A Quantitative Approach to Design Low-cost Edge-CRAN

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- Background
- Edge-CRAN
- TCO Minimization Problem
- Numerical Results
- Conclusion

- **Background**
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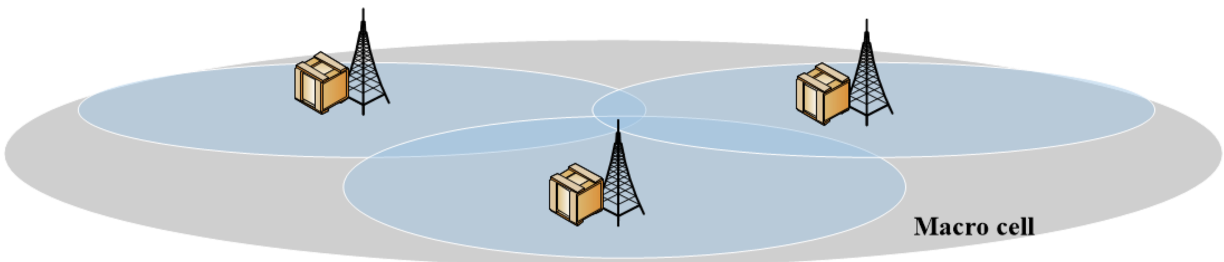
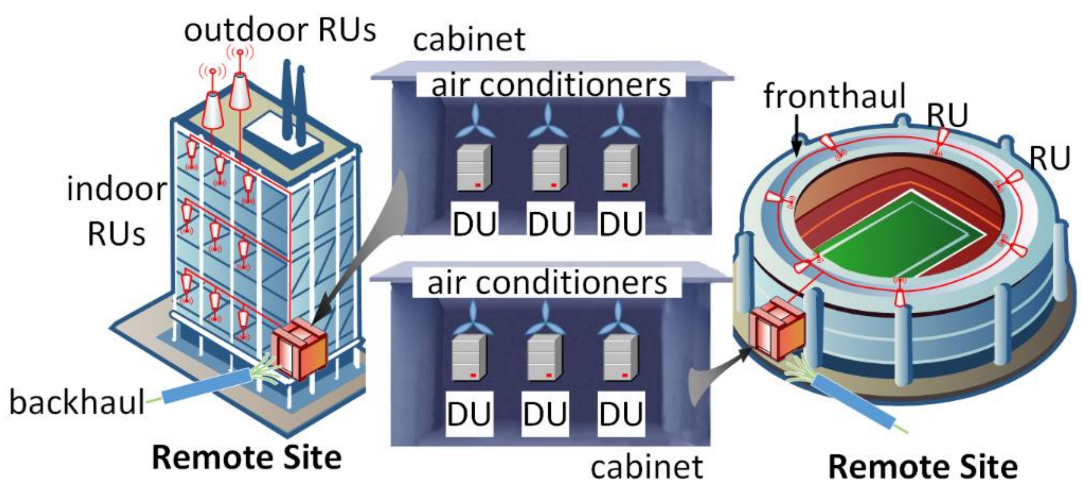
Background

- **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)

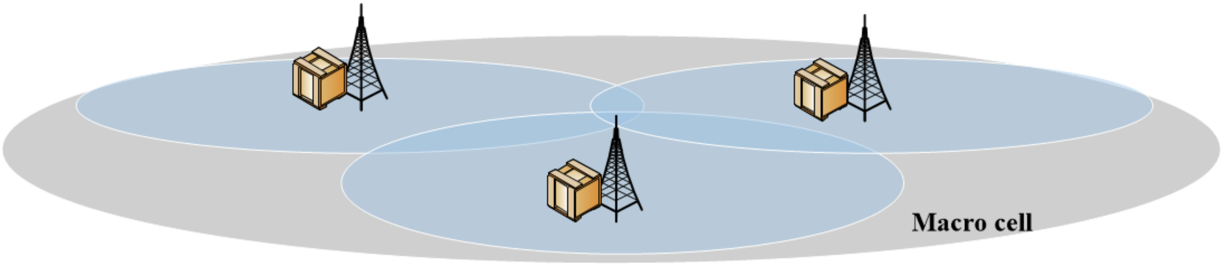
- **A base station (BS) at remote site**
  - A base station system = DUs + RUs + infrastructure
  - In urban area, RUs are placed at "the top of a mast". DUs are placed at a "cabinet". Each RU is paired with one DU via fronthaul.
  - Infrastructure: air conditioners, lighting system, cabinet etc.





