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Designing Reliable Virtualized Radio Access Networks

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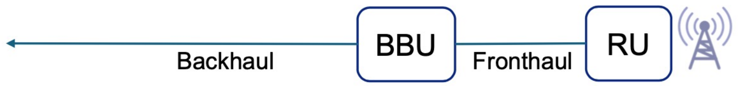
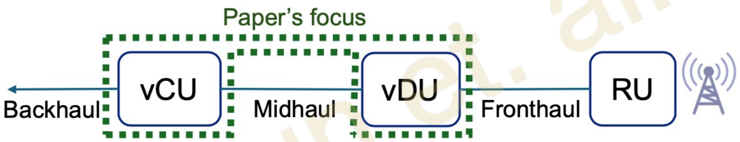
Virtualized Radio Access Networks (vRAN or Cloud RAN)

Horizontal Disaggregation (CU/DU) of RAN Functions

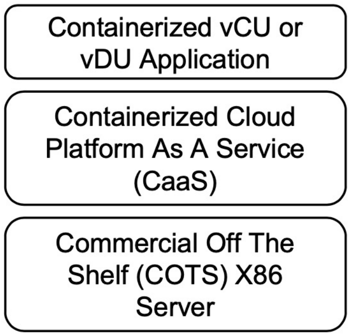


(a) Traditional Distributed Radio Access Networks (dRAN) Architecture with Baseband Units (BBU)



(b) Disaggregated dRAN Architecture with virtualized Distributed Unit (vDU) and virtualized Central Unit (vCU)

Vertical Disaggregation or Virtualization of RAN Functions



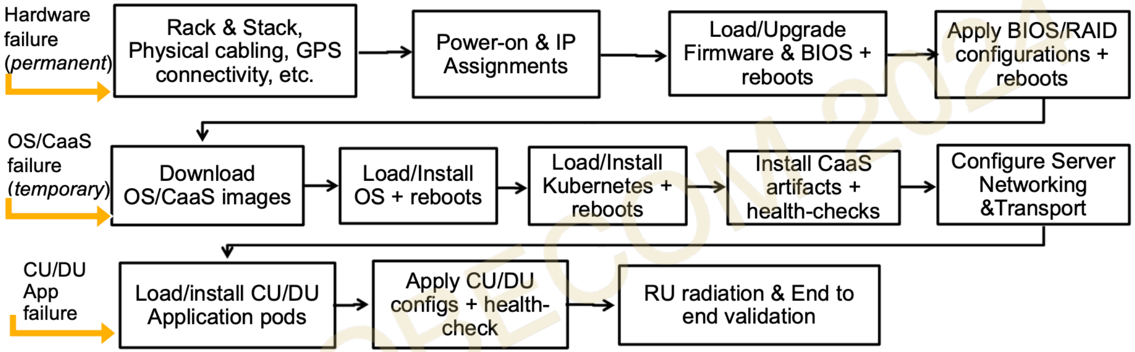
(c) Virtualized RAN Stack

How does disaggregation impact availability?
Do we need hardware/software replication?

→ Analytical Modeling

First focus on cloudification of RAN – vCU & vDU

What can fail in vRAN?



1. **Hardware (*permanent*) failures**
   a team needs to drive to the location of failure

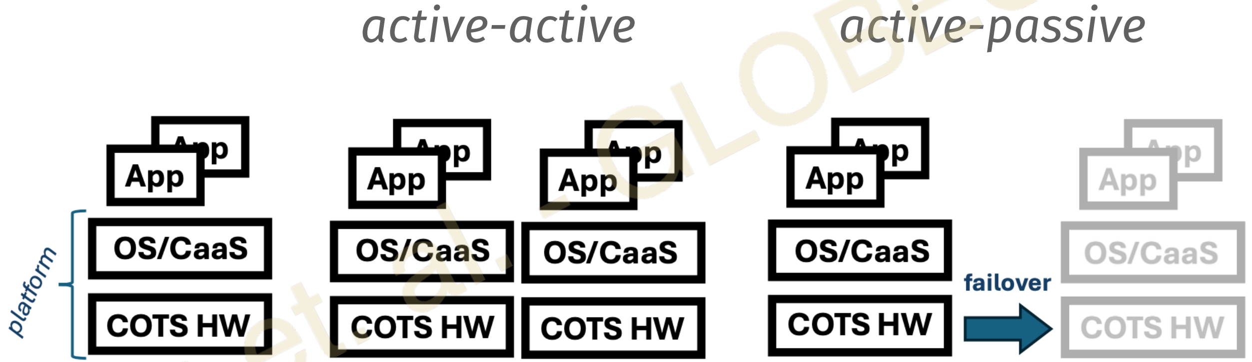
2. **OS/CaaS (*temporary*) failures**
   Cloud platform needs reboot

