ns-3 Public Safety Communications documentation

Release psc-dev

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CONTENTS

This is documentation for *ns-3* models relating to public safety communications, extracted from the overall *ns-3 Model Library* documentation.

This document is written in reStructuredText for Sphinx and is maintained in the `doc/psc-models` directory of the PSC repository.

PUBLIC SAFETY COMMUNICATIONS

1.1 Public Safety Communications Overview

ns-3 support for public safety communications (PSC) is based on relatively new capabilities for 4G LTE systems introduced in 3GPP Release 12 and later releases. Device-to-Device (D2D) Proximity Services (ProSe) communications are terms relating to features allowing for UEs to discover each other, synchronize, and communicate with each other, with or without the use of an eNodeB. These services make use of a so-called *sidelink* channel between UEs.

Support for public safety communications is distributed among the following four *ns-3* modules:

1. `psc`: (this module) Support for models and scenarios that are specific to public safety communications.

2. `lte`: Support for ProSe (sidelink communications).

3. `buildings`: Support for pathloss models including building effects, as defined by 3GPP with relevance to public safety scenarios.

4. `antenna`: Parabolic antenna model as described in 3GPP document TR 36.814

Documentation for the PSC features implemented in the *ns-3* `lte`, `buildings`, and `antenna` modules is provided in the respective module documentation. This chapter documents the *ns-3* `psc` module.

At present, the majority of the code related to public safety communications is found in the ProSe implementation in the `lte` module. This is because the ProSe services of sidelink communications, discovery, and synchronization are deeply connected to the LTE models and difficult to factor into a separate module. Features intrisic to the low-level operation of ProSe in LTE are found in the `lte` module.

The `psc` module now includes an extensive model of mission-critical push-to-talk (MCPTT) for use in off-network scenarios, an energy consumption model for flying a (single/multi)rotor unmanned aerial vehicle (UAV), and a UDP-based application to generate many-to-many traffic models in a scenario.

There is no support for legacy public safety communications such as land mobile radio system (LMRS). While IPv4 has been the main focus of development, some of the LTE sidelink example programs now feature an option to use IPv6.

Future extensions to this module or other related modules such as LTE are planned for the following features:

1. support for on-network modes of MCPTT, and possibly other public safety applications

2. UE-to-network relay

3. public safety scenario support code and example programs

1.1.1 Acknowledgments

Public safety communications features are based on development led by the Wireless Networks Division of the U.S. National Institute of Standards and Technology, described in publications (*[NIST2016]* and *[NIST2017]*). Users of the

D2D features of *ns-3* are requested to cite *[NIST2017]* in academic publications based on these models.

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1.2 UDP Group Echo Server

The class `ns3::UdpGroupEchoServer` implements a group echo server that echoes received UDP datagrams to a set of clients. The policy of generating replies can be tailored through the use of attributes.

The relevance of this model to public safety communications is that such scenarios often require a many-to-many group communications application, and existing *ns-3* applications are not suitable to generate such traffic.

The UDP group echo implementation is authored by Fernando J. Cintron (fernando.cintron@nist.gov) and is derived from the UdpEchoServer found in the *ns-3* applications module.

1.2.1 Model Description

The implementation is provided in the following files:

- `src/psc/model/udp-group-echo-server.{h,cc}` The model itself

- `src/psc/helper/udp-group-echo-helper.{h,cc}` Helper code for configuration

Additionally, a simple example is provided at `src/psc/examples/example-udp-group-echo.cc`.

The model is based on the `ns3::UdpEchoServer`, but differs in that the existing server only handles one client, while the group echo server handles one or more clients. The behavior of the `ns3::UdpEchoServer` can be reproduced (i.e., it is a special case of this object).

The model works as follows. The UdpGroupEchoServer is an *ns-3* application, listening for UDP datagrams on a configured UDP port. Upon receipt of a datagram for the first time from a client, the server records the client and a timestamp for when the packet was received. The server then decides whether to forward the packet back to one or more clients, on a pre-configured 'EchoPort'. The set of possible clients is built dynamically based on received packets.

There are a few configurable policies:

1. The server may be configured to echo only to the client that originated the packet (similar to the `UdpEchoServer`).

2. The server may be configured to echo to a group of clients including the sender. Furthermore, the sending client may be excluded from the response.

3. The server may be configured to echo to a group of clients including the sender, so long as the server has heard from each client within a configurable timeout period. Furthermore, the sending client may be excluded from the response.

Attributes

The following is the list of attributes:

- `Port`: Port on which the server listens for incoming packets, default value of 9.
- `EchoPort`: Port on which the server echoes packets to client, default value of 0.
- `Mode`: Mode of operation, either no group session (reply to sender only), timeout limited session (replicate to all clients for which a packet has been received from them within the configured timeout period), and infinite session (reply to all known clients). The default is no group session.
- `Timeout`: Inactive client session expiration time, default of zero seconds.
- `EchoClient`: Whether the server echoes back to the sending client, default value of true.,

Trace sources

The model also provides a `Rx` trace source for all received datagrams.

1.2.2 Usage

A simple example based on CSMA links is provided in the file `src/psc/examples/example-udp-group-echo.cc`.

```
//   *      *
// n0   n1   ... n(nExtra)  n(1+nExtra)
// |    |     |     |              |
// ===========================
//     LAN 10.1.2.0
```

By default, node n0 is the client and node n1 is the server, although additional nodes can be added with the `--nExtra` argument. If there are more nodes, the highest numbered node is the server.

Each client is configured with an on-off traffic generator that sends traffic at random times to the server. The following program options exercise some of the configuration of the server:

```
$ ./waf --run 'example-udp-group-echo --PrintHelp'

Program Options:
  --nExtra:      Number of "extra" CSMA nodes/devices [0]
  --echoClient:  Set EchoClient attribute [true]
  --mode:        Set Mode attribute (InfSession|NoGroupSession|TimeoutLimited)
→[InfSession]
  --timeout:     Set Timeout attribute [+0.0ns]
  --verbose:     Tell echo applications to log if true [true]
  --enablePcap:  Enable PCAP file output [false]
  --time:        Simulation time [10]
```

By default, the number of extra CSMA nodes/devices is zero, so there will be only one client and one server. By running with the existing defaults, the program will configure the server to echo back to the client, use the 'InfSession'

mode of operation (to echo without considering timeout value) and a timeout value of 0 (which is not used in this mode). Logging is also enabled, and running the program with defaults yields output such as:

```
$ ./waf --run 'example-udp-group-echo'
...

8.7006 server received 41 bytes from 10.1.2.1 port 49153
Client found; old timestamp: 8.6806
New timestamp: 8.7006
8.7006 number of clients: 1
-----------------------------------------------------------
             Client     Session
-----------------------------------------------------------
         10.1.2.1:49153         0
===========================================================
8.7006 server sent 41 bytes to 10.1.2.1 port 49153
```

This shows that node 10.1.2.1 sent data at time 8.7006 that was echoed back to the client. Running with the option `--nExtra=2` shows:

```
$ ./waf --run 'example-udp-group-echo --nExtra=2'

...

9.99949 server received 41 bytes from 10.1.2.1 port 49153
Client found; old timestamp: 9.97949
New timestamp: 9.99949
9.99949 number of clients: 3
-----------------------------------------------------------
             Client     Session
-----------------------------------------------------------
         10.1.2.1:49153         0
         10.1.2.2:49153 0.00647334
         10.1.2.3:49153 0.00426833
===========================================================
9.99949 server sent 41 bytes to 10.1.2.1 port 49153
9.99949 server sent 41 bytes to 10.1.2.2 port 49153
9.99949 server sent 41 bytes to 10.1.2.3 port 49153
```

Here, one packet sent leads to three packets echoed, and the data under the 'Session' column shows the time in seconds since the last packet was received from each client. In mode 'InfSession', there is no explicit timeout, but if we set a timeout to be something small, such as 5ms, and set the mode to 'TimeoutLimited', we can suppress the response to node 10.1.2.2 because it has last polled the server over 6ms ago.

```
$ ./waf --run 'example-udp-group-echo --nExtra=2 --timeout=5ms --mode=TimeoutLimited'

...

9.99949 server received 41 bytes from 10.1.2.1 port 49153
9.99949 number of clients: 3
-----------------------------------------------------------
             Client     Session
-----------------------------------------------------------
         10.1.2.1:49153         0
         10.1.2.2:49153 0.00647334 **Session Expired!**
         10.1.2.3:49153 0.00426833
===========================================================
9.99949 server sent 41 bytes to 10.1.2.1 port 49153
```

```
9.99949 server sent 41 bytes to 10.1.2.3 port 49153
```

As seen above, the session has expired to 10.1.2.2 with this timeout and mode setting, so the echo response is suppressed.

The C++ code for setting the server is fairly standard *ns-3* syntax and container/helper-based code, as exemplified below:

```
uint16_t serverPort = 9;
// Attributes 'timeout', 'mode', 'echoClient' may be set above
UdpGroupEchoServerHelper echoServer (serverPort);
echoServer.SetAttribute ("Timeout", TimeValue (timeout));
echoServer.SetAttribute ("Mode", StringValue (mode));
echoServer.SetAttribute ("EchoClient", BooleanValue (echoClient));
ApplicationContainer serverApps = echoServer.Install (csmaNodes.Get (nCsma - 1));
serverApps.Start (Seconds (1.0));
serverApps.Stop (Seconds (simTime));
```

1.3 UAV Mobility Energy Model

The class `ns3::psc::UavMobilityEnergyModel` implements an Energy Model that bases the current on how a Node is moving.

This model is roughly based on the energy model released under the GNU GPL v2 found here: ns3-urbanuavmobility

The model is intended to provide simple energy costs for flying a (single/multi)rotor unmanned aerial vehicle (UAV). The default costs are not intended to perfectly model reality, but rather to consider flight time in cases where otherwise it may have been neglected.

1.3.1 Model Description

The implementation is provided in the following files:

- `src/psc/model/uav-mobility-energy-model.{h,cc}` The model
- `src/psc/model/uav-mobility-energy-model-helper.{h,cc}` A helper

A low-level example may be found in:

`src/psc/examples/uav-mobility-energy-example.cc`.

An example using the helper may be found in:

`src/psc/examples/uav-mobility-energy-helper-example.cc`.

The model sets the current based on five basic modes for movement:

- **STOP:** Not Moving
- **HOVER:** The Node has a velocity of 0 m/s, but the Node is off of the ground (z > 0)
- **ASCEND/DESCEND:** The Node is moving only on the z-axis
- **MOVE:** The Node is moving on the x-axis or y-axis. Any z movement is added to the calculated current.

The current set when the Node is stopped (not above the ground [z = 0]) is zero amps, and is not configurable.

The current set when the Node is hovering is fixed and may be set through the `HoverCurrent` attribute.

The model connects to the `CourseChange` trace in the MobilityModel aggregated onto the Node passed to `ConnectMobility ()` or `Init ()`. When the attached MobilityModel notifies this model of a course change this model queries the current velocity and position of the Node. The model will use the velocity and position to determine the state this model should be in (e.g. Ascending, Hovering, Stopped). Each state will incur a different current draw from the attached EnergySource. This model then notifies the attached EnergySource of this new current via `UpdateEnergySource ()`.

When the attached EnergySource depletes, this model will be notified and the `EnergyDepleted` trace will be called. However, there is no default behavior beyond this. So, if you want your Node to do something when the attached EnergySource depletes (i.e. Crash to the ground) then your program must connect to the `EnergyDepleted` trace and implement the desired behavior. See the example for how to go about this.

The current for ascending, descending, and moving is calculated based on the speed at which the Node is moving (except for descending which is based on the inverted speed [1/speed]) multiplied by a conversion factor. Each mode has its own conversion factor and is configurable through the `AscendEnergyConversionFactor`, `DescendEnergyConversionFactor`, and `MoveEnergyConversionFactor` attributes respectively.

Attributes

The model exposes the following attributes:

- **AscendEnergyConversionFactor:** The conversion factor applied to the speed of the Node when it is ascending. In $\frac{A}{m/s}$.

- **DescendEnergyConversionFactor:** The conversion factor applied to the inverted speed of the Node when it is descending. In $\frac{A}{(m/s)^{-1}}$.

- **MoveEnergyConversionFactor:** The conversion factor applied to the speed of the Node when it is moving. In $\frac{A}{m/s}$.

- **HoverCurrent:** The fixed amperage set when the Node is hovering. In amperes.

- **EnergySource:** The energy source this model draws from.

Trace sources

The model exposes the following trace sources:

- **EnergyDepleted:** Called when the attached Energy Source has indicated that it is depleted.

- **EnergyRecharged:** Called when the attached Energy Source has indicated that it has been recharged.

- **TotalEnergyConsumption:** The total energy consumed by the model. In Joules.

- **State:** The current mobility state detected by the model along with the velocity. The possible states may be found in `ns3::psc::UavMobilityEnergyModel::State`

- **Current:** The current draw from the attached energy source, along with the velocity.

1.3.2 Tests

The following tests have been written for this model and may be found in `src/psc/test/uav-mobility-energy-model-test.cc`:

- **UavMobilityEnergyModelTestCaseEnergyConsumption:** Tests if the model correctly sets the current on the EnergySource as well as if the correct amount of energy is deducted from the EnergySource.

- **UavMobilityEnergyModelTestCaseZeroEnergyCost:** The model supports making any of the possible states consume no energy. Configure each state as such and make sure no energy is consumed.

- **UavMobilityEnergyModelTestCaseMoveEnergy:** Move combines the cost of the 2D movement (x, y) and the ascend/descend cost (z). Tests that when a Node has both 2D movement and is ascending that the ascend/descend cost is accounted for and is correct, along with the 2D movement only.

- **UavMobilityEnergyModelTestCaseLowEnergyTrace:** Tests if the `EnergyDepleted` trace is actually called.

- **UavMobilityEnergyModelTestCaseLiIonEnergySource:** Make sure the model actually draws energy from another EnergySource that is not the BasicEnergySource.

- **UavMobilityEnergyModelTestCaseMobilityModel:** Tests that the model correctly integrates with a MobilityModel. Tests that the MOVE state is correctly determined from the attached MobilityModel

- **UavMobilityEnergyModelTestCaseChangeCostsRuntime:** The model supports changing the cost of any of the states (except for STOP) while the simulation is running. Tests if this feature actually works.

- **UavMobilityEnergyModelTestCaseTotalEnergyConsumption:** The model tracks the total Joules consumed over the lifetime of the model. This total is available through both the `GetTotalEnergyConsumption ()` and through the `TotalEnergyConsumption` trace source. Validate this total is correct from both sources.

- **UavMobilityEnergyModelTestCaseInitialVelocity:** Tests if a velocity set before the simulation starts works correctly.

- **UavMobilityEnergyModelTestCaseState:** Tests if the model correctly sets the state and that the `State` trace has the correct state.

- **UavMobilityEnergyModelTestCaseTraceCurrent;** Tests if the model correctly sets the current and that the `Current` trace has the correct current.

- **UavMobilityEnergyModelTestCaseAttributeEnergySource:** Tests if setting the EnergySource through the `EnergySource` attribute works properly.

- **UavMobilityEnergyModelTestCaseFixedStateChangeSpeed:** Assures that if the speed/velocity at which the Node is moving is changed, but the state does not (i.e. moving, then moving faster in the same direction) that the current is updated (and the `Current` trace notified) and the state remains the same (and the `State` trace is not notified)

- **UavMobilityEnergyModelTestCaseVelocityTraces:** Several of the traces have the velocity from the MobilityModel included. Validate that the included velocities are correct.

1.3.3 Usage

The model may be installed on any Node with a Mobility Model installed. The helper may also be used for a simpler installation. The helper will create any of the necessary components on the Node and install and init the model.

Each Node requires exactly one Energy Source passed to `SetEnergySource()` and an aggregated MobilityModel when it is passed to `ConnectMobility ()` when using the low-level API. Alternatively, both the EnergySource and Node may be passed to `Init ()` for convenience. If the helper is used, it allows for a passed Energy Source, or an Energy Source aggregated onto the Node.

1.4 Mission Critical Push-to-Talk (MCPTT)

An MCPTT service provides a reliable, always-on, always-available means of communication for first responders. This communication can be one-to-one or one-to-many. There are two modes of operation: on-network and off-network. In on-network mode, communication takes place via a client/server setup, which means that, in LTE, a

UE sends signals to an eNodeB, and talks with an MCPTT server via the core-network. But in off-network mode, communication is supported by UE devices in a peer-to-peer like fashion, where signals are only sent from UE to UE.

A call is the logical channel between MCPTT applications. Call control is the protocol used to create and manage these logical channels. There are three types of calls that can take place between a set of users: basic, broadcast, and private. A basic group call is one where a logical channel is setup for a group of users associated with a particular group ID so that members of the group can contend to talk in order to communicate with the other members of the group. A broadcast group call is like a basic group call, but only the initiator is allowed to speak, and once the initiator is done speaking the call is terminated. A private call exists when there is a logical channel between two applications for two users to communicate. Each type of call may be basic, imminent peril, or emergency, and this "call status" dictates which physical resources are used by this call.

When off-network, all call control messages are sent to all other applications using the same socket. When a user wants to start or join a group call for a particular group ID, the UE sends out periodic "GROUP CALL PROBE" messages. If a UE with same group ID is already part of an on-going call, the UE that received the probe will respond with a "GROUP CALL ANNOUNCEMENT" message. When a UE who is not part of an on-going call receives this "GROUP CALL ANNOUNCEMENT" message, the UE then automatically joins the call or waits for the user to choose between joining the call or ignoring the call. This announcement message is also sent periodically by members of an on-going call. While part of a group call, floor control (described in the following paragraph) is used to control which UE has permission to send media, and thus, which user is allowed to talk, at any given time during a call. A user may also change the "status" of a call at any point and this is communicated via the "GROUP CALL ANNOUNCEMENT" message.

In an MCPTT group call, only a single member of the group is allowed to talk at a time, and during this time all other group members need to listen. This is facilitated by the floor control protocol. The protocol consists of floor participants and a floor control server. The floor participants make requests to the floor control server, while the floor control server receives and handles these requests. In the on-network version there is a centralized MCPTT server that acts as the floor control server, but in the off-network case, the UE of the current speaker is the one acting as the floor control server (also known as the current arbitrator). It is optional to use floor control for a private call.

When off-network, all floor control messages are sent to all members of the group. When a user wants to talk, which is indicated by a PTT press during a call, the UE requests permission to send data by sending a "Floor Request" message. The current arbitrator of the call, which is the device of the user who is currently allowed to speak, will send a "Floor Granted" message to give permission to another UE to transmit media, allowing the requesting user to speak to the other members of the group, a "Floor Deny" message to deny the UE permission to send media, or a "Floor Queue Info" message if the UE must wait to transmit media. After sending a request, if the UE does not receive an appropriate message after a given amount of time, the UE will assume that there is currently no arbitrator and will send a "Floor Taken" message, giving itself permission to transmit media.

1.4.1 Design Documentation

The MCPTT model was implemented based on the 3GPP specifications TS 24.379 *[TS24379]* and TS 24.380 *[TS24380]* release 14.4.0. This includes off-network models for floor control, basic group calls, broadcast group calls, and private calls. There are also several test cases that were invented by NIST that are also included with this model. This model was created and is intended to be used with the Proximity Services (ProSe) which is provided by LTE.

The MCPTT model includes:

- A set of classes that can be used to model an MCPTT application using call control and floor control in the off-network case

- Helper classes to act as a sink for time-sensitive message and state change traces that can be used to capture the behavior of the different off-network MCPTT state machines (i.e. protocols)

- A helper class that allows users to configure and deploy MCPTT applications in a scenario with nodes

- A few examples that show how the model can be used

- Test cases produced by NIST to check state machine behavior

The MCPTT model does not take into account security. The model only goes as far as including dummy variables in appropriate messages that would carry security fields. Also, the MCPTT model currently does not make use of ProSe Per-Packet Priority (PPPP). Even though the MCPTT model includes and appropriately maintains PPPP as specified in the standards, there currently is no support in ProSe for this feature and, thus, it is not used.

Note: **MCPTT was created specifically for LTE, and the main component that ties** MCPTT to LTE is the use of PPPP, which is provided to lower layers of LTE when sending messages for physical resource selection, but the current implementation of the off-network model does not make use of this feature since there is currently no support for it in the current ns-3 implementation of ProSe. This means that the current MCPTT model is capable of being used over more technologies than just LTE since it is just an application in *ns-3*.

Design

In *ns-3*, the `ns3::McpttHelper` is the main class that a user should use to initialize and install applications to an `ns3::Node`. This helper can be used to initially configure some of the components that are associated with an MCPTT application, such as the application's data rate when generating media, the random variable that should be used to simulate a PTT, the IP address used by the application when addressing the group, etc. Once created and installed, it is up to the user to setup calls. This can be done before or after the application is started but not "dynamically" by the application itself. So if a user wanted a scenario with three UE's that will eventually take part in the same on-going group call, the user will have to first query the `ns3::McpttPttApplication` objects of the three `ns3::Node`'s to create those calls. Once the calls are created, the user will also have to query the application to select the current call to reflect things such as a PTT or call release at any given time throughout the simulation.

In the following code snippet, a basic group call is created for N users with group ID 1. One second after the applications are started, the first user will push the PTT button.

```
ObjectFactory callFac;
callFac.SetTypeId (McpttCallMachineGrpBasic::GetTypeId ());
callFac.Set ("GroupId", UintegerValue (1));
ObjectFactory floorFac;
floorFac.SetTypeId (McpttFloorMachineBasic::GetTypeId ());

for (uint32_t idx = 0; idx < clientApps.GetN (); idx++)
  {
    Ptr<McpttPttApp> pttApp =
      DynamicCast<McpttPttApp, Application> (clientApps.Get (idx));
    pttApp->CreateCall (callFac, floorFac);
    pttApp->SelectCall (0);

    if (idx == 0)
      {
        Simulator::Schedule (Seconds (start.GetSeconds () + 1.0),
          &McpttPttApp::TakePushNotification, pttApp);
      }
  }
```

MCPTT Application

The `ns3::McpttPttApp` is the core component of the MCPTT model. It is the object used to manages calls and provide an API with functions that would be available to a user like, starting a call, releasing a call, entering an emergency alert, etc. It also houses a few entities to help simulate the behavior of how an MCPTT application may be used. This class also implements the `ns3::McpttMediaSink` interface, which allows for an instance of the `ns3::McpttMediaSrc` class to generate and pass media messages for transmission, and the

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`ns3::McpttPushable` interface, which can be attached to by an `ns3::McpttPusher` to simulate button push and release events.

The `ns3::McpttMediaSrc` is simply a class that generates RTP media messages to be sent. It is used by the application to help model data traffic in the network. It is a rather simple traffic model but can be configured to alter data rate and message size.

The `ns3::McpttMsgParser` is a class that reads the header of a packet to determine which message is being received. This class is used by the application as well as in some test cases.

The `ns3::McpttPusher` is class used to simulate the pushing of a button. The application uses this class to simulate a user that is using the PTT button. This model is also simple but allows the user to configure it with a random variable to reflect how often a user may push and release the PTT button.

The `ns3::McpttCall` class simply aggregates the components needed to have an MCPTT call. This includes a channel for both floor control and media messages, and state machines for call control and floor control.

The `ns3::McpttChan` class is a wrapper around the `ns3:Socket` class to provide an interface similar to the functions required by the specifications, as well as handle opening and closing sockets on the fly. This class is used by the `ns3::McpttCall` and `ns3::McpttPttApp` classes.

The `ns3::McpttCallMachine` is an interface created to handle the different types of calls that are available. This includes functions for starting and leaving calls. There are many subclasses: * `ns3::McpttCallMachineGrpBasic` for basic group calls * `ns3::McpttCallMachineGrpBroadcast` for broadcast group calls * `ns3::McpttCallMachinePrivate` for private calls, and * `ns3::McpttCallMachineNull` to "turn-off" call control. Each of the state machines except for the null state machine have several classes associated with each to represent the different states of the state machine. For example, the class `ns3::McpttCallMachineGrpBroadcastStateB1` is a model of the "B1: start-stop" state of the Broadcast call control state machine from the 3GPP standard describing call control.

The `ns3::McpttFloorMachine` is an interface created to represent the floor control protocol. There are two subclasses: - `ns3::McpttFloorMachineBasic` for the floor control protocol - `ns3::McpttFloorMachineNull` to "turn-off" floor control

Just like the state machines for call control, the `ns3:McpttFloorMachineBasic` class has an `ns3::McpttFloorMachineBasicState` member which is derived by many classes such as `ns3:McpttFloorMachineBasicStateHasPerm` to represent the different states of the floor control state machine.

The `ns3::McpttEmergAlertMachine` is an interface to represent the state machine used to maintain a user's emergency alert status. This can be found in TS 24.379 *[TS24379]*. There is currently one subclass: - `ns3::McpttEmergAlertMachineBasic` for the emergency alert protocol

In the standard, there is one emergency alert machine associated with one user, but in the current implementation there is an emergency alert machine associated with each `ns3::McpttCallMachineGrpBasic` instance. Unlike the previous state machines, there is no "state" class associated with this machine, all the logic is self-contained.

The `ns3::McpttCallTypeMachine` is an interface for the call type machines described in the standard. These state machines exist to maintain the call type (e.g. basic, emergency, etc.) of a call. There are two subclasses: * `ns3::McpttCallTypeMachineGrpBasic` for a basic group call, and * `ns3::McpttCallTypeMachinePriv` for a private call.

These state machines are also self-contained and are not associated with any "state" classes.

Most state machines, if not all, have many members that are of the types `ns3::McpttCounter` and `ns3::McpttTimer`. These classes are used to provide an API to mirror the actions that can be requested of counters and timers that are defined throughout the standards. The `ns3::McpttCounter` class provides an interface that can be used as counters are described in the standard with functions like, "Increment" and "Reset". The `ns3::McpttTimer` class does the same for timers described in the standard with functions like "Start", "Stop", and "Restart". The `ns3::McpttTimer` is simply a wrapper around the `ns3::Timer` class.