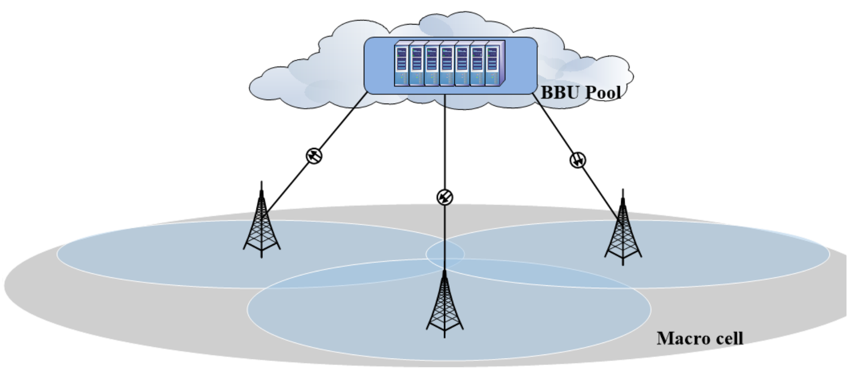
DRAN

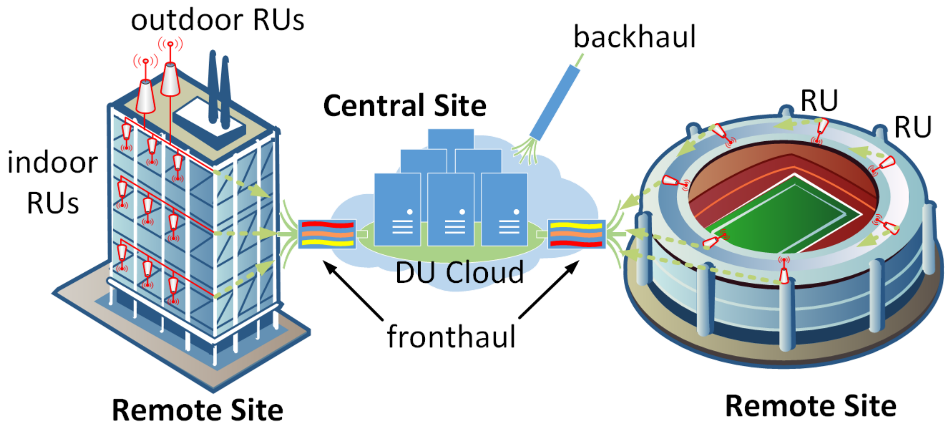
- **Not a scalable solution for 5G**
  - Do not satisfy latency requirement for advanced radio coordination techniques, e.g. CoMP (among multiple BSs).
  - DUs are expensive resources, but cannot be shared.
  - All DUs are placed at cabinet, which is not cost- and energy-efficient.
    - New frequency 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.

