5G Implementation in Defect Inspection Facility

5G Network Foundation Course Finals

Inspection Facility

- *Focus in Automotive parts*
- *Have 5 Inspection Line*

Scenario Information: What we working on?

Parts to be Inspect

Piston

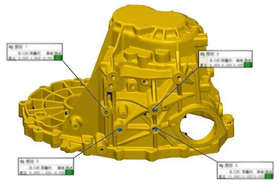
Gearbox Housing

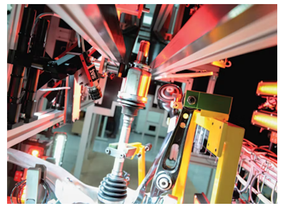
Suspension Rods

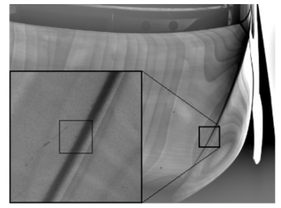
Body Panel

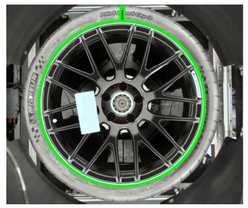
Wheel Rim

Inspection Requirements









Detection Surface				
6 (4 in High Res)	6 (2 in High Res)	8 (3 in High Res)	4 (1 in High Res)	6 in Normal Res
Minimum Defect Size				
1 mm/pixel	1 mm/pixel	1 mm/pixel	1 mm/pixel	3 mm/pixel

Detection Details

- High resolution indicates 1920x1080 / Normal resolution is 800x600 (pixel).
- Camera record in 30 Frame per Second (fps) is capable to detect defects accurately.
- All the recordings and detection results have to sent to central database for QC reports.

Project Objectives: Trade-offs

- **Design and validate URLLC network slices** to meet sub-10 ms latency for high-precision streams.
- **Integrate Multi-Access Edge Computing (MEC)** nodes at the factory floor to offload inference and minimize core-network latency
- **Benchmark open-source 5G stacks** under mixed URLLC/eMBB traffic replicating our five inspection lines.

Defect-Detection Performance Requirements

Default 0.32

$$\text{Bitrate (bps)} = \text{Width (px)} \times \text{Height (px)} \times \text{Frame rate (fps)} \times \text{BPP}$$

Critical inspection faces (1920x1080)

- End-to-end latency ≤ 10 ms
- Packet-loss rate ≤ 10^{-5}

$1920 \times 1080 \times 30 \times 0.32 \approx 19{,}907{,}712$ bps ≈ 19.9 Mbps

Non-Critical inspection faces (800x600)

- Support ≥ N simultaneous streams
- Average one-way latency ≤ 50 ms

$800 \times 600 \times 30 \times 0.32 \approx 4{,}608{,}000$ bps ≈ 4.6 Mbps

Mapping to 5G QoS

URLLC slice

- Latency Budget: ≤ 10 ms
- Reliability ≥ 99.999% (packet-loss ≤ 10^{-5})
- Guaranteed Bitrate

eMBB slice

- Throughput 5 Mbps per 600p stream
- Latency Target: ≤ 50 ms
- lower than URLLC but above standard best-effort

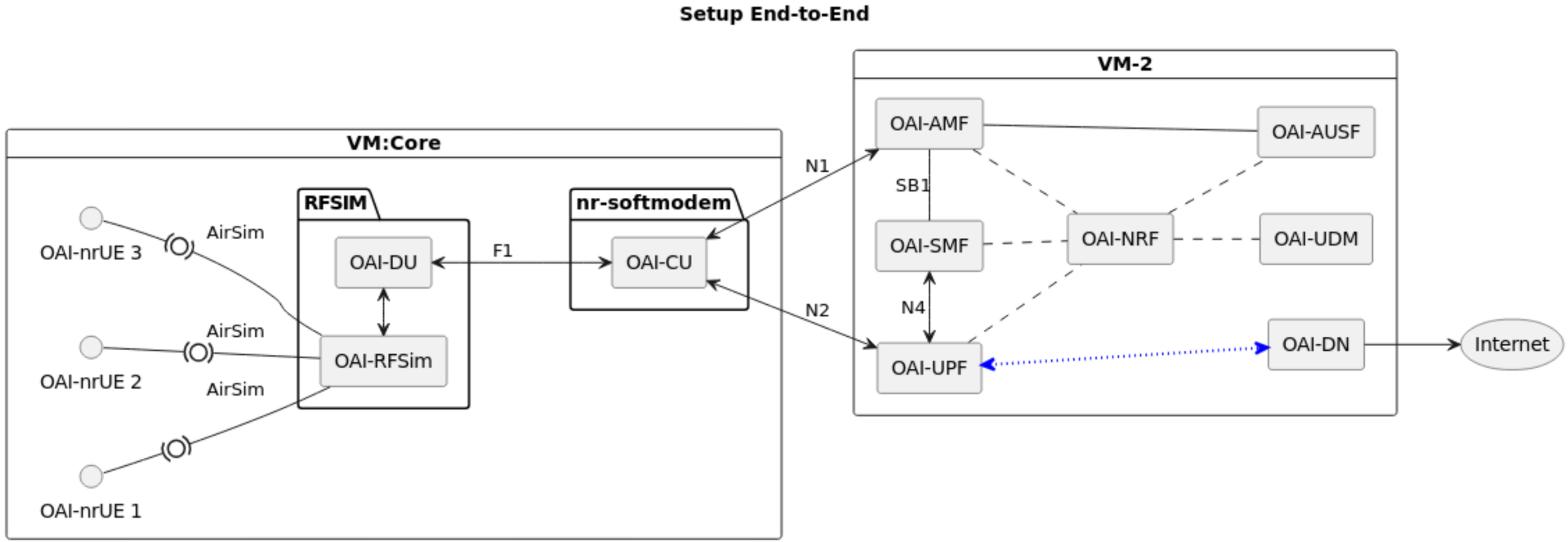
Quality of Service (QoS) in the Scenario

