A Quantitative Approach to Design Low-cost Edge-CRAN

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Background

- **5G is happening**
  - 1000x more traffic
  - 10x lower latency
  - New ecosystem and value chain → More revenue!
  - Cost and energy consumption should be affordable
**Distributed Radio Access Network (DRAN)**

- **A base station (BS) at remote site**
  - A base station system = DUs + RUs + infrastructure
  - In urban area, RUs are placed at “the top of a mast”. DUs are placed at a “cabinet”. Each RU is paired with one DU via fronthaul.
  - Infrastructure: air conditioners, lighting system, cabinet etc.
DRAN

- Not a scalable solution for 5G
  - Do not satisfy latency requirement for advanced radio coordination techniques, e.g. CoMP (among multiple BSs).
  - DUs are expensive resources, but cannot be shared.
  - All DUs are placed at cabinet, which is not cost- and energy-efficient.
    - New frequency bands are licensed in 5G
    - A remote site is densified with more RUs, and thus more DUs.
    - Cost of cabinet increases dramatically.
Cloud Radio Access Network (CRAN)

- **CRAN**
  - DUs are centralized at a central site, so cabinet is not needed.
  - DUs can be virtualized and shared as a “DU cloud”.
  - Multiplexing gain: on-demand resource allocation and infrastructure sharing.
CRAN

- **A too costly solution for some network operators.**
  - Due to the DU centralization, all I/Q samples generated by RUs must be transported to central site.
  - A single RU, with a 20 MHz carrier and 2*2 antennas, will generate 2.5 Gbps I/Q samples in downstream.
  - Network operators need to build their own optical transport network, or rent bandwidth from a third-party fiber owner.
  - The cost of upgrading the backhaul to fronthaul may counteract the cost saving of CRAN.
Functional Split

- **Reconsider CRAN.**
  - Functional split: several conceivable points to split the wireless baseband processing chain for dual-site processing.
  - Dual-site processing:
    - place some processing functions (PFs) at remote site for baseband pre-processing, relaxing bandwidth requirement.
    - If computational resources are general-purpose, innovative applications and services can be provided to users rapidly, e.g. mobile edge computing, fog computing, IoT etc.

**GOPS**: Giga Operations Per Second, indicating how much computational resources needed by a PF.

**Midhaul**: transport network between remote site and central site, corresponding to the same network segment, backhaul and fronthaul, as in DRAN and CRAN, respectively.
Edge-Cloud Radio Access Network (e-CRAN)

- A 4D (Dynamic) architecture:
  - Dynamic fronthaul topology
  - Dynamic bandwidth provisioning.
  - Dynamic function provisioning.
  - Dynamic power provisioning.
Ok, now forget about 4D 😞

• Research problems:
  ➢ Is this architecture too costly?
  ➢ What is the optimal functional split?
  ➢ How much computational resources to centralize or distribute?
TCO Minimization Problem

- **Total cost of Ownership**
  - The sum of the build-out costs, the so-called capital expenditure (CAPEX), and the operation and maintenance costs, the so-called operational expenditures (OPEX), for a given period of time.

<table>
<thead>
<tr>
<th>TCO items</th>
<th>CAPEX</th>
<th>OPEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment (Eq)</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Civil Work (CW)</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Installation and Commissioning (IC)</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>Operation and Maintenance (OM)</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Power Bill (PB)</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Site Rental (SR)</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>Fiber Rental (FR)</td>
<td>×</td>
<td>✓</td>
</tr>
</tbody>
</table>
TCO Minimization Problem

- **TCO for a BS system in DRAN**
  - \( T_i^{\text{mast}} \): cost of TCO item \( i \) at the top of a mast (“mast” for short).
  - \( T_i^{\text{cab}} \): cost of TCO item \( i \) at cabinet (“cab” for short).
  - \( T_{\text{FR}}^{\text{DRAN}} \): fiber rental cost for backhaul.
  - \( T_{\text{DRAN}} = T_{\text{FR}}^{\text{DRAN}} + \sum_{i \in X} (T_i^{\text{mast}} + T_i^{\text{cab}}) \)

- **TCO for a BS system in CRAN**
  - \( T_i^{\text{mast}} \): the same as in DRAN.
  - \( T_i^{\text{CS}} \): cost of TCO item \( i \) at central site (“CS” for short).
    - \( T_i^{\text{CS}} = T_i^{\text{cab}} \cdot (1 - mg) \)
    - \( mg \): multiplexing gain
  - \( T_{\text{FR}}^{\text{CRAN}} \): fiber rental cost for fronthaul.
    - \( T_{\text{FR}}^{\text{CRAN}} = T_{\text{FR}}^{\text{DRAN}} \cdot ml \)
    - \( ml \): multiplexing loss
  - \( T_{\text{CRAN}} = T_{\text{FR}}^{\text{CRAN}} + \sum_{i \in X} (T_i^{\text{mast}} + T_i^{\text{CS}}) \)
TCO Minimization Problem

