An end-to-end tour of a simulation

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WNS3, March 2nd 2009

Outline

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1. How a simulation is built
2. Diving in: topology construction
3. Diving In: an End To End Tour of a Packet

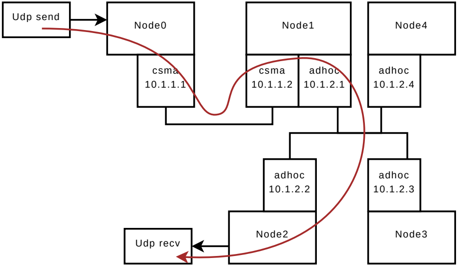
The ns-3 API

There are two ways to interact with the ns-3 API:

- Construct a simulation with the *Container* API:
  - Apply the same operations on sets of objects
  - Easy to build topologies with repeating patterns
- Construct a simulation with the *low-level* API:
  - Instanciate every object separately, set its attributes, connect it to other objects.
  - Very flexible but potentially complex to use

The best way to understand how they work and relate to each other is to use both on the same example

The Testcase



- One csma link
- One wifi infrastructure network
- Two ip subnetworks
- One udp traffic generator
- One udp traffic receiver
- Global god ip routing

The *Container* Version

Fire up an editor and look at the code

The *Low-Level* Version

Fire up an editor and look at the code

Outline

Why are objects so complicated to create ?

We do:

```
Ptr<Node> node0 = CreateObject<Node> ();
```

Why not:

```
Node *node0 = new Node ();
```

Or:

```
Node node0 = Node ();
```

Templates: the Nasty Brackets

- Contain a list of *type* arguments
- Parameterize a class or function from input type
- In ns-3, used for:
    - Standard Template Library
    - Syntactical sugar for low-level facilities
- Saves a lot of typing
- No portability/compiler support problem
- Sometimes painful to decipher error messages.

Memory Management

It is hard in C++:

- No garbage collector
- Easy to forget to delete an object
- Pointer cycles
- Ensure coherency and uniformity

So, we use:

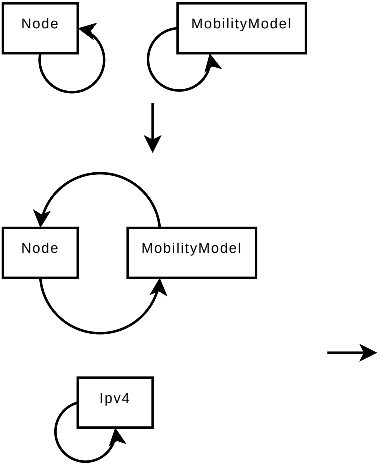
- Reference counting: track number of pointers to an object (`Ref`+`Unref`)
- Smart pointers: `Ptr<>`, `Create<>` and, `CreateObject<>`
- Sometimes, explicit `Dispose` to break cycles

Why don't we have a MobileNode ?

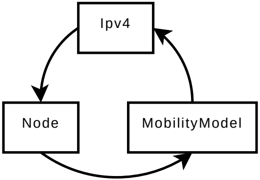
```
Ptr<Node> node = CreateObject<Node> ();
Ptr<MobilityModel> mobility = CreateObject<...> ();
node->AggregateObject (mobility);
```

- Some nodes need an IPv4 stack, a position, an energy model.
- Some nodes need just two out of three.
- Others need other unknown features.
- The obvious solution: add everything to the Node base class, but:
  - The class will grow uncontrollably over time
  - Everyone will need to patch the class
  - Slowly, every piece of code will depend on every other piece of code
  - A maintenance nightmare...
- A better solution:
  - Separate functionality belongs to separate classes
  - Objects can be aggregated at runtime to obtain extra functionality

Object aggregation



- A circular singly linked-list
- AggregateObject is a constant-time operation
- GetObject is a O(n) operation
- Aggregate contains only one object of each type



The ns-3 type system

- The aggregation mechanism needs information about the type of objects are runtime
- The attribute mechanism needs information about the attributes supported by a specific object
- The tracing mechanism needs information about the trace sources supported by a specific object

All this information is stored in `ns3::TypeId`:

- The parent type
- The name of the type
- The list of attributes (their name, their type, etc.)
- The list of trace sources (their name, their type, etc.)