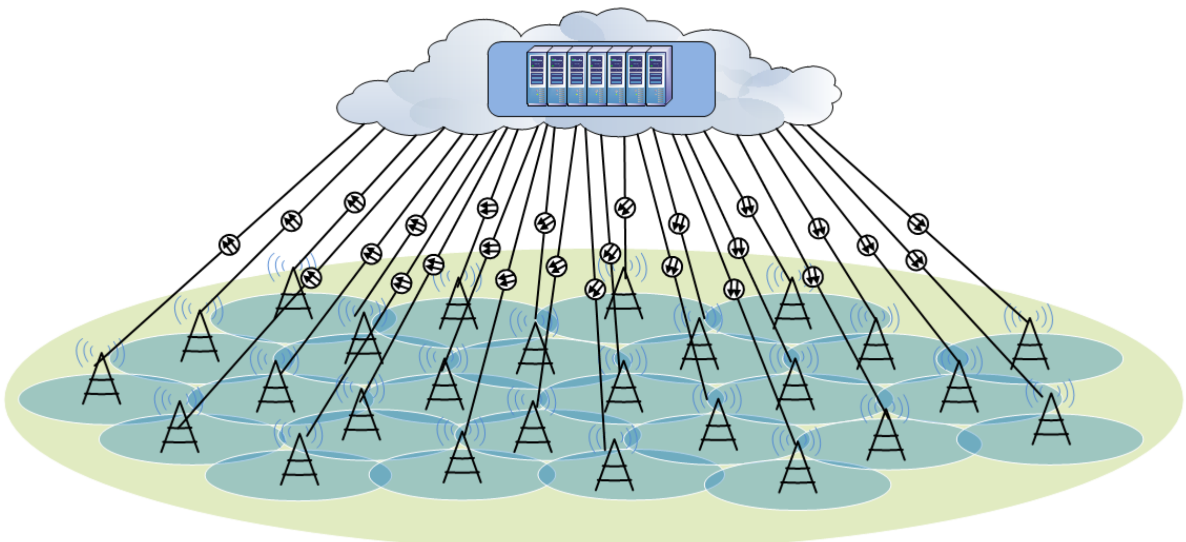




DRAN

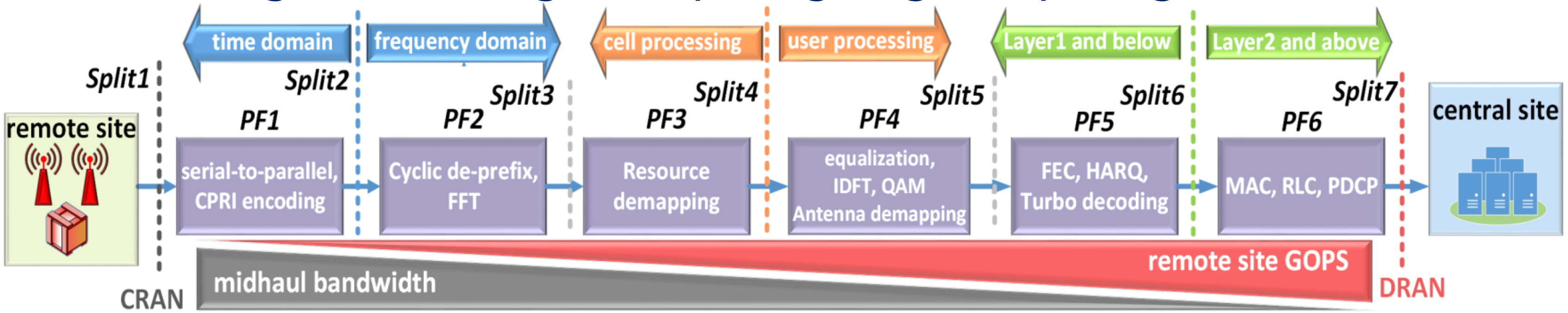
CRAN

- **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

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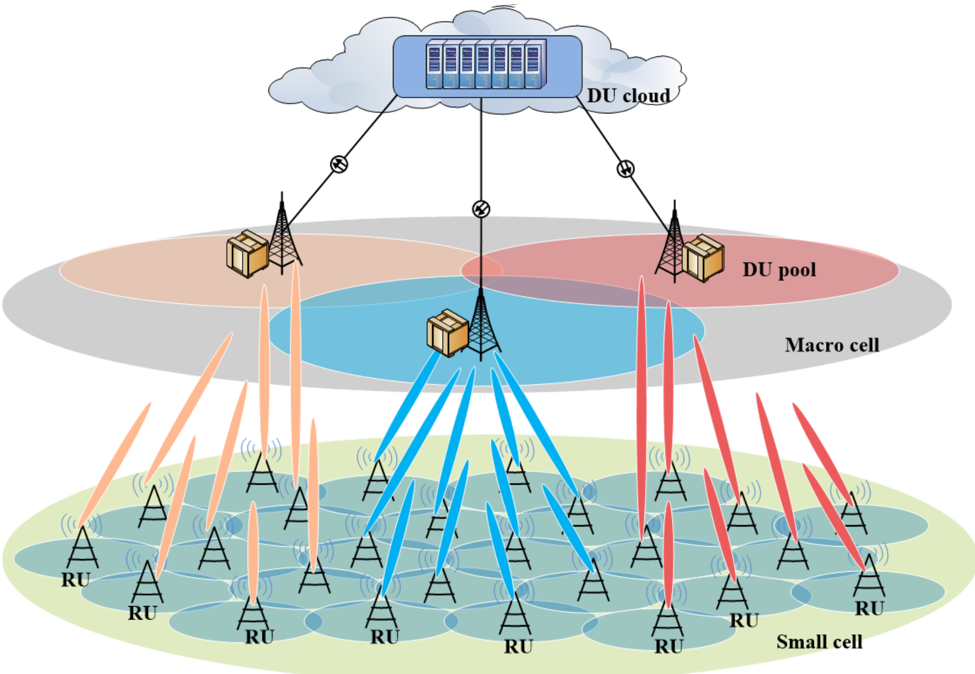
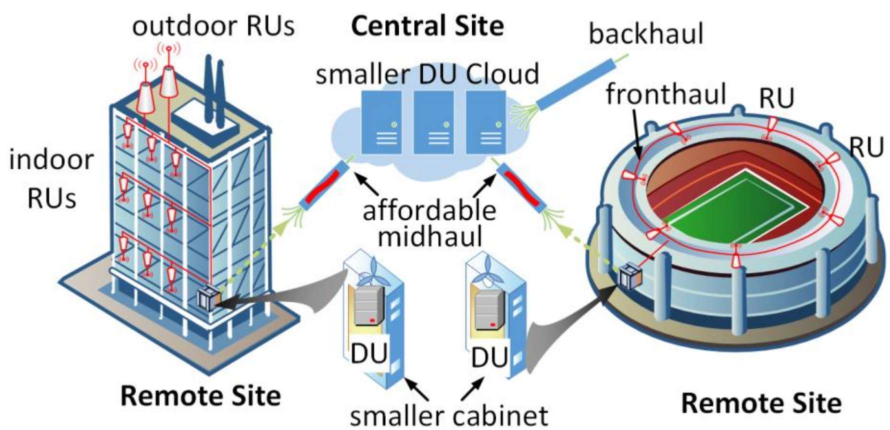
Edge-Cloud Radio Access Network (e-CRAN)