- TCO for a BS system in e-CRAN
  - Unscalable items:
    - TCO item whose cost is directly related to human power.
    - The cabinet cost should be fully counted as long as site visit happens.
    \[ T_i^{e\text{CRAN}} = T_i^{\text{mast}} + T_i^{\text{cab}} + T_i^{\text{CS}}, \ i \in \{\text{IC, CW, OM}\} \]
  - Scalable items:
    - TCO item whose cost is not (directly) related to human power.
    - Cabinet cost can be (linearly or non-linearly) scalable with computational resources placed at remote site.
    \[ T_i^{e\text{CRAN}} = T_i^{\text{mast}} + T_i^{\text{cab}} \cdot \frac{h_{RS}}{H} + T_i^{\text{CS}} \cdot \frac{H-h_{RS}}{H}, \ i \in \{\text{Eq, PB, SR}\} \]
    - \( h_{RS} \): computational resources placed at remote site. \( H \) is total computational resources needed by a BS.
    \[ T_F^{e\text{CRAN}} = T_F^{\text{CRAN}} - (T_F^{\text{CRAN}} - T_F^{\text{DRAN}}) \cdot \frac{B_{\text{CRAN}}-b_{\text{eRAN}}}{B_{\text{CRAN}}-B_{\text{DRAN}}} \]
    - \( b_{e\text{RAN}} \) is midhaul bandwidth in e-CRAN.
  - \( T_{e\text{CRAN}} = T_F^{e\text{CRAN}} + \sum_{i \in X} T_i^{e\text{CRAN}} \)

<table>
<thead>
<tr>
<th>TCO items</th>
<th>Scalable</th>
<th>Unscalable</th>
</tr>
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<tbody>
<tr>
<td>Equipment (Eq)</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Civil work (CW)</td>
<td>×</td>
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</tr>
<tr>
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<td>×</td>
<td>√</td>
</tr>
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<td>×</td>
<td>√</td>
</tr>
<tr>
<td>Power bill (PB)</td>
<td>√</td>
<td>×</td>
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</tr>
<tr>
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<td>√</td>
<td>×</td>
</tr>
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</table>
TCO Minimization Problem

• Given
  - \( C \): a set of RU-DU pairs within a BS, with heterogeneous configurations
  - \( S = \{1, \ldots, 7\} \): a set of split options as depicted.
  - \( T_i^{\text{mast}}, T_i^{\text{cab}}, T_i^{\text{DRAN}} \): cost of TCO item \( i \) in DRAN. TCO of CRAN can be calculated as described, when multiplexing gain and loss are given.

<table>
<thead>
<tr>
<th>RU-DU Type</th>
<th>Spectrum band</th>
<th>Carrier Bandwidth (B)</th>
<th>Antennas (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type1</td>
<td>2.6 GHz</td>
<td>20 MHz</td>
<td>8*8</td>
</tr>
<tr>
<td>Type2</td>
<td>1.8 GHz</td>
<td>10 MHz</td>
<td>4*4</td>
</tr>
<tr>
<td>Type3</td>
<td>700 MHz</td>
<td>10 MHz</td>
<td>2*2</td>
</tr>
<tr>
<td>Type4</td>
<td>3.5 GHz</td>
<td>20 MHz</td>
<td>16*16</td>
</tr>
</tbody>
</table>
TCO Minimization Problem

- Given

- \( H_{RS}^{up} [\cdot], H_{RS}^{down} [\cdot] \): Mapping from a upstream/downstream split to computational resources placed at remote site.

- Functional split complexity (GOPS) sub-model [1].

\[
\begin{align*}
G_1 &= G_1^{ref} \cdot \frac{B}{B^{ref}} \cdot \frac{A}{A^{ref}} \\
G_2 &= G_2^{ref} \cdot \frac{B}{B^{ref}} \cdot \frac{A}{A^{ref}} \\
G_3 &= G_3^{ref} \cdot \frac{B}{B^{ref}} \cdot \frac{A}{A^{ref}} \cdot \frac{L}{L^{ref}} \\
G_4 &= G_4^{ref} \cdot \frac{B}{B^{ref}} \cdot \left( \frac{A}{A^{ref}} \right)^3 \cdot \frac{L}{L^{ref}} \\
G_5 &= G_5^{ref} \cdot \frac{B}{B^{ref}} \cdot \frac{A}{A^{ref}} \cdot \frac{L}{L^{ref}} \\
G_6 &= G_6^{ref} \cdot \frac{A}{A^{ref}}
\end{align*}
\]

