Domain: Satcom

Current Version: 1.0.0

URL: LEO User Link

Description:

Links to Related Documents: None

Keywords: DEVS, LEO, constellation, satcom, handover

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