The `ns3::McpttMsg` class is a base class for all MCPTT off-network messages. This class is derived from by the `ns3::McpttCallMsg` class for call control messages, the `ns3::McpttFloorMsg` for floor control, and the `ns3::McpttMediaMsg` for RTP media messages. The `ns3::McpttCallMsg` and `ns3::McpttFloorMsg` classes both have many subclasses to represent each floor control or call control message used in the off-network portion of the standard. For example, the `ns3::McpttFloorMsgRequest` class represents the "Floor Request" message described in TS 24.380 *[TS24380]*. These classes are sent between the MCPTT applications and are consumed by the appropriate state machines throughout the simulation.

As mentioned above, the `ns3::McpttMediaMsg` class is used to represent an RTP media message, but the actual header for an RTP packet is modeled by the `ns3::McpttRtpHeader` class. This class just defines the fields needed for a basic RTP header which is used by the media message.

The `ns3::McpttCallMsgField` and `ns3::McpttFloorMsgField` classes represent call control and floor control message fields, respectively. These classes are also just used as a base and have many child classes. For example, the `ns3::McpttFloorMsgRequest` class, which represents a "Floor Request" message contains a member of type `ns3::McpttFloorMsgFieldUserId` that describes the ID of the MCPTT user making the floor request.

The `ns3::McpttEntityId` class only exist for simulation to associate an ID with various entities described in the standard. One may find that counters, timers, and various states have an ID, and this ID just helps distinguish between multiple objects of the same type.

The `ns3::McpttFloorQueue` class is a wrapper around the `std::vector` class that provides an interface for the floor queue that is described in TS 24.380 *[TS24380]*. This class is only associated with a floor machine for use when queueing is enabled in floor control. One can enable queueing in floor control for a particular call, simply by setting the capacity of this queue to a size greater than zero.

The `ns3::McpttQueuedUserInfo` class is used by the `ns3::McpttFloorQueue` class to represent the structure of information needed to store for a user when they are placed in the queue, and made to wait to transmit during floor control.

Helpers

There are four helpers:

- `ns3::McpttHelper` for deploying MCPTT applications,
- `ns3::McpttMsgStats` for tracing transmitted MCPTT application messages,
- `ns3::McpttProseCollisionDetector` for examining ProSe operation, and
- `ns3::McpttStateMachineStats` for tracing state machine state transitions.

As stated previously, the `ns3::McpttHelper` is used to configure and deploy MCPTT applications. This is the class that a user should use to configure settings that will be common across the applications and use it to create several copies of the same configuration.

The `ns3::McpttMsgStats` class has the necessary sink functions to connect to and trace messages sent from app to app. One can set the name of the output file by setting the `ns3::McpttMsgStats::OutputFileName` attribute. The user can also specify which types of messages should be captured. So if a user wanted to capture all message types the user should then set, `ns3::McpttMsgStats::CallControl`, `ns3::McpttMsgStats::FloorControl`, and `ns3::McpttMsgStats::Media` attributes to "true". If the user also wishes to include not just the type of message in the trace but also the contents of the message the user can set `ns3::McpttMsgStats::IncludeMessageContent` to "true" as well.

The `McpttProseCollisionDetector` class is used in the setup delay example for detecting when collisions occur in the PSCCH and PSSCH of the ProSe Sidelink channel.

The `ns3::McpttStateMachineStats` class has the necessary functions to act as a sink to trace state transitions of the various state machines throughout a simulation. One can set the name of the output file by setting the

`ns3::McpttStateMachineStats::OutputFileName` attribute.

Scope and Limitations

Only the logic of the protocols described for call control and floor control were meant to be captured by the current MCPTT model. There is a feature described throughout the call control document called PPPP or Prose Per-Packet Priority that is taken into consideration at the application but is not propagated to the lower layers as specified because currently this feature is not supported by the ProSe model.

1.4.2 User Documentation

Examples

There are three examples in the 'psc/examples' folder:

- `example-mcptt.cc` is a basic scenario with two users deployed randomly using the *SimpleWireless* module which models a very simplistic wireless communications channel for two devices,

- `example-mcptt-prose.cc` is simple as well but is deployed over ProSe instead of the *SimpleWireless* module, and

- `mcptt-setup-delay.cc` is a scenario configured specifically for simulating a single PTT to determine how long it would take a user to join a call or request the floor while communicating over ProSe.

For the setup delay example, one can use the message and state machine traces to compute there own metrics or if the log component `McpttProseExample` is enabled at the "logic" level, the user will see the computed setup delays and reported error cases.

Traces

There are currently only two traces that can be activated by using the `ns3::McpttHelper`, and this can be done by following the example given below, after all the applications have been created.

```
NS_LOG_INFO ("Enabling MCPTT traces...");
mcpttHelper.EnableMsgTraces (); // Enable message trace
mcpttHelper.EnableStateMachineTraces (); // Enable state trace
```

The `ns3::McpttMsgStats` class is used for tracing MCPTT messages at the application layer and produces a file with the default name "mcptt_msg_stats.txt" with the following file format.

```
time(ms)      userid   rx/tx    bytes
```

There may also be an additional field at the end of the row called "message" that will be included if the `ns3::McpttMsgStats::IncludeMessageContent` attribute is set to "true". The "time(ms)" column describes the time (in milliseconds) at which a message was sent/received. The "userid" column contains the user ID of the MCPTT user that sent/received the message. The "rx/tx" column indicates if the message was sent or received, i.e. if "rx" is the value in the column then that means the message was received, while a value of "tx" indicates that the message was sent. The "bytes" columns indicates the size (in bytes) of the message that was generated at the application layer. The "message" column, if present, includes the string representation of the message that was sent and includes message field names and values.

The `ns3::McpttStateMachineStats` is used for tracing state machine state transitions and produces a file with the default name, "mcptt_state_machine_stats.txt", with the following format.

```
time(ms)      userid  callid  typeid  oldstate        newstate
```

The "time(ms)" column describes the time (in milliseconds) at which the state transition took place. The "userid" column contains the user ID of the MCPTT user that the state machine is associated with. The "callid" column contains the ID of the call the state machine is associated with. The "typeid" column contains the string representation of the state machine's `ns3::TypeId`. The "oldstate" column contains the string representation of the `ns3::McpttEntityId` which gives the name of the state that the state machine was in BEFORE the transition took place. And finally, the "newstate" column contains the string representation of the `ns3::McpttEntityId` which gives the name of the state that the state machine was in AFTER the transition took place.

1.4.3 Testing Documentation

The National Institute of Standards and Technology (NIST) used the 3GPP standards to create over 50 test cases. More information about those test cases can be found in NIST technical report NISTIR 8236 *[NIST.IR.8236]*.

LTE D2D MODELS

This chapter is an excerpt of the LTE module documentation chapter, containing the D2D-related models that have been added to the *ns-3* LTE module.

2.1 Design Documentation

2.2 LTE Sidelink

2.2.1 Overview

This section describes the *ns-3* support for LTE Device to Device (D2D) communication based on the model published in *[NIST2016] [NIST2017]*.

3GPP introduced D2D Proximity Services (ProSe) in release 12 to allow ProSe enabled devices to exchange information directly, i.e., without traversing the eNB. Figure *Non-Roaming Reference Architecture* shows new ProSe entities and the new interfaces added to the network *[TS23303]*.

Fig. 2.1: Non-Roaming Reference Architecture

At the time of writing this documentation only the new radio interface, i.e., PC5 is implemented. This interface is also known as Sidelink at physical layer. The model supports all the three following LTE D2D functionalities defined under ProSe services:
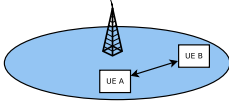
1. Direct communication

2. Direct discovery

3. Synchronization

These LTE D2D functionalities can operate regardless of the network status of the UEs. Thus, four scenarios were identified by 3GPP *[TR36843]*:

1A. Out-of-Coverage

1B. Partial-Coverage

1C. In-Coverage-Single-Cell

1D. In-Coverage-Multi-Cell

At this stage, the model has been tested for scenario 1A and 1C. The Table *ns-3 LTE Sidelink supported/tested scenarios* gives more information about the support of these two scenarios for all the three ProSe services.

Table 2.1: ns-3 LTE Sidelink supported/tested scenarios

#	Description	UE A	UE B	Direct Communication	Direct Discovery	Synchronization	Example
1A	Out-of-Coverage	Out-of-Coverage	Out-of-Coverage	Yes RA = Mode 2	Yes RA = Type 1	Yes Autonomous synchronization	
1C	In-Coverage Single Cell	In-Coverage	In-Coverage	Yes RA = Mode 1 RA = Mode 2	Yes RA = Type 1	Yes Network synchronization	
RA = Resource Allocation							

The model is developed in a way that simulating the above ProSe services are not interdependent. In the following, we describe all the changes introduced in the *ns-3* LTE architecture and its protocol stack to realize Sidelink functionality.

2.2.2 Architecture

eNB architecture

There is no change in the eNB data (fig-ca-enb-data-plane), control (fig-ca-enb-ctrl-plane) plane and neither in its PHY/channel (fig-lte-enb-phy) model.

UE architecture

There is no change in the UE data (fig-ca-ue-data-plane) and control (fig-ca-ue-ctrl-plane) plane. However, in order to receive packets transmitted by other UEs in the uplink channel a new instance of the `SpectrumPhy` class, as shown in Figure *PHY and channel model architecture for the UE*, is added to the PHY/channel architecture of the UE.

NAS

In LTE module, the NAS layer functionality is provided by `EpcUeNas` class. In addition to its existing capabilities, this class has been extended to support LTE ProSe services. In particular, direct communication and direct discovery.
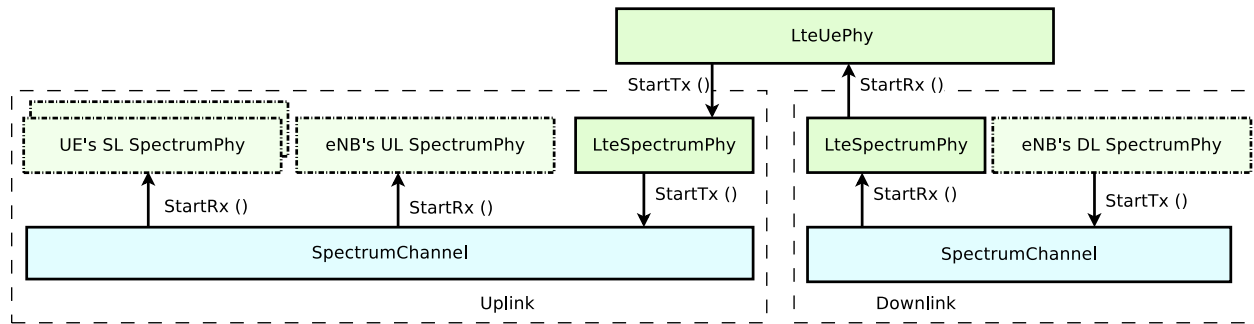
Fig. 2.2: PHY and channel model architecture for the UE

For direct communication, it supports the functions to activate/deactivate Sidelink bearers. Since, there is no EPS bearer for Sidelink communication, the existing TFT can not be used to map IP packets to a Sidelink bearer. Therefore, a new type of TFT, called `LteSlTft` is implemented. It maps IP packets to the Sidelink bearers based only on their destination IP address. Moreover, the `Send` function has been extended for both UE NAS "Active" and "Off" states. In the active state, if there is a Sidelink bearer established between the source and the destination UE, it utilizes Sidelink bearer to send the packet, thus, prioritizing a Sidelink bearer over normal LTE uplink bearer. On the other hand, in off state in which previously UE was unable to send the packets, is now able to use a Sidelink bearer, if established.

For the direct discovery, it conveys the information, e.g., list of discovery applications and the nature of the application, i.e., announcing or monitoring to `LteUeRrc` class.

RRC

The RRC layer has been modified to support all the three ProSe services. Among all the new changes a major modification, which is common in both eNB and UE RRC is the addition of two new classes called, `LteSlEnbRrc` and `LteSlUeRrc`. Both the classes serves a common purpose of holding Sidelink resource pool (i.e, communication and discovery) configuration done through the functions added to the `LteHelper` class. Figures *Relationship between LteEnbRrc and LteSlEnbRrc* and *Relationship between LteUeRrc and LteSlUeRrc* show the relationship between `LteEnbRrc<-->LteSlEnbRrc` and `LteUeRrc<-->LteSlUeRrc` classes.

Note: Only the key responsibilities of the new classes are shown. For complete view of these classes please refer to their class APIs.
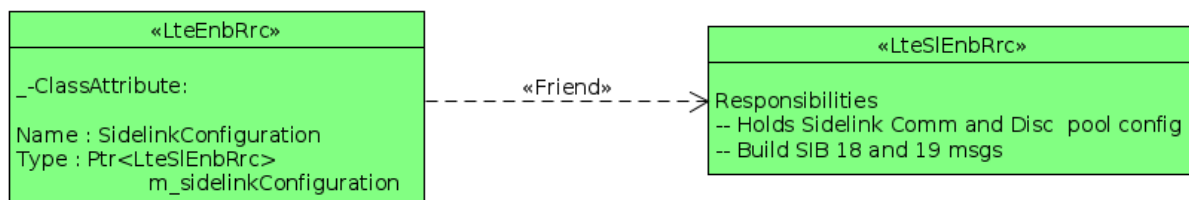
Fig. 2.3: Relationship between LteEnbRrc and LteSlEnbRrc

The following Figure *ns-3 LTE Sidelink pool configuration flow* shows the interaction among the classes to configure a Sidelink pool.

The Sidelink pools, for both in-coverage and out-of-coverage scenarios are configured through the user's simulation script. Moreover, all the RRC SAP classes, i.e., control and data including the `LteRrcSap` class have been extended to support Sidelink functionalities.

In the following we will explain the remaining modifications specifically introduced in the eNB and UE RRC layer.
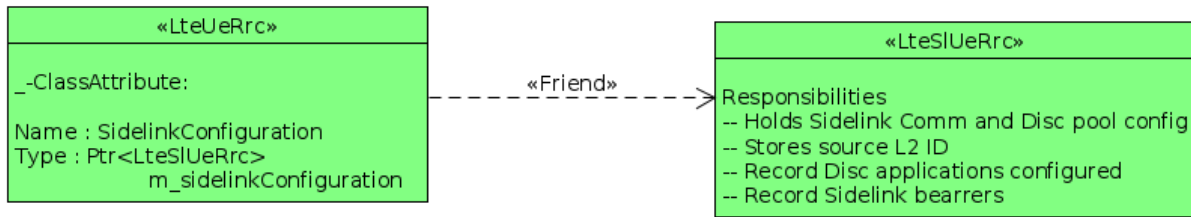
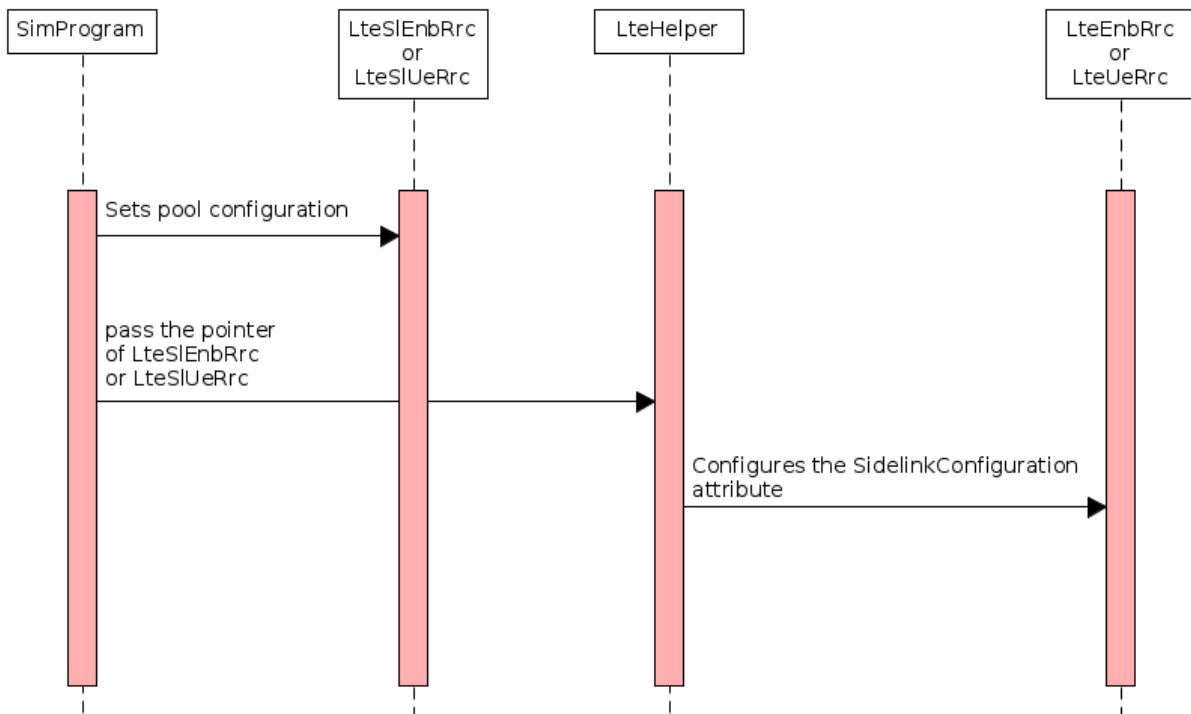Fig. 2.4: Relationship between LteUeRrc and LteSlUeRrc

Fig. 2.5: ns-3 LTE Sidelink pool configuration flow

eNB RRC

To support in-coverage Sidelink scenarios, SIB18 and SIB19 were added to broadcast Sidelink resource pool configuration for communication and discovery respectively. For simplicity, we use the same periodicity (default : 80 ms) of all the SIB messages, which could be configured by changing the attribute `SystemInformationPeriodicity` value. The resource pools are configured through `LteHelper` as discussed earlier. Similar to other SIB messages, SIB18 and SIB19 are defined in `LteRrcSap class`. By receiving these SIB messages, a UE can deduce the type of ProSe service an eNB can support. The eNB is also now capable of processing `SidelinkUeInformation` messages sent by the UEs [TS36331]. In general, this type of message contains information related to the frequency UE is intended to use for Sidelink, resources required by the UE for Sidelink communication or discovery and a list of destination identities, i.e., group ids. We note that, **at this moment only one Tx/Rx pool and one group per UE** is supported. In response to the `SidelinkUeInformation`, eNB sends an `RrcConnectionReconfiguration` message containing the resource allocation information as per the supported ProSe services. In case of in-coverage Sidelink communication, resource allocation is performed as per MODE1, which is also reffered as `Scheduled` mode *[TR36843]*. In this mode, the `RrcConnectionReconfiguration`, as per the standard, includes the specifications of the pool to be used and the timing specification for Sidelink Buffer Status Report (SL-BSR) transmission and re-transmission. On the other hand, if the pool is for MODE 2, i.e., `UeSelected` mode, it only includes the dedicated pool specifications.

For the in-coverage discovery, only `Type1`, i.e. UE selected resource allocation is supported.

UE RRC

The `LteUeRrc` class has been extended to support all the ProSe services for both, in-coverage and out-of-coverage mode. To highlight all the modifications, lets discuss them in context of each ProSe service.

Sidelink direct communication

The UE RRC now supports the creation of Sidelink bearers for both in-coverage and out-of-coverage scenarios. A new function `DoActivateSidelinkRadioBearer` is implemented for this purpose. If the configuration of the TFT used indicates the nature of the Sidelink radio bearer as''Bidirectional'', the creation of Sidelink bearers for Tx and Rx, which is to populate the Tx/Rx pool configuration along with the list of destinations to the lower layers, occurs at the same time. Only the creation of PDCP/RLC instances for TX bearer is done in `DoActivateSidelinkRadioBearer` function. The creation of PDCP/RLC instances for Rx occurs upon the reception of first Sidelink packet [TS36300]. For the in-coverage case, the bearer establishment procedure involves the communication with the eNB by sending `SidelinkUeInformation` message for the sake of resource allocation as shown in Figures *ns-3 LTE Sidelink in-coverage radio bearer activation (Tx)* and *ns-3 LTE Sidelink in-coverage radio bearer activation (Rx)*.

For the out-of-coverage scenario, the Sidelink bearer activation and the resource allocation is done by the UE autonomously. Figure *ns-3 LTE Sidelink out-of-coverage radio bearer activation (Tx)* and *ns-3 LTE Sidelink out-of-coverage radio bearer activation (Rx)* show sequence diagrams of the out-of-coverage Sidelink bearer activation for TX and RX respectively.

As mentioned earlier, the UE RRC is now also capable of processing new SIB18 message and the Sidelink direct communication configuration received in `RrcConnectionReconfiguration` message. For in-coverage scenarios, resource allocation can be done in MODE 1 and MODE 2. In MODE 1, the resources are set to "Scheduled" and the eNB is responsible of scheduling the exact number of resources (i.e., with the help of the scheduler), while in MODE 2, resources are "UeSelected" and a UE receives only one dedicated resource pool through `RrcConnectionReconfiguration` message to choose the resources from [TS36331]. By standard the SIB18 message is used as an indicator that an eNB supports ProSe communication services, thus, the UE transmits `SidelinkUeInformation` if it has received SIB18 message. A UE in "IDLE_CAMPED_NORMALLY" or in

Fig. 2.6: ns-3 LTE Sidelink in-coverage radio bearer activation (Tx)

EpcUeNas	LteUeRrc	LteSlUeRrc	LteUeMac0	LteUePhy0	LteEnbRrc

Prior to the establishment of Sidelink radio bearer UE Rrc has received SIB18 and has populated the Sidelink Rx pool information to UE MAC and PHY by calling SetSlRxPools(pool).

ActivateSidelinkRadio
Bearer (group, tx, rx)

LteUeRrc::DoActivate
SidelinkRadioBearer
function

alt
[if (rx)]

AddSlDestination
(group)

AddSlDestination
(group)

SendSidelinkUeInforma
tion ()

SendRrcConnectionRec
onfiguration (rnti, msg)

LteUeRrc::DoRecvRrcC
onnectionReconfiguration
function

ApplySidelinkDedicate
dConfiguration (msg)

ApplySidelinkDedicated
Configuration
function

RemoveSlTxPool ()

ReceivePhyPdu
(Ptr<Packet> p)

LteUeMac::
DoReceivePhyPdu
function

NotifySidelinkRecep
tion (lcid, srcL2Id,
dstL2Id)

LteUeRrc::
DoNotifySidelink
Reception function

AddSlrb (srcL2Id,
dstL2Id, lcid)

AddSlrb function

Also
creates
PDCP/RLC
instances

NotifySidelinkReception
(lcid, srcL2Id, dstL2Id)

AddSidelinkRadioBearer
(slbInfo)