The ns-3 type system

It is not very complicated to use:

- Derive from the ns3::Object base class
- Define a GetTypeId static method:

```
class Foo : public Object {
public:
  static TypeId GetTypeId (void);
};
```

- Define the features of your object:

```
  static TypeId tid = TypeId ("ns3::Foo")
    .SetParent<Object> ()
    .AddAttribute ("Name", "Help", ...)
    .AddTraceSource ("Name", "Help", ...);
  return tid;
```

- call NS_OBJECT_ENSURE_REGISTERED

XXX: maybe add more details.

Outline

Application Transmission I

User writes:

```
Ptr<Application> app = ...;
app->Start (Seconds (1.0));
```

`Application::Start`:

```
m_startEvent = Simulator::Schedule (startTime,
               &Application::StartApplication, this);
```

Application Transmission II

User calls `Simulator::Run`:

```
m_socket = Socket::CreateSocket (GetNode(), m_tid);
m_socket->Bind ();
m_socket->Connect (m_peer);
...
m_startStopEvent = Simulator::Schedule(offInterval,
                   &OnOffApplication::StartSending, this);
```

`Socket::CreateSocket`:

```
Ptr<SocketFactory> socketFactory;
socketFactory = node->GetObject<SocketFactory> (tid);
s = socketFactory->CreateSocket ();
```

Application Transmission III

`OnOffApplication::StartSending`:

```
m_sendEvent = Simulator::Schedule(nextTime,
                   &OnOffApplication::SendPacket, this);
```

`OnOffApplication::SendPacket`:

```
Ptr<Packet> packet = Create<Packet> (m_pktSize);
m_txTrace (packet);
m_socket->Send (packet);
...
m_sendEvent = Simulator::Schedule(nextTime,
                   &OnOffApplication::SendPacket, this);
```

Summary: how applications access network stacks

How to use a new protocol Foo:

```
Ptr<SocketFactory> factory =
   node->GetObject<FooSocketFactory> ();
Ptr<Socket> socket = factory->CreateSocket ();
socket->...
```

How to implement a new protocol Foo:

- Create FooSocketFactory, a subclass of SocketFactory
- Aggregate FooSocketFactory to a Node during topology construction (for UDP, done by InternetStackHelper::Install)
- From FooSocketFactory::CreateSocket, create instances of type FooSocket, a subclass of Socket

Note: Magic COW Packets I

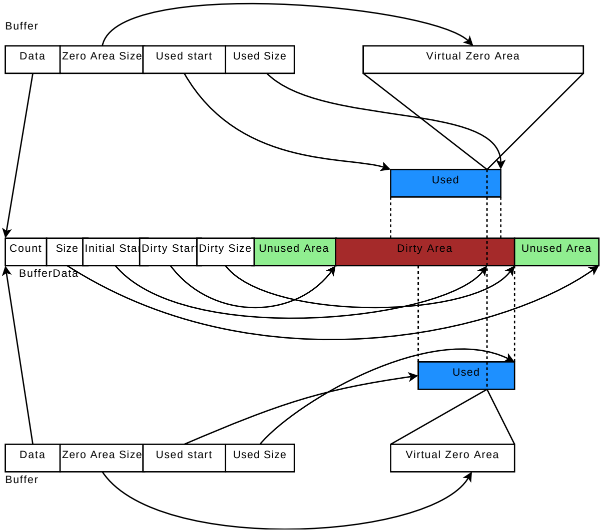
ns-3 packets contain a lot of information:

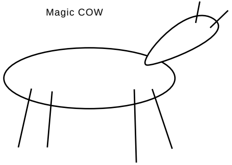
- Buffer: a byte buffer which contains payload, headers, trailers, all in real network format
- Metadata: information about the type of headers and trailers located in the byte buffer
- Tags: extra user-provided information, very useful for end-to-end simulation-only stuff: timestamps for rtt calculations, etc.

ns-3 packets are magic:

- They are reference-counted
- They have Copy On Write semantics: `Packet::Copy` does not create a new packet buffer: it creates a new reference to the same packet buffer
- Payload is zero-filled and never allocated by default: only headers and trailers use memory

Note: Magic COW Packets II





UDP Transmission I

`UdpSocketImpl::Send` eventually calls `UdpSocketImpl::DoSendTo` which calls `UdpL4Protocol::Send`:

```
UdpHeader udpHeader;
...
udpHeader.SetDestinationPort (dport);
udpHeader.SetSourcePort (sport);
packet->AddHeader (udpHeader);
Ptr<Ipv4L3Protocol> ipv4 =
        m_node->GetObject<Ipv4L3Protocol> ();
ipv4->Send (packet, saddr, daddr, PROT_NUMBER);
```