TCO Minimization Problem

- **Given**
  - \( \Gamma^\text{up} [\cdot], \Gamma^\text{down} [\cdot] \): mapping from a upstream/downstream split to required midhaul bandwidth.
  - Functional split Bandwidth sub-model [2].

\[
\begin{align*}
R_1 &= \alpha_1 \cdot f_s \cdot A \\
R_2 &= \alpha_2 \cdot f_s \cdot A \\
R_3 &= \alpha_3 \cdot A \cdot n_{PRB} \\
R_4 &= \alpha_4 \cdot L \cdot A \cdot n_{PRB} + \beta_4 \cdot A \\
R_5 &= \alpha_5 \cdot L \cdot n_{PRB} + \beta_5 \\
R_6 &= \alpha_6 \cdot L \cdot n_{PRB} \\
R_7 &= \alpha_7 \cdot L \cdot n_{PRB}
\end{align*}
\]

TCO Minimization Problem

- **Decision variables**
  - $s^\text{up}_c$: upstream split for RU-DU pair $c$.
  - $s^\text{down}_c$: downstream split for RU-DU pair $c$.
  - $h_{RS}$: total GOPS of the BS placed at a RS.
  - $b_{h\text{RAN}}$: total required midhaul bandwidth of the BS.

- **Objective**
  - Minimize TCO of a BS in e-CRAN: $T_{eCRAN} = T_{FR}^{eCRAN} + \sum_{i \in X} T_i^{eCRAN}$

- **Constraints**
  - The GOPS placed at RS is equal to the sum GOPS incurred by downstream and upstream splits of all RU-DU pairs within the BS.
    - $h_{RS} = \sum_{c \in C} (H_{RS}^\text{up} [s^\text{up}_c] + H_{RS}^\text{down} [s^\text{down}_c])$
  - The required midhual bandwidth of the BS is equal to the sum bandwidth incurred by downstream and upstream splits of all RU-DU pairs.
    - $b_{h\text{RAN}} = \sum_{c \in C} (\Gamma^\text{up} [s^\text{up}_c] + \Gamma^\text{down} [s^\text{down}_c])$
Numerical Results

- **Simulation settings**
  - We consider 6 different BS configurations, consisting of 4 RU-DU types.
  - For example, Conf1 only has Type1 RU-DU pair, while Conf5 has all four types, with proportion: 1:1:1:10.
  - For each configuration, we obtain the optimal (minimized) TCO of a BS system in e-CRAN, using IBM CP Optimizer. Each TCO value is unified by TCO of DRAN, which is fixed as 1.

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<td>16*16</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>BS configuration</th>
<th>Type1</th>
<th>Type2</th>
<th>Type3</th>
<th>Type4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conf 1</td>
<td>::1</td>
<td>∞</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>Conf 2</td>
<td>::1</td>
<td>::1</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>Conf 3</td>
<td>::1</td>
<td>::1</td>
<td>::1</td>
<td>∞</td>
</tr>
<tr>
<td>Conf 4</td>
<td>::1</td>
<td>::1</td>
<td>::1</td>
<td>::1</td>
</tr>
<tr>
<td>Conf 5</td>
<td>::1</td>
<td>::1</td>
<td>::1</td>
<td>::10</td>
</tr>
<tr>
<td>Conf 6</td>
<td>::1</td>
<td>::1</td>
<td>::1</td>
<td>::20</td>
</tr>
</tbody>
</table>
Numerical Results

- **TCO for a BS system in e-CRAN**
  - e-CRAN achieves lower TCO than DRAN and CRAN, up to 14.7%.
  - Where does the saving come from?
    - Lower fiber rental cost than CRAN, thanks to dual-site processing.
    - Lower costs of scalable items than DRAN.
  - Higher costs of unscalable items, which can counteract cost savings.
  - More cost saving in 5G BS configurations.