- **A 4D (Dynamic) architecture:**
  - **D**ynamic fronthaul topology
  - **D**ynamic bandwidth provisioning.
  - **D**ynamic function provisioning.
  - **D**ynamic power provisioning.





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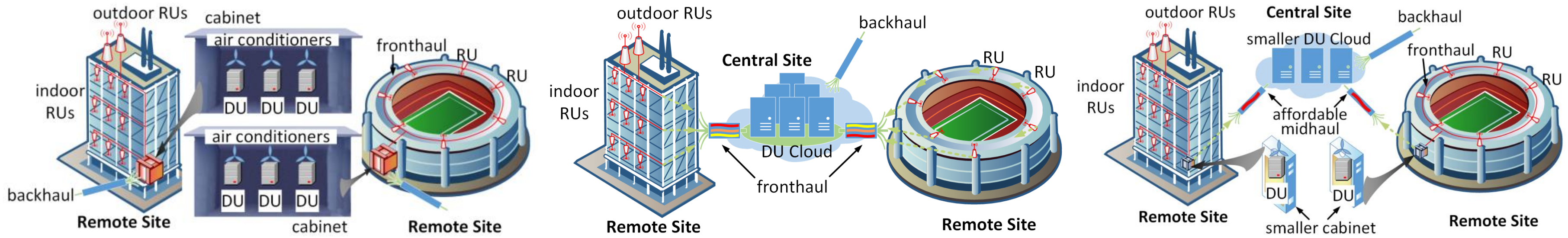
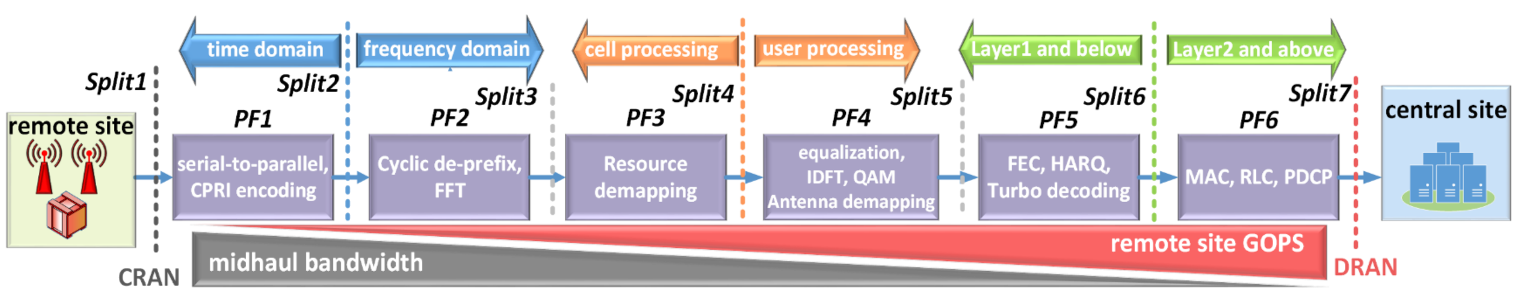
Ok, now forget about 4D :-P

- **Research problems:**
  - Is this architecture too costly?
  - What is the optimal functional split?
  - How much computational resources to centralize or distribute?