- key performance that the network must satisfy, including *Latency*, *Reliability*, and *Throughput* (bitrate).
- In the Defect Inspection scenario, different camera streams have vastly different requirements for image quality and latency:
    - **High Resolution :** Used for Critical Inspection → Requires low latency and high reliability, otherwise it will affect real-time alerts and decision-making.
    - **Normal Resolution :** Used for **Non-Critical Inspection** → Can tolerate higher latency and may use a more relaxed eMBB channel.

Slice Type	Use Case	Resolution / Bitrate	Latency	Reliability
URLLC	Critical Inspection	1920x1080 @ 30fps (19.9 Mbps)	≤ 10 ms	≥ 99.999% (Packet-Loss ≤ 10^{-5})
eMBB	Non-Critical Inspection	800*600 @30fps (4.6 Mbps)	≤ 50 ms	Best-Effort

Overall System Architecture

- This diagram illustrates the complete architecture of our 5G network system, showing the interconnections between different network components and layers.



Network Configuration Setup

- Detailed view of the network configuration parameters and settings required for establishing the 5G network connections.

```
Context: greign-smo                          <0> all      <a>       Attach      <ctrl-k>  Kill            <o> Show Node
Cluster: microk8s-cluster                    <1> default  <ctrl-d>  Delete      <l>       Logs            <f> Show PortForward
User:    admin                                            <d>       Describe    <p>       Logs Previous   <t> Transfer
K9s Rev: v0.32.5 ⚡v0.50.6                                <e>       Edit        <shift-f> Port-Forward    <y> YAML
K8s Rev: v1.27.16                                         <?>       Help        <z>       Sanitize
CPU:     54%↓                                             <shift-j> Jump Owner  <s>       Shell
MEM:     65%
                                                                  Pods(all)[13] </site-00>
```

NAMESPACE↑	NAME	PF	READY	STATUS	RESTARTS	CPU	MEM	%CPU/R	%CPU/L	%MEM/R	%MEM/L	IP	NODE	AGE
site-00	e2e-mysql-5dbff6b9f-chspc	●	1/1	Running	0	9	444	4	4	86	86	10.1.248.37	smo-nnag	72m
site-00	oai-amf-84dcc5c68-4scwr	●	2/2	Running	0	28	5	n/a	n/a	n/a	n/a	10.1.248.38	smo-nnag	72m
site-00	oai-ausf-599cc96c5d-d5vql	●	2/2	Running	0	50	3	n/a	n/a	n/a	n/a	10.1.248.10	smo-nnag	72m
site-00	oai-cu-644cb9c49-46q9d	●	2/2	Running	0	1	128	n/a	n/a	n/a	n/a	10.1.248.62	smo-nnag	72m
site-00	oai-du-f6658ddd6-6b4hp	●	2/2	Running	0	1152	1088	n/a	n/a	n/a	n/a	10.1.248.42	smo-nnag	72m
site-00	oai-nr-ue-00-6d9c98d886-rmbn6	●	1/1	Running	0	439	477	n/a	n/a	n/a	n/a	10.1.248.22	smo-nnag	72m
site-00	oai-nr-ue-01-c87c7d566-djx2f	●	1/1	Running	0	447	475	n/a	n/a	n/a	n/a	10.1.248.45	smo-nnag	72m
site-00	oai-nrf-5b6f9bb56-s4h7f	●	2/2	Running	0	50	3	n/a	n/a	n/a	n/a	10.1.248.29	smo-nnag	72m
site-00	oai-smf-57695c9f8d-6ngwk	●	2/2	Running	0	20	5	n/a	n/a	n/a	n/a	10.1.248.2	smo-nnag	72m
site-00	oai-traffic-server-6d9d9b44d9-2gh9l	●	1/1	Running	0	5	2	n/a	n/a	n/a	n/a	10.1.248.7	smo-nnag	72m
site-00	oai-udm-555d58587c-c755c	●	2/2	Running	0	46	3	n/a	n/a	n/a	n/a	10.1.248.32	smo-nnag	72m
site-00	oai-udr-5b75b99c74-r8w92	●	2/2	Running	0	42	4	n/a	n/a	n/a	n/a	10.1.248.43	smo-nnag	72m
site-00	oai-upf-56d669ddf9-p85vg	●	3/3	Running	0	18	6	18	n/a	4	n/a	10.1.248.31	smo-nnag	72m