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<td>Equipment (Eq)</td>
<td>√</td>
<td>×</td>
<td>√</td>
<td>×</td>
</tr>
<tr>
<td>Civil work (CW)</td>
<td>√</td>
<td>×</td>
<td>×</td>
<td>√</td>
</tr>
<tr>
<td>Install and commission (IC)</td>
<td>√</td>
<td>×</td>
<td>×</td>
<td>√</td>
</tr>
<tr>
<td>Operation and maintain (OM)</td>
<td>×</td>
<td>√</td>
<td>×</td>
<td>√</td>
</tr>
<tr>
<td>Power bill (PB)</td>
<td>×</td>
<td>√</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Site rental (SR)</td>
<td>×</td>
<td>√</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Fiber rental (FR)</td>
<td>×</td>
<td>√</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

TCO saving 14.7%
Numerical Results

- Optimal splits for different BS configurations
  - Consistent optimal splits for Type1 and Type 4 RU-DU.
  - RU-DU pairs in a BS may choose different functional splits.
  - Their split combination can approach to an equilibrium point with respect to computational resource placement and midhaul bandwidth requirement.
  - This equilibrium point can lead to a minimized TCO for e-CRAN.

### Consistent Optimal Splits

<table>
<thead>
<tr>
<th>BS configuration</th>
<th>Type1</th>
<th>Type2</th>
<th>Type3</th>
<th>Type4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conf 1</td>
<td>↓5, ↑3, ::1</td>
<td>∞</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>Conf 2</td>
<td>↓5, ↑3, ::1</td>
<td>↓5, ↑3, ::1</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>Conf 3</td>
<td>↓5, ↑3, ::1</td>
<td>↓5, ↑3, ::1</td>
<td>↓5, ↑6, ::1</td>
<td>∞</td>
</tr>
<tr>
<td>Conf 4</td>
<td>↓5, ↑3, ::1</td>
<td>↓5, ↑6, ::1</td>
<td>↓5, ↑6, ::1</td>
<td>↓5, ↑3, ::1</td>
</tr>
<tr>
<td>Conf 5</td>
<td>↓5, ↑3, ::1</td>
<td>↓5, ↑6, ::1</td>
<td>↓6, ↑6, ::1</td>
<td>↓5, ↑3, ::10</td>
</tr>
<tr>
<td>Conf 6</td>
<td>↓5, ↑3, ::1</td>
<td>↓5, ↑6, ::1</td>
<td>↓6, ↑6, ::1</td>
<td>↓5, ↑3, ::20</td>
</tr>
</tbody>
</table>

↓ downstream functional split; ↑ upstream functional split.
:: proportion of a RU-DU type. For example, in e-CRAN5, the proportion of 4 RU-DU configurations is 1:1:1:10, which means for every RU-DU pair with Conf1, there are 10 RU-DU pairs with Conf4.

With Conf1, there are 10 RU-DU pairs with Conf4.
Numerical Results

- Impact of fiber ownership on TCO and optimal splits
  - For a fiber-rich operator, CRAN is the best choice.
  - For a fiber-short operator, e-CRAN can be an economical choice.
  - The optimal split is dependent on fiber ownership.

<table>
<thead>
<tr>
<th>Fiber ownership</th>
<th>Multiplexing loss</th>
<th>TCO CRAN</th>
<th>TCO e-CRAN</th>
<th>Optimal Split</th>
</tr>
</thead>
<tbody>
<tr>
<td>☺☺☺</td>
<td>200%</td>
<td>0.7</td>
<td>0.75</td>
<td>▼1, ▲1</td>
</tr>
<tr>
<td>☺</td>
<td>3600%</td>
<td>0.81</td>
<td>0.89</td>
<td>▼5, ▲1</td>
</tr>
<tr>
<td>☻</td>
<td>5080%</td>
<td>0.90</td>
<td>0.90</td>
<td>▼5, ▲3</td>
</tr>
<tr>
<td>☹</td>
<td>5800%</td>
<td>0.94</td>
<td>0.91</td>
<td>▼5, ▲3</td>
</tr>
<tr>
<td>☻☻☻☻</td>
<td>14700%</td>
<td>1.31</td>
<td>0.98</td>
<td>▼5, ▲6</td>
</tr>
</tbody>
</table>

☺ fiber-rich network operator; ☻ fiber-short network operator.
Background

Edge-CRAN

TCO Minimization Problem

Numerical Results

Conclusion
Conclusion

- We proposed an Edge Cloud Radio Access Network (e-CRAN) architecture.
- We model an intrinsic trade-off between centralization and distribution of computational resources in e-CRAN.
- We found that there is no “one-size-fits-all” solution for splitting wireless baseband processing chain. Because it can be different for various RU-DU types, BS configurations, downstream or upstream, and fiber ownership.
- We showed that the TCO of e-CRAN can be lower than DRAN and CRAN, with proper functional splits.
- Our quantitative approach can find optimal splits for a given BS, and estimate the TCO of e-CRAN compared to DRAN.