(a) DRAN (b) CRAN (c) e-CRAN



- Background
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- **TCO Minimization Problem**
- Numerical Results
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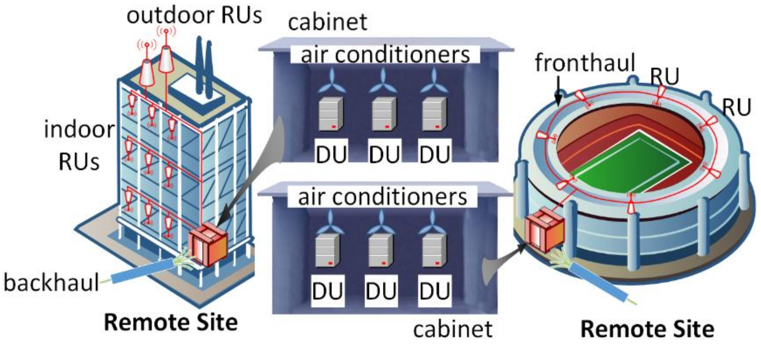
TCO Minimization Problem

- **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.

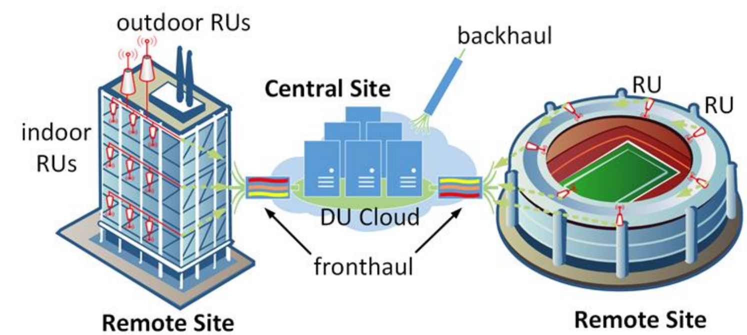
TCO items	CAPEX	OPEX
Equipment (Eq)	√	×
Civil Work (CW)	√	×
Installation and Commissioning (IC)	√	×
Operation and Maintenance (OM)	×	√
Power Bill (PB)	×	√
Site Rental (SR)	×	√
Fiber Rental (FR)	×	√

TCO Minimization Problem

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



TCO items
Equipment (Eq)
Civil Work (CW)
Installation and Commissioning (IC)
Operation and Maintenance (OM)
Power Bill (PB)
Site Rental (SR)
Fiber Rental (FR)



TCO Minimization Problem

TCO items	Scalable	Unscalable
Equipment (Eq)	√	×
Civil work (CW)	×	√
Install and commission (IC)	×	√
Operation and maintain (OM)	×	√
Power bill (PB)	√	×
Site rental (SR)	√	×
Fiber rental (FR)	√	×

- **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.
    - ✓ $T_i^{eCRAN} = T_i^{mast} + T_i^{cab} + T_i^{CS},\ i \in \{IC, CW, OM\}$
  - 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.
    - ✓ $T_i^{eCRAN} = T_i^{mast} + T_i^{cab} \cdot \frac{h_{RS}}{H} + T_i^{CS} \cdot \frac{H - h_{RS}}{H},\ \ i \in \{Eq, PB, SR\}$
    - ✓ h_{RS}: computational resources placed at remote site. H is total computational resources needed by a BS.
    - ✓ $T_{FR}^{eCRAN} = T_{FR}^{CRAN} - \left(T_{FR}^{CRAN} - T_{FR}^{DRAN}\right) \cdot \frac{B_{CRAN} - b_{hRAN}}{B_{CRAN} - B_{DRAN}}$
    - ✓ $b_{\boldsymbol{e}CRAN}$ is midhaul bandwidth in e-CRAN.
  - $T_{eCRAN} = T_{FR}^{eCRAN} + \sum_{i \in X} T_i^{eCRAN}$

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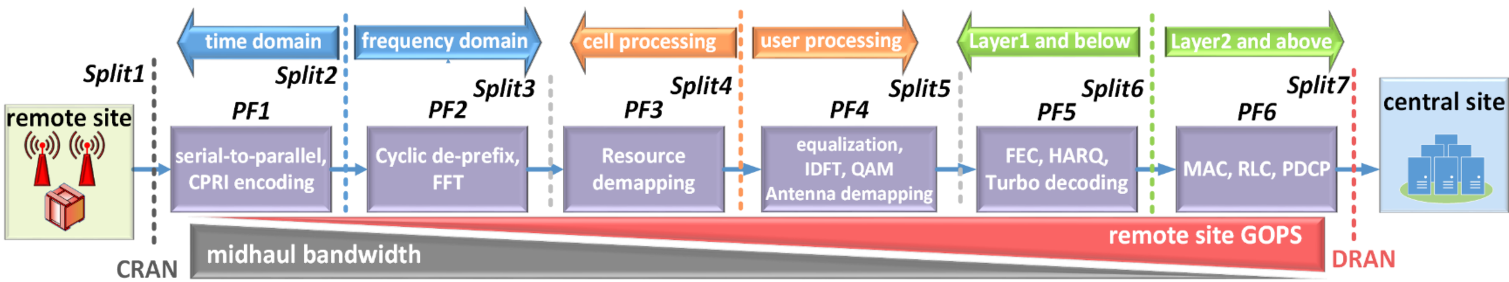
TCO Minimization Problem