AddLc (lcid, srcL2Id,
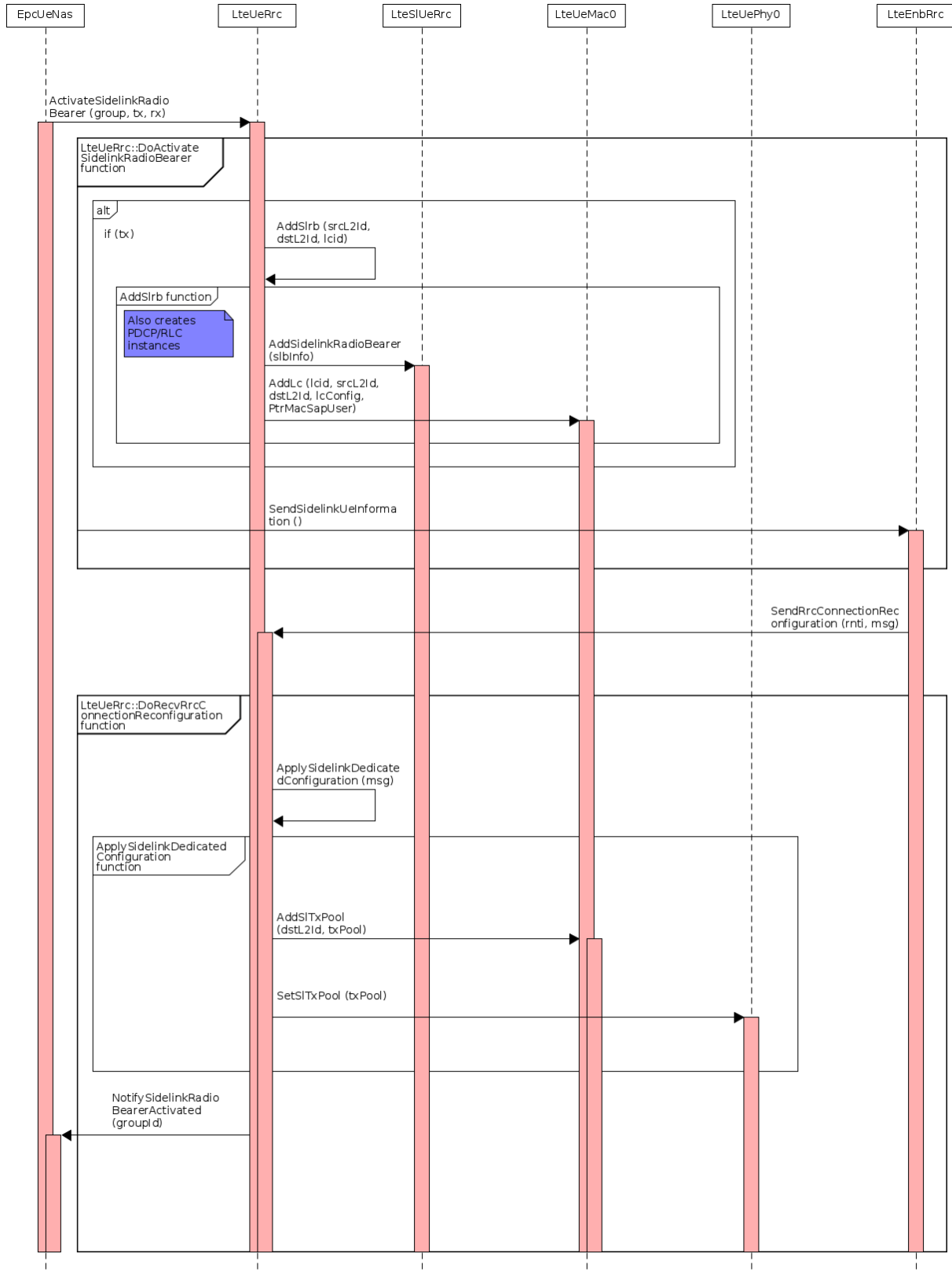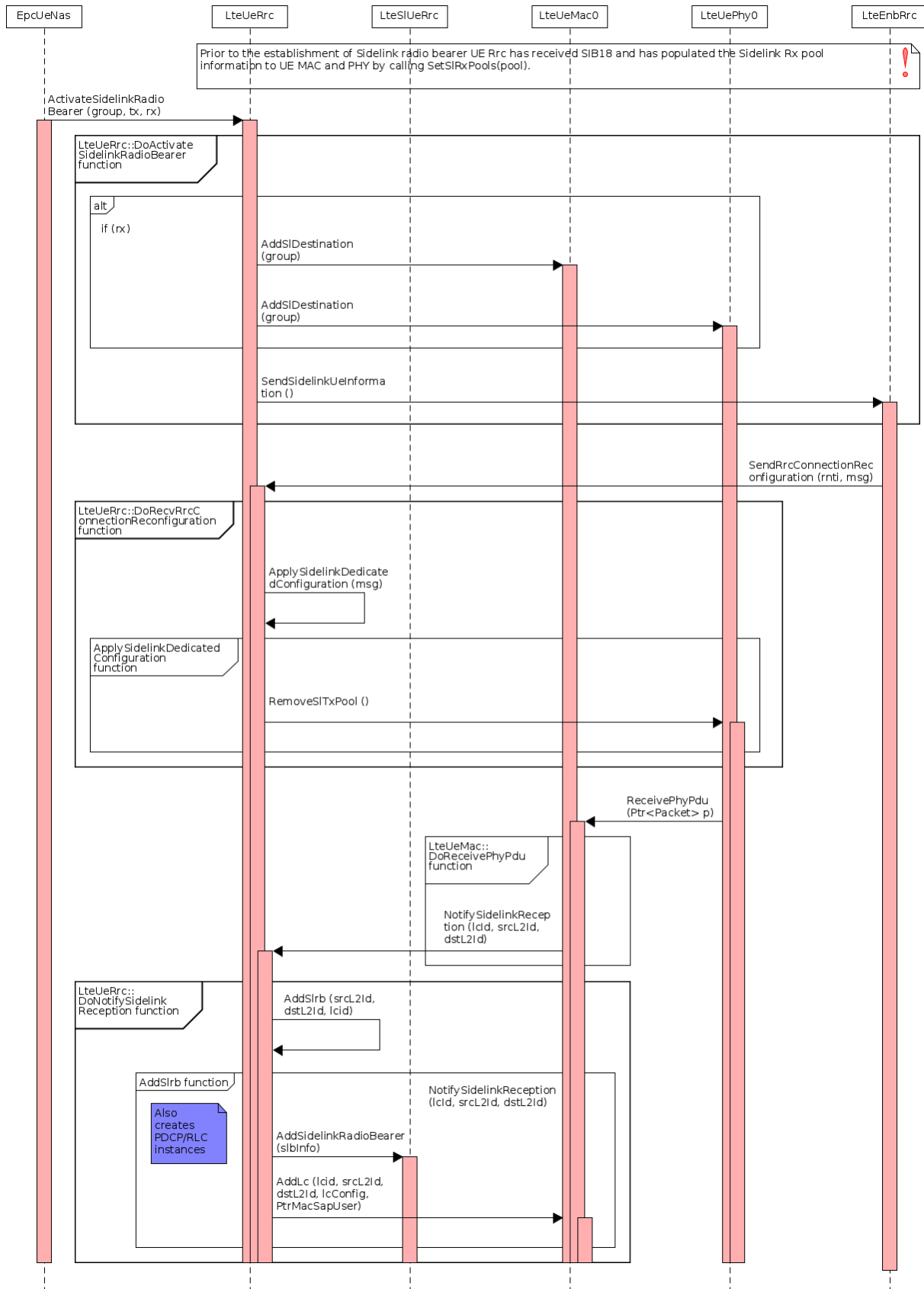dstL2Id, lcConfig,
PtrMacSapUser)

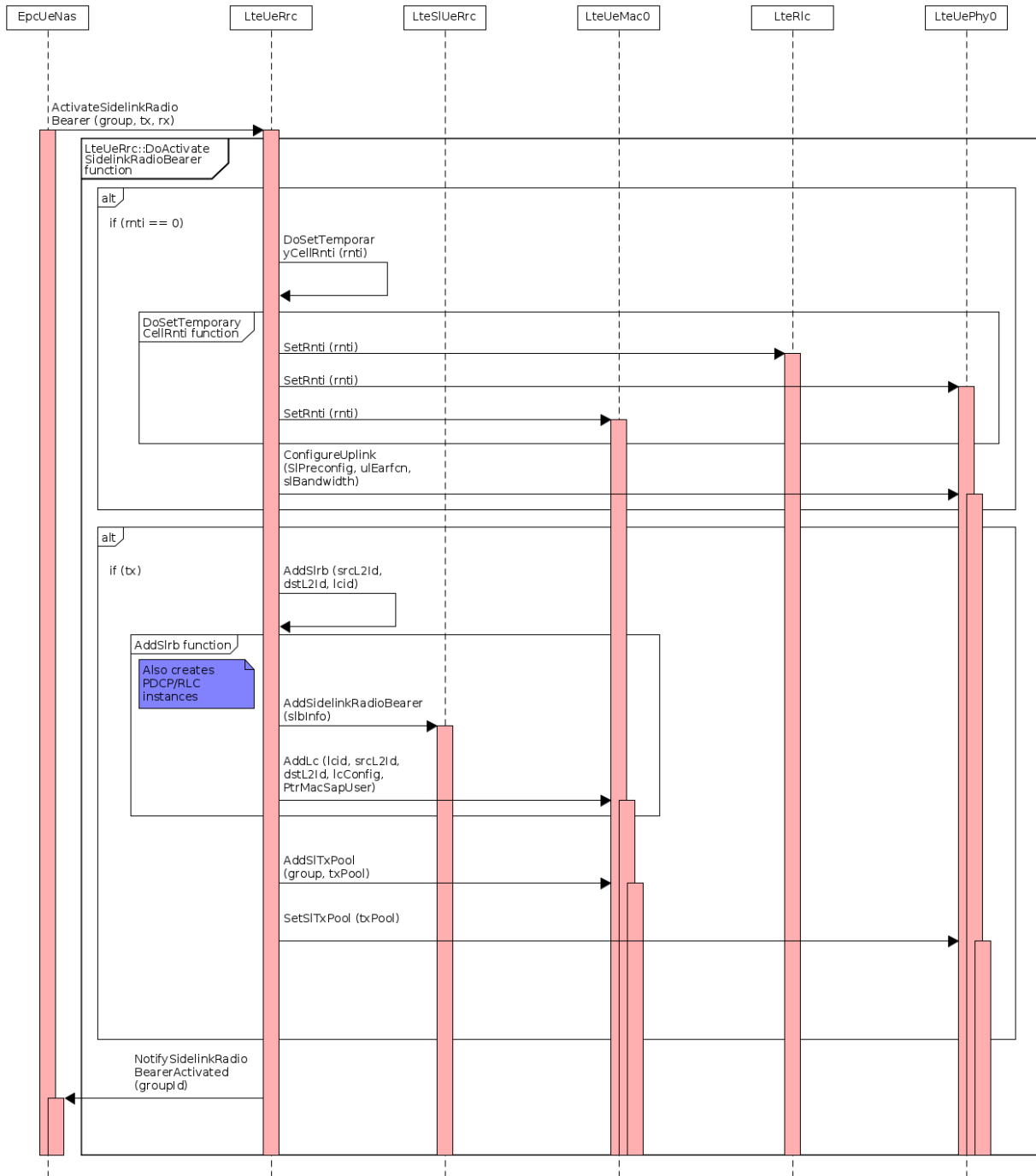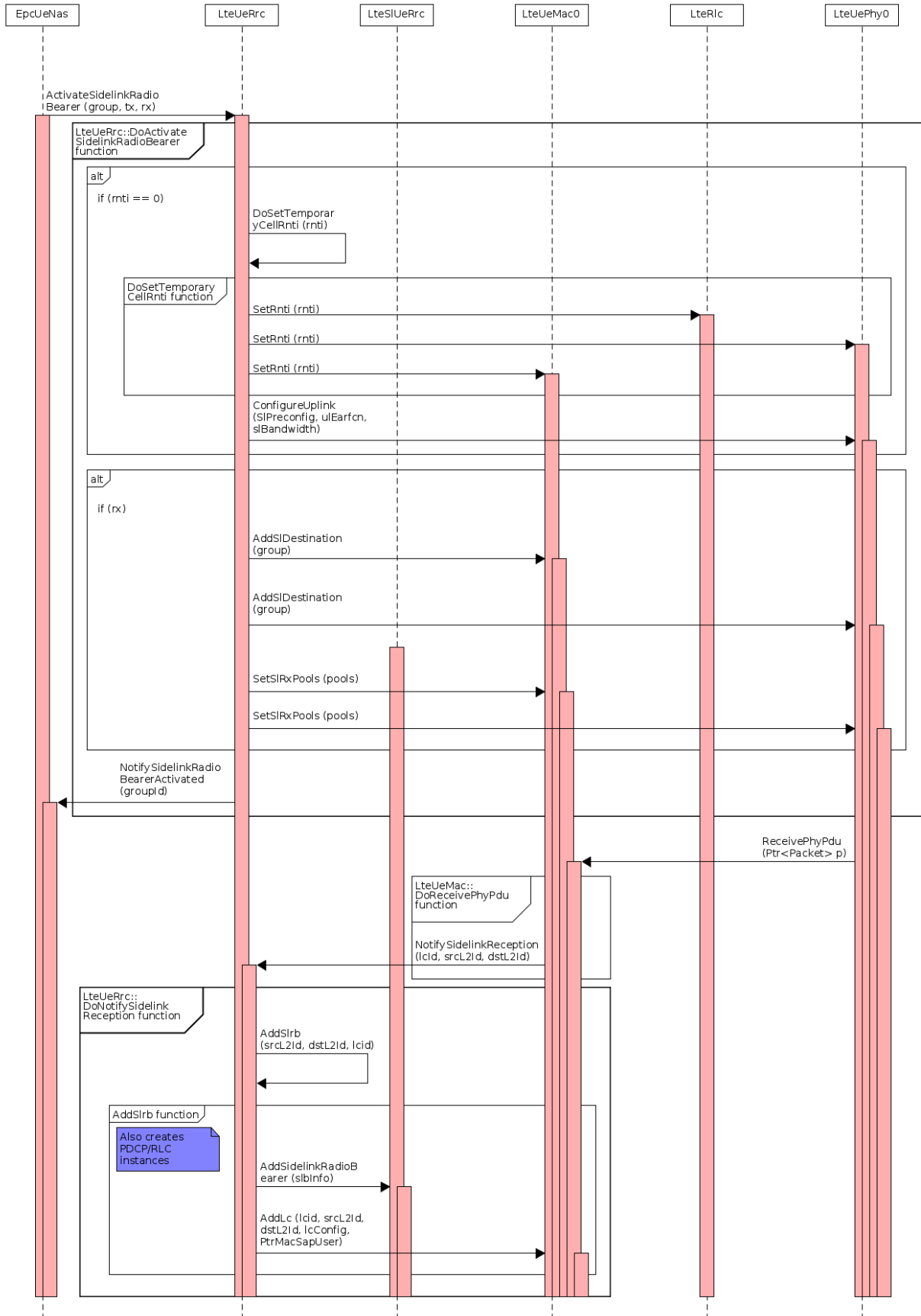Fig. 2.8: ns-3 LTE Sidelink out-of-coverage radio bearer activation (Tx)

Fig. 2.9: ns-3 LTE Sidelink out-of-coverage radio bearer activation (Rx)

"CONNECTED_NORMALLY" is able to receive SIB18 messages, upon which, Rx pools are updated and also populated to the MAC and PHY layers. On the other hand, if the UE is out-of-coverage it uses a pre-configured pool and MODE 2 for resource allocation.

Sidelink direct discovery

For the Sidelink discovery, `LteUeRrc` class now supports creation/removal of discovery applications for both in-coverage and out-of-coverage scenarios. This procedure triggers the process of conveying the list of applications and the resource pool configuration to the lower layers (Tx or Rx depending on type of discovery application). Similar to the direct communication, for in-coverage scenario, this process triggers the communication with the eNB by transmitting the `SidelinkUeInformation` message for resource allocation, followed by the eNB `RrcConnectionReconfiguration` message. An in-coverage UE only transmits `SidelinkUeInformation` if it has received SIB19 message. We note that, for in-coverage scenario, "Scheduled" mode is not supported yet. The model supports only `Type1`, i.e., "UeSelected" resource allocation. An in-coverage UE can receive a list of multiple pools (only 1 pool is supported now) with the criteria of selection either `RANDOM` or `RSRSPBased` via the `RrcConnectionReconfiguration` message. A UE in "IDLE_CAMPED_NORMALLY" or in "CONNECTED_NORMALLY" is able to receive SIB19 messages, upon which, Rx pools are updated and also populated to the MAC and PHY layers. On the other hand, in out-of-coverage scenarios, the UE only uses the pre-configured pool.

Note: At this stage only one pool is supported

Sidelink synchronization

The `LteUeRrc` class holds the main implementation for performing Sidelink synchronization. In particular, it supports

- Activation/Deactivation of Sidelink Synchronization Signal (SLSS)

- The configuration of the SLSS

- Delivering of the configured SLSS to phy layer for transmission

- Reception and L3 filtering of the SLSS from other UEs

- Selection of a Synchronization Reference UE (SyncRef)

- Notification of SyncRef change to the lower layers

By setting the attribute `UeSlssTransmissionEnabled == true` enables the transmission of SLSS. The purpose of synchronization process is to align the frame and subframe number of a UE with a SyncRef. An SLSS from a SyncRef is considered detectable if;

$$SRSRP_{strongestSyncRef}[dBm] - MinSrsrp[dBm] > syncRefMinHyst[dB] \qquad (2.1)$$

$MinSrsrp$ is the minimum threshold for detecting SLSS configured using `MinSrsrp` attribute of `LteUeRrc` class and $syncRefMinHyst$ is the pre-configured hysteresis value, which could be configured from the user's simulation script. In case more than one SyncRefs are detected during a scanning period (Refer to the UE phy section below for details), a SyncRef with the highest Sidelink RSRP (S-RSRP) is selected. Upon re-selection of the SyncRef, if a better SyncRef is detected the UE selects this new SyncRef if;

$$SRSRP_{NewStrongestSyncRef}[dBm] - SRSRP_{OldStrongestSyncRef}[dBm] > syncRefDiffHyst[dB]$$

where $syncRefDiffHyst$ is a threshold representing how higher the S-RSRP of the newly detected SyncRef should be than the currently selected SyncRef's S-RSRP to consider a change. On the other hand, if the S-RSRP of the

previously selected SyncRef satisfies the (2.1) and its S-RSRP is greater than a pre-configured $syncTxThreshOoC$ (i.e. out-of-coverage synchronization threshold) [TS36331] the SyncRef is considered as valid till the next re-selection.

In case, the previously selected SyncRef is not valid anymore and no other SyncRef has been detected, the UE itself becomes a SyncRef by choosing SLSS-ID and the Sidelink synchronization offset indicator. Different from the standard [TS36331], the current implementation for the sake of simplicity selects a SLSS-ID as `SLSS-ID = IMSI * 10`, while the synchronization offset indicator, as per the standard, is randomly selected between the two pre-configured offsets, i.e., `syncOffsetIndicator1` and `syncOffsetIndicator2`. We note that, when a Synchronization process is followed by ProSe group communication or discovery, a UE could only be able to receive a message from other UE, if they have same SLSS-ID and the group id is known to the receiving UE. However, when simulating only ProSe communication or discovery the SLSS-ID of all the UEs are initialized to 0 and the UE receives the transmission if the group id is known. Moreover, the transmission of the SLSS is subjective to the data transmission by the UE. At the beginning of every Sidelink Control (SC) period, a notification by the UE MAC layer is sent to the UE RRC, indicating if there is data to be transmitted. The function `DoNotifyMacHasSlDataToSend` and `DoNotifyMacHasNoSlDataToSend` of `LteUeRrc` class serve this purpose. If there is no data to be transmitted the UE stops transmitting the SLSS.

PDCP

The `LtePdcp` class has been extended to include ProSe source Layer 2 ID and the ProSe Layer-2 Group ID to identify the PDCP/RLC pair to be used in the receiving UE. The reason is that in Sidelink, each radio bearer is associated with one PDCP entity. And, each PDCP entity is associated to one RLC entity, since it uses RLC-UM mode for the transmission / reception [TS36323]. Thus, given the nature of Sidelink communication, i.e., one to many, it may happen that multiple UEs transmit to a single UE, assigning LCIDs independently. It may happen that two UEs select same LCID for the same group. Therefore, for a receiving UE to distinguish between two Sidelink Radio bearers (SLRBs) with the similar LCIDs requires additional identifiers.

RLC

Similar to the PDCP layer, the RLC layer now has ProSe source Layer 2 ID and the ProSe Layer-2 Group ID. This is achieved by extending the structure of `TransmitPduParameters` of `LteMacSapProvider` class. As mentioned earlier, only RLC-UM mode is used for Sidelink. Moreover, `LteRlcUm` class is also extended in accordance to the specification define in section 7.1 of [TS36322]. It says that "For RLC entity configured for Sidelink Traffic Channel (STCH), the state variables `VR(UR)` and `VR(UH)` are initially set to the SN of the first received PDU". A new attribute named "ChannelType" is introduced, which is set to type `STCH` for Sidelink.

MAC

Among the following eNB and UE specific enhancements for ProSe, one of the important change, irrespective of the eNB or UE implementation, is the limitation to the maximum frame number, which is now set to 1024. This is because all the computations to determine correctly the boundaries of ProSe communication and discovery periods and their resource allocation considers the maximum frame number to be 1024. This limitation also helps us to implement the rollover constraints more accurately, e.g., to have a configurable offset to be applied at the beginning of each communication and discovery periods. This change mainly impacted all the schedulers. In particular, every scheduler maintains a map of uplink resource allocation using the SFnSF (i.e., combination of frame and subframe number) as an unique key to update the PUSCH based CQIs. By limiting the frame number to 1024, means that a combination could repeat after 10 sec of simulation, thus, a c++ map would not allow to insert new allocation information with the same SFnSF combination. To handle this, we appropriately remove any old allocation information before inserting a new one.

eNB Mac

`LteEnbMac` has been extended to support in-coverage ProSe communication, i.e., Mode 1 resource allocation. The SAP between the `LteEnbRrc` and `LteEnbMac` is extended to receive the pool configuration to be conveyed to the scheduler to schedule the resources. If the type of resource allocation for the configured resource pool is `Scheduled` the eNB MAC is now capable of receiving Sidelink Buffer status Report (SLBSR) from the UEs. To achieve this, the `structure MacCeListElement_s` in `ff-mac-common.h` file is extended to support BSR of type SLBSR. The reporting of the BSR in uplink is the same as shown in Figure fig-ca-uplink-bsr. To handle the scheduling of Sidelink resources for MODE 1, a scheduler `RrSlFfMacScheduler` based on the existing Round Robin implementation is also provided. Thus, making it the only scheduler, for the time being, in LTE module capable of supporting Sidelink and normal LTE resource scheduling. It also makes sure that Sidelink and the uplink resources are not scheduled in the same subframe.

For Sidelink discovery, as stated before, the "Scheduled" mode is not implemented yet.

UE Mac

The `LteUeMac` is extended to support all the three ProSe services. In the following we explain these extensions in context of each ProSe service.

Sidelink direct communication

The UE MAC is now capable of receiving the RLC buffer status notifications with extended Sidelink identifiers, i.e., laye 2 source and destination ids. A tuple `SidelinkLcIdentifier` of `LteUeMac` holds the LCID, SrsL2Id and DstL2Id, which is then used as a key for a c++ map storing all the buffer status notifications from RLC layer. For "Scheduled" resources, i.e., MODE 1, a UE is now capable of processing the Sidelink DCI (i.e., DCI 5 [TS36212]) message containing the resource allocation information for PSCCH and PSSCH transmissions. A UE for transmitting PSCCH uses the PSCCH resource indicated in the SL DCI from the eNB. To ensure the reliability of Sidelink Control information (SCI), each control message is transmitted twice using two different subframe, each utilizing 1 RB belonging to the configured resource block pool [TS36213]. Thus, supporting 2 PSCCH transmissions per grant. While the PSSCH (i.e. Data) transmissions are computed asper the current frame and subframe number and the information including in the SL DCI, i.e., Time Resource Pattern Index (iTrp), Starting RB index and the total number of RBs to be used. Since there are no HARQ feedbacks in Sidelink PSSCH, each transport block is transmitted using 4 HARQ transmissions (i.e., RV = 4). Hence, for each grant every transport block is transmitted using 4 subframes.

On the other hand, for the "UeSelected" resource scheduling, i.e., MODE 2, `LteUeMac` now have following new attributes:

- Ktrp
- SetTrpIndex
- SlGrantMcs
- SlGrantSize

Where Ktrp and SetTrpIndex are used to specify the number of active subframes and the index of the TRP respectively [TS36213]. The last two attributes are used to specify the MCS and the number of RBs (per subframe) to be used for Sidelink transmissions. Different from the "Scheduled" mode, in "UeSelected" mode a UE chooses a random PSCCH resource among the available resources and similarly transmits twice using two subframes. While for transmitting PSSCH it uses a pre-configured pool configuration to determine RBs and subframe for 4 PSSCH transmissions. Moreover, upon the reception of a PHY PDU the `LteUeMac` class is now able to notify UE RRC to establish a Sidelink radio bearer for the reception.

Sidelink direct discovery

In case of direct discovery, the `LteUeMac` class is responsible of creating and scheduling the discovery messages. It is `LteUeMac` class where ProSe APP code is assigned to each announcing discovery application and then is embedded in the discovery messages. We note that, the discovery messages are modeled as control messages. Each discovery message can be retransmitted up to 3 times. The number of retransmissions is provided by the eNB with the pool configuration if the UE is in-coverage, or is specified by the pre-configured pool configuration for out-of-covergae scenarios. Each discovery message occupies 2 contiguous RBs in a subframe belonging to the assigned pool.

Sidelink synchronization

For the Sidelink synchronization, `LteUeMac` receives notification from `LteUePhy` upon change of time, i.e, change of frame and subframe number when a new SyncRef is selected.

PHY

eNB PHY

The LTE module of *ns-3* at the time of writing this documentation does not support Radio Link Failure (RLF) functionality. Therefore, to simulate out-of-coverage scenarios a workaround has been implemented to disable eNB PHY layer. An eNB can be disable by configuring the attribute "DisableEnbPhy" of `LteHelper`.

UE PHY

As shown in Figure *PHY and channel model architecture for the UE*, to receive the Sidelink transmission in the uplink channel the `LteUePhy` includes an additional `LteSpectrumPhy` instance. In particular, the function `DoConfigureUplink`, which is called by `LteUeRrc` is responsible of adding this new instance to the channel. The `LteUePhy` class is extensively edited to support all the three ProSe services.

Sidelink direct communication

The `LteUePhy` is now capable of receiving and transmitting Sidelink control messages. In particular, DCI format 5, and SCI format 0 is now supported [TS36212]. The UE PHY receives the information related to the Sidelink communication pool from the UE RRC in order to compute the boundaries of an SC period to correctly map the frame/subframe and the RBs associated with the PSCCH and PSSCH. At the beginning of each subframe, it checks if the Sidelink transmission pool is added, it make sure to initialize it in order to compute exactly the frame and subframe number of the next SC period. This is needed to remove the Sidelink transmission grant associated to the previous SC period, since a grant is valid only for one SC period.

Sidelink direct discovery

For the discovery, the `LteUePhy` now also supports the transmission and reception of the discovery messages. The discovery message structure is implemented as per *[TS24334]* with two additional identifiers, i.e., UE RNTI and the PSDCH resource number. We note that, the discovery message is modeled as a broadcast control message, thus, is received by every UE. Similar to the direct communication, the UE PHY receives the information related to the Sidelink discovery pool from the UE RRC in order to compute the boundaries of a discovery period to correctly map the frame/subframe and the RBs associated with the PSDCH. At the beginning of each subframe, it checks if the discovery transmission pool is added, it make sure to initialize it in order to compute exactly the frame and subframe

number of the next discovery period. A UE upon the reception of a discovery message, simply passes it to the MAC layer, which in turn delivers it to the RRC for further filtering.

Sidelink synchronization

The `LteUePhy` is extended to support Sidelink synchronization functionality. In particular, it supports:

- Transmission and reception of SLSS
- Scheduling of SLSS scanning periods
- Measuring S-RSRP and reporting it to the RRC layer
- Synchronizing to the chosen SyncRef
- Performing change of timing
- Scheduling of the SyncRef re-selection process

In the current implementation, all the UEs by default are perfectly synchronized, i.e., all the UEs in a simulation upon being initialized pick the same frame and subframe 1 to start with. Therefore, to simulate synchronization and to make every UE to pick a random frame and subframe number a new attribute "UeRandomInitialSubframeIndication" is introduced. We note that, in our model a UE being synchronized to a SyncRef refers to a state, where both the UEs have similar SLSS-ID and are aligned on frame and subframe level. The SLSS is represented by MIB-SL, which is modeled as a broadcast control message. MIB-SL is implemented as per the standard, [TS36331], with additional metadata fields: SLSSID, MIB-SL creation time, MIB-SL reception time and the reception offset. The S-RSRP of the SLSS received by a UE is computed as explained in the section sec-phy-ue-measurements. Only those SLSS are considered detected, which have the S-RSRP greater than the configured minimum S-RSRP and for which MIB-SL has been decoded successfully. The minimum S-RSRP is configured through the attribute "MinSrsrp". The modeled synchronization process can be categorized by three sequential processes:

1. Scanning
2. Measurement
3. Evaluation

To tailor these processes, the following new attributes have been introduced in the `LteUePhy` class.