Network Topology

- Visual representation of how different network elements are connected, including the relationship between Central Units (CU) and Distributed Units (DU).

```
Context: greign-smo                          <0> tail   <6> 1h   <shift-c> Clear              <t> Toggle Timestamp
Cluster: microk8s-cluster                    <1> head            <c>       Copy               <w> Toggle Wrap
User:    admin                               <2> 1m              <m>       Mark
K9s Rev: v0.32.5 ⚡v0.50.6                   <3> 5m              <ctrl-s>  Save
K8s Rev: v1.27.16                            <4> 15m             <s>       Toggle AutoScroll
CPU:     60%↑                                <5> 30m             <f>       Toggle FullScreen
MEM:     65%
                                                  Logs(site-00/oai-amf-84dcc5c68-4scwr)[tail]
                                          Autoscroll:On      FullScreen:Off     Timestamps:Off     Wrap:Off
init-udr Ncat: 0 bytes sent, 0 bytes received in 3.59 seconds.
amf [2025-06-02 05:52:09.738] [amf_sbi] [info] Receive Update NF Instance Request, handling ...
amf [2025-06-02 05:52:09.738] [amf_sbi] [info] Send HTTP message to http://oai-nrf:80/nnrf-nfm/v1/nf-instances/1220adeb-3748-4dd0-87f6-7cf054f04573
amf [2025-06-02 05:52:09.738] [amf_sbi] [info] HTTP message Body: [{"op":"replace","path":"/nfStatus","value":"REGISTERED"}]
amf [2025-06-02 05:52:09.741] [amf_sbi] [info] Get response with HTTP code (204)
amf [2025-06-02 05:52:09.741] [amf_sbi] [info] Could not get JSON content from the response
amf [2025-06-02 05:52:16.916] [amf_app] [info]
amf    |-----------------------------------------------------------------------------------------------------------------------------------|
amf    |-------------------------------------------------------------------gNBs' Information-------------------------------------------------------------|
amf    |  Index |              Status              |             Global Id             |             gNB Name              |               PLMN                |
amf    |    1   |           Disconnected           |               0x00                |                                   |                ,                  |
amf    |    2   |             Connected            |              0xE000               |              oai-cu               |              001,01               |
amf    |-----------------------------------------------------------------------------------------------------------------------------------|
amf
amf    |-----------------------------------------------------------------------------------------------------------------------------------|
amf    |-------------------------------------------------------------------UEs' Information-------------------------------------------------------------|
amf    |  Index |     5GMM State     |        IMSI        |        GUTI        |   RAN UE NGAP ID   |   AMF UE NGAP ID   |        PLMN        |       Cell Id      |
amf    |    1   |   5GMM-REGISTERED  |   001010000000100  | 0010101004100000001|        0x01        |        0x01        |       001,01       |      0xE00000      |
amf    |    2   |   5GMM-REGISTERED  |   001010000000101  | 0010101004100000002|        0x02        |        0x02        |       001,01       |      0xE00000      |
amf    |-----------------------------------------------------------------------------------------------------------------------------------|
```

CU / DU Socket Connection Diagram

- Specific illustration of the Central Unit socket configuration, showing the connection parameters and communication protocols used.

```
root@oai-cu-644cb9c49-2gmkv:/opt/oai-gnb# netstat -apn4
Active Internet connections (servers and established)
Proto Recv-Q Send-Q Local Address           Foreign Address         State       PID/Program name
sctp                10.1.248.62:38472                               LISTEN      1/nr-softmodem
sctp        0      0 10.1.248.62:37795       10.1.248.39:38412       ESTABLISHED 1/nr-softmodem
udp         0      0 10.1.248.62:2152        0.0.0.0:*                           1/nr-softmodem
udp         0      0 10.1.248.62:2153        0.0.0.0:*                           1/nr-softmodem
root@oai-cu-644cb9c49-2gmkv:/opt/oai-gnb#
```