- **Given**
  - C: a set of RU-DU pairs within a BS, with heterogeneous configurations

RU-DU Type	Spectrum band	Carrier Bandwidth (B)	Antennas (A)
Type1	2.6 GHz	20 MHz	8*8
Type2	1.8 GHz	10 MHz	4*4
Type3	700 MHz	10 MHz	2*2
Type4	3.5 GHz	20 MHz	16*16

  - S = {1,..,7}: a set of split options as depicted.

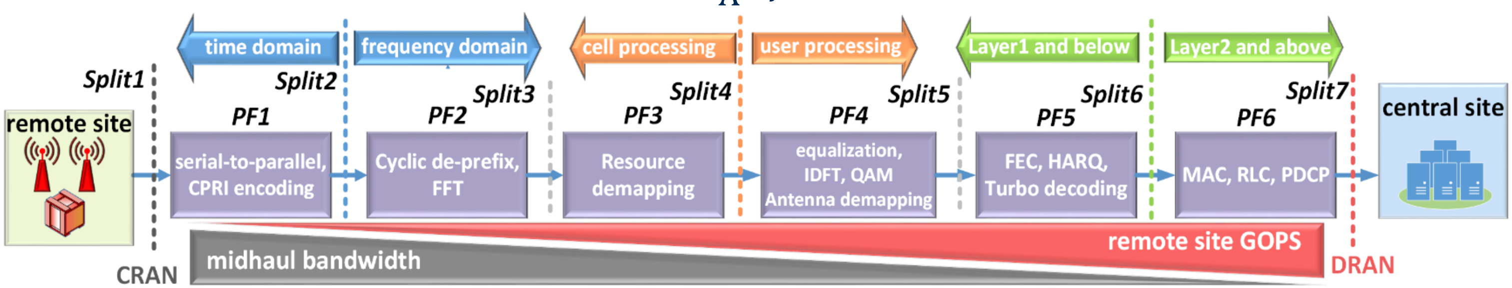


  - $T_i^{mast}, T_i^{cab}, T_{FR}^{DRAN}$: cost of TCO item *i* in DRAN. TCO of CRAN can be calculated as described, when multiplexing gain and loss are given.

TCO Minimization Problem

- **Given**
  - $\mathcal{H}_{RS}^{up}[\cdot], \mathcal{H}_{RS}^{down}[\cdot]$: Mapping from a upstream/downstream split to computational resources placed at remote site.
    - Functional split complexity (GOPS) sub-model [1].

$$G_1 = G_1^{ref} \cdot \frac{B}{B^{ref}} \cdot \frac{A}{A^{ref}}$$
$$G_2 = G_2^{ref} \cdot \frac{B}{B^{ref}} \cdot \frac{A}{A^{ref}}$$
$$G_3 = G_3^{ref} \cdot \frac{B}{B^{ref}} \cdot \frac{A}{A^{ref}} \cdot \frac{L}{L^{ref}}$$
$$G_4 = G_4^{ref} \cdot \frac{B}{B^{ref}} \cdot (\frac{A}{A^{ref}})^3 \cdot \frac{L}{L^{ref}}$$
$$G_5 = G_5^{ref} \cdot \frac{B}{B^{ref}} \cdot \frac{A}{A^{ref}} \cdot \frac{L}{L^{ref}}$$
$$G_6 = G_6^{ref} \cdot \frac{A}{A^{ref}}$$