- UeSlssScanningPeriod
- UeSlssInterScanningPeriodMin
- UeSlssInterScanningPeriodMax
- UeSlssMeasurementPeriod
- UeSlssEvaluationPeriod
- NSamplesSrsrpMeas

For more information about these attributes the reader is referred to the API of `LteUePhy` class. After the scanning process, only 6 detected SycRefs with the highest S-RSRP are measured during the measurement period. Moreover, if a UE receives multiple SLSS from different UEs but have the same SLSS-ID and the reception offset, they are considered as different S-RSRP samples of the same SyncRef. The start of the measurement and evaluation processes are subject to the detection of at least 1 SynchRef during the scanning process. At least one SyncRef selection process within 20 seconds is scheduled as per the standard [TS36331]. The MIB-SL is transmitted with a fixed periodicity of 40 ms [TS36331]. The `LteUeRrc` class is responsible of scheduling and delivering the MIB-SL to `LteUePhy` class. Once a suitable SyncRef is selected, the change of timing is performed upon subframe indication, i.e., before the next subframe to avoid any miss alignments. We also note that the transmission of a MIB-SL has priority over the transmission of SCI, if they are scheduled in the same subframe. On the other hand, an MIB-SL can not be transmitted if a SyncRef scanning or measurement process is in progress. The `LteUeMac` and `LteUeRrc` class are

notified about the successful change of timings using the existing SAP interfaces, i.e., `LteUeCphySapUser` and `LteUePhySapUser` respectively.

LteSpectrumPhy

As mentioned before, the `LteUePhy` class includes an additional `LteSpectrumPhy` instance to receive Sidelink transmissions from other UEs. Therefore, new functions are implemented in `LteSpectrumPhy` class to relay the received Sidelink transmission to the `LteUePhy` class. To model the half duplex for Sidelink, since it is difficult for the UE to receive and transmit at the same time using the same frequency, a new attribute "CtrlFullDuplexEnabled" is introduced. This attribute is "false" by default, thus, all the Sidelink simulations are performed using half duplex mode. To notify `LteUePhy` about the reception of SLSS a new function `SetLtePhyRxSlssCallback` is implemented, which is hooked to the `ReceiveSlss` fucntion of `LteUePhy` through a callback, while installing UE devices in the `LteHelper` class. For other Sidelink signals, i.e., control and data the already implemented callbacks are utilized.

The `LteSpectrumPhy` class is still responsible for evaluating the TB BLER, however, with the introduction of new physical Sidelink channels, i.e., PSCCH, PSSCH, PSDCH and PSBCH a new physical error model `LteNistErrorModel` is implemented. This error model uses the BLER vs SNR curves for LSM from *[NISTBLERD2D]*, for all the Sidelink physical channels. In particular, these curves are obtained by extending the LTE toolbox in Matlab and performing Monte Carlo simulations by considering AWGN channel and SISO mode for transmission. In the following, we plot these curves for each Sidelink physical channel.
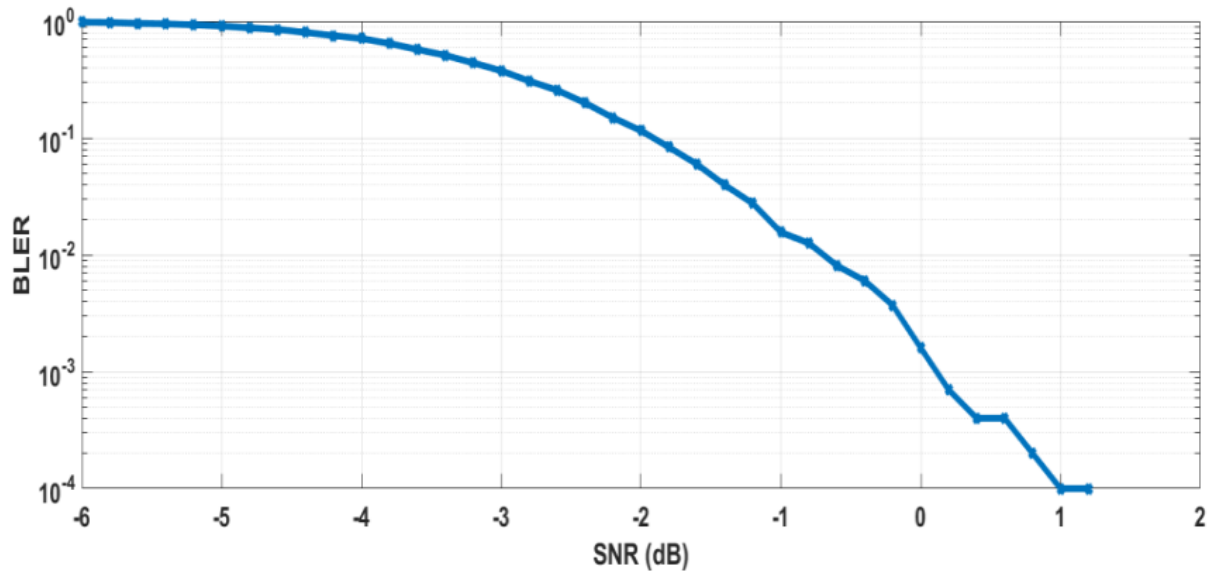
Fig. 2.10: BLER vs SNR of PSCCH (First transmission)

Different from the already existing error models, e.g., `LteMiErrorModel`, which uses the Mutual Information Based Effective SINR (MIESM) technique for soft combining process sec-data-phy-error-model, the `LteNistErrorModel` uses a weighted averaging algorithm explained in *[NISTBLERD2D]* for this purpose. Therefore, a new class `LteSlHarq` is implemented to store the SINR values of each Sidelink transmission that is used for soft combining process of the retransmission. It is to be noted that, as per the standard, no HARQ feedback is available for any Sidelink physical channels. Moreover, to handle interference in D2D scenarios, since all the Sidelink physical channels employ broadcast solution, a new interference model is implemented. This is needed because unlike LTE implementation in which unwanted signals are filtered on the basis of a cell id embedded in transmitted/received `LteSpectrumSignalParameters`, for D2D scenarios two signals received at the same time could be intended for a single UE. This overlapping of signal could occur in out-of-coverage scenarios, where two UEs pick an identical resource to transmit. To tackle such conditions two new classes, `LteSlInterference` and

Fig. 2.11: BLER vs SNR of PSBCH

Fig. 2.12: BLER vs SNR of PSDCH

Fig. 2.13: BLER vs SNR of PSSCH (HARQ 1)

Fig. 2.14: BLER vs SNR of PSSCH (HARQ 2)

Fig. 2.15: BLER vs SNR of PSSCH (HARQ 3)

Fig. 2.16: BLER vs SNR of PSSCH (HARQ 4)

`LteSlChunkProcessor` are implemented.

The `LteSpectrumPhy` class, at the time of reception maintains a vector to store the information about the received signal(s). These signals including the overlapping ones (i.e., they occur at the same time and have e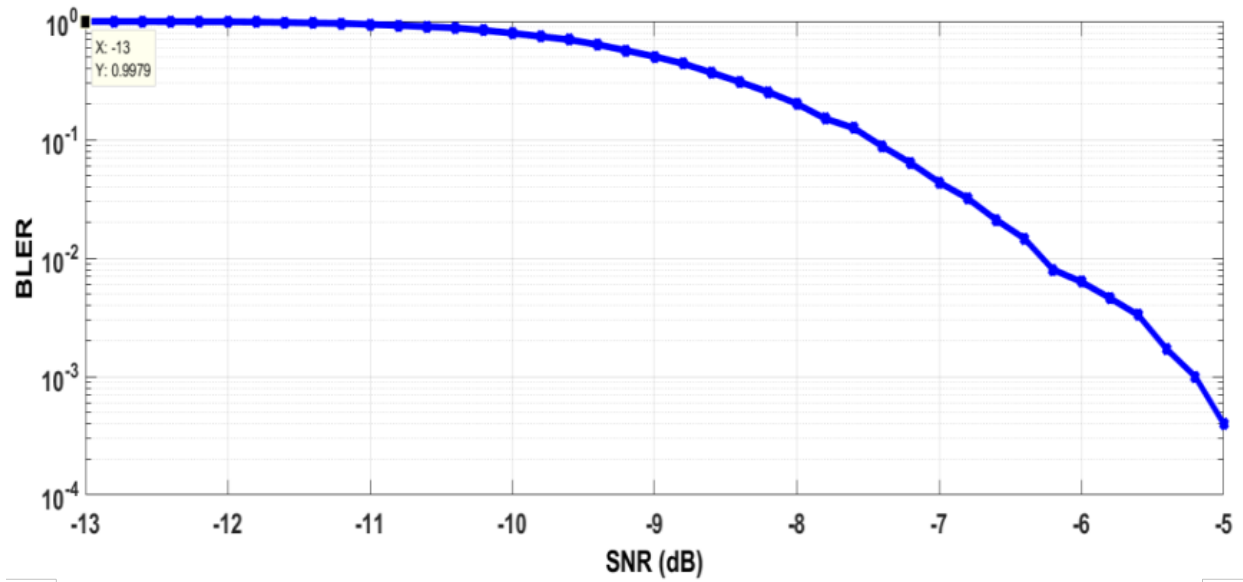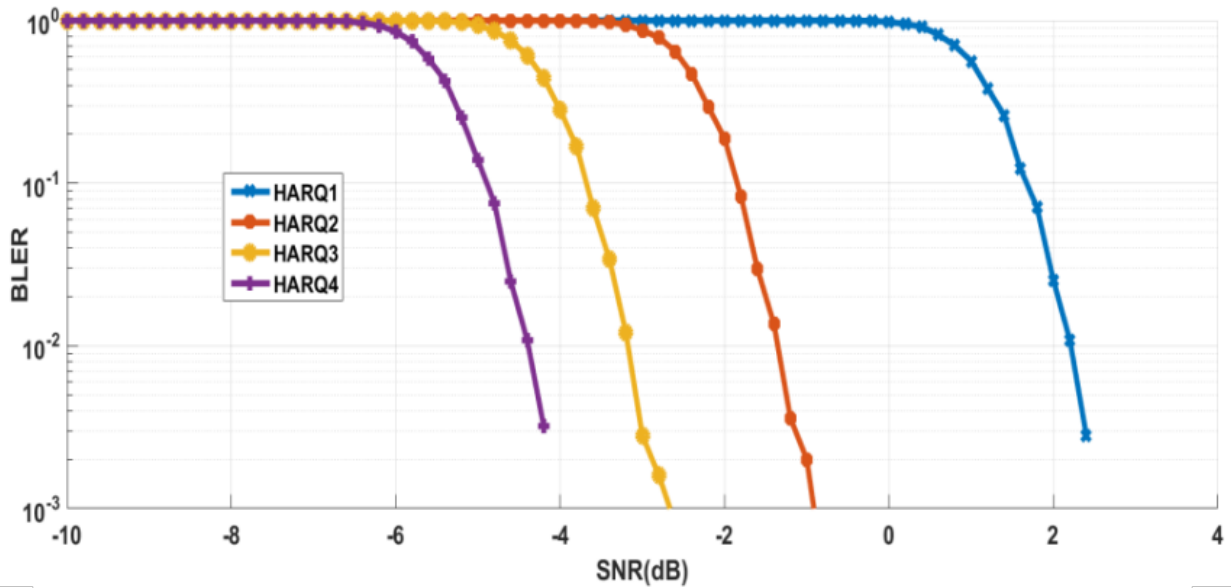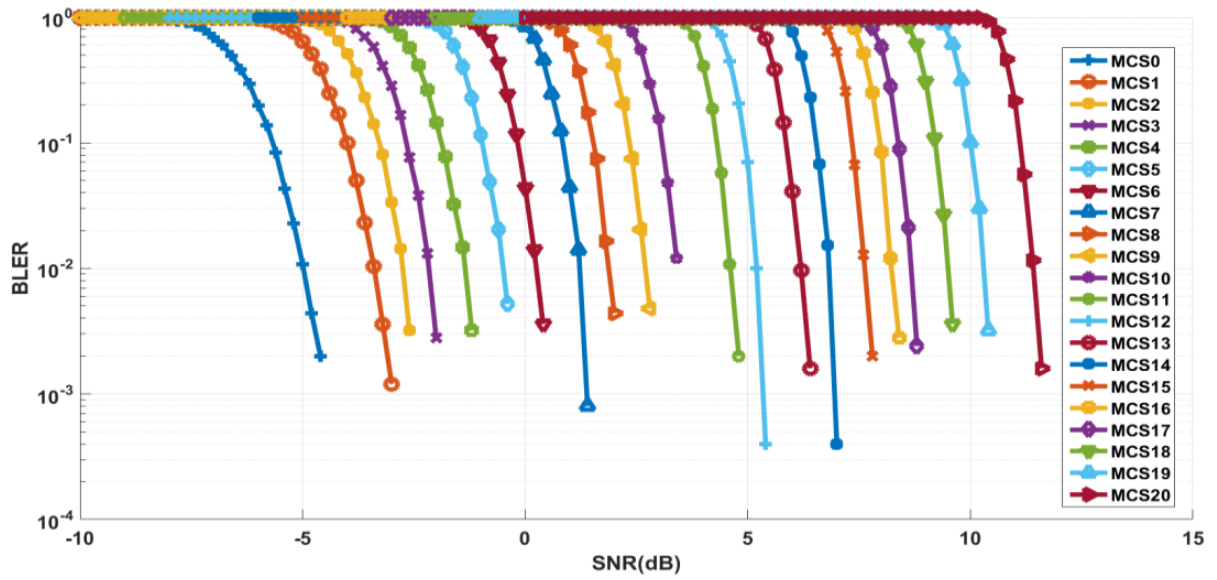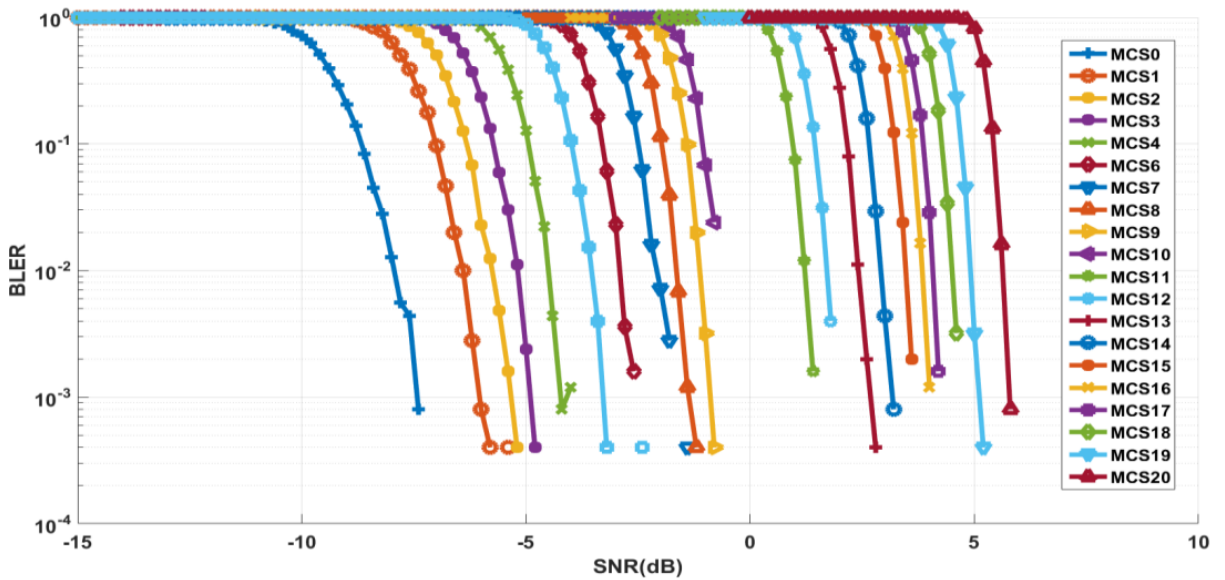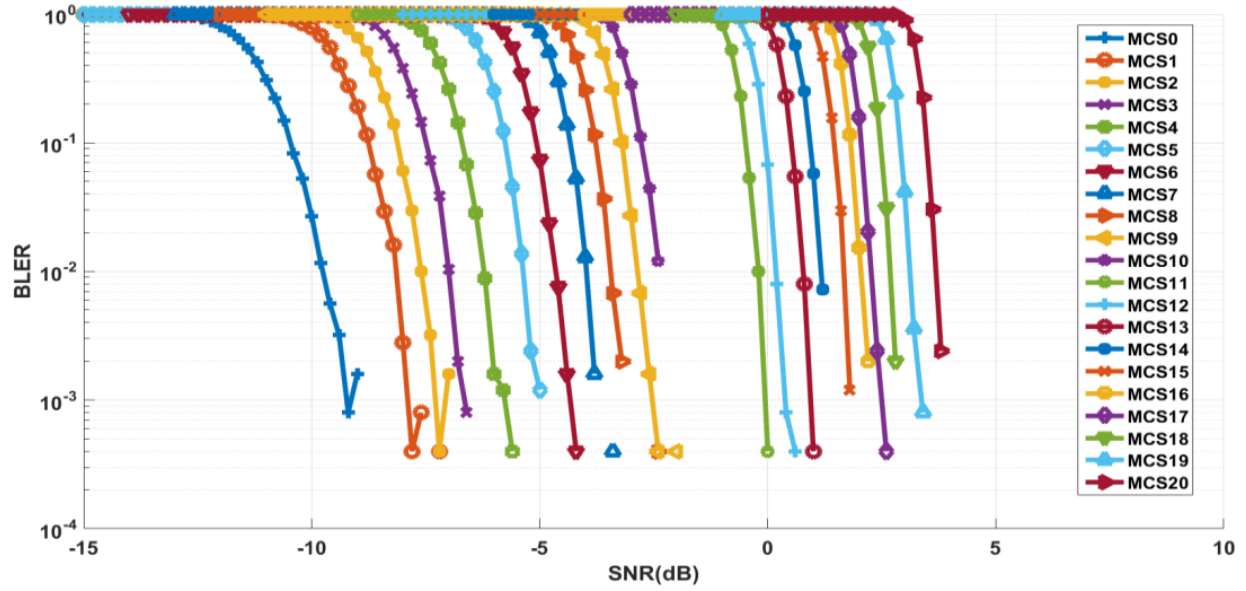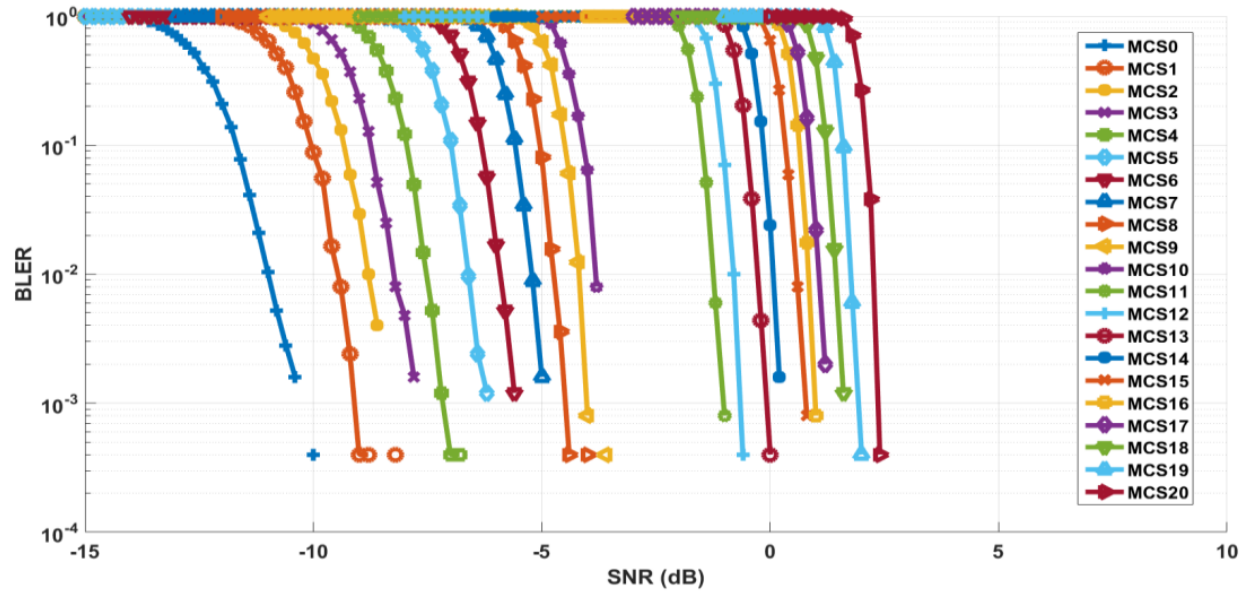qual duration) are passed to `LteSlInterference` class, which maintains the indexing of each signal by storing them into a vector. Once the signal(s) duration is elapsed, a call to `ConditionallyEvaluateChunk` function is invoked. This function iterates over this vector and computes the perceived SINR, interference, and the power of each signal, which are then passed to the respective `LteSlChunkProcessor` instance along with their signal id. Similarly, each `LteSlChunkProcessor` instance maintain its assigned values by storing them in a vector as per the signal id. For example, an `LteSlChunkProcessor` initialized to store the computed SINR values will maintain a vector containing the SINR of each overlapping signal as per their signal id. In the end, each vector is passed to the respective function, which are hooked through a callback in `LteHelper` class at the time of installing the UE device. For instance, the `UpdateSlSinrPerceived` function of `LteSpectrumPhy` receive the vector of perceived SINR values.

Based on the BLER computation in `LteSpectrumPhy`, the messages received on Sidelink physical channels can be divided into three types.

1. The messages whose BLER computation is performed without HARQ, e.g., SCI and MIB-SL

2. The messages whose BLER computation is performed with HARQ and follow the control information, e.g., Sidelink data

3. The messages whose BLER computation is performed with HARQ but do not have the control information, e.g., Discovery messages

For first type of messages, we compute the average SINR per RB for each received TB and sort them in the descending order of the SINR. Then, we try to decode them by computing the BLER with the help of `LteNistErrorModel`. For the second type of signals, we have the transport block information available in `m_expectedSlTbs` given by `LteUePhy` class. With this information, we perform a TB to SINR index mapping and retrieve the SINR of the expected TB from the perceived SINR vector. Then, this SINR and the HARQ info (if it is the retransmission) along with other parameters are used to compute the BLER of this message. Finally, the third type of messages, similar to the first type, are decoded by first storing them in desending order of the SINR, since we do not have the prior information about the TB. The only difference, is that the discovery messages can be retransmitted up to 3 times, therefore, we maintain the HARQ history of each transmission and use it along with other parameters for computing the BLER. We also note that for type 1 and type 3 messages, if the received TBs collide, i.e., they use the same RBs, the UE will try to decode the sorted TBs one at a time, and if any of the TB is decoded the remaining TB(s) are marked corrupted, thus, are not received by the UE. Alternatively, by setting the `DropRbOnCollisionEnabled` attribute all the colliding TBs can be dropped irrespective of their perceived SINR.

2.2.3 Frequency Hopping

The D2D model also supports the frequency hopping on Sidelink PSSCH for the "UeSelected" resource scheduling, i.e., MODE 2. At the time of writing this documentation, only the *inter-subframe* hopping mode, with constant (i.e., Type 1) and pseudo-random (Type 2) is supported.

Note: The documentation for this section will be extended in the later release of the D2D code. Users, interested to gain further information are referred to *[NISTFREQHOPP]*

2.2.4 Helpers

Four helper objects are used to setup simulations and configure the various components. These objects are:

- `LteHelper`, which takes care of the configuration of the LTE/Sidelink radio access network, as well as of coordinating the setup and release of EPS and Sidelink radio bearers and start/stop ProSe discovery. The `LteHelper` class provides both the API definition and its implementation.

- `EpcHelper`, which takes care of the configuration of the Evolved Packet Core. The `EpcHelper` class is an abstract base class, which only provides the API definition; the implementation is delegated to the child classes in order to allow for different EPC network models.

- `CcHelper`, which takes care of the configuration of the `LteEnbComponentCarrierMap`, basically, it creates a user specified number of `LteEnbComponentCarrier`. `LteUeComponentCarrierMap` is currently created starting from the `LteEnbComponentCarrierMap`. `LteHelper:InstallSingleUeDevice`, in this implementation, is needed to invoke after the `LteHelper:InstallSingleEnbDevice` to ensure that the `LteEnbComponentCarrierMap` is properly initialized.

- `LteSidelinkHelper`, this helper class is provided to ease the burden of a user to configure public safety scenarios involving Sidelink. In particular, it uses other helper classes, e.g., LteHelper to activate/deactivate Sidelink bearers, create groups for Sidelink broadcast or groupcast communication and Lte3gppHexGridEnbTopologyHelper to associate UEs to a Sidelink group or an eNB using wrap around method.

Note: Wrap-around functionality is not fully supported yet.

It is possible to create a simple LTE-only simulations by using the `LteHelper` alone, or to create complete LTE-EPC simulations by using both `LteHelper` and `EpcHelper`. When both helpers are used, they interact in a master-slave fashion, with the `LteHelper` being the Master that interacts directly with the user program, and the `EpcHelper` working "under the hood" to configure the EPC upon explicit methods called by the `LteHelper`. The exact interactions are displayed in the Figure *Sequence diagram of the interaction between LteHelper and EpcHelper.*.