IPv4 Transmission I

`Ipv4L3Protocol::Send`:

```
Ipv4Header ipHeader;
...
ipHeader.SetSource (source);
ipHeader.SetDestination (destination);
ipHeader.SetProtocol (protocol);
ipHeader.SetPayloadSize (packet->GetSize ());
...
ipHeader.SetTtl (...);
...
Lookup (ipHeader, packet,
   MakeCallback (&Ipv4L3Protocol::SendRealOut, this));
```

IPv4 Transmission II

Ipv4L3Protocol::Lookup searches a protocol which has an outgoing route for the packet and calls Ipv4L3Protocol::SendRealOut:

```
packet->AddHeader (ipHeader);
Ptr<Ipv4Interface> outInterface =
   GetInterface (route.GetInterface ());
outInterface->Send (packet, ipHeader.GetDestination ())
```

Down, in ArpIpv4Interface:

```
Ptr<ArpL3Protocol> arp = m_node->GetObject<ArpL3Protocol> ();
Address hardwareDestination;
arp->Lookup (p, dest, GetDevice (), m_cache, &hardwareDestinat
GetDevice ()->Send (p, hardwareDestination,
                   Ipv4L3Protocol::PROT_NUMBER);
```

Note: How Do you Implement a new Header ? I

The class declaration:

```
class MyHeader : public Header
...
  void SetData (uint16_t data);
  uint16_t GetData (void) const;
...
  static TypeId GetTypeId (void);
  virtual TypeId GetInstanceTypeId (void) const;
  virtual void Print (std::ostream &os) const;
  virtual void Serialize (Buffer::Iterator start) const;
  virtual uint32_t Deserialize (Buffer::Iterator start);
  virtual uint32_t GetSerializedSize (void) const;
private:
  uint16_t m_data;
```

Note: How Do you Implement a new Header ? II

The implementation:

```
void
MyHeader::Serialize (Buffer::Iterator start) const
{
  start.WriteHtonU16 (m_data);
}
uint32_t
MyHeader::Deserialize (Buffer::Iterator start)
{
  m_data = start.ReadNtohU16 ();
  return 2;
}
```

Note: How Do you Implement a new Header ? III

What really matters:

- Copy/Paste the code for `GetTypeId` and `GetInstanceTypeId`
- Make sure `GetSerializedSize` returns enough for `Serialize`
- Make sure `Hton` are balanced with `Ntoh`
- Remember that what is written in `Buffer::Iterator` must be faithful the the real network representation of the protocol header

Arp

`ArpL3Protocol::Lookup`:

- Try to find a matching live entry
- If needed, send an ARP request on `NetDevice::Send`
- Wait for reply

`ArpL3Protocol::Receive`:

- If request for us, send reply
- If reply, check if request pending, update cache entry, flush packets from cache entry

CsmaNetDevice Transmission

`CsmaNetDevice::Send`:

- Add ethernet header and trailer
- Queue packet in tx queue
- Perform backoff if medium is busy
- When medium is idle, start transmission (delay is bytes*8/throughput)
- When transmission completes, request packet forwarding on medium

`CsmaChannel::TransmitEnd`:

- Apply propagation delay on transmission
- Distribute packet to all devices on the medium for reception

`CsmaNetDevice::Receive`:

- Remove ethernet header and trailer
- Filter unwanted packets
- Apply packet error model
- Call device *receive* callback

Summary: From layer 2 to layer 3

During topology setup:

- Call `Node::RegisterProtocolHandler` to register a layer 3 protocol handler by its protocol number
- `Node::AddDevice` sets device *receive* callback to `Node::NonPromiscReceiveFromDevice`

At runtime:

- Device calls *receive* callback to send packet to layer 3
- `Node::NonPromiscReceiveFromDevice` searches matching protocol handlers by protocol number

IPv4 Reception

`Ipv4L3Protocol::Receive`:

- Remove IPv4 header, verify checksum
- Forward packet to matching raw IPv4 sockets
- If needed, forward packet down to outgoing interfaces
- If needed, forward packet up the stack to matching layer 4 protocol with `Ipv4L3Protocol::GetProtocol`