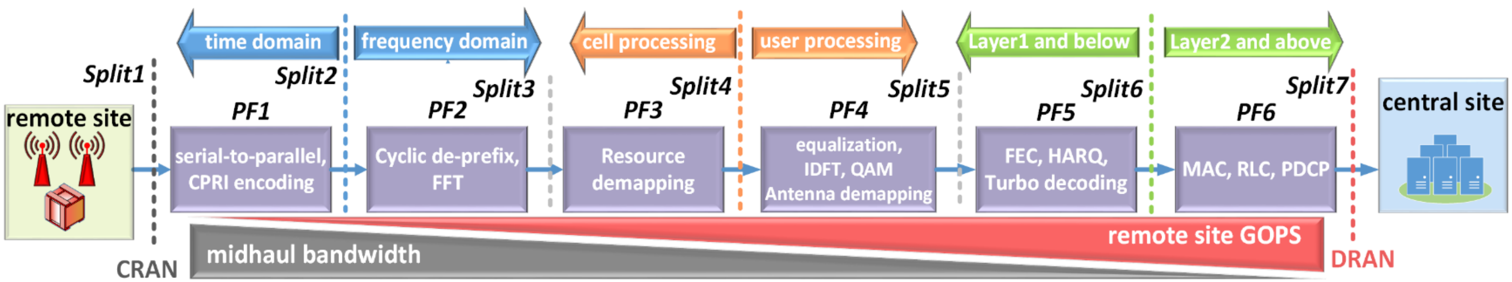


[1] C. Desset, et al. "Flexible power modeling of LTE base stations," Proc. Wireless Communications and Networking Conference (WCNC), Shanghai, China, 2012.

TCO Minimization Problem

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

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



[2] Small Cell Forum, “Functional splits and use cases for small cell virtualization.” Jan. 2016.

TCO Minimization Problem

- **Decision variables**
  - s_c^{up}: upstream split for RU-DU pair *c*.
  - s_c^{down}: downstream split for RU-DU pair *c*.
  - h_{RS}: total GOPS of the BS placed at a RS.
  - b_{hRAN}: 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
    - ✓ $h_{RS} = \sum_{c \in C}(\mathcal{H}_{RS}^{up}[s_c^{up}] + \mathcal{H}_{RS}^{down}[s_c^{down}])$
  - the required midhual bandwidth of the BS is equal to the sum bandwidth incurred by downstream and upstream splits of all RU-DU pairs.
    - ✓ $b_{hRAN} = \sum_{c \in C}(\Gamma^{Up}[s_c^{Up}] + \Gamma^{Down}[s_c^{Down}])$

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Numerical Results

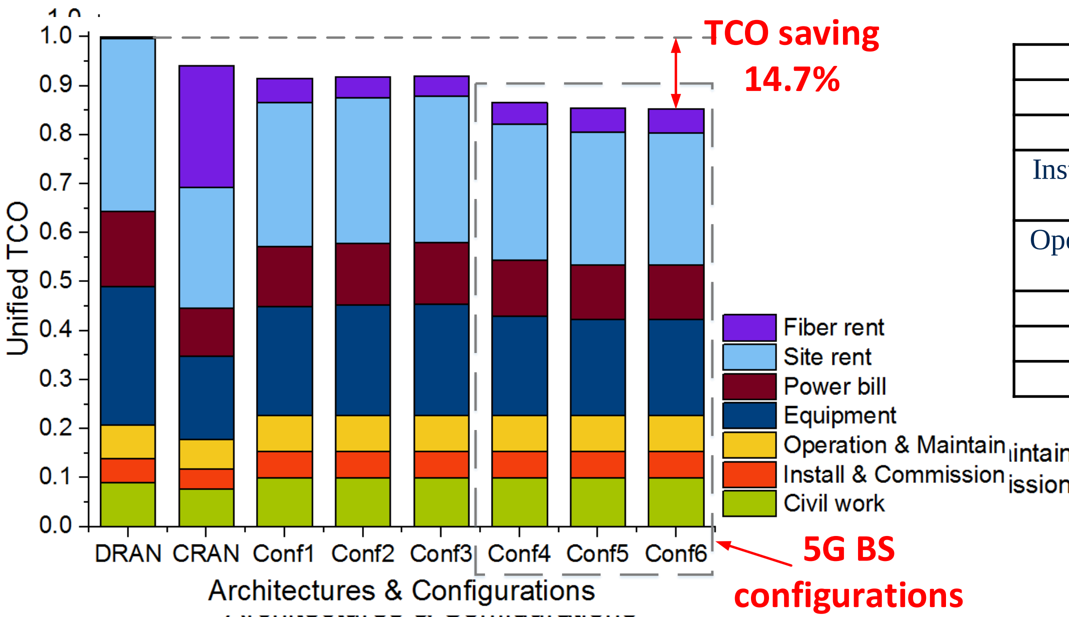
- **Simulation settings**
  - We consider 6 different BS configurations, consisting of 4 RU-DU types.
  - For example, Conf1 only has Type1 RU-DU pair, while Conf5 has all four types, with proportion: 1:1:1:10.
  - For each configuration, we obtain the optimal (minimized) TCO of a BS system in e-CRAN,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