3. **CU/DU Application failures**
   Software containers need reboot

	Parameter	Value	Reference
Perm	$MTTF_h$	10 – 100 years	[1]-[3]
	$MTTR_h$	10 hours	This study
Temp.	$MTTF_o$	17 – 70 days	[4]
	$MTTR_o$	0.5 min - 1.5 hours	[5], This study
App.	$MTTF_s$	7 – 52 days	[6]
	$MTTR_s$	1 s – 30 min	[7]-[9], This study

MTTF: Mean time to fail
MTTR: Mean time to recover

Replication types in consideration

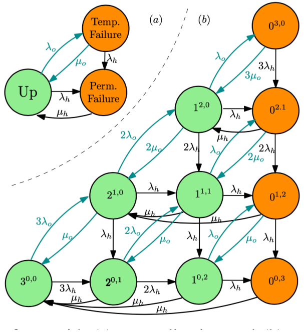


(a) *A cluster without platform replication*

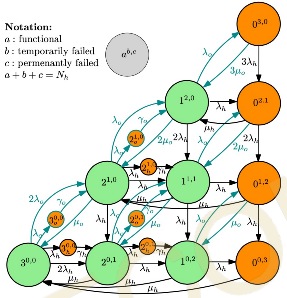
(b) A cluster with *active-active platform* replication

(c) A cluster with *active-passive platform* replication

Modeling Approach

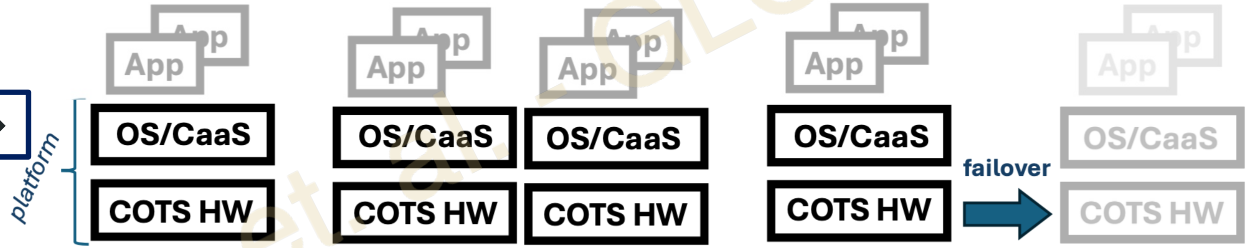


active-active



active-passive

2 Platform Models →



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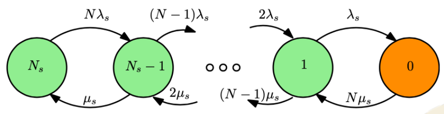
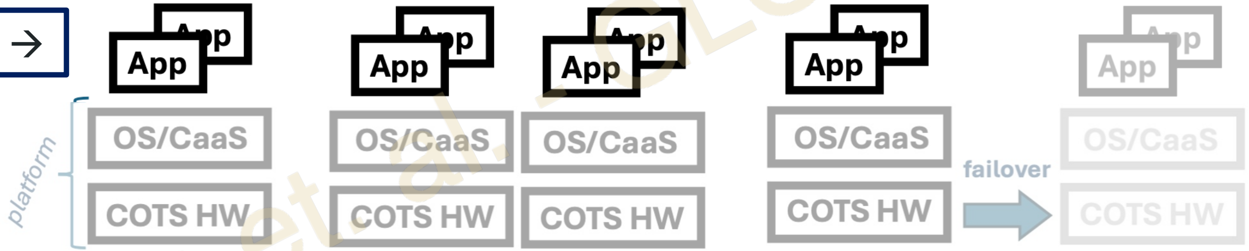
- We use *Continuous Time Markov Chains* within the context of Machine-Repair Problems to model the DU and the CU.