2.3 User Documentation

2.3.1 Sidelink simulation output

Similarly, for the Sidelink the LTE model currently supports the output to file of PHY and MAC level KPIs. You can enable them in the following way:

```
Ptr<LteHelper> lteHelper = CreateObject<LteHelper> ();

// configure all the simulation scenario here...

lteHelper->EnableSlPscchMacTraces ();
lteHelper->EnableSlPsschMacTraces ();

lteHelper->EnableSlRxPhyTraces ();
lteHelper->EnableSlPscchRxPhyTraces ();

Simulator::Run ();
```

The Sidelink MAC level KPIs are gathered at UE MAC and are written into two files, first one for PSCCH and the second for PSSCH. These KPIs are basically the trace of resource allocation for the Sidelink control and data transmissions for every SC period in MODE 1 and MODE 2. For PSCCH KPIs the format is the following:

1. Simulation time in milliseconds at which the SC period starts (**Note : PSCCH transmission start time will depend on the PSCCH resource index**)

2. Cell ID

3. unique UE ID (IMSI)

4. Sidelink-specific UE ID (RNTI)

5. Current frame number
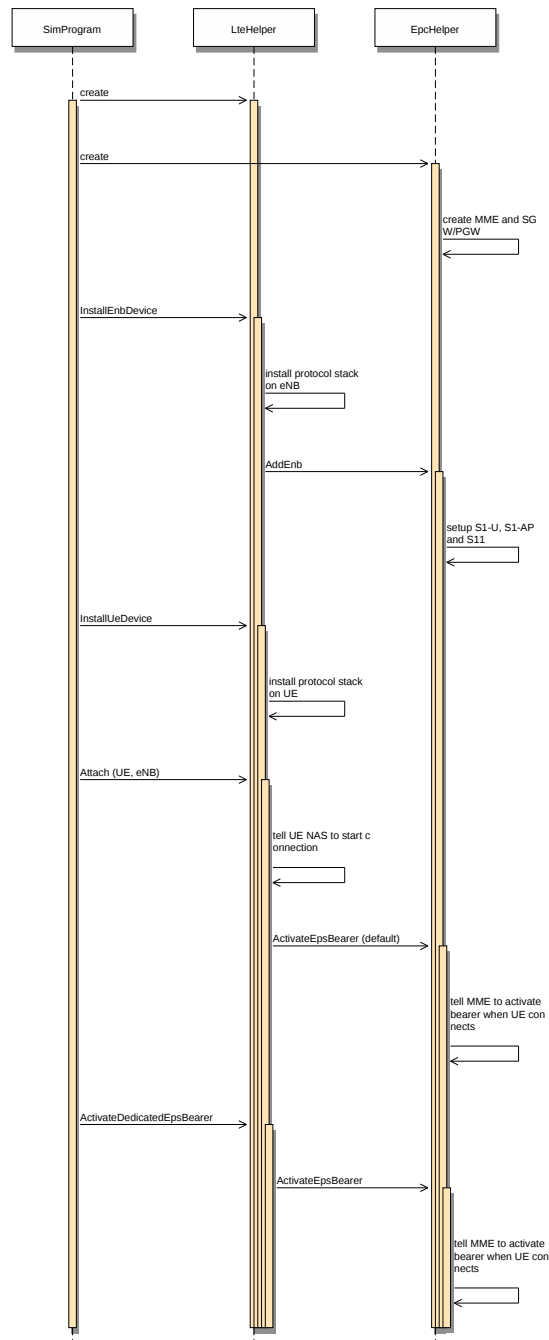
Fig. 2.17: Sequence diagram of the interaction between `LteHelper` and `EpcHelper`.

6. Current subframe number

7. PSCCH resource index

8. Frame number for the first PSCCH transmission

9. Subframe number for the first PSCCH transmission

10. Frame number for the second PSCCH transmission

11. Subframe number for the second PSCCH transmission

12. MCS

13. Transport block size

14. Index of the first RB used for PSSCH (i.e., Data)

15. Total number of RBs allocated for PSSCH

16. Time Resource Pattern Index (iTRP) used for PSSCH

while for PSSCH MAC KPIs the format is:

1. Simulation time in milliseconds at which the PSSCH transmission starts

2. Cell ID

3. unique UE ID (IMSI)

4. Sidelink-specific UE ID (RNTI)

5. Frame number at which the SC period starts

6. Subframe number at which the SC period starts

7. Frame number at which the PSSCH transmission starts

8. Subframe number at which the PSSCH transmission starts

9. Current frame number

10. Current subframe number

11. MCS

12. Transport block size

13. Index of the first RB used for PSSCH

14. Total number of RBs allocated for PSSCH

The names of the files used for Sidelink MAC KPI output can be customized via the ns-3 attributes `ns3::MacStatsCalculator::SlUeCchOutputFilename` and `ns3::MacStatsCalculator::SlUeSchOutputFilename`.

Sidelink PHY KPIs are distributed in two different files whose names are configurable through the following attributes

1. ns3::PhyRxStatsCalculator::SlPscchRxOutputFilename

2. ns3::PhyRxStatsCalculator::SlRxOutputFilename

In the SlPscchRx file, the following content is available:

1. Simulation time in milliseconds

2. Cell ID (Fixed to 0 for Sidelink)

3. unique UE ID (IMSI)

4. Sidelink-specific UE ID (RNTI)

---

5. MCS

6. Transport block size in bytes

7. PSCCH resource index

8. Total number of RBs for PSSCH

9. Index of the first RB used for PSSCH

10. Time Resource Pattern Index (iTRP) used for PSSCH

11. Hopping value

12. Layer 2 group destination id

13. Correctness in the reception of the TB (correct = 1 : error = 0)

And Finally, in SlRx file the parameters included are:

1. Simulation time in milliseconds

2. Cell ID (Fixed to 0 for Sidelink)

3. unique UE ID (IMSI)

4. Sidelink-specific UE ID (RNTI) **Note: For PSDCH reception, it is the RNTI of the UE transmitting discovery messages.**

5. Layer of transmission

6. MCS

7. Transport block size in bytes

8. Redundancy version

9. New Data Indicator flag

10. Correctness in the reception of the TB (correct = 1 : error = 0)

11. Average perceived SINR per RB in linear units

Note: This file is used to store the above parameters for both PSSCH and PSDCH reception.

2.3.2 LTE Sidelink PHY Error Model

The Sidelink physical error model consists of the data, control, and the discovery error model. All of them are active by default. It is possible to deactivate them with the ns3 attribute system, in detail:

```
Config::SetDefault ("ns3::LteSpectrumPhy::SlCtrlErrorModelEnabled", BooleanValue␣
→(false));
Config::SetDefault ("ns3::LteSpectrumPhy::SlDataErrorModelEnabled", BooleanValue␣
→(false));
Config::SetDefault ("ns3::LteSpectrumPhy::SlDiscoveryErrorModelEnabled", BooleanValue␣
→(false));
```

Besides the error models, one more attribute, i.e., "DropRbOnCollisionEnabled" is also introduced only for the Sidelink transmissions. This is implemented by keeping in mind the scenarios in which the resources are autonomously scheduled by a UE, which increases the probability of two UEs choosing the same RBs to transmit. Therefore, causing a collision between the TBs. By using this attribute, a user can choose to drop such collided TBs. It can be configured as follows:

```
Config::SetDefault ("ns3::LteSpectrumPhy::DropRbOnCollisionEnabled", BooleanValue
↪(true));
```

2.3.3 LTE Sidelink

A new directory "d2d-examples" in the LTE module examples directory holds the examples for simulating ProSe services, i.e., direct communication, direct discovery, and synchronization. These examples can be divided into the following two categories:

1. Simple examples

These examples covers in-coverage and out-of-coverage ProSe communication using a simple scenario. The examples included in this category are the following:

- lte-sl-in-covrg-comm-mode1

- lte-sl-in-covrg-comm-mode2

- lte-sl-out-of-covrg-comm

2. Detailed examples

These examples can be used to simulate out-of-coverage ProSe communication, discovery and synchronization. In particular, these examples covers the simulation scenarios used for the study published in *[NIST2017]*. The users interested in the extensive simulation campaigns described in this study, are referred to a "README.txt" file for more information. The examples included in this category are:

- wns3-2017-pscch

- wns3-2017-pssch

- wns3-2017-synch

- wns3-2017-discovery

The Sidelink example scripts follow the same rules as writing an LTE simulation script, however, there are additional configurations required to simulate Sidelink. Following are some rules of thumb for writing Sidelink scripts;

- Sidelink simulations require EPC.

- eNB should be disabled to simulate out-of-coverage scenarios.

- Sidelink pools should be configured before the start of the simulation.

- `Lte3gppHexGridEnbTopologyHelper` can not be use without initializing eNB nodes and appropriate antenna model.

- It is possible to avoid the initialization of eNB nodes in out-of-coverage scenarios, if hexagonal ring topology is not used.

In general, all the D2D examples are highly parameterizable and could be divided in three parts:

1. Configuration of LTE and Sidelink default parameters, e.g., the ones configured by calling `Config::SetDefault` function

2. Topology configuration

3. Sidelink pool configuration

In the following, we will discuss all the examples from the "Simple examples" category and the two examples from "Detailed examples" category, which are wns3-2017-synch and wns3-2017-discovery. We choose wns3-2017-synch, since it also simulates the PSCCH and PSSCH.

lte-sl-in-covrg-comm-mode1

This example simulates an in-coverage MODE 1 ProSe communication by using the following scenario.
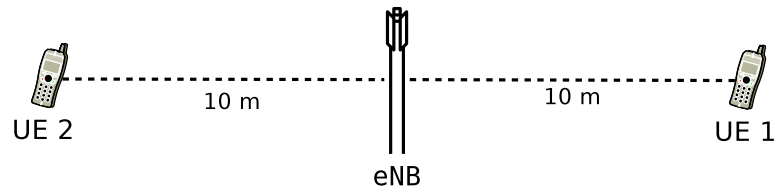
Fig. 2.18: Sidelink simple in-coverage scenario

Both the UEs are in-coverage of the eNB where UE1 sends the data to UE2 via Sidelink by using the resources assigned by the eNB. A user can configure the simulation time and the output of NS logs of the specified classes by using the corresponding global variables in the simulation script. For example, a user can run the simulation as follows:

```
./waf --run "lte-sl-in-covrg-comm-mode1 --simTime=7 --enableNsLogs=false"
```

The simulation time is in seconds. Moreover, this example can support IPv6 instead of the default IPv4 if the `--useIPv6` command-line argument is provided.

Configuration of LTE and Sidelink default parameters

The simulation script begins with the configuration of the parameters of the Sidelink scheduler as follows.

- Configure the Sidelink scheduler :

```
Config::SetDefault ("ns3::RrSlFfMacScheduler::Itrp", UintegerValue (0));
Config::SetDefault ("ns3::RrSlFfMacScheduler::SlGrantSize", UintegerValue (5));
```

The `ns3::RrSlFfMacScheduler` is a very simple round robin scheduler, which uses a fixed TRP index value and number of RBs to be allocated to a UE.

- Configure the frequency and the bandwidth :

```
Config::SetDefault ("ns3::LteEnbNetDevice::DlEarfcn", UintegerValue (100));
Config::SetDefault ("ns3::LteUeNetDevice::DlEarfcn", UintegerValue (100));
Config::SetDefault ("ns3::LteEnbNetDevice::UlEarfcn", UintegerValue (18100));
Config::SetDefault ("ns3::LteEnbNetDevice::DlBandwidth", UintegerValue (50));
Config::SetDefault ("ns3::LteEnbNetDevice::UlBandwidth", UintegerValue (50));
```

We use the LTE Band 1 for both LTE and Sidelink communication.

- Configure the error models :

```
// For PSSCH
Config::SetDefault ("ns3::LteSpectrumPhy::SlDataErrorModelEnabled",
                                        BooleanValue (true));

// For PSCCH
Config::SetDefault ("ns3::LteSpectrumPhy::SlCtrlErrorModelEnabled",
                                        BooleanValue (true));

Config::SetDefault ("ns3::LteSpectrumPhy::DropRbOnCollisionEnabled",
                                        BooleanValue (false));
```

- Configure the transmit power of the eNB and the UEs :

```
Config::SetDefault ("ns3::LteUePhy::TxPower", DoubleValue (23.0));
Config::SetDefault ("ns3::LteEnbPhy::TxPower", DoubleValue (30.0));
```

The powers configured are in dBm.

Topology configuration

- Instantiating LTE, EPC and Sidelink helpers :

```
Ptr<LteHelper> lteHelper = CreateObject<LteHelper> ();
Ptr<PointToPointEpcHelper>  epcHelper = CreateObject<PointToPointEpcHelper> ();
lteHelper->SetEpcHelper (epcHelper);

Ptr<LteSidelinkHelper> proseHelper = CreateObject<LteSidelinkHelper> ();
proseHelper->SetLteHelper (lteHelper);
```

- Configuring the pathloss model :

```
lteHelper->SetAttribute ("PathlossModel",
                         StringValue ("ns3::Cost231PropagationLossModel"));
```

- Enabling the Sidelink :

```
lteHelper->SetAttribute ("UseSidelink", BooleanValue (true));
```

Note : Attribute ``UseSidelink`` must be set before installing the UE devices.

- Configuring the scheduler :

```
lteHelper->SetSchedulerType ("ns3::RrSlFfMacScheduler");
```

- Creating the eNB and UE nodes and setting their mobility :

```
NodeContainer enbNode;
enbNode.Create (1);
NodeContainer ueNodes;
ueNodes.Create (2);

Ptr<ListPositionAllocator> positionAllocEnb =
                                   CreateObject<ListPositionAllocator> ();
positionAllocEnb->Add (Vector (0.0, 0.0, 30.0));
Ptr<ListPositionAllocator> positionAllocUe1 =
                                   CreateObject<ListPositionAllocator> ();
positionAllocUe1->Add (Vector (10.0, 0.0, 1.5));
Ptr<ListPositionAllocator> positionAllocUe2 =
                                   CreateObject<ListPositionAllocator> ();
positionAllocUe2->Add (Vector (-10.0, 0.0, 1.5));

//Install mobility
MobilityHelper mobilityeNodeB;
mobilityeNodeB.SetMobilityModel ("ns3::ConstantPositionMobilityModel");
mobilityeNodeB.SetPositionAllocator (positionAllocEnb);
mobilityeNodeB.Install (enbNode);

MobilityHelper mobilityUe1;
```

```
mobilityUe1.SetMobilityModel ("ns3::ConstantPositionMobilityModel");
mobilityUe1.SetPositionAllocator (positionAllocUe1);
mobilityUe1.Install (ueNodes.Get (0));

MobilityHelper mobilityUe2;
mobilityUe2.SetMobilityModel ("ns3::ConstantPositionMobilityModel");
mobilityUe2.SetPositionAllocator (positionAllocUe2);
mobilityUe2.Install (ueNodes.Get (1));
```

- Installing LTE devices to the nodes :

```
NetDeviceContainer enbDevs = lteHelper->InstallEnbDevice (enbNode);
NetDeviceContainer ueDevs = lteHelper->InstallUeDevice (ueNodes);
```

Sidelink pool configuration

This example simulates an in-coverage scenario, therefore, the eNB will be configured with a pre-configured dedicated Sidelink pool. As mentioned in *RRC*, in this scenario the `LteSlEnbRrc` class will be responsible for holding this per-configured pool configuration. The pool configuration starts by setting a flag in `LteSlEnbRrc` as an indication that the Sidelink is enabled. It is configured as follows:

```
Ptr<LteSlEnbRrc> enbSidelinkConfiguration = CreateObject<LteSlEnbRrc> ();
enbSidelinkConfiguration->SetSlEnabled (true);
```

For configuring Sidelink parameters, the "setup" structure of the field "commTxResources-r12" of IE "SL-Preconfiguration" defined in the standard [TS36331] is converted into a C++ structure. This example uses this structure to configure the pool parameters for Sidelink control. The pool configuration is done by using the `LteSlPreconfigPoolFactory` in the following manner,

```
LteRrcSap::SlCommTxResourcesSetup pool;

pool.setup = LteRrcSap::SlCommTxResourcesSetup::SCHEDULED;
//BSR timers
pool.scheduled.macMainConfig.periodicBsrTimer.period =
                                      LteRrcSap::PeriodicBsrTimer::sf16;
pool.scheduled.macMainConfig.retxBsrTimer.period = LteRrcSap::RetxBsrTimer::sf640;
//MCS
pool.scheduled.haveMcs = true;
pool.scheduled.mcs = 16;
//resource pool
LteSlResourcePoolFactory pfactory;
pfactory.SetHaveUeSelectedResourceConfig (false); //since we want eNB to schedule

//Control
pfactory.SetControlPeriod("sf40");
pfactory.SetControlBitmap(0x00000000FF); //8 subframes for PSCCH
pfactory.SetControlOffset(0);
pfactory.SetControlPrbNum(22);
pfactory.SetControlPrbStart(0);
pfactory.SetControlPrbEnd(49);

pool.scheduled.commTxConfig = pfactory.CreatePool ();

uint32_t groupL2Address = 255;
```

```
enbSidelinkConfiguration->AddPreconfiguredDedicatedPool (groupL2Address, pool);
lteHelper->InstallSidelinkConfiguration (enbDevs, enbSidelinkConfiguration);
```

The resources for data are computed by the scheduler on the basis of the scheduler's attributes configured in the start of this simulation script and the above pool configuration.

Similarly, for the UEs we need to enable the Sidelink in `LteSlUeRrc` by setting a flag and a pre-configuration object, which will be initialized with the pool configurations once the UE receives an `RrcConnectionReconfiguration` message from the eNB, as shown in Figures *ns-3 LTE Sidelink in-coverage radio bearer activation (Tx)* and *ns-3 LTE Sidelink in-coverage radio bearer activation (Rx)*:

```
//pre-configuration for the UEs
Ptr<LteSlUeRrc> ueSidelinkConfiguration = CreateObject<LteSlUeRrc> ();
ueSidelinkConfiguration->SetSlEnabled (true);
LteRrcSap::SlPreconfiguration preconfiguration;
ueSidelinkConfiguration->SetSlPreconfiguration (preconfiguration);
lteHelper->InstallSidelinkConfiguration (ueDevs, ueSidelinkConfiguration);
```

- Installing the IP stack on the UEs and assigning IP address :

```
//Install the IP stack on the UEs and assign IP address
InternetStackHelper internet;
internet.Install (ueNodes);
Ipv4InterfaceContainer ueIpIface;
ueIpIface = epcHelper->AssignUeIpv4Address (NetDeviceContainer (ueDevs));

// set the default gateway for the UE
Ipv4StaticRoutingHelper ipv4RoutingHelper;
for (uint32_t u = 0; u < ueNodes.GetN (); ++u)
  {
    Ptr<Node> ueNode = ueNodes.Get (u);
    // Set the default gateway for the UE
    Ptr<Ipv4StaticRouting> ueStaticRouting =
                    ipv4RoutingHelper.GetStaticRouting (ueNode->GetObject<Ipv4>
→());
    ueStaticRouting->SetDefaultRoute (epcHelper->GetUeDefaultGatewayAddress (),
→1);
  }
```

The above configuration is similar to any usual LTE example with EPC.

- Attaching the UEs to the eNB :

```
lteHelper->Attach (ueDevs);
```

- Installing applications and activating Sidelink radio bearers. Note that two configuration options (IPv4 and IPv6) are supported; we only document below the IPv4 path through the code :

```
Ipv4Address groupAddress4 ("225.0.0.0"); //use multicast address as destination
...
remoteAddress = InetSocketAddress (groupAddress4, 8000);
localAddress = InetSocketAddress (Ipv4Address::GetAny (), 8000);
...
OnOffHelper sidelinkClient("ns3::UdpSocketFactory", remoteAddress);
sidelinkClient.SetConstantRate (DataRate ("16kb/s"), 200);

ApplicationContainer clientApps = sidelinkClient.Install (ueNodes.Get (0));
//onoff application will send the first packet at :
```

```
//(2.9 (App Start Time) + (1600 (Pkt size in bits) / 16000 (Data rate)) = 3.0 sec
clientApps.Start (slBearersActivationTime + Seconds (0.9));
clientApps.Stop (simTime - slBearersActivationTime + Seconds (1.0));

ApplicationContainer serverApps;
PacketSinkHelper sidelinkSink ("ns3::UdpSocketFactory", localAddress);
serverApps = sidelinkSink.Install (ueNodes.Get (1));
serverApps.Start(Seconds (2.0));
```

In this example, an "OnOff" application is installed in the UE 1, which sends a 200 byte packet with the constant bit rate of 16 kb/s. On the other hand, the UE 2 is configured with the "PacketSink" application.

The Sidelink radio bearers are activated by calling the `ActivateSidelinkBearer` method of `LteSidelinkHelper` as follows:

```
//Set Sidelink bearers
Ptr<LteSlTft> tft = Create<LteSlTft> (LteSlTft::BIDIRECTIONAL,
                                             groupAddress4, groupL2Address);
proseHelper->ActivateSidelinkBearer (Seconds (2.0), ueDevs, tft);
```

The `ActivateSidelinkBearer` method takes the following three parameters as input,

1. Time to activate the bearer

2. Devices for which the bearer will be activated

3. The Sidelink traffic flow template

The `tft` in this example is an object of `LteSlTft` class created by initializing its following parameters,

1. Direction of the bearer, i.e., "Transmit", "Receive" or Bidirectional

2. An IPv4 multicast address of the group

3. Sidelink layer 2 group address (used as Sidelink layer 2 group id)

   • Activating the Sidelink traces :

   ```
   lteHelper->EnableSlPscchMacTraces ();
   lteHelper->EnableSlPsschMacTraces ();

   lteHelper->EnableSlTxPhyTraces ();
   lteHelper->EnableSlRxPhyTraces ();
   lteHelper->EnableSlPscchRxPhyTraces ();
   ```

The above code will enable all the Sidelink related traces. We note that, the user can also use the classical function "LteHelper::EnableTraces ()", but this will also output the LTE traces.

Upon the completion of the simulation, the following trace files can be found in the repository's root folder,

   • SlUeMacStats.txt

   • SlSchUeMacStats.txt

   • SlPscchRxPhyStats.txt

   • SlRxPhyStats.txt

For more information related to the above files please refer to the sec-sidelink-simulation-output section.

   • UePacketTrace.tr

The information in this file is obtained by using the traces "TxWithAddresses" and "RxWithAddresses" of `OnOff` and `PacketSink` application, respectively. Following table shows the snippet of the data from this file for the two UEs,

Table 2.2: UePacketTrace.tr

Time (sec)	tx/rx	NodeID	IMSI	PktSize (bytes)	IP[src]	IP[dst]
3	tx	2	1	200	7.0.0.2:49153	225.0.0.0:8000
3.08893	rx	3	2	200	7.0.0.2:49153	7.0.0.3:8000

The first row shows that the UE 1 with node id 2 and IMSI 1 transmits a multicast packet of 200 bytes and the UE 2 receives the packet transmitted by the UE 1. As per the client's application data rate and ON time, i.e., 16 kb/s and 2 seconds, respectively, a total of 20 packets are sent and received by the transmitting and the receiving UE.

lte-sl-in-covrg-comm-mode2

This example simulates an in-coverage MODE 2 ProSe communication using the same scenario *Sidelink simple in-coverage scenario*, used for previous example. The only difference is that the resources are not scheduled by the eNB, instead, the UE 1 selects the resources autonomously from a pool specified by the eNB through `RrcConnectionReconfiguration` message. Besides using the same scenario, this example also has the same application, therefore, in the following, we will discuss only those configurations, which are MODE 2 specific. A user can run the simulation as follows:

```
./waf --run "lte-sl-in-covrg-comm-mode2 --simTime=7 --enableNsLogs=false"
```

The simulation time is in seconds. Similarly, this example supports IPv6 as an option if the `--useIPv6` argument is provided.

Configuration of LTE and Sidelink default parameters

- Configuring parameters for PSSCH resource selection :

```
// Fixed MCS and the number of RBs
Config::SetDefault ("ns3::LteUeMac::SlGrantMcs", UintegerValue (16));
Config::SetDefault ("ns3::LteUeMac::SlGrantSize", UintegerValue (5));

// For selecting subframe indicator bitmap
Config::SetDefault ("ns3::LteUeMac::Ktrp", UintegerValue (1));
//use default Trp index of 0
Config::SetDefault ("ns3::LteUeMac::UseSetTrp", BooleanValue (true));
```

The above parameters of `LteUeMac` class enable the UE to select the time (i.e., frame/subframe) and the frequency (i.e., RBs) resources autonomously. If the attribute "UseSetTrp" is false, a UE will select the TRP index randomly from the range of values depending on the KTRP value [TS36213].

- Configure the error models :

```
// For PSSCH
Config::SetDefault ("ns3::LteSpectrumPhy::SlDataErrorModelEnabled",
                                             BooleanValue (true));

// For PSCCH
Config::SetDefault ("ns3::LteSpectrumPhy::SlCtrlErrorModelEnabled",
                                             BooleanValue (true));
```

```
Config::SetDefault ("ns3::LteSpectrumPhy::DropRbOnCollisionEnabled",
                                                BooleanValue (false));
```

Along with the error model configuration, by setting the "DropRbOnCollisionEnabled" attribute all the TBs collided in time and frequency are dropped. This attribute could be of particular interest for the users, e.g., to study the impact of collisions in MODE 2. In this example, this attribute has no impact as only one UE is acting as a transmitter. It is included just to make the users aware of this attribute.

Topology configuration

- There is no need to configure the scheduler, since this example uses MODE 2 for resource selection.

Sidelink pool configuration

The Sidelink pool configuration is similar to the MODE 1 configuration, e.g., the configuration for Sidelink control is the same. However, the following additional configurations are needed for in-coverage MODE 2.

```
LteRrcSap::SlCommTxResourcesSetup pool;

pool.setup = LteRrcSap::SlCommTxResourcesSetup::UE_SELECTED;
pool.ueSelected.havePoolToRelease = false;
pool.ueSelected.havePoolToAdd = true;
pool.ueSelected.poolToAddModList.nbPools = 1;
pool.ueSelected.poolToAddModList.pools[0].poolIdentity = 1;

//Data
pfactory.SetDataBitmap(0xFFFFFFFFFF);
pfactory.SetDataOffset(8); //After 8 subframes of PSCCH
pfactory.SetDataPrbNum(25);
pfactory.SetDataPrbStart(0);
pfactory.SetDataPrbEnd(49);
```

Compared to MODE 1, the pool resources are now indicated as "UE_SELECTED" along with other parameters. Moreover, now we need to configure the pool parameters related to the data, i.e., PSSCH. In addition to the subframe indicator bitmap specified by KTRP and iTRP, Mode 2 introduces another level of subframe filtering for the subframe pool via "DataBitmap" to limit the number of possible values for iTRP. The PSSCH transmission occurs on the filtered subframes after applying TRP bitmap on this "DataBitmap". Users interested to learn about how it is done are referred to *4. SidelinkCommPoolPsschTestCase*.