RU-DU Type	Spectrum band	Carrier Bandwidth (B)	Antennas (A)
Type1	2.6 GHz	20 MHz	8*8
Type2	1.8 GHz	10 MHz	4*4
Type3	700 MHz	10 MHz	2*2
Type4	3.5 GHz	20 MHz	16*16

BS configuration	Type1	Type2	Type3	Type4
Conf 1	::1	∞	∞	∞
Conf 2	::1	::1	∞	∞
Conf 3	::1	::1	::1	∞
Conf 4	::1	::1	::1	::1
Conf 5	::1	::1	::1	::10
Conf 6	::1	::1	::1	::20

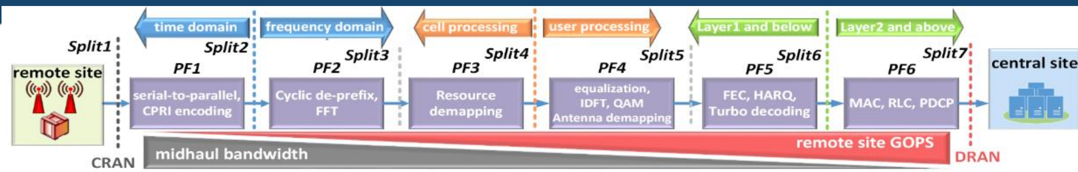
Numerical Results

- **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.



TCO items	CAPEX	OPEX	Scalable	Unscalable
Equipment (Eq)	√	×	√	×
Civil work (CW)	√	×	×	√
Install and commission (IC)	√	×	×	√
Operation and maintain (OM)	×	√	×	√
Power bill (PB)	×	√	√	×
Site rental (SR)	×	√	√	×
Fiber rental (FR)	×	√	√	×

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

BS configuration	Type1	Type2	Type3	Type4
Conf 1	↓5, ↑3, ::1	∞	∞	∞
Conf 2	↓5, ↑3, ::1	↓5, ↑3, ::1	∞	∞
Conf 3	↓5, ↑3, ::1	↓5, ↑3, ::1	↓5, ↑6, ::1	∞
Conf 4	↓5, ↑3, ::1	↓5, ↑6, ::1	↓5, ↑6, ::1	↓5, ↑3, ::1
Conf 5	↓5, ↑3, ::1	↓5, ↑6, ::1	↓6, ↑6, ::1	↓5, ↑3, ::10
Conf 6	↓5, ↑3, ::1	↓5, ↑6, ::1	↓6, ↑6, ::1	↓5, ↑3, ::20

Different split combinations

↓ 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.

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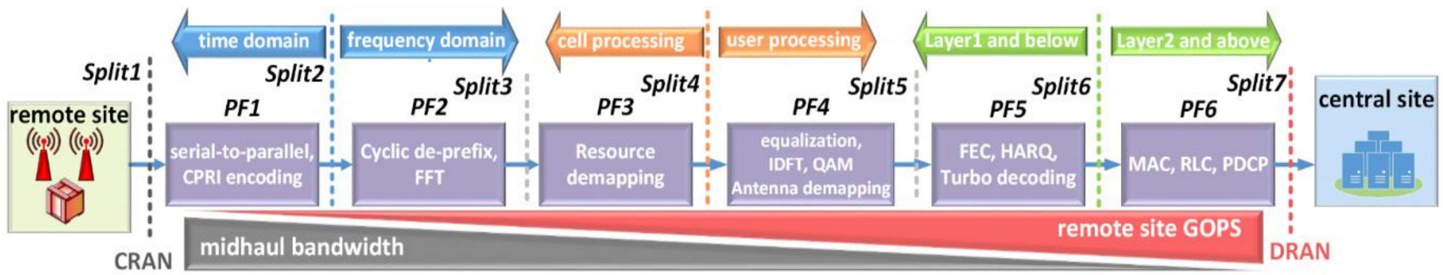
Numerical Results

- **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.

Fiber ownership	Multiplexing loss	TCO CRAN	TCO e-CRAN	Optimal Split
☺☺☺	200%	0.7	0.75	↓1, ↑1
☺	3600%	0.81	0.89	↓5, ↑1
😐	5080%	0.90	0.90	↓5, ↑3
☹	5800%	0.94	0.91	↓5, ↑3
☹☹☹	14700%	1.31	0.98	↓5, ↑6

☺ fiber-rich network operator; ☹ fiber-short network operator.



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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.

Thank You !

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