Modeling Approach



(b) Replicated

1 Application Model →



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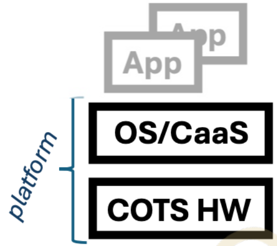
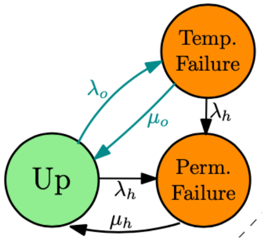
Modeling the platform



(a) *A cluster without platform replication*

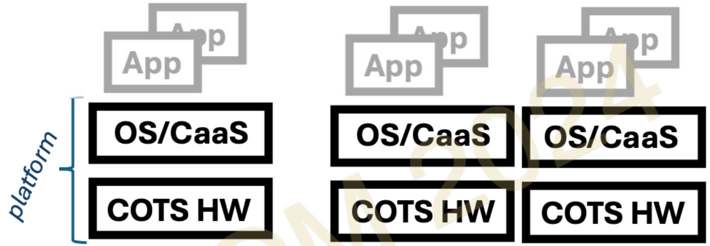
Simplest case



1. **Hardware (*permanent*) failures**
   $\lambda_h = 1/MTTF_h$ and $\mu_h = 1/MTTR_h$
2. **OS/CaaS (*temporary*) failures**
   $\lambda_o = 1/MTTF_o$ and $\mu_o = 1/MTTR_o$

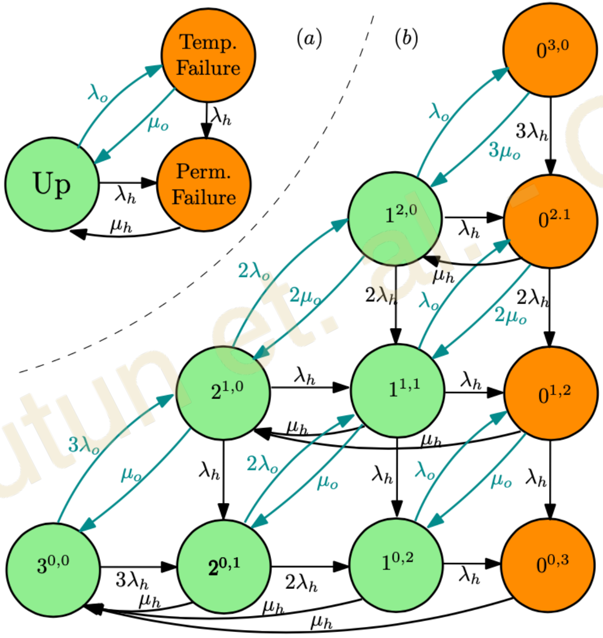
- Exponentially distributed repair times and times between failures assumed.
- We solve for steady state probabilities, analytically or numerically.