Finally, at the end of the simulation the trace files, similar to the previous example, can be found in the repository's root folder. One important difference, compared to MODE 1, is that in the trace files "SlUeMacStats.txt" and "SlPsc-chRxPhyStats.txt" the parameters, e.g., PSCCH resource index and the starting RB for PSSCH are randomly selected by the UE for every SC period. Furthermore, a similar amount of packets, i.e. 20, are sent and received by the UEs.

lte-sl-out-of-covrg-comm

This example simulates an out-of-coverage MODE 2 ProSe communication by using the following scenario.

This example allows a user to configure the simulation time and the output of NS logs of the specified classes by using the corresponding global variables in the simulation script. For example, a user can run the simulation as follows:

```
./waf --run "lte-sl-out-of-covrg-comm --simTime=7 --enableNsLogs=false"
```

The simulation time is in seconds, and `--useIPv6` can be used to run the example with IPv6 instead of IPv4.
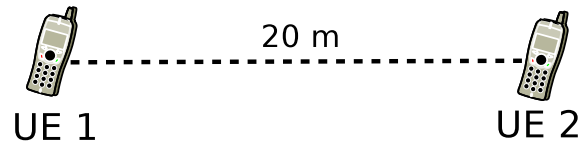
Fig. 2.19: Sidelink simple out-of-coverage scenario

Configuration of LTE and Sidelink default parameters

- Configuring parameters for PSSCH resource selection :

```
// Fixed MCS and the number of RBs
Config::SetDefault ("ns3::LteUeMac::SlGrantMcs", UintegerValue (16));
Config::SetDefault ("ns3::LteUeMac::SlGrantSize", UintegerValue (5));

// For selecting subframe indicator bitmap
Config::SetDefault ("ns3::LteUeMac::Ktrp", UintegerValue (1));
//use default Trp index of 0
Config::SetDefault ("ns3::LteUeMac::UseSetTrp", BooleanValue (true));
```

The above parameters of `LteUeMac` class enable the UE to select the time (i.e., frame/subframe) and the frequency (i.e., RBs) resources autonomously. If the attribute "UseSetTrp" is false, a UE will select the TRP index randomly from the range of values depending on the KTRP value [TS36213].

- Configure the frequency :

```
uint32_t ulEarfcn = 18100;
uint16_t ulBandwidth = 50;
```

Here, it is not necessary to configure the EARFCNs and the bandwidth of the UE and eNB for the two reasons. First, in this example we will not instantiate the eNB node, thus, setting these attributes would have no impact. Second, both the UEs will use only the Sidelink to communicate, therefore, the EARFCN and the bandwidth are specified in the pool configuration. At this stage, the above two variables are initialized to be used later to configure the pathloss model and the Sidelink pool. Similar, to the previous simple examples, we use the LTE Band 1 for Sidelink communication.

- Configure the error models :

```
// For PSSCH
Config::SetDefault ("ns3::LteSpectrumPhy::SlDataErrorModelEnabled",
                                              BooleanValue (true));

// For PSCCH
Config::SetDefault ("ns3::LteSpectrumPhy::SlCtrlErrorModelEnabled",
                                              BooleanValue (true));

Config::SetDefault ("ns3::LteSpectrumPhy::DropRbOnCollisionEnabled",
                                              BooleanValue (false));
```

Along with the error model configuration, by setting the "DropRbOnCollisionEnabled" attribute all the TBs collided in time and frequency are dropped. This attribute could be of particular interest for the users, e.g., to study the impact of collisions in MODE 2. In this example, this attribute has no impact as only one UE is acting as a transmitter. It is included just to make the users aware of this attribute.

- Configure the transmit power for the UEs :

```
Config::SetDefault ("ns3::LteUePhy::TxPower", DoubleValue (23.0));
```

The power configured is in dBm.

Topology configuration

- Instantiating LTE, EPC and Sidelink helpers :

```
Ptr<LteHelper> lteHelper = CreateObject<LteHelper> ();
Ptr<PointToPointEpcHelper>  epcHelper = CreateObject<PointToPointEpcHelper> ();
lteHelper->SetEpcHelper (epcHelper);

Ptr<LteSidelinkHelper> proseHelper = CreateObject<LteSidelinkHelper> ();
proseHelper->SetLteHelper (lteHelper);
```

- Enabling the Sidelink :

```
lteHelper->SetAttribute ("UseSidelink", BooleanValue (true));
```

Note : Attribute ``UseSidelink`` must be set before installing the UE devices.

- Configuring the pathloss model and bypass the use of eNB nodes

```
(1)

  lteHelper->SetAttribute ("PathlossModel",
                           StringValue ("ns3::Cost231PropagationLossModel"));

(2)

  lteHelper->Initialize ();

(3)

  double ulFreq = LteSpectrumValueHelper::GetCarrierFrequency (ulEarfcn); //18100
  NS_LOG_LOGIC ("UL freq: " << ulFreq);
  Ptr<Object> uplinkPathlossModel = lteHelper->GetUplinkPathlossModel ();
  Ptr<PropagationLossModel> lossModel = uplinkPathlossModel->
                                        GetObject<PropagationLossModel> ();
  NS_ABORT_MSG_IF (lossModel == NULL, "No PathLossModel");
  bool ulFreqOk = uplinkPathlossModel->
                    SetAttributeFailSafe ("Frequency", DoubleValue (ulFreq));

  if (!ulFreqOk)
    {
    NS_LOG_WARN ("UL propagation model does not have a Frequency attribute");
    }
```

The use of eNB nodes can be bypassed by using the above commands strictly in the order they are listed. The command "lteHelper->Initialize ()" basically performs the channel model initialization of all the component carriers. Therefore, it is necessary to configure any desired pathloss model before issuing this command. The commands in step 3 are to properly configure the frequency attribute of the pathloss model used, which is normally done in `InstallSingleEnb` method of `LteHelper`.

- Creating the UE nodes and setting their mobility :

```
NodeContainer ueNodes;
ueNodes.Create (2);

Ptr<ListPositionAllocator> positionAllocUe1 =
                                 CreateObject<ListPositionAllocator> ();
positionAllocUe1->Add (Vector (0.0, 0.0, 1.5));
Ptr<ListPositionAllocator> positionAllocUe2 =
                                 CreateObject<ListPositionAllocator> ();
positionAllocUe2->Add (Vector (20.0, 0.0, 1.5));

//Install mobility
MobilityHelper mobilityUe1;
mobilityUe1.SetMobilityModel ("ns3::ConstantPositionMobilityModel");
mobilityUe1.SetPositionAllocator (positionAllocUe1);
mobilityUe1.Install (ueNodes.Get (0));

MobilityHelper mobilityUe2;
mobilityUe2.SetMobilityModel ("ns3::ConstantPositionMobilityModel");
mobilityUe2.SetPositionAllocator (positionAllocUe2);
mobilityUe2.Install (ueNodes.Get (1));
```

- Installing LTE devices to the nodes :

```
NetDeviceContainer ueDevs = lteHelper->InstallUeDevice (ueNodes);
```

Sidelink pool configuration

This example simulates an out-of-coverage scenario, therefore, both the UEs are configured with a pre-configured Sidelink communication pool. As mentioned in *RRC*, in this scenario the LteSlUeRrc class will be responsible for holding this per-configured pool configuration. The pool configuration starts by setting a flag in LteSlUeRrc as an indication that the Sidelink is enabled. It is configured as follows:

```
Ptr<LteSlUeRrc> ueSidelinkConfiguration = CreateObject<LteSlUeRrc> ();
ueSidelinkConfiguration->SetSlEnabled (true);
```

For configuring Sidelink communication pre-configured pool parameters, the IE "SL-Preconfiguration" defined in the standard [TS36331] is converted into a C++ structure and similar to the basic LTE layer 3 messages it can be found in LteRrcSap class. This example uses this structure to configure the Sidelink communication pool parameters. The pool configuration is done by using the LteSlPreconfigPoolFactory in the following manner,

```
LteRrcSap::SlPreconfiguration preconfiguration;

preconfiguration.preconfigGeneral.carrierFreq = ulEarfcn; //18100
preconfiguration.preconfigGeneral.slBandwidth = ulBandwidth; // 50 RBs
preconfiguration.preconfigComm.nbPools = 1;

LteSlPreconfigPoolFactory pfactory;

//Control
pfactory.SetControlPeriod("sf40");
pfactory.SetControlBitmap(0x00000000FF); //8 subframes for PSCCH
pfactory.SetControlOffset(0);
pfactory.SetControlPrbNum(22);
pfactory.SetControlPrbStart(0);
pfactory.SetControlPrbEnd(49);
```

```
//Data
pfactory.SetDataBitmap(0xFFFFFFFFFF);
pfactory.SetDataOffset(8); //After 8 subframes of PSCCH
pfactory.SetDataPrbNum(25);
pfactory.SetDataPrbStart(0);
pfactory.SetDataPrbEnd(49);

preconfiguration.preconfigComm.pools[0] = pfactory.CreatePool ();

ueSidelinkConfiguration->SetSlPreconfiguration (preconfiguration);
lteHelper->InstallSidelinkConfiguration (ueDevs, ueSidelinkConfiguration);
```

In addition to the subframe indicator bitmap specified by KTRP and iTRP, Mode 2 introduces another level of sub-frame filtering for the subframe pool via "DataBitmap" to limit the number of possible values for iTRP. The PSSCH transmission occurs on the filtered subframes after applying TRP bitmap on this "DataBitmap". Users interested to learn about how it is applied are referred to *4. SidelinkCommPoolPsschTestCase*.

- Installing the IP stack on the UEs and assigning IP addresses (IPv4 code statements shown below) :

```
InternetStackHelper internet;
internet.Install (ueNodes);
uint32_t groupL2Address = 255;
Ipv4Address groupAddress4 ("225.0.0.0");      //use multicast address as␣
→destination
remoteAddress = InetSocketAddress (groupAddress4, 8000);
localAddress = InetSocketAddress (Ipv4Address::GetAny (), 8000);
...
Ipv4InterfaceContainer ueIpIface;
ueIpIface = epcHelper->AssignUeIpv4Address (NetDeviceContainer (ueDevs));
Ipv4StaticRoutingHelper ipv4RoutingHelper;
for (uint32_t u = 0; u < ueNodes.GetN (); ++u)
  {
    Ptr<Node> ueNode = ueNodes.Get (u);
    // Set the default gateway for the UE
    Ptr<Ipv4StaticRouting> ueStaticRouting =
            ipv4RoutingHelper.GetStaticRouting (ueNode->GetObject<Ipv4> ());
    ueStaticRouting->SetDefaultRoute
                              (epcHelper->GetUeDefaultGatewayAddress (), 1);
  }
```

- Installing applications and activating Sidelink radio bearers :

```
//Set Application in the UEs
OnOffHelper sidelinkClient("ns3::UdpSocketFactory", remoteAddress);
sidelinkClient.SetConstantRate (DataRate ("16kb/s"), 200);

ApplicationContainer clientApps = sidelinkClient.Install (ueNodes.Get (0));
//onoff application will send the first packet at :
//(2.9 (App Start Time) + (1600 (Pkt size in bits) / 16000 (Data rate)) = 3.0 sec
clientApps.Start (slBearersActivationTime + Seconds (0.9));
clientApps.Stop (simTime - slBearersActivationTime + Seconds (1.0));

ApplicationContainer serverApps;
PacketSinkHelper sidelinkSink ("ns3::UdpSocketFactory", localAddress);
serverApps = sidelinkSink.Install (ueNodes.Get (1));
serverApps.Start(Seconds (2.0));
```

In this example, an "OnOff" application is installed in the UE 1, which sends a 200 byte packet with the constant bit

---

rate of 16 kb/s. On the other hand, the UE 2 is configured with the "PacketSink" application.

The Sidelink radio bearers are activated by calling the `ActivateSidelinkBearer` method of `LteSidelinkHelper` as follows:

```
//Set Sidelink bearers
Ptr<LteSlTft> tft = Create<LteSlTft> (LteSlTft::BIDIRECTIONAL,
                                      groupAddress4, groupL2Address);
proseHelper->ActivateSidelinkBearer (Seconds (2.0), ueDevs, tft);
```

The `ActivateSidelinkBearer` method takes the following three parameters as input,

1. Time to activate the bearer

2. Devices for which the bearer will be activated

3. The Sidelink traffic flow template

The `tft` in this example is an object of `LteSlTft` class created by initializing its following parameters,

1. Direction of the bearer, i.e., "Transmit", "Receive" or Bidirectional

2. An IPv4 multicast address of the group

3. Sidelink layer 2 group address (used as Sidelink layer 2 group id)

   • Activating the Sidelink traces :

   ```
   lteHelper->EnableSlPscchMacTraces ();
   lteHelper->EnableSlPsschMacTraces ();

   lteHelper->EnableSlTxPhyTraces ();
   lteHelper->EnableSlRxPhyTraces ();
   lteHelper->EnableSlPscchRxPhyTraces ();
   ```

The above code will enable all the Sidelink related traces.

Upon the completion of the simulation, the following trace files can be found in the repository's root folder,

   • SlUeMacStats.txt

   • SlSchUeMacStats.txt

   • SlPscchRxPhyStats.txt

   • SlRxPhyStats.txt

For more information related to the above files please refer to the sec-sidelink-simulation-output section.

   • UePacketTrace.tr

   The information in this file is obtained by using the traces "TxWithAddresses" and "RxWithAddresses" of `OnOff` and `PacketSink` application, respectively. Following table shows the snippet of the data from this file for the two UEs,

Table 2.3: UePacketTrace.tr

Time (sec)	tx/rx	NodeID	IMSI	PktSize (bytes)	IP[src]	IP[dst]
3	tx	1	1	200	7.0.0.2:49153	225.0.0.0:8000
3.08893	rx	2	2	200	7.0.0.2:49153	7.0.0.3:8000

The first row shows that the UE 1 with node id 1 and IMSI 1 transmits a multicast packet of 200 bytes and the UE 2 receives the packet transmitted by the UE 1. As per the client's application data rate and ON time, i.e., 16 kb/s and 2 seconds, respectively, a total of 20 packets are sent and received by the transmitting and the receiving UE.

In the following we will discuss the detailed examples mentioned above, however, we will mainly discuss about the topology and the Sidelink configuration, since the example scripts already contain the details of the default attributes and also, most of them are already covered by the previous examples.

wns3-2017-synch

The scenario in this example is composed of 1 hexagonal cell site divided into 3 sectors. Each sector has 1 UE, i.e., 3 in total, which are randomly dropped. These UEs are then grouped in a single group by choosing randomly one UE as a transmitter while the other 2 UEs act as receivers.

Topology configuration

In the following, we walk through the example line by line and discuss each important topology configuration. However, some configuration parameters are skipped, which are already elaborated in the previous sections of LTE. Therefore, it is highly recommended for the new users to go through the basic LTE configuration before digging into D2D examples.

- Randomizing the frame and subframe number of the UEs :

```
Config::SetDefault ("ns3::LteUePhy::UeRandomInitialSubframeIndication",
                                              BooleanValue (unsyncSl));
```

As mentioned in the design documentation *Sidelink synchronization*, by default all the UEs are perfectly synchronized, i.e., all the UEs in a simulation upon being initialized pick the same frame and subframe 1 to start with. Therefore, to simulate synchronization and to make every UE to pick a random frame and subframe number the attribute "UeRandomInitialSubframeIndication" should be set.

- Instantiating `LteSidelinkHelper` and setting `LteHelper` :

```
Ptr<LteSidelinkHelper> proseHelper = CreateObject<LteSidelinkHelper> ();
proseHelper->SetLteHelper (lteHelper);
```

- Instantiating `Lte3gppHexGridEnbTopologyHelper` and setting `LteHelper`

```
Ptr<Lte3gppHexGridEnbTopologyHelper> topoHelper =
                        CreateObject<Lte3gppHexGridEnbTopologyHelper> ();
topoHelper->SetLteHelper (lteHelper);
```

- Disabling the eNB for out-of-coverage scenario :

```
lteHelper->DisableEnbPhy (true);
```

Note : Call to disable eNB PHY should happen before installing the eNB devices

- Configure the parameters for hexagonal ring topology :

```
topoHelper->SetNumRings (numRings); // 1 Ring
topoHelper->SetInterSiteDistance (isd); // 500 m
topoHelper->SetMinimumDistance (10); // in meter
topoHelper->SetSiteHeight (32); // in meter
```

The code above will set the parameters to build 1 ring, i.e., 1 hexagonal site, which will have 500 meters of inter-site distance between the sites, if the number of rings is more than 1. The minimum distance between an eNB and the UEs is set to 10 m and the eNB is at the height of 32 m above the ground.

- Creating eNB nodes :

```
NodeContainer sectorNodes;
sectorNodes.Create (topoHelper->GetNumNodes ());
```

Call to `topoHelper->GetNumNodes ()` will return 3, which in turns would create 3 sector nodes, since, it requires 3 eNBs to cover one hexagon.

- Fixing eNB mobility and installing eNB devices :

```
MobilityHelper mobilityeNodeB;
mobilityeNodeB.SetMobilityModel ("ns3::ConstantPositionMobilityModel");
mobilityeNodeB.Install (sectorNodes);
NetDeviceContainer enbDevs = topoHelper->
                                    SetPositionAndInstallEnbDevice (sectorNodes);
```

The call `SetPositionAndInstallEnbDevice` will compute the position of each site and the antenna orientation of each eNB. The antenna orientation of each eNB in a hexagon is 30, 150 and 270 degrees, respectively [TS25814] *[TR36814]*. As mentioned before, even if the eNB PHY is disabled, the hexagonal topology requires to instantiate the eNB nodes to form the sectors of an hexagon. It is also to be noted that the use of antenna models, e.g., `Parabolic3dAntennaModel`, `ParabolicAntennaModel`, or `CosineAntennaModel` is needed to configure antenna orientation. Moreover, the function `SetPositionAndInstallEnbDevice` is also responsible to call `InstallEnbDevice` of `LteHelper` for each eNB in this scenario.

- Creating UE nodes :

```
NodeContainer ueResponders;
ueResponders.Create (ueRespondersPerSector * sectorNodes.GetN ());
```

This will create 3 UE nodes in total, 1 for each sector of hexagonal site.

- Enabling Sidelink

```
lteHelper->SetAttribute ("UseSidelink", BooleanValue (true));
```

Note : Attribute ''UseSidelink'' must be set before installing the UE devices.

- Fixing UE mobility and installing UE devices :

```
MobilityHelper mobilityResponders;
mobilityResponders.SetMobilityModel ("ns3::ConstantPositionMobilityModel");
topoHelper->DropUEsUniformlyPerSector (ueResponders);
```

This will place 1 UE per sector by choosing their position randomly with in the sector, taking into account the configured minimum eNB to UE distance of 10 m. This will also install the UE devices by calling `InstallUeDevice` of `LteHelper`. The installation of the IP stack and IP address assignment is done in a similar fashion as explain in sec-evolved-packet-core

- Creating groups of UEs :

```
double ulEarfcn = enbDevs.Get (0)->GetObject<LteEnbNetDevice> ()->GetUlEarfcn ();
double ulBandwidth = enbDevs.Get (0)->GetObject<LteEnbNetDevice> ()->
                                                GetUlBandwidth ();

std::vector < NetDeviceContainer > createdgroups;
createdgroups = proseHelper->AssociateForBroadcast (ueTxPower, ulEarfcn,
                                        ulBandwidth, ueRespondersDevs,
                                        -112, numGroups,
                                        LteSidelinkHelper::
                                                SLRSRP_PSBCH);
```

The `AssociateForBroadcast` function will basically form the specified number of groups, i.e., 1 in this example, by choosing the transmitting UE randomly from the total number of UEs. After choosing the transmitting UE, the receiving UEs of the group are selected if the Sidelink RSRP, calculated as per the method defined in [TS36214], between the transmitting UE and the receiving UE is higher than -112 dBm. In this example, UE node 4 with IMSI 1 is selected as a transmitter while remaining 2 UEs will act as receivers. It is to be noted that `AssociateForBroadcast` is only responsible for forming the groups and not installing any application.

All the UEs in a group are stored in a `NetDeviceContainer`, such that the first UE in this container is the transmitter of the group. Finally, this `NetDeviceContainer` is stored in a vector (createdgroups), which is used to install appropriate application in UE devices.

- Installing applications and activating Sidelink radio bearers :

```
**Note : Only IPV4 is supported at this stage**

// Client Application :

 uint32_t groupL2Address = 0x00;

 Ipv4AddressGenerator::Init (Ipv4Address ("225.0.0.0"), Ipv4Mask ("255.0.0.0"));
 Ipv4Address groupRespondersIpv4Address = Ipv4AddressGenerator::
                                     NextAddress (Ipv4Mask ("255.0.0.0"));

 std::vector < NetDeviceContainer >::iterator gIt;
 for (gIt = createdgroups.begin (); gIt != createdgroups.end (); gIt++)
  {
   //Create sidelink bearers
   //Use Tx for the group transmitter and Rx for all the receivers
   //split Tx/Rx
   NetDeviceContainer txUe ((*gIt).Get (0));
   NetDeviceContainer rxUes = proseHelper->
                                    RemoveNetDevice ((*gIt), (*gIt).Get (0));
   Ptr<LteSlTft> tft = Create<LteSlTft> (LteSlTft::TRANSMIT,
                                 groupRespondersIpv4Address, groupL2Address);

   //Sidelink bearer activation
   proseHelper->ActivateSidelinkBearer (Seconds (1.0), txUe, tft);
   tft = Create<LteSlTft>
               (LteSlTft::RECEIVE, groupRespondersIpv4Address, groupL2Address);
   proseHelper->ActivateSidelinkBearer (Seconds (1.0), rxUes, tft);

     .
     .
     .

   UdpEchoClientHelper echoClientHelper
                               (groupRespondersIpv4Address, grpEchoServerPort);
   clientRespondersApps = echoClientHelper.Install ((*gIt).Get (0)->GetNode ());

     .
     .
     .

   groupL2Address++;
   groupRespondersIpv4Address = Ipv4AddressGenerator::
                                     NextAddress (Ipv4Mask ("255.0.0.0"));
  }

// Server Application :
```

```
    PacketSinkHelper clientPacketSinkHelper ("ns3::UdpSocketFactory",
                          InetSocketAddress (Ipv4Address::GetAny (), echoPort));
    ApplicationContainer clientRespondersSrvApps =
                              clientPacketSinkHelper.Install (ueResponders);
```

In the previous step we obtained the vector `createdgroups`, containing a group formed by one transmitter UE and 2 receiver UEs. Now, it is easy to anticipate that the client application will be installed in the transmitter UE and the receiver UEs will have server application. In this example, a user can configure any of the two client applications, i.e., `OnOff` and `UdpEchoClientApplication`, where the later one is the default client application.

The Sidelink radio bearers for Tx (for transmitting UE) and Rx (for receiving UEs) are activated by calling the *ActivateSidelinkBearer'* method of `LteSidelinkHelper`.

Finally, a `PacketSink` application is installed as a server application in the receiving UEs.

Sidelink pool configuration

This example simulates an out-of-coverage scenario, therefore, all the UEs will be configured with a pre-configured Sidelink pool. As mentioned in *RRC*, in this scenario the `LteSlUeRrc` class will be responsible for holding this per-configured pool configuration. The pool configuration starts by setting a flag in `LteSlUeRrc` as an indication that the Sidelink is enabled. It is configured as follows:

```
Ptr<LteSlUeRrc> ueSidelinkConfiguration = CreateObject<LteSlUeRrc> ();
ueSidelinkConfiguration->SetSlEnabled (true);
```

For configuring Sidelink pre-configured pool parameters, the IE "SL-Preconfiguration" defined in the standard [TS36331] is converted into a C++ structure and similar to the basic LTE layer 3 messages it can be found in `LteRrcSap` class. This example uses this structure to configure the Sidelink pool parameters for control, data and synchronization in the following manner,

```
LteRrcSap::SlPreconfiguration preconfiguration;

preconfiguration.preconfigGeneral.carrierFreq = 23330;
preconfiguration.preconfigGeneral.slBandwidth = 50;
preconfiguration.preconfigComm.nbPools = 1;

//control
preconfiguration.preconfigComm.pools[0].scCpLen.cplen = LteRrcSap::SlCpLen::NORMAL;
preconfiguration.preconfigComm.pools[0].scPeriod.period = LteRrcSap::
                                            PeriodAsEnum (slPeriod).period;
preconfiguration.preconfigComm.pools[0].scTfResourceConfig.prbNum = pscchRbs;
preconfiguration.preconfigComm.pools[0].scTfResourceConfig.prbStart = 3;
preconfiguration.preconfigComm.pools[0].scTfResourceConfig.prbEnd = 46;
preconfiguration.preconfigComm.pools[0].scTfResourceConfig.offsetIndicator.offset = 0;
preconfiguration.preconfigComm.pools[0].scTfResourceConfig.subframeBitmap.
                                            bitmap = pscchTrpNumber;

//data
preconfiguration.preconfigComm.pools[0].dataCpLen.cplen = LteRrcSap::SlCpLen::NORMAL;
preconfiguration.preconfigComm.pools[0].dataHoppingConfig.hoppingParameter = 0;
preconfiguration.preconfigComm.pools[0].dataHoppingConfig.numSubbands = LteRrcSap::
                                            SlHoppingConfigComm::ns4;
preconfiguration.preconfigComm.pools[0].dataHoppingConfig.rbOffset = 0;

preconfiguration.preconfigComm.pools[0].trptSubset.subset = std::bitset<3> (0x7);
```

```
preconfiguration.preconfigComm.pools[0].dataTfResourceConfig.prbNum = 25;
preconfiguration.preconfigComm.pools[0].dataTfResourceConfig.prbStart = 0;
preconfiguration.preconfigComm.pools[0].dataTfResourceConfig.prbEnd = 49;
preconfiguration.preconfigComm.pools[0].dataTfResourceConfig.offsetIndicator.
                                              offset = pscchLength;
preconfiguration.preconfigComm.pools[0].dataTfResourceConfig.subframeBitmap.bitmap =
                                     std::bitset<40>(0xFFFFFFFFFF);

preconfiguration.preconfigComm.pools[0].scTxParameters.alpha = LteRrcSap::
                                              SlTxParameters::al09;
preconfiguration.preconfigComm.pools[0].scTxParameters.p0 = -40;
preconfiguration.preconfigComm.pools[0].dataTxParameters.alpha = LteRrcSap::
                                              SlTxParameters::al09;
preconfiguration.preconfigComm.pools[0].dataTxParameters.p0 = -40;

//Synchronization
preconfiguration.preconfigSync.syncOffsetIndicator1 = 18;
preconfiguration.preconfigSync.syncOffsetIndicator2 = 29;
preconfiguration.preconfigSync.syncTxThreshOoC = syncTxThreshOoC;
preconfiguration.preconfigSync.syncRefDiffHyst = syncRefDiffHyst;
preconfiguration.preconfigSync.syncRefMinHyst = syncRefMinHyst;
preconfiguration.preconfigSync.filterCoefficient = filterCoefficient;
```

Finally, the configured pool is stored in `LteSlUeRrc` class by calling `SetSlPreconfiguration` function

```
ueSidelinkConfiguration->SetSlPreconfiguration (preconfiguration);
```

Then, by calling the `InstallSidelinkConfiguration` method of `LteHelper` class it configures the `LteUeRrc` attribute named "SidelinkConfiguration" of a UE, which is nothing but a pointer to the `LteSlUeRrc` object used to configure the pool:

```
lteHelper->InstallSidelinkConfiguration (ueRespondersDevs, ueSidelinkConfiguration);
```

This interaction of classes to populate the Sidelink pool is also depicted in *ns-3 LTE Sidelink pool configuration flow*.

