Routing Systems in Mobile, Ad-hoc/Cellular 5G Networks

Service Based 5G CP Architecture

Y. Richard Yang

http://zoo.cs.yale.edu/classes/cs434/

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Admin

Projects update

- Week 3 (Apr 16 - Apr 22): Proposal iteration; reading more related work/systems
  - Week 4 (Apr 23 - Apr 29): Prototyping; Mid-point checkpoint; meet w/ the instructor
  - Week 5 (Apr 30 - May 6): Refinement; iterations
  - Week 6 (May 7 - May 13): Final implementation, final report (6-8 pages)
Recap: Decentralized Routing Analysis and Guidance

- In the general case, decentralized routing decision can be unstable.
- In the general case, designing a decision process (protocol) satisfying transitivity, unanimity and independence of irrelevant alternatives (IIA) => centralized control (dictator).
- $P$-graph captures BGP decision process dependency.
- A sufficient condition for BGP stability is that the $P$-graph has no dependency loop.
- Current Internet economics => $P$-graph has no loop!
Recap: MANET Routing

- Important for settings such as military scenarios, sensor networks, rescue operations
- Two main new issues: wireless, mobility
- A main type of MANET routing is link state protocol but using Internet link state (e.g., OSPF directly) has issues, e.g.,
  - send to all links except the incoming link may not be possible in wireless
Recap: OLSRv2 Basic Idea

- Based on regular link state flooding protocol in wireless networks
  - each node forwards a packet once and only once

- OLSR key idea: Multipoint Relaying (MPR)
  - Restricts the set of nodes retransmitting a packet from all nodes (in regular flooding) to a subset of all nodes called multipoint relaying (MPR) nodes
Recap: OLSRv2 Key Idea: Detail

- Let $N_1(n)$ and $N_2(n)$ be the 1-hop, and 2-hop neighbors of node $n$.
- Select flooding MPR($n$): a subset of $N_1(n)$ so that $N_1(\text{MPR}(n))$ covers $N_2(n)$.
- After receiving a broadcast from $n$, only nodes in MPR($n$) rebroadcast.
OLSR Key Idea: Multipoint Relaying (MPR)

Regular flooding 1

Regular flooding 2
OLSR Key Idea: Multipoint Relaying (MPR)

Regular flooding 1

MPR flooding 1
OLSR Key Idea: Multipoint Relaying (MPR)

Regular flooding 2

MPR flooding 2
OLSR Key Idea: Multipoint Relaying (MPR)

Regular flooding 3

MPR flooding 3
Why Flooding MPR Works

- Assume a broadcast from node s can reach a set D nodes using regular broadcast
- Claim: if only the MPR(x) of each node x receiving the data rebroadcast (join flooding), then the same set D receives the message
  - Assume otherwise. MPR covers a smaller set $D_{mpr}$.
    - Assume d in D but not $D_{mpr}$
    - There is a path from s to d in regular broadcast
    - Consider the first link (x0->x) of the path that leads to a node x not in $D_{mpr}$
    - x does not receive in MPR implies x0 does not broadcast
    - x0 receives implies a neighbor y of x0 broadcast
      - y broadcast, x is a 2-hop neighbor of y, and y selects MPR to cover all 2-hop neighbors -> x should receive
Outline

- Admin and recap
- Networking systems in Mobile, ad-hoc network (MANET)
  - OLSRv2
    - Basic idea
    - Details
Protocol Goals

- **Constraints**
  - For each router to
    - identify all destinations in the network
    - identify a sufficient subset of links in the network, in order that shortest routes can be calculated to all available destinations.

- **Optimize**
  - flooding reduction (reducing the number of transmissions to distribute link state)
    - control traffic being flooded through the network using hop-by-hop forwarding, but with a router only needing to forward control traffic that is first received directly from one of the routers that have selected it as a flooding MPR (its "flooding MPR selectors")
  - topology reduction (reducing the number of links distributed)
    - routers declare link state information for their routing MPR selectors, if any.
    - routers that are not selected as routing MPRs need not send any link state information.
Protocol Components

- HELLO protocol to discover local neighborhood
  - Wireless links can be asymmetric (why?)
  - OLSR local neighborhood discovery focuses on symmetric links (why?)