Modeling the platform



(a) *A cluster without platform replication*
(b) A cluster with *active-active platform* replication

Active-active platform model



1. **Hardware (*permanent*) failures**
   $\lambda_h = 1/MTTF_h$ and $\mu_h = 1/MTTR_h$

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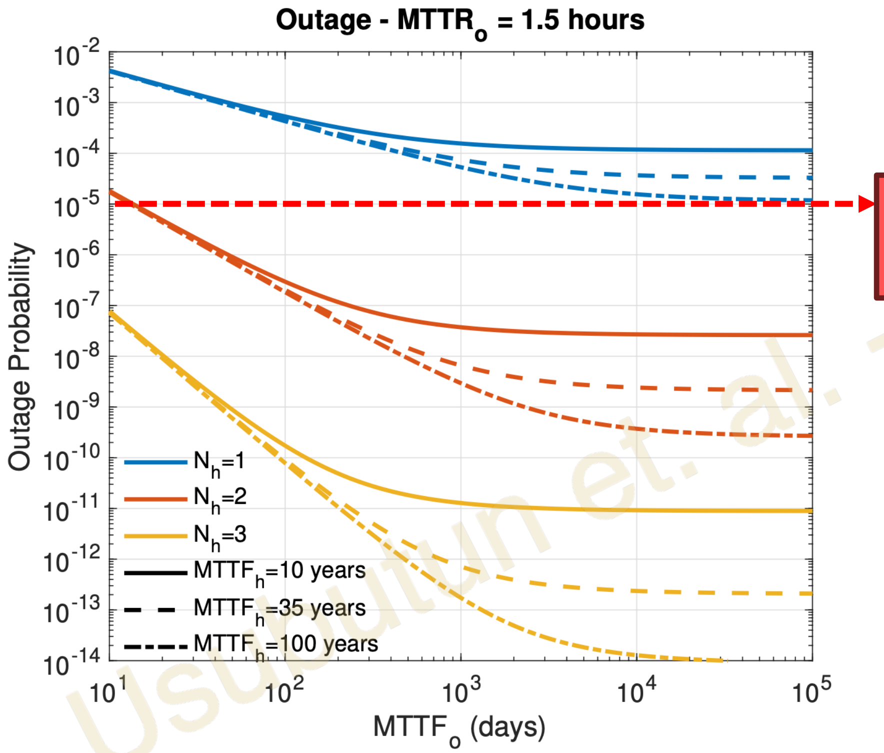
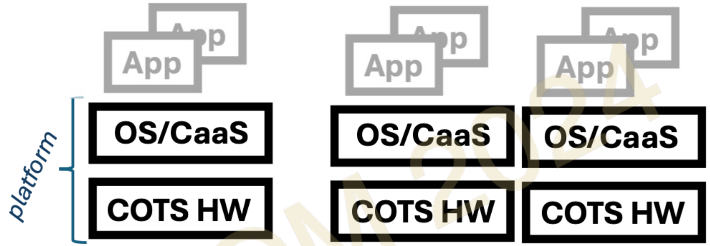
Active-active platforms



MTTR_h = 10 hours



(a) *A cluster without platform replication*

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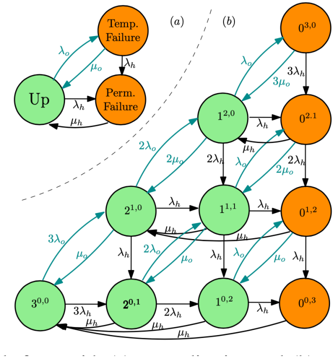
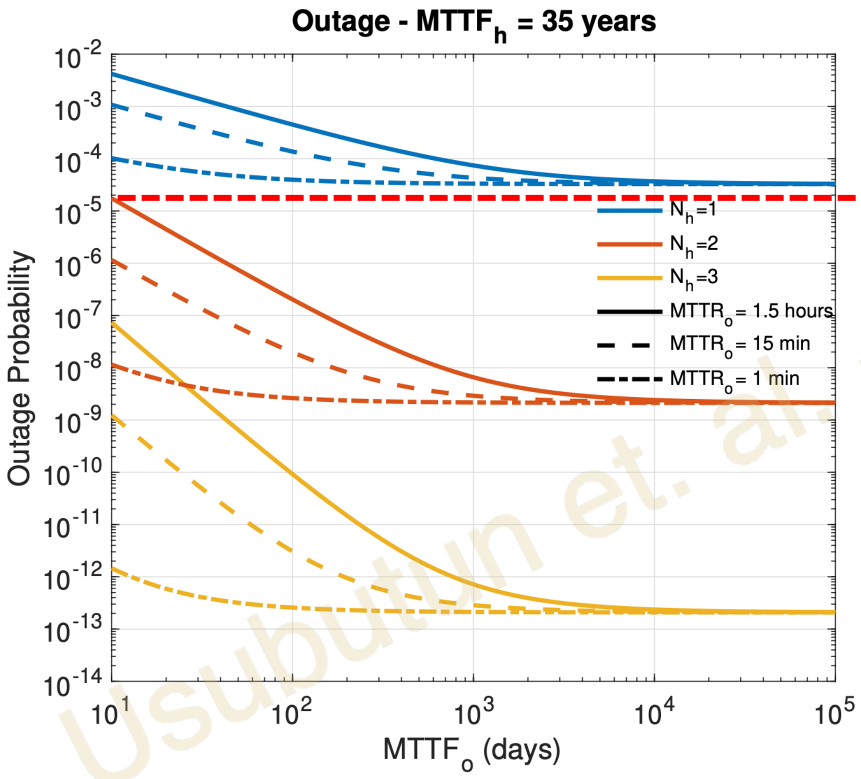
Hardware replication necessary to reach 5-nines availability!