Alternatively, the pool configuration for control and data can also be done in a semi-automatic way by using the `LteSlPreconfigPoolFactory`. This would ease the configuration of the pool by only changing the parameters of interest and leaving the rest as default. For example, the above configuration can also be done as follows,

```
preconfiguration.preconfigGeneral.carrierFreq = 23330;
preconfiguration.preconfigGeneral.slBandwidth = 50;
preconfiguration.preconfigComm.nbPools = 1;

LteSlPreconfigPoolFactory pfactory;

//Control
pfactory.SetControlPrbStart (3);
pfactory.SetControlPrbEnd (46);

//Data
pfactory.SetDataOffset (pscchLength);

//Synchronization
preconfiguration.preconfigSync.syncOffsetIndicator1 = 18;
preconfiguration.preconfigSync.syncOffsetIndicator2 = 29;
preconfiguration.preconfigSync.syncTxThreshOoC = syncTxThreshOoC;
preconfiguration.preconfigSync.syncRefDiffHyst = syncRefDiffHyst;
preconfiguration.preconfigSync.syncRefMinHyst = syncRefMinHyst;
```

```
preconfiguration.preconfigSync.filterCoefficient = filterCoefficient;

preconfiguration.preconfigComm.pools[0] = pfactory.CreatePool ();

ueSidelinkConfiguration->SetSlPreconfiguration (preconfiguration);

lteHelper->InstallSidelinkConfiguration (ueRespondersDevs, ueSidelinkConfiguration);
```

Upon the completion of the simulation, the information related to the topology and the data related to the synchronization process gathered through the traces is written to the following files,

- nPositions.txt

  This file stores the position of all the nodes, i.e., eNBs and the UEs in the simulation.

- prose-connections.txt

  This file stores the information, e.g., Node id, and IMSI of the transmitting and the corresponding receiving UEs.

- FirstScan.txt

  This file stores the start time (in ms) of the first scanning period and the IMSI of each UE nodes. The start time for each UE is randomly chosen between 2000 ms and 4000 ms defined by the variables "firstScanTimeMin" and "firstScanTimeMax" in the simulation script.

- SyncRef.txt

  The information in this file is gathered by listening to the trace "ChangeOfSyncRef" of `LteUeRrc`.

Table 2.4: SyncRef.txt

Time (ms)	IMSI	prev SLSSID	prev RxOff-set	prev Fra-meNo	prev Sfra-meNo	curr SLSSID	curr RxOff-set	curr Fra-meNo	curr Sfra-meNo
0	1	0	0	0	0	141969	0	0	0
0	2	0	0	0	0	199946	0	0	0
0	3	0	0	0	0	105029	0	0	0
20025	1	141696	0	985	5	10	0	985	5
20585	2	199946	0	161	5	10	3	17	5
21567	3	105029	0	856	2	10	3	115	7
50000	1	10	0	910	10	0	0	0	0
50000	2	10	0	910	10	0	0	0	0
50000	3	10	0	910	10	0	0	0	0

  It is to be noted that the data in first and last three rows of above table are written by this simulation script to mark the start and end of the simulation. From row 4 we can observe that the UE with IMSI 1 becomes the SyncRef, this can be deduced by looking at its SLSS-ID, which is `SLSS-ID = IMSI * 10` as explained in *RRC*. On the other hand, UEs with IMSI 2 and 3 selects IMSI 1 as their SyncRef and use the same SLSS-ID, as shown in row 5 and 6.

- pscr-ue-pck.tr

  The information in this file is obtained by using the traces "TxWithAddresses" and "RxWithAddresses" of `UdpEchoClient` and `PacketSink` application respectively. Following table shows the snippet of data from this file for all the three UEs,

Table 2.5: pscr-ue-pck.tr

Time (ms)	tx/rx	NID	IMSI	UEtype	size (bytes)	IP[src]	IP[dst]
21690	t	4	1	resp	40	7.0.0.2:49153	225.0.0.1:8000
21690	r	5	2	resp	40	7.0.0.2:49153	7.0.0.3:8000
21690	r	6	3	resp	40	7.0.0.2:49153	7.0.0.4:8000

The first row shows that the first UE with node id 4 and IMSI 1 acts as a transmitter and sends a multicast packet of 40 bytes. Similarly, the other two UEs act as receiver and receive the packet transmitted by the first UE.

- TxSlss.txt

  This file stores the information gathered by listening to the trace "SendSLSS" of `LteUeRrc`. Following is the snippet of the information stored in this file.

Table 2.6: TxSlss.txt

Time (ms)	IMSI	SLSSID	txOffset (ms)	inCoverage	FrameNo	SframeNo
20040	1	10	29	0	986	9
20080	1	10	29	0	990	9
20120	1	10	29	0	994	9
20160	1	10	29	0	998	9

It can be observed that UE with IMSI 1 being a SyncRef is transmitting SLSS with a fixed periodicity of 40 ms. Moreover, at the time when this UE chose to become a SyncRef it randomly selects one of the two configured offsets, i.e., syncOffsetIndicator1 and syncOffsetIndicator2. In this example, it has selected syncOffsetIndicator2, which is set to 29 ms.

wns3-2017-discovery

This example deploys 10 out-of-coverage UEs, distributed randomly within an area of 100 m x 100 m. This example script also illustrates how an out-of-coverage Sidelink related simulation can be performed without instantiating the eNB nodes.

Topology configuration

Compared to the topology of the synchronization example that we discussed before, this example is very simple. For instance, it does not use hexagonal topology or form groups of UEs, i.e, it does not use `Lte3gppHexGridEnbTopologyHelper` and `LteSidelinkHelper`. The `LteHelper` and `PointToPointEpcHelper` are initialized in the same way like any other LTE example with EPC. Also, the call to disable the eNB PHY can also be skipped, since it does not instantiates the eNB nodes. Moreover, this example only focuses on simulating ProSe out-of-coverage discovery, therefore, there is no need to configure the IP of the UEs since discovery is purely a MAC layer application where the messages are filtered on the basis of ProSeAppCode.

The first Sidelink related configuration in this example is to enable the Sidelink.

- Enabling Sidelink

```
lteHelper->SetAttribute ("UseSidelink", BooleanValue (true));
```

Note : Attribute ''UseSidelink'' must be set before installing the UE devices.

- Work-around to bypass the use of eNB nodes

```
(1)

  lteHelper->SetAttribute ("PathlossModel",
                                   StringValue ("ns3::FriisPropagationLossModel
↪"));

(2)

  lteHelper->Initialize ();

(3)

  double ulFreq = LteSpectrumValueHelper::GetCarrierFrequency (23330);
  NS_LOG_LOGIC ("UL freq: " << ulFreq);
  Ptr<Object> uplinkPathlossModel = lteHelper->GetUplinkPathlossModel ();
  Ptr<PropagationLossModel> lossModel = uplinkPathlossModel->
                                         GetObject<PropagationLossModel>
↪();
  NS_ABORT_MSG_IF (lossModel == NULL, "No PathLossModel");
  bool ulFreqOk = uplinkPathlossModel->
                           SetAttributeFailSafe ("Frequency", DoubleValue
↪(ulFreq));

  if (!ulFreqOk)
    {
      NS_LOG_WARN ("UL propagation model does not have a Frequency attribute");
    }
```

The use of eNB nodes can be bypassed by using the above commands strictly in the order they are listed. The
command "lteHelper->Initialize ()" basically performs the channel model initialization of all the component carriers.
Therefore, it is necessary to configure any desired pathloss model before issuing this command. The commands
in step 3 are to properly configure the frequency attribute of the pathloss model used, which is normally done in
`InstallSingleEnb` method of `LteHelper`.

- Creating the UE node, fixing their mobility, and installing UE devices :

```
NodeContainer ues;
ues.Create (nbUes);

//Position of the nodes
Ptr<ListPositionAllocator> positionAllocUe =
                                    CreateObject<ListPositionAllocator>
↪();

for (uint32_t u = 0; u < ues.GetN (); ++u)
  {
    Ptr<UniformRandomVariable> rand = CreateObject<UniformRandomVariable> ();
    double x = rand->GetValue (-100,100);
    double y = rand->GetValue (-100,100);
    double z = 1.5;
    positionAllocUe->Add (Vector (x, y, z));
  }

// Install mobility

MobilityHelper mobilityUe;
mobilityUe.SetMobilityModel ("ns3::ConstantPositionMobilityModel");
mobilityUe.SetPositionAllocator (positionAllocUe);
```

```
mobilityUe.Install (ues);

NetDeviceContainer ueDevs = lteHelper->InstallUeDevice (ues);
```

The above commands will simply create 10 UEs and position each UE at a random location in an area of 100 m x 100 m. The UE devices are installed in a usual way by calling `InstallUeDevice` of `LteHelper` class.

- Configuring discovery applications and starting the discovery process :

```
std::map<Ptr<NetDevice>, std::list<uint32_t> > announceApps;
std::map<Ptr<NetDevice>, std::list<uint32_t> > monitorApps;
for (uint32_t i = 1; i <= nbUes; ++i)
  {
    announceApps[ueDevs.Get (i - 1)].push_back ((uint32_t)i);
    for (uint32_t j = 1; j <= nbUes; ++j)
      {
        if (i != j)
          {
            monitorApps[ueDevs.Get (i - 1)].push_back ((uint32_t)j);
          }
      }
  }


for (uint32_t i = 0; i < nbUes; ++i)
  {
    // true for announce
    Simulator::Schedule (Seconds (2.0), &SlStartDiscovery,
                                    lteHelper, ueDevs.Get (i),
                                    announceApps.find (ueDevs.Get (i))->second,␣
→true);

    // false for monitor
    Simulator::Schedule (Seconds (2.0), &SlStartDiscovery,
                                    lteHelper, ueDevs.Get (i),
                                    monitorApps.find (ueDevs.Get (i))->second,␣
→false);
  }
```

Given the broadcast nature of the discovery process, the applications are configured such that each UE will be able to transmit discovery messages with one ProSeAppCode, i.e., one announce app and will be able to monitor/receive the discovery messages from all other UEs (Notice the two `for` loops at the beginning). The UE device index in the `NetDeviceContainer` is used as a ProSeAppCode, which is later in `LteUeRrc` is converted into a 184 bitset *[TS23003]*. Finally, at 2 sec the method "SlStartDiscovery" implemented in this example calls the `StartDiscovery` of `LteHelper` class to start the discovery process.

Sidelink pool configuration

This example simulates an out-of-coverage scenario, therefore, all the UEs will be configured with a pre-configured Sidelink discovery pool. As mentioned in *RRC*, in this scenario the `LteSlUeRrc` class will be responsible for holding this per-configured pool configuration. The pool configuration starts by setting a flag in `LteSlUeRrc` as an indication that the Sidelink discovery is enabled. It is configured as follows:

```
Ptr<LteSlUeRrc> ueSidelinkConfiguration = CreateObject<LteSlUeRrc> ();
ueSidelinkConfiguration->SetDiscEnabled (true);
```

For configuring Sidelink discovery pre-configured pool parameters, the IE "SL-Preconfiguration" defined in the standard [TS36331] is converted into a C++ structure and similar to the basic LTE layer 3 messages it can be found in `LteRrcSap` class. This example uses this structure to configure the Sidelink discovery pool parameters in the following way,

```
LteRrcSap::SlPreconfiguration preconfiguration;

preconfiguration.preconfigGeneral.carrierFreq = 23330;
preconfiguration.preconfigGeneral.slBandwidth = 50;
preconfiguration.preconfigDisc.nbPools = 1;

preconfiguration.preconfigDisc.pools[0].cpLen.cplen = LteRrcSap::SlCpLen::NORMAL;
preconfiguration.preconfigDisc.pools[0].discPeriod.period = LteRrcSap::
                                              SlPeriodDisc::rf32;
preconfiguration.preconfigDisc.pools[0].numRetx = 0;
preconfiguration.preconfigDisc.pools[0].numRepetition = 1;
preconfiguration.preconfigDisc.pools[0].tfResourceConfig.prbNum = 10;
preconfiguration.preconfigDisc.pools[0].tfResourceConfig.prbStart = 10;
preconfiguration.preconfigDisc.pools[0].tfResourceConfig.prbEnd = 49;
preconfiguration.preconfigDisc.pools[0].tfResourceConfig.offsetIndicator.offset = 0;
preconfiguration.preconfigDisc.pools[0].tfResourceConfig.subframeBitmap.
                                        bitmap = std::bitset<40>(0x11111);
preconfiguration.preconfigDisc.pools[0].txParameters.txParametersGeneral.alpha =
                                        LteRrcSap::SlTxParameters::al09;

preconfiguration.preconfigDisc.pools[0].txParameters.txParametersGeneral.p0 = -40;

preconfiguration.preconfigDisc.pools[0].txParameters.txProbability =
                           SidelinkDiscResourcePool::TxProbabilityFromInt (txProb);

NS_LOG_INFO ("Install Sidelink discovery configuration in the UEs...");
ueSidelinkConfiguration->SetSlPreconfiguration (preconfiguration);
lteHelper->InstallSidelinkConfiguration (ueDevs, ueSidelinkConfiguration);
```

Alternatively, the discovery pool configuration can also be done in a semi-automatic way by using the `LteSlDiscResourcePoolFactory`. This would ease the configuration of the pool by only changing the parameters of interest and leaving the rest as default. For example, the above configuration can also be done as follows,

```
preconfiguration.preconfigGeneral.carrierFreq = 23330;
preconfiguration.preconfigGeneral.slBandwidth = 50;
preconfiguration.preconfigComm.nbPools = 1;

LteSlDiscPreconfigPoolFactory pfactory;
pfactory.SetDiscPrbEnd (49);

preconfiguration.preconfigDisc.pools[0] = pfactory.CreatePool ();

ueSidelinkConfiguration->SetSlPreconfiguration (preconfiguration);
lteHelper->InstallSidelinkConfiguration (ueDevs, ueSidelinkConfiguration);
```

Upon the completion of the simulation a user can find the following files containing the information of the simulated discovery process.

- discovery_nodes.txt

  This file stores the position of all the UEs in the simulation.

- discovery-out-announcement-mac.tr

This file logs the discovery message transmissions (announcements) by listening to the "Discovery-Announcement" trace of `LteUeMac` class. Following is the snippet from this file,

Table 2.7: discovery-out-announcement-mac.tr

Time (s)	IMSI	RNTI	ProSeAppCode
2.236	1	1	1
2.236	3	3	3
2.236	5	5	5
2.236	9	9	9

- discovery-out-announcement-phy.tr

  Similar to the information in "discovery-out-announcement-mac.tr" file this file contains the information about the discovery announcements but with the perspective of phy layer. In particular, it is obtained by listening to the "DiscoveryAnnouncement" trace of `LteUePhy` class. Following is the snippet from this file,

Table 2.8: discovery-out-announcement-phy.tr

Time (s)	IMSI	CellId	RNTI	ProSeAppCode
2.24	1	0	1	1
2.24	3	0	3	3
2.24	5	0	5	5
2.24	9	0	9	9

By comparing the traces from UE MAC and UE PHY, one can notice that the phy layer transmits a particular discovery messages exactly after 4 ms of the processing delay between UE MAC and PHY. The CellId is 0 because of out-of-coverage scenario.

- discovery-out-monitoring.tr

  This file contains the information about the reception of discovery messages by each UE. The data is obtained by listening to the "DiscoveryMonitoring" trace of `LteUeRrc` class. Following is snippet from this file,

Table 2.9: discovery-out-monitoring.tr

Time (s)	IMSI	CellId	RNTI	ProSeAppCode
2.24093	2	0	2	3
2.24093	2	0	2	9
2.24093	2	0	2	1
2.24093	2	0	2	5

From the above table it can be observed that the UE with IMSI 2 has received the discovery messages with ProSeApp-Code of 3,9,1,5. In other words, this UE has discovered 4 other UEs transmitting their discovery announcements using the ProSeAppCode of 3, 9, 1, 5 respectively.

2.4 Testing Documentation

2.5 LTE Sidelink tests

2.5.1 Unit Tests

Sidelink Communication pool

The test suite `Sidelink-comm-pool` checks the validity of Sidelink communication parameters computed during a simulation, e.g., the expected starting frame and subframe number, index of the starting Resource Block (RB), and the number of RBs in a subframe. The test suite contains a pre-configured communication pool for which these parameters are computed. Table *Sidelink communication pool configuration* below lists the configuration of the pool used.

Table 2.10: Sidelink communication pool configuration

Parameter	Value
Control period	sf120 (120 ms)
Control bitmap	0x0000000003 (40 bits)
Number of control RBs	1
First control RB index	10
End control RB index	40
Control Offset	80 ms
Data Bitmap	0xCCCCCCCCCC (40 bits)
Number of data RBs	1
First data RB index	0
End data RB index	49
Data Offset	8 ms

There are four test cases:

1. SidelinkCommPoolNextFrameSubframeTestCase

This test checks the starting frame and subframe number of the next Sidelink Control (SC) period given the current frame and subframe number. Let Fr be the current frame number and Sf the current subframe number. The absolute subframe number Sf_{abs}, since the $Sf = 0$ of $Fr = 0$ is give by :

$$Sf_{\text{abs}} = 10 * (Fr \bmod 1024) + Sf \bmod 10;$$

The number of current Sidelink control period $ScPr_{\text{cur}}$ is calculated as,

$$ScPr_{\text{cur}} = \left\lfloor \frac{Sf_{\text{abs}} - Sc_{\text{offset}}}{ScPr} \right\rfloor$$

where Sc_{offset} is the Sidelink control offset and $ScPr$ is the Sidelink control period from Table *Sidelink communication pool configuration*. The range of $ScPr_{\text{cur}}$ is : $0 \leq ScPr_{\text{cur}} < \frac{10240}{ScPr}$

If the frame number is the last period, the next SC period will start after Sc_{offset}

Finally, the next start frame and subframe number is calculated as,

$$Next_{\text{start}} = Sc_{\text{offset}} + ScPr_{\text{cur}} * ScPr$$

$$Fr_{\text{next}} = \frac{Next_{\text{start}}}{10} \bmod 1024$$

$$Sf_{\text{next}} = Next_{\text{start}} \bmod 10$$

Three different configuration has been tested:

1. $Fr = 0$ and $Sf = 5$

For this configuration, the expected behavior is that the next Sidelink control period will start in frame number 8 and subframe 0 because of the Sc_{offset} of 80 msec.

2. $Fr = 1023$ and $Sf = 0$

This configuration tests the roll over upon reaching the maximum frame number range. Here, the expected behavior is to have a Sc_{offset} of 80 msec once again starting from $Sf = 0$ of $Fr = 0$.

3. $Fr = 1002$ and $Sf = 0$

This configuration reflects the condition when the current frame and subframe number are part of an on going Sidelink control period. The expected behavior is that the next period will start in frame 1004 and subframe 0, i.e., right after the remaining frames/subframes of the current Sidelink control period.

2. SidelinkCommPoolResourceOpportunityTestCase

This test takes the PSCCH resource and transmission number as an input and verifies the frame, subframe number, index of the starting RB, and the number of RBs available in a subframe. The total number of resources in a PSCCH pool are calculated as per [TS36213] 14.2.1.1.

$$RES_{\text{PSCCH}} = L_{\text{PSCCH}} * \left\lfloor \frac{RB_{\text{PSCCH}}}{2} \right\rfloor$$

where

$L_{\text{PSCCH}} = 2$ is the total number of subframes available for PSCCH in this pool

$RB_{\text{PSCCH}} = 2$ (i.e., RB 10 and RB 40) is the total number of resource blocks per subframe available for PSCCH in this pool.

Hence, $RES_{\text{PSCCH}} = 2$

These resources in time and frequency are indexed from 0 to $RES_{\text{PSCCH}} - 1$. In this test, it will range from 0 -> 1, therefore, we test both the PSCCH resources to verify the frame/subframe number, index of the starting RB and the total number of RBs in a subframe available for Sidelink Control Information (SCI) transmission. We note that, to ensure the reliability of the SCI message delivery, each message is transmitted in two identical instances, where each instance occupies one RB. The two instances are transmitted over two different subframes. Therefore, for each PSCCH resource there will be two transmissions. As per [TS36213] 14.2.1.1, for a resource index n_{PSCCH} first transmission occurs in RB $a1$ of subframe $b1$ where

$$a1 = \left\lfloor \frac{n_{\text{PSCCH}}}{L_{\text{PSCCH}}} \right\rfloor$$
$$b1 = n_{\text{PSCCH}} \bmod L_{\text{PSCCH}}$$

and the second transmission occurs in RB $a2$ of subframe $b2$ where

$$a2 = \left\lfloor \frac{n_{\text{PSCCH}}}{L_{\text{PSCCH}}} \right\rfloor + \left\lfloor \frac{RB_{\text{PSCCH}}}{2} \right\rfloor$$
$$b2 = (n_{\text{PSCCH}} + 1 + \frac{n_{\text{PSCCH}}}{L_{\text{PSCCH}}} \bmod (L_{\text{PSCCH}} - 1)) \bmod L_{\text{PSCCH}}$$

$RES_{\text{PSCCH}} = 2$ would mean that we have following four configuration to verify,

1. $n_{\text{PSCCH}} = 0$, Transmission 0:

For $n_{\text{PSCCH}} = 0$, the expected behavior is that the first transmission of PSCCH would be in $RB = 10$ of $Fr = 0$ and $Sf = 0$ and number of RBs for this transmission would be 1.

2. $n_{\text{PSCCH}} = 0$, Transmission 1:

For $n_{\text{PSCCH}} = 0$, the expected behavior is that the second transmission of PSCCH would be in $RB = 40$ of $Fr = 0$ and $Sf = 1$ and number of RBs for this transmission would be 1.

3. $n_{\text{PSCCH}} = 1$, Transmission 0:

For $n_{\text{PSCCH}} = 1$, the expected behavior is that the first transmission of PSCCH would be in $RB = 40$ of $Fr = 0$ and $Sf = 0$ and number of RBs for this transmission would be 1.

4. $n_{\text{PSCCH}} = 1$, Transmission 1:

For $n_{\text{PSCCH}} = 1$, the expected behavior is that the second transmission of PSCCH would be in $RB = 10$ of $Fr = 0$ and $Sf = 1$ and number of RBs for this transmission would be 1.

3. SidelinkCommPoolSubframeOpportunityTestCase

This test verifies index/indices of the RBs available for a given frame - subframe number. The following three configurations have been tested.

1. $Fr = 8$ and $Sf = 0$

This configuration refers to the start of SC period, i.e., after 80 ms of offset from $Fr = 0$ and $Sf = 0$. Thus, we should be on the first subframe of the control channel. The expected RB indices available for this subframe are 10 and 40.

2. $Fr = 8$ and $Sf = 1$

This configuration refers to second subframe of the SC period. The expected RB indices available for this subframe are 10 and 40.

3. $Fr = 8$ and $Sf = 2$

This configuration refers the subframe number, which is not part of SC period as indicated by control bit map. Thus, in this subframe none of the resource block will be allocated for PSCCH transmission.

4. SidelinkCommPoolPsschTestCase

This test checks for the frame-subframe number for PSSCH transmissions. In this test beside the parameters from the pool configuration, an important parameter, i.e., Time Resource Pattern index (iTRP) is provided. All the tests are performed with $iTRP = 5$, which corresponds to the bit map of (0,0,0,0,0,1,0,0) give by the table Table 14.1.1.1.1-1 of [TS36213]. Every transmission on PSSCH is transmitted using 4 HARQ processes using 4 different subframes. Therefore, this test verifies the frame and subframe number of all the 4 transmissions.

1. $Fr = 0$, $Sf = 5$, $iTRP = 5$, Transmission 0

Starting from $Fr = 0$, the first PSSCH transmission should occur on subframe :

$$Sf_{\text{T0}} = Sc_{\text{offset}} + Data_{\text{offset}} + Sf_{\text{TRP}}$$

where Sc_{offset} and $Data_{\text{offset}}$ values are from the Table *Sidelink communication pool configuration* and Sf_{TRP} are obtained after applying TRP bit map on active bits of data bit map. For example,

```
        TRP bit map                    TRP bit map
  ┌─────────────────────┐        ┌─────────────────────┐
  │0 0    0 0    0 1    0 0│      │0 0    0 0    0 1    0 0│
  0|0|1|1|0|0|1|1|0|0|1|'1'|0|0|1|1|0|0|1|1|0|0|1|1|0|0|1|'1'|0|0|1|1|0|0|1|1|0|0|1|1
  |----------------------------------------Data bit map----------------------------------------|
```

If we apply the TRP bit map on the active bits of data bit map, starting from the least significant bit (lbs) of TRP bit map the sixth bit indicates an active subframe. In other words, an offset of 11 subframes as per data bit map, hence, $Sf_{\text{TRP}} = 11$. By using above equation the first PSSCH transmission since subframe 0, would occur on $80 + 8 + 11 = 99$ subframe, i.e. $Fr = 9$ and $Sf = 9$.