- Flooding MPR selection and routing MPR selection algorithms

- TC (topology control) protocol to sync link state
Building Block: Local Neighborhood Discovery (HELLO)

- A good methodology of designing a distributed protocol
  - write down the computation using state variables at different nodes
  - protocol is then to share the distributed state variables

- Local state variables at each node $n$
  - $N_1_{rcv}(n)$: the set of nodes whose direct broadcast $n$ can receive
  - $N1(n)$: $n$’s 1-hop neighbors using symmetric links
  - $N2(n)$: $n$’s 2-hop neighbors using symmetric links

- Exercise: relationship among (distributed) state variables
  \[ N1(n) = \{ x \in N1_{rcv}(n) : n \in N1_{rcv}(x) \} \]
  \[ N2(n) = \text{union} \{ N1(x) : x \in N1(n) \} \setminus N1(n) \]

Exercise: What variables does node $n$ need from neighbors?
Exercise: Recursive Equation to Protocol

- Event driven, asynchronous neighbor discovery protocol at node \( n \) (compute \( N1(n) \), and \( N2(n) \) at each node \( n \))

  - Upon hear a Hello message from node \( x \)
    - \( N1_{rcv}(n) += \{x\}; \) update \( N1(n) \), \( N2(n) \) using \( N1(x) \), \( N1_{rcv}(x) \)

  - The \( \text{DEAD\_INTERVAL} \) timer of a node \( x \) in \( N1_{rcv}(n) \) expires
    - \( N1_{rcv}(n) -= \{x\}; \) update \( N1(n) \), \( N2(n) \)

  - Periodically, broadcasts Hello message
    - Sends \( N1(n) \), \( N1_{rcv}(n) \)

Offline exercise:
Does the protocol converge even if asynchronous?
Exercise: What is a reasonable algorithm to select flooding MPR(n)?

OLSRv2 recommendation (at node n)
- \( MPR = \text{EMPTY}; N2 = N2(n) \)
- While true
  - Identify \{all \( y \) in \( N2 \): There is only one node \( x(y) \) in \( N1(n) \) to cover \( y \}\}
    - For each \( y \), \( MPR += x(y) \), \( N2 -= y \) and all covered by \( x(y) \)
  - For remaining \( N2 \), for each remaining \( x \) in \( N1(n) \), compute how many \( y \) in \( N2 \) \( x \) covers, pick \( x_{\text{max}} \) that has the largest cover; \( MPR += x_{\text{max}} \), \( N2 -= \) those \( x_{\text{max}} \) covers

Exercise: Assume all links have cost 1. Are there links n can locally omit but still guarantee shortest path?
Offline Exercise

- Additional details in the protocol, e.g.,
  - Each node can indicate willingness to be MPR
  - Systematic protocol to reduce topology by selecting routing MPR (only edges from selector to MPR) so that the distance does not grow after omitting some edges
Summary: OSLRv2

- Adaptation of Internet link state flooding to wireless networks
  - Flooding MPRs to reduce the number of rebroadcasts
  - Routing MPRs to reduce the number of links to be broadcast
Outline

- Admin and recap
- Networking systems in mobile, ad-hoc network (MANET)
- Networking systems in 5G (mobile/cellular) core network
Basic 5G Core Structure

Discussion: What key challenges do you see in 5g cellular routing (networking)?

Focus data-path requirements:
- Roaming (UE location can change)
- QoS (beyond best effort data traffic)
- Scaling
Outline

- Admin and recap
- Networking systems in mobile, ad-hoc network (MANET)
- Networking systems in 5G (mobile/cellular) core network
  - User (data) plane (path)
Cellular/5G Data Path Handling Roaming

- Using flooding of link state to handle roaming (mobility) is not scalable in large-scale networks (why?)
- Exercise: do you have any proposal?
- 5G basic idea:
  - Only involved ingress/egress nodes are involved
  - $\Rightarrow$ routing using tunneling from ingress to egress
5GC Data Path Basic Idea: Downlink

Q: What does a UPF need to know to forward to UE?

Access Node (AN) Tunnel: tunnel at gNB, for UPF to forward downlink traffic to UE.

Identification: gNB IP+UE Tunnel Endpoint ID TEID_an
5GC Data Path Basic Idea: Uplink

Q: What does a gNB need to know to forward to the right UPF?

Core Node (CN) Tunnel
(for gNB to forward uplink traffic to the right UPF):

Identification: UPF IP+UE Tunnel Endpoint ID TEID_cn
Exercise: What may a packet from gNB->UPF for UE to Internet (DN) look like?
5GC Packet Example

Data (overlay uplink): UE -> DN traffic
Capture (N3 underlay): GTP-U Packet gNB -> UPF
**5GC Packet Example**

Data (uplink): UE -> DN
Capture N6: UPF -> DN

```
No. | Time     | Source        | Destination  | Protocol | Length | Info
--- | -------- | ------------- | ------------ | -------- | ------ | ---
1066 25.377180 | 10.10.101.1 | 192.0.2.10   | GTP <UDP>  | 198 49158 → 32769 Len=100
1067 25.377732 | 10.10.101.1 | 192.0.2.10   | UDP        | 146 49158 → 32769 Len=100

Frame 1007: 146 bytes on wire (1168 bits), 146 bytes captured (1168 bits) on interface -, id 0
Ethernet II, Src: 02:00:a5:03:01:01 (02:00:a5:03:01:01), Dst: 02:00:a5:03:01:02 (02:00:a5:03:01:02)
802.1Q Virtual LAN, PRI: 0, DEF: 0, ID: 1530
Internet Protocol Version 4, Src: 10.10.101.1, Dst: 192.0.2.10
0100 .... = Version: 4
.... 0101 = Header Length: 20 bytes (5)
Differentiated Services Field: 0x00 (DSCP: CS0, ECN: Not-ECT)
0000 00.. = Differentiated Services Codepoint: Default (0)
.... ..00 - Explicit Congestion Notification: Not ECN-Capable Transport (0)
Total Length: 128
Identification: 0x3492 (13458)
Flags: 0x0000
...0 0000 0000 0000 = Fragment offset: 0
Time to live: 63
Protocol: UDP (17)
Header checksum: 0x15c6 [validation disabled]
[Header checksum status: Unverified]
Source: 10.10.101.1
Destination: 192.0.2.10
User Datagram Protocol, Src Port: 49158, Dst Port: 32769
Data (100 bytes)
```
5GC Packet Example

Data (downlink): DN -> UE
Capture N6: DN->UPF

<table>
<thead>
<tr>
<th>No.</th>
<th>Time</th>
<th>Source</th>
<th>Destination</th>
<th>Protocol</th>
<th>Length</th>
<th>Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>1010</td>
<td>25.400532</td>
<td>192.0.2.10</td>
<td>10.10.101.1</td>
<td>GTP &lt;UDP&gt;</td>
<td>190 32769 -&gt; 49158 Lcn=100</td>
<td></td>
</tr>
<tr>
<td>1011</td>
<td>25.500249</td>
<td>192.0.2.10</td>
<td>10.10.101.1</td>
<td>UDP</td>
<td>146 32769 -&gt; 49158 Len=100</td>
<td></td>
</tr>
</tbody>
</table>

Frame 1011: 146 bytes on wire (1168 bits), 146 bytes captured (1168 bits) on interface Eth2, id 0
Ethernet II, Src: 02:00:a5:e1:00:0b (02:00:a5:e1:00:0b), Dst: 02:00:a5:03:01:01 (02:00:a5:03:01:01)
082.1Q Virtual LAN, PRI: 0, DEI: 0, ID: 1710

Internet Protocol Version 4, Src: 192.0.2.10, Dst: 10.10.101.1

0100 .... = Version: 4
.... 0101 = Header Length: 20 bytes (5)

Differentiated Services Field: 0x00 (DSCP: CS0, ECN: Not-ECT)
0000 00.. = Differentiated Services Codepoint: Default (0)
.... .00 = Explicit Congestion Notification: Not ECN-Capable Transport (0)
Total Length: 128
Identification: 0x3495 (13461)

Flags: 0x0000
...0 0000 0000 0000 = Fragment offset: 0
Time to live: 64

Protocol: UDP (17)
Header checksum: 0xc14c3 [validation disabled]
[Header checksum status: Unverified]
Source: 192.0.2.10
Destination: 10.10.101.1

User Datagram Protocol, Src Port: 32769, Dst Port: 49158
Data (100 bytes)
**5GC Packet Example**

Data (overlay downlink): DN->UE

Capture (N3 underlay): GTP-U Packet UPF->gNB
Data Path: QoS + Tunnel

- AN tunnel for a UE is identified by:
  - gNB’s IP address
  - TEID_an
- CN tunnel for a UE is identified by:
  - UPF’s IP address
  - TEID_cn
- A QoS Flow is mapped to a DRB based on QFI
- PDU Session, QFI, QoS Flow, N3 GTP_U tunnel, TEID_an and TEID_cn are per UE
Exercises

- Assume the UE moves from gNB1 to gNB2. What should happen?
- What may the control plane (set up the state at the data plane) looks like?
Outline

- Admin and recap
- Networking systems in mobile, ad-hoc network (MANET)
- Networking systems in 5G (mobile/cellular) core network
  - User (data) plane (path)
  - Control plane
**5GC Control Plane (CP) Architecture**

- **Service Base Architecture (SBA):** each network function (NF) in CP exposes HTTP/2 ReSTful APIs.
- **Separation of Compute and Data to enable stateless Network Functions (NFs) in the Control Plane for scalability and resilience.**
Example 5G CP NF (Offline Read)

- **AMF** — Access and Mobility Management Function terminates the control plane of different access networks onto the 5GC and control which UEs can access the 5GC to exchange traffic with DNs. It also manages the mobility of UEs when they roam from one gNB to another for session continuity, whenever possible.

- **SMF** — Session Management Function keeps trace of PDU sessions and QoS Flows in the 5GS for UEs and make sure their states and status are in sync between Network Functions in Control and User Planes. It also receives PCC (Policy and Charging Control) Rules from PCF (Policy Charging Function) and convert PCC Rules into *SDF Templates*, *QoS Profiles* and *QoS Rules* for UPF, gNB and UE respectively for QoS Flows establishment, modification and release etc...

- **UPF** — User Plane Function forwards UE traffic between access networks such as gNBs in 5G-RAN and DNs. It also enforces QoS on UE’s uplink and downlink traffic in 5GC based on the *SDF Templates* sent by SMF over the N4 PFCP (Packet Forwarding Control Packet) interface for the UEs.

- **UDM** — Unified Data Management stores UE encryption key to decrypt UE SUCI (Subscriber Concealed Identifier) to SUPI (Subscriber Permanent Identifier). It also stores UEs’ subscription data.

- **AUSF** — Authentication Server Function offers services to UDM for it to authenticate UEs for accessing the 5GS.

- **gNB** — 5G New Radio (NR) implements various advanced 5G RF technology such as massive MIMO, beam forming, cell densification etc...
5G CP Core NFs
5G CP QoS Setup

**QoS Rules** (Packet Filter, QFI), DNN, UL/DN Session AMBR, PDU Session Type, UE address, S-NSSAI, Precedence

**QoS Profile** (QFI, UL/DL UE-AMBR, PDU Session Type, 5QI, ARP, RQoS, MFBR, GFBR, Notification control, Packet loss rate) & CN’s IP & TEID.cn

**SDF Template** (QFI, PDR, RQoS, User ID, Precedence, FAR, QER, URR, BAR, UE address, PDN type, etc..), AN’s IP & TEID.an

Diagram:
- AMF
- SMF
- UPF
- DN
- UE
- gNB
- N3 GTP-U Tunnel
- N1
- N2
- N3
- N4
Messages 1 to 7 — UE Subscription Verification and Authorization; SMF Selection
Message 1: 
**UE/AFM to SMF — PDU Session Establishment Request**
Messages 8 to 10 — UPF selection; PDU Session Context Creation for UPF
Message 10a: SMF to UPF — N4 Session Establishment/Modification Request
Exercise

- How may you schedule packets among all flows to give a flow a given rate?
Messages 11 to 14 — PDU Session Context Creation for gNB and UE (First UL packet ready)
Message 11: (N2 for gNB) NamfCommunication_N1N2MessageTransfer from SMF to AMF
Message 11: (N1 for UE) — Namf-Communication_N1N2_Message Transfer from SMF to AMF
SST (Slice/Service Type)

- 001 — eMBB (enhanced Mobile Broadband)
- 002 — URLLC (ultra-reliable low latency communication)
- 003 — MIoT (Massive IoT)
- 004 — V2X (Vehicle to Vehicle communication)
Messages 15 to 16 — Update UPF with gNB’s AN Tunnel for UE (First DL Packet Ready)
Message 15 — Nsmf-PDUSession_UpdateSMContext Request from AMF to SMF

- N2 message container from Access Node or gNB
- gNB’s IP and TEID
5G Key Pointers

- 5G architecture TS 23.501
- 5G procedure TS 23.502
- Specification of messages OpenAPI
Networking System Journey

- Routers in a network need to discover attached networks
  - Basic link-state broadcast
- Basic link state is not scalable (multiaccess domain)
  - Introduce networks in graph model, elect designed router, neighboring -> adjacency
- Basic link state is not scalable (large graph)
  - Divide into areas, with a backbone connecting areas; abstracting other areas
- Basic link state transport is not reliable, persistent
  - State synchronization, reliable transport
- Link state is not scalable in large, global setting; does not support decentralization/heterogenous/local decisions
  - Introduce one more abstraction level (autonomous system); link state routing -> policy path vector routing
- Generic decentralization/local decision can be unstable
  - Internet economics provides the “invisible hand” (not a contribution of network system design)
- Internet link state flooding is inefficient in mobile networks
  - Discover and distribute Flooding MPR, routing MPR to reduce overhead
- Update networking system due to mobility is not scalable in large wireless (e.g., cellular) networks
  - Limit mobility-awareness only to ingress and egress nodes, by establishing tunnels
- Provide generic, extensible signaling systems in mobile, cellular networking
  - Extensible, Service oriented architecture in 5G core
Additional Pointers

- See schedule page for several decks of slides on
  - Providing QoS
  - Implementing multicast
  - Link layer design
  - Physical basic ideas