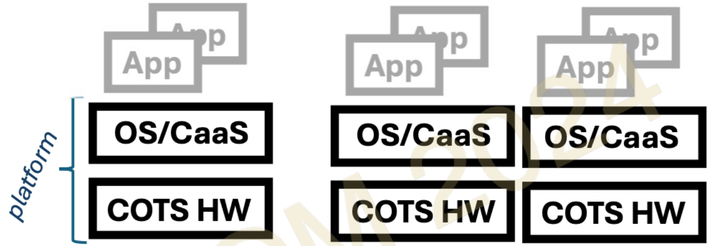
Result 1:

Lines: HW MTTF
x-axis: OS/CaaS MTTF

Active-active platforms



$\text{MTTR}_h = 10$ hours



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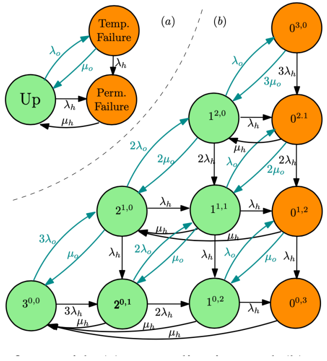
Hardware replication necessary to reach 5-nines availability!

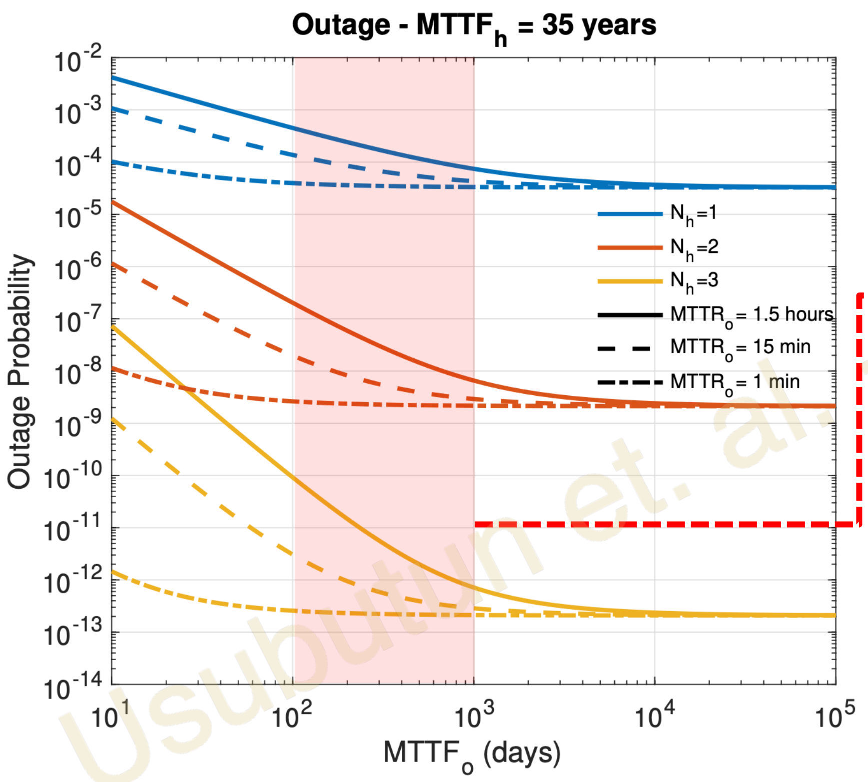
Result 2:

<u>Lines:</u> **OS/CaaS MTTR**

<u>x-axis:</u> OS/CaaS MTTF



Active-active platforms



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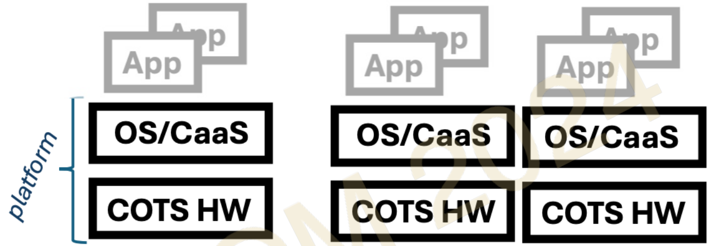

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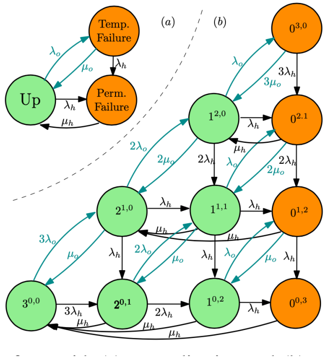
How often OS/CaaS platform fails and how fast we repair makes 1 to 3 nines of difference!

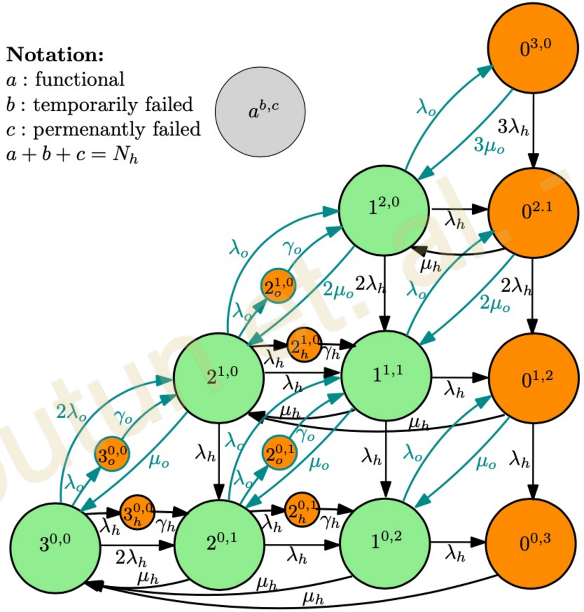
Result 2:

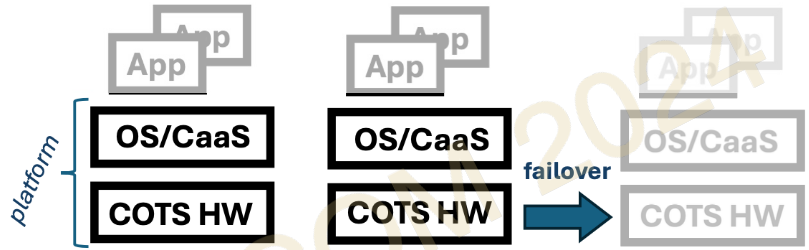
<u>Lines:</u> **OS/CaaS MTTR**
<u>x-axis:</u> OS/CaaS MTTF



Modeling the platform (2)

Active-passive platform model





(a) *A cluster without platform replication* (c) A cluster with *active-passive platform* replication

1. **Failover from hardware (*permanent*) failures**