Wifi Transmission

WifiNetDevice::Send is fairly simple:

```
LlcSnapHeader llc;
llc.SetType (protocolNumber);
packet->AddHeader (llc);
m_txLogger (packet, realTo);
m_mac->Enqueue (packet, realTo);
```

It's an AP so, in NqapWifiMac::ForwardDown:

```
  WifiMacHeader hdr;
  hdr.SetAddr1 (to);
  hdr.SetAddr2 (GetAddress ());
  hdr.SetAddr3 (from);
...
  m_dca->Queue (packet, hdr);
```

Wifi Transmission: DcaTxop

DcaTxop::Queue:

- Queue outgoing packet in WifiMacQueue
- Use DCF (DcfManager and DcfState to obtain a tx opportunity

When the tx opportunity happens, DcaTxop::NotifyAccessGranted is called:

- Dequeue packet
- Prepare the first fragment if needed
- Enable RTS if needed
- Call MacLow::StartTransmission
- Wait for notifications about transmission success or failure from MacLow
- Eventually, start retransmissions, send more fragments

Wifi Transmission: MacLow I

- MacLow::StartTransmission starts a CtsTimeout or an AckTimeout timer and, then calls WifiPhy::SendPacket:

```
if (m_txParams.MustSendRts ())
  SendRtsForPacket ();
else
  SendDataPacket ();
```

- MacLow::CtsTimeout and MacLow::NormalAckTimeout notify upper layers

Wifi layer 1

From the perspective of layer 2, it is a black box whose content is the topic of some presentations this afternoon !

Wifi Reception: MacLow

MacLow::ReceiveOk handles incoming packets:

```
WifiMacHeader hdr;
packet->RemoveHeader (hdr);
if (hdr.IsRts ())
  ...
else if (hdr.IsCts () &&
  ...
else if (hdr.IsAck () &&
  ...
else if (hdr.GetAddr1 () == m_self)
  ...
else if (hdr.GetAddr1 ().IsGroup ())
  ...
```

And notifies upper layers with its *receive* callback

Wifi Reception: Defragmentation, Duplicate Detection

MacRxMiddle::Receive:

```
if (IsDuplicate (hdr, originator))
  return;
Ptr<Packet> agregate = HandleFragments (packet, hdr, originato
if (agregate == 0)
  return;
m_callback (agregate, hdr);
```

Wifi Reception: `MacHigh`

- `NqstaWifiMac::Receive`:

```
else if (hdr->IsData ())
  ...
else if (hdr->IsProbeReq () ||
         hdr->IsAssocReq ())
  ...
else if (hdr->IsBeacon ())
  ...
else if (hdr->IsProbeResp ())
  ...
else if (hdr->IsAssocResp ())
  ...
```

- `WifiNetDevice::ForwardUp`: call the device *receive* callback

Summary: From Layer 3 to Layer 4

- During topology setup, call `Ipv4L3Protocol::Insert` to register a layer 4 protocol with its protocol number
- At runtime:
  - Call `Ipv4L3Protocol::GetProtocol`
  - Call `Ipv4L4Protocol::Receive`

UDP Reception

```
UdpHeader udpHeader;
packet->RemoveHeader (udpHeader);
Ipv4EndPointDemux::EndPoints endPoints =
  m_endPoints->Lookup (destination,
                       udpHeader.GetDestinationPort (),
                       source,
                       udpHeader.GetSourcePort (), ...);
for (endPoint = endPoints.begin ();
     endPoint != endPoints.end (); endPoint++)
  {
    (*endPoint)->ForwardUp (...);
  }
```

`Ipv4EndPoint::ForwardUp` calls into `UdpSocketImpl::ForwardUp`

Application Reception I

UdpSocketImpl::ForwardUp

```
if ((m_rxAvailable + packet->GetSize ()) <= m_rcvBufSize)  {
  m_deliveryQueue.push (packet);
  m_rxAvailable += packet->GetSize ();
  NotifyDataRecv ();
}
```

PacketSink::HandleRead:

```
packet = socket->RecvFrom (from)
```

Application Reception II

UdpSocketImpl::Recv

```
if (m_deliveryQueue.empty() )
  {
    m_errno = ERROR_AGAIN;
    return 0;
  }
Ptr<Packet> p = m_deliveryQueue.front ();
if (p->GetSize () <= maxSize)
  {
    m_deliveryQueue.pop ();
    m_rxAvailable -= p->GetSize ();
  }
return p;
```