Similarly, the remaining three transmissions and all other transmissions will occur every 16 ms. This has been tested by the following tests.

2. $Fr = 0$, $Sf = 5$, $iTRP = 5$, Transmission 1

The transmission should occur after 16 ms of transmission 0, i.e., in $Fr = 11$, $Sf = 5$.

3. $Fr = 0$, $Sf = 5$, $iTRP = 5$, Transmission 2

The transmission should occur after 16 ms of transmission 1, i.e., in $Fr = 13$, $Sf = 1$.

4. $Fr = 0$, $Sf = 5$, $iTRP = 5$, Transmission 3

The transmission should occur after 16 ms of transmission 2, i.e., in $Fr = 14$, $Sf = 7$.

Sidelink discovery pool

The test suite `Sidelink-disc-pool` checks the validity of Sidelink discovery parameters computed during a simulation, e.g., the expected starting frame and subframe number, index of the starting Resource Block (RB) and the number of RBs in a subframe. The test suite contains a pre-configured discovery pool for which these parameters are computed. Table *Sidelink discovery pool configuration* below lists the configuration of the pool used.

Table 2.11: Sidelink discovery pool configuration

Parameter	Value
Discovery cyclic prefix length	NORMAL
Discovery period	rf32 (320 ms)
Number of retransmissions	0
Number of repetition	1
Number of RBs	1
First RB index	10
End RB index	11
Offset	80 ms
Bitmap	0x0000000003 (40 bits)

There are three test cases:

1. SidelinkDiscPoolNextFrameSubframeTestCase

This test checks the starting frame and subframe number of the next Discovery Period (DiscPr) given the current frame and subframe number. Let Fr be the current frame number and Sf the current subframe number. The absolute subframe number Sf_{abs}, since $Sf = 0$ of $Fr = 0$ is given by :

$$Sf_{\mathrm{abs}} = 10 * (Fr \bmod 1024) + Sf \bmod 10;$$

The number of current discovery period $DiscPr_{\mathrm{cur}}$ is calculated as,

$$DiscPr_{\mathrm{cur}} = \left\lfloor \frac{Sf_{\mathrm{abs}} - Disc_{\mathrm{offset}}}{DiscPr} \right\rfloor$$

where $Disc_{\mathrm{offset}}$ is the discovery offset and $DiscPr$ is the discovery period from Table *Sidelink discovery pool configuration*. The range of $DiscPr_{\mathrm{cur}}$ is : $0 \leq DiscPr_{\mathrm{cur}} < \frac{10240}{DiscPr}$

If the frame number is the last period, the next DiscPr will start after $Disc_{\mathrm{offset}}$

Finally the next start frame and subframe number are calculated as,

$$Next_{\mathrm{start}} = Disc_{\mathrm{offset}} + DiscPr_{\mathrm{cur}} * DiscPr$$

$$Fr_{\mathrm{next}} = \frac{Next_{\mathrm{start}}}{10} \bmod 1024$$

$$Sf_{\mathrm{next}} = Next_{\mathrm{start}} \bmod 10$$

Four different configurations have been tested:

1. $Fr = 0$ and $Sf = 5$

For this configuration, the expected behavior is that the next discovery period will start in frame number 8 and subframe 0 because of the $Disc_{\text{offset}}$ of 80 msec.

2. $Fr = 8$ and $Sf = 0$

Here, we are at the start of first discovery period the next discovery period will start after $DiscPr = 320ms$ in frame number 40 and subframe 0.

3. $Fr = 1023$ and $Sf = 0$

This configuration tests the roll over upon reaching the maximum frame number range. Here the expected behavior is to have a $Disc_{\text{offset}}$ of 80 msec once again starting from frame number 0.

4. $Fr = 800$ and $Sf = 0$

This configuration reflects the condition when the current frame and subframe number are part of an on going discovery period. The expected behavior is that the next discovery period will start in frame 808 and subframe 0, i.e., right after the remaining frames/subframes of the current discovery period.

2. SidelinkDiscPoolResourceOpportunityTestCase

This test takes as input the PSDCH resource number from the configured pool and checks for the correct frame/subframe number of the starting RB and the total number of RBs in a subframe assigned for Sidelink discovery. The computation of these parameters are done as per 14.3.1 and 14.3.3 of [TS36213]. Specifically, the methods `GetPsdchTransmissions` and `ComputeNumberOfPsdchResources` in `lte-sl-pool.cc`, respectively implements the mentioned clauses of the standard.

The total number of resources for PSDCH are calculated as,

$$RES_{\text{PSDCH}} = \left\lfloor \frac{L_{\text{PSDCH}}}{Retx + 1} \right\rfloor * \left\lfloor \frac{RB_{\text{PSDCH}}}{2} \right\rfloor$$

where

$L_{\text{PSDCH}} = 2$ is the total number of subframes available for PSDCH in this pool

$Retx = 0$ is the total number of retransmission allowed

$RB_{\text{PSDCH}} = 2$ (i.e., RB 10 and RB 11) is the total number of resource blocks per subframe available for PSDCH in this pool.

These resources in time and frequency are indexed from 0 to $RES_{\text{PSDCH}} - 1$. In this test, it will range from 0 -> 1, therefore, we test both the PSDCH resources to verify the frame/subframe number, index of the starting RB and the total number of RBs in a subframe available for Sidelink discovery.

1. PsdchResourceNo:0

By selecting the PsdchResourceNo = 0 the expected frame and subframe would be 0 and since, the first RB index of the configured pool is 10 the index of the starting RB is expected to be 10 and, at last, the total number of resource blocks are expected to be 2.

2. PsdchResourceNo:1

Compared to the PsdchResourceNo:0 case, by choosing resource number 1 we expect the discovery transmission to occur on subframe = 1.

3. SidlelinkDiscPoolRbsPerSubframeTestCase

This test checks for the total number of resource blocks available in a single subframe and also verifies the indices of the resource blocks. The following three configurations have been tested.

1. $Fr = 8$ and $Sf = 0$

If we go to 80 ms, we should be on the first subframe of the discovery channel and RB 10 and 11 should be assigned for discovery transmission.

2. $Fr = 8$ and $Sf = 1$

If we go to 81 ms, we should be on the second subframe of the discovery channel and RB 10 and 11 should be assigned for discovery transmission.

2. $Fr = 8$ and $Sf = 2$

If we go to 82 ms, we we should be outside the discovery channel and there should be no resource block assignment during this subframe.

System Tests

In-coverage Sidelink communication

The test suite `sidelink-in-coverage-comm` is a system test to test in-coverage Sidelink communication. In particular, it contains two cases to test Mode 1 and Mode 2 for Sidelink communication, respectively. In Mode 1, D2D communications are assisted by the eNodeB, i.e., resource scheduling is performed dynamically by the eNodeB. In Mode 2, UEs manage resource scheduling autonomously relying on pre-configured settings, and both, PSCCH and PSSCH, resources are selected at random from their respective resource pools.

This test creates a scenario with two UEs, which are in coverage of one eNodeB. One of the UE will send traffic directly to the other UE via Sidelink as per configured mode, i.e., Mode 1 or Mode 2. Default configuration will send 10 packets per second for 2 seconds. The expected output is that the receiver UE node would receive 20 packets.

Out of coverage Sidelink communication

Similar to the in-coverage test, the test suite `sidelink-out-of-coverage-comm` is a system test to test the out of coverage Sidelink communication. This test creates a scenario with two out of coverage UEs, where one of the UE will send traffic directly to the other UE via Sidelink. Default configuration will send 10 packets per second for 2 seconds. The expected output is that the receiver UE node would receive 20 packets.

BUILDINGS MODULE

This chapter is an excerpt of the Buildings module documentation chapter, containing the 3GPP-related models that have been added to the *ns-3* buildings module.

3.1 Design documentation

3.1.1 3GPP aligned propagation loss models

In the following we describe all the propagation loss models, which are compliant with 3GPP standards. In particular, following propagation loss models are implemented:

- Hybrid3gppPropagationLossModel

- IndoorToIndoorPropagationLossModel

- OutdoorToIndoorPropagationLossModel

- OutdoorToOutdoorPropagationLossModel

- ScmUrbanMacroCellPropagationLossModel

- UrbanMacroCellPropagationLossModel

Hybrid3gppPropagationLossModel

The `Hybrid3gppPropagationLossModel` pathloss model is a combination of the following pathloss models:

- IndoorToIndoorPropagationLossModel

- OutdoorToIndoorPropagationLossModel

- OutdoorToOutdoorPropagationLossModel

- UrbanMacroCellPropagationLossModel

This wrapper class is created to make it easier to evaluate the pathloss in different environments, e.g., Macro cell, D2D outdoor, indoor, hybrid (i.e. outdoor to indoor) and with buildings. The following pseudo-code illustrates how the different pathloss models are integrated in `Hybrid3gppPropagationLossModel`:

```
if (Macro Cell Communication)
   then
      L = UrbanMacroCell
else (D2D communication)
   if (NodeA is outdoor)
      then
```

```
        if (NodeB is outdoor)
            then
                L = OutdoorToOutdoor
            else
                L = OutdoorToIndoor
    else (NodeA is indoor)
        if (NodeB is indoor)
            then
                L = IndoorToIndoor
            else
                L = OutdoorToIndoor
```

IndoorToIndoorPropagationLossModel

The model is defined by 3GPP for D2D indoor to indoor scenarios *[TR36843] [TR36814]*. It considers LOS and NLOS scenarios for 700 MHz frequency (Public Safety use cases) by taking into account the shadowing according to a log-normal distribution. For the case when UE is inside the same building as hotspot the standard deviation is 3 dB and 4 dB for LOS and NLOS, respectively. For the scenario when UE is in a different building the standard deviation is 10 dB.

UE is inside a different building as the indoor hotzone

$$L_{\mathrm{NLOS}}[\mathrm{dB}] = max(131.1 + 42.8 \log_{10}(R), 147.4 + 43.3 \log_{10}(R))$$

UE is inside the same building as the indoor hotzone

$$L_{\mathrm{LOS}}[\mathrm{dB}] = 89.5 + 16.9 \log_{10}(R)$$
$$L_{\mathrm{NLOS}}[\mathrm{dB}] = 147.4 + 43.3 \log_{10}(R)$$

where the probability of LOS is given as:

$$Prob(R) = \begin{cases} 1 & \text{if } R \leq 0.018Km \\ e^{\frac{-(R-0.018)}{0.027}} & \text{if } 0.018Km \leq R \leq 0.037Km \\ 0.5 & \text{if } R \geq 0.037Km \end{cases}$$

According to the standard *[TR36843]*, the pathloss for 700 MHz band is computed by applying $20 \log_{10}(f_{\mathrm{c}})$ to the pathloss at 2 GHz as follows,

$$LOSS[\mathrm{dB}] = LOSS + 20 \log_{10}(\tfrac{f_{\mathrm{c}}}{2}) \quad \text{if } 0.758GHz \leq f_{\mathrm{c}} \leq 0.798GHz .$$

where

f_{c} : frequency [GHz]

R : distance between the hotspot and UE [Km]

OutdoorToIndoorPropagationLossModel

This model is implemented for outdoor to indoor scenarios as per the specifications in *[TR36843]*. The model supports both Line-of-Sight (LOS) and Non Line-of-Sight (NLOS) scenarios by taking in to account the shadowing according to a log-normal distribution with standard deviation of 7 dB for both the scenarios.

The pathloss equations used by this model is:

$$L_{\mathrm{LOS}}[\mathrm{dB}] = PL\_B1\_tot(d_{in} + d_{out}) + 20 + 0.5d_{in}$$

$$L_{\mathrm{NLOS}}[\mathrm{dB}] = PL\_B1\_tot(d_{in} + d_{out}) + 20 + 0.5d_{in} - 0.8h_{ms}$$

PL_B1_tot is computed as follows,

$$PL\_B1\_tot(d_{in} + d_{out}) = max(PL_{freespace}(d), PL\_B1(d_{in} + d_{out}))$$

where $PL_{freespace}$ is free space path loss from Eq. 4.24 in *[winner]*.

$$PL_{freespace} = 20 \log_{10}(d) + 46.4 + 20 \log_{10}(\frac{f_{\mathrm{c}}}{5})$$

and PL_B1 is the path loss from Winner + B1 channel model for LOS and NLOS scenarios in hexagonal layout *[winnerfinal]*:

For LOS

$$PL\_B1_{\mathrm{LOS}}[\mathrm{dB}] = \begin{cases} 22.7 \log_{10}(d_{in} + d_{out}) + 27 + 20 \log_{10}(f_{\mathrm{c}}) + LOS_{offset} & \text{if } 3m \leq d \leq d_{\mathrm{BP}} \\ \\ 40 \log_{10}(d_{in} + d_{out}) + 7.56 - 17.3 \log_{10}(h'_{\mathrm{bs}})- & \text{if } d_{\mathrm{BP}} \leq d \leq 5000m \\ 17.3 \log_{10}(h'_{\mathrm{ms}}) + 2.7 \log_{10}(f_{\mathrm{c}}) + LOS_{offset} \end{cases}$$

where the LOS_{offset} is 0 dB and the breakpoint distance is given by:

$$d_{\mathrm{BP}} \approx 4h'_{\mathrm{bs}}h'_{\mathrm{ms}}(\frac{f_{\mathrm{c}}[Hz]}{c})$$

the LOS probability is computed as follows:

$$P_{\mathrm{LOS}} = min(\frac{18}{d}, 1)(1 - e^{\frac{-d}{36}}) + e^{\frac{-d}{36}}$$

and the effective antenna height of the eNB and UE is computed as:

$$h'_{\mathrm{bs}} = h_{\mathrm{bs}} - 1$$

$$h'_{\mathrm{ms}} = h_{\mathrm{ms}} - 1$$

For NLOS

The model supports frequency bands of 700 MHz for Public Safety and 2 GHz for general scenarios in NLOS. The pathloss equations used are the following:

for 700 MHz:

$$PL\_B1_{\mathrm{NLOS}}[\mathrm{dB}] = \begin{cases} (44.9 - 6.55 \log_{10}(h_{\mathrm{bs}})) \log_{10}(d_{in} + d_{out}) + 5.83 \log_{10}(h_{\mathrm{bs}})+ & \text{if } 3m \leq d \leq 2000m \\ 16.33 + 26.16 \log_{10}(f_{\mathrm{c}}) + NLOS_{offset} \end{cases}$$

for 2 GHz:

$$PL\_B1_{\text{NLOS}}[\text{dB}] = \begin{cases} (44.9 - 6.55\log_{10}(h_{\text{bs}}))\log_{10}(d_{in} + d_{out}) + 5.83\log_{10}(h_{\text{bs}}) + & \text{if } 3m \leq d \leq 2000m \\ 14.78 + 34.97\log_{10}(f_{\text{c}}) + NLOS_{offset} \end{cases}$$

where the $NLOS_{offset}$ is 5 dB.

The remaining parameters used in the above equations are:

f_{c} : frequency [GHz]

d : distance between the eNB and UE [m]

d_{in} : distance from the wall to the indoor terminal [m]

d_{out} : distance between the outdoor terminal and the point on the wall that is nearest to the the indoor terminal [m]

h_{bs} : eNB antenna height above the ground [m]

h_{ms} : UE antenna height above the ground [m]

h'_{bs} : effective antenna height of the eNB [m]

h'_{ms} : effective antenna height of the UE [m]

LOS_{offset} : line-of-sight offset

$NLOS_{offset}$: non line-of-sight offset

c : speed of light in vacuum ($3x10^8 m/s$)

OutdoorToOutdoorPropagationLossModel

This propagation loss model is defined by 3GPP for Device to Device (D2D) outdoor to outdoor scenario *[TR36843]*. The model supports both LOS and NLOS scenarios by taking in to account the shadowing according to a log-normal distribution with standard deviation of 7 dB for both the scenarios.

The pathloss equation used by this model is:

$$PL\_B1\_tot(d) = max(PL_{freespace}(d), PL\_B1(d))$$

where $PL_{freespace}$ is free space path loss from Eq. 4.24 in *[winner]*.

$$PL_{freespace} = 20\log_{10}(d) + 46.4 + 20\log_{10}(\frac{f_{\text{c}}}{5})$$

and PL_B1 is the path loss from Winner + B1 channel model *[winnerfinal]* for hexagonal layout and is given by:

$$L_{\text{LOS}}[\text{dB}] = \begin{cases} 22.7\log_{10}(d) + 27 + 20\log_{10}(f_{\text{c}}) + LOS_{offset} & \text{if } 3m \leq d \leq d_{\text{BP}} \\ 40\log_{10}(d) + 7.56 - 17.3\log_{10}(h'_{\text{bs}}) - 17.3\log_{10}(h'_{\text{ms}}) + 2.7\log_{10}(f_{\text{c}}) + LOS_{offset} & \text{if } d_{\text{BP}} \leq d \leq 5000m \end{cases}$$

where the breakpoint distance is given by:

$$d_{\text{BP}} \approx 4h'_{\text{bs}}h'_{\text{ms}}(\frac{f_{\text{c}}[Hz]}{c})$$

The implemented model supports two range of frequency bands 700 MHz and 2 GHz in NLOS scenarios. The pathloss equations are the following:

for 700 MHz:

$$L_{\text{NLOS}}[\text{dB}] = \begin{cases} (44.9 - 6.55\log_{10}(h_{\text{bs}}))\log_{10}(d) + 5.83\log_{10}(h_{\text{bs}}) + & \text{if } 3m \leq d \leq 2000m \\ 16.33 + 26.16\log_{10}(f_{\text{c}}) + NLOS_{offset} \end{cases}$$

for 2 GHz:

$$L_{\text{NLOS}}[\text{dB}] = \begin{cases} (44.9 - 6.55 \log_{10}(h_{\text{bs}})) \log_{10}(d) + 5.83 \log_{10}(h_{\text{bs}}) + & \text{if } 3m \leq d \leq 2000m \\ 14.78 + 34.97 \log_{10}(f_{\text{c}}) + NLOS_{offset} \end{cases}$$

and the probability of LOS is:

$$P_{\text{LOS}} = min(\frac{18}{d}, 1)(1 - e^{\frac{-d}{36}}) + e^{\frac{-d}{36}}$$

According to the standard while calculating Winner + B1 pathloss the following values shall be used

$$h_{\text{bs}} = h_{\text{ms}} = 1.5m$$

$$h_{\text{bs}}^{'} = h_{\text{ms}}^{'} = 0.8m$$

$$LOS_{offset} = 0dB$$

$$NLOS_{offset} = -5dB$$

where

f_{c} : frequency [GHz]

d : distance between the eNB and UE [m]

h_{bs} : eNB antenna height above the ground [m]

h_{ms} : UE antenna height above the ground [m]

$h_{\text{bs}}^{'}$: effective antenna height of the eNB [m]

$h_{\text{ms}}^{'}$: effective antenna height of the UE [m]

LOS_{offset} : line-of-sight offset

$NLOS_{offset}$: non line-of-sight offset

c : speed of light in vacuum ($3x10^8 m/s$)

We note that, the model returns a free space path loss value if the distance between a transmitter and a receiver is less than 3 m.

ScmUrbanMacroCellPropagationLossModel

This propagation loss model is based on the specifications defined for 3GPP Spatial Channel Model (SCM) *[TR25996]* for NLOS urban macro-cell scenario. The pathloss is based on the modified COST231 Okumura Hata urban propagation model for frequencies ranging from 150 – 2000 MHz. The model also considers shadowing according to a log-normal distribution with standard deviation of 8 dB, as defined in the standard *[TR25996]*.

The pathloss expression used by this model is:

$$L[\text{dB}] = (44.9 - 6.55 \log_{10}(h_{\text{bs}})) \log_{10}(\frac{d}{1000}) + 45.5 + (35.46 - 1.1(h_{\text{ms}})) \log_{10}(f_{\text{c}}) - 13.82 \log_{10}(h_{\text{bs}}) + 0.7(h_{\text{ms}}) + C$$

where

f_{c} : frequency [MHz]

h_{bs} : eNB antenna height above the ground [m]

h_{ms} : UE antenna height above the ground [m]

d : distance between the eNB and UE [m]

C : Constant factor

The value of $C = 3dB$ for urban macro-cell scenario.

UrbanMacroCellPropagationLossModel

This propagation loss model is developed and documented by 3GPP in *[TR36814]*. The implemented model covers an urban macro-cell scenario for the frequency range of 2 - 6 GHz with different antennas, building heights and street widths. It is designed for both LOS and NLOS scenarios by taking in to account the shadowing according to a log-normal distribution with standard deviation of 4 dB and 6 dB, for LOS and NLOS, respectively.

The pathloss expressions used by this model are:

$$L_{\text{LOS}}[\text{dB}] = \begin{cases} 22\log_{10}(d) + 28 + 20\log_{10}(f_{\text{c}}) & \text{if } 10m \leq d \leq d_{\text{BP}} \\ 40\log_{10}(d) + 7.8 - 18.0\log_{10}(h_{\text{bs}}^{'}) - 18.0\log_{10}(h_{\text{ms}}^{'}) + 2\log_{10}(f_{\text{c}}) & \text{if } d_{\text{BP}} \leq d \leq 5000m \end{cases}$$

$$L_{\text{NLOS}}[\text{dB}] = \begin{cases} 161.04 - 7.1\log_{10}(W) + 7.5\log_{10}(h) - & \text{if } 10m \leq d \leq 5000m \\ (24.37 - 3.7(\frac{h}{h_{\text{bs}}})^2)\log_{10}(h_{\text{bs}}) + (43.42 - 3.1\log_{10}(h_{\text{bs}}))(\log_{10}(d) - 3) + \\ 20\log_{10}(f_{\text{c}}) - (3.2 - (\log_{10}(11.75h_{\text{ms}}))^2 - 4.97) \end{cases}$$

where the breakpoint distance is given by:

$$d_{\text{BP}} \approx 4h_{\text{bs}}^{'}h_{\text{ms}}^{'}(\frac{f_{\text{c}}[Hz]}{c})$$

The probability of LOS is given by:

$$P_{\text{LOS}} = min(\frac{18}{d}, 1)(1 - e^{\frac{-d}{63}}) + e^{\frac{-d}{63}}$$

and the effective antenna heights of the eNB and UE are computed as:

$$h_{\text{bs}}^{'} = h_{\text{bs}} - 1$$

$$h_{\text{ms}}^{'} = h_{\text{ms}} - 1$$

and the above parameters are

f_{c} : frequency [GHz]

d : distance between the eNB and UE [m]

h : average height of the building [m]

W : street width [m]

h_{bs} : eNB antenna height above the ground [m]

h_{ms} : UE antenna height above the ground [m]

$h_{\text{bs}}^{'}$: effective antenna height of the eNB [m]

$h_{\text{ms}}^{'}$: effective antenna height of the UE [m]

c : speed of light in vacuum ($3\text{x}10^8 m/s$)

The model returns 0 dB loss if the distance between a transmitter and a receiver is less than 10 m. Therefore, a user should carefully deploy the UEs, such that, the distance between an eNB and a UE is 10 m or above.

ANTENNA MODULE

This chapter is an excerpt of the Antenna module documentation chapter, containing the parabolic antenna models that have been added to the *ns-3* antenna module.

4.1 Design documentation

4.1.1 Provided models

In this section we describe the PSC-related antenna radiation pattern models that are included within the antenna module.

ParabolicAntennaModel

This model is based on the parabolic approximation of the main lobe radiation pattern. It is often used in the context of cellular system to model the radiation pattern of a cell sector, see for instance *[R4-092042a]* and *[Calcev]*. The antenna gain in dB is determined as:

$$g_{dB}(\phi, \theta) = -\min\left(12\left(\frac{\phi - \phi_0}{\phi_{3dB}}\right)^2, A_{max}\right)$$

where ϕ_0 is the azimuthal orientation of the antenna (i.e., its direction of maximum gain), ϕ_{3dB} is its 3 dB beamwidth, and A_{max} is the maximum attenuation in dB of the antenna. Note that this radiation pattern is independent of the inclination angle θ.

Parabolic3dAntennaModel

Another 3GPP-defined antenna model is the `Parabolic3dAntennaModel`, drawn from 3GPP TR 36.814 *[TR36814]*. The model, for 3-sector cell sites with fixed antenna patterns, is defined in Table A.2.1.1-2, 3GPP Case 1 and 3 (Macro-cell). Both a horizontal and vertical antenna pattern is defined, and an equation for combining the two methods is provided. So in contrast to `ParabolicAntennaModel`, different horizontal and vertical configuration parameters are required. The attributes `HorizontalBeamwidth`, `Orientation`, `MaxHorizontalAttenuation`, `VerticalBeamwidth`, and `MaxVerticalAttenuation` are configured with the suggested default values. In addition, attributes for mechanical and electrical tilt are defined; these help to adjust the azimuth angle with respect to the reference system of the antenna.

4.2 Testing Documentation

In this section we describe the PSC-related test suites included with the antenna module that verify its correct functionality.

The unit test suite `parabolic-antenna-model` checks that the `ParabolicAntennaModel` class works properly. Several test cases are provided that check for the antenna gain value calculated at different directions and for different values of the orientation, the maximum attenuation and the beamwidth. The reference gain is calculated by hand. Each test case passes if the reference gain in dB is equal to the value returned by `ParabolicAntennaModel` within a tolerance of 0.001, which accounts for the approximation done for the calculation of the reference values.

The unit test suite `parabolic-3d-antenna-model` is based on the `ParabolicAntennaModel` tests. A sequence of test cases at different directions is defined:

1. test horizontal plane with a 60 deg beamwidth; gain is -20dB at +-77.460 degrees from boresight

2. test positive orientation with a 60 deg beamwidth; gain is -10dB at +-54.772 degrees from boresight

3. test negative orientation and different beamwidths with a 80 deg beamwidth; gain is -20dB at +- 73.030 degrees from boresight

4. test vertical plane

5. test tilt

The reference gain is calculated by hand. Each test case passes if the reference gain in dB is equal to the value returned by `Parabolic3dAntennaModel` within a tolerance of 0.001, which accounts for the approximation done for the calculation of the reference values.

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