- Detailed representation of the Distributed Unit socket setup, demonstrating the interface configurations and data flow paths.

```
<<K9s-Shell>> Pod: site-00/oai-du-f6658ddd6-485mx | Container: gnbdu
root@oai-du-f6658ddd6-485mx:/opt/oai-gnb# netstat -apn4
Active Internet connections (servers and established)
Proto Recv-Q Send-Q Local Address           Foreign Address         State       PID/Program name
tcp         0      0 0.0.0.0:4043            0.0.0.0:*               LISTEN      1/nr-softmodem
tcp    122904 185958 10.1.248.45:4043         10.1.248.40:39770       ESTABLISHED 1/nr-softmodem
tcp    245808  58572 10.1.248.45:4043         10.1.248.22:43670       ESTABLISHED 1/nr-softmodem
sctp        0      0 10.1.248.45:54523       10.1.248.35:38472       CLOSE       1/nr-softmodem
udp         0      0 10.1.248.45:2153        0.0.0.0:*                           1/nr-softmodem
root@oai-du-f6658ddd6-485mx:/opt/oai-gnb#
```

Simulation

- **tos 184:** DSCP EF (Expedited Forwarding) for critical camera traffic
- **tos 0**: Best effort for monitoring camera traffic
- **l 188**: Small packets for low latency (critical)
- **l 1400**: Standard packets for throughput (monitoring)
- **P 20 & P 10**: Simulates 20 & 10 camera streams for monitoring

- Camera I (Normal-Res)

```
iperf3 -c 12.1.1.1 -b 19.9M -u -t 10 -l 188 -P 20 -p 5201
```

```
[  5]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[  7]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[  9]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 11]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 13]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 15]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 17]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 19]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 21]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 23]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 25]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 27]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 29]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 31]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 33]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 35]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 37]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 39]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 41]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[ 43]   8.00-9.00   sec   594 KBytes  4.87 Mbits/sec  3236
[SUM]   8.00-9.00   sec  11.6 MBytes  97.3 Mbits/sec  64720
```

- Camera II (High-Res)

```
iperf3 -c 12.1.1.1 -b 23M -u -t 10 -l 1400 -P 10 -p 5202
```

```
[  5]   7.00-8.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[  7]   7.00-8.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[  9]   7.00-8.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 11]   7.00-8.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 13]   7.00-8.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 15]   7.00-8.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 17]   7.00-8.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 19]   7.00-8.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 21]   7.00-8.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 23]   7.00-8.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[SUM]   7.00-8.00   sec  27.4 MBytes   230 Mbits/sec  20540
- - - - - - - - - - - - - - - - - - - - - - - - -
[  5]   8.00-9.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[  7]   8.00-9.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[  9]   8.00-9.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 11]   8.00-9.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 13]   8.00-9.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 15]   8.00-9.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 17]   8.00-9.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 19]   8.00-9.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 21]   8.00-9.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[ 23]   8.00-9.00   sec  2.74 MBytes  23.0 Mbits/sec  2054
[SUM]   8.00-9.00   sec  27.4 MBytes   230 Mbits/sec  20540
^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A^[[A
```

Analysis

- **Test Configuration**
  - Tool: iperf3 version 12.1.1.1
  - Buffer Size: Camera I: 19.9M, Camera II: 23M
  - Test Duration: 10 seconds each
  - Parallel Streams: Camera I: 20, Camera II: 10
  - Port: Camera I: 5201, Camera II: 5202
- **Analysis Summary**
  - Camera I (Normal Resolution):
    - Lower individual stream throughput but higher parallelism
    - 20 concurrent streams at ~4.87 Mbits/sec each
    - Total aggregate throughput: 97.3 Mbits/sec
  - Camera II (High Resolution):
    - Higher individual stream throughput with moderate parallelism
    - 10 concurrent streams at ~23.0 Mbits/sec each
    - Total aggregate throughput: 230 Mbits/sec (2.4x faster overall)
- The high-resolution camera achieves significantly better overall performance despite using fewer parallel connections, indicating more efficient per-stream utilization.

Metric	Camera I (Normal-Res)	Camera II (High-Res)
Individual Stream Performance		
Data per Stream	594 KBytes	2.74 MBytes
Bitrate per Stream	4.87 Mbits/sec	23.0 Mbits/sec
Test Duration	8.00-9.00 sec	7.00-8.00 sec
Aggregate Performance		
Total Data Transferred	11.6 MBytes	27.4 MBytes
Total Bitrate	97.3 Mbits/sec	230 Mbits/sec
Number of Streams	20	10
Efficiency Metrics		
Data per Stream Ratio	1x	4.6x
Bitrate per Stream Ratio	1x	4.7x
Total Throughput Ratio	1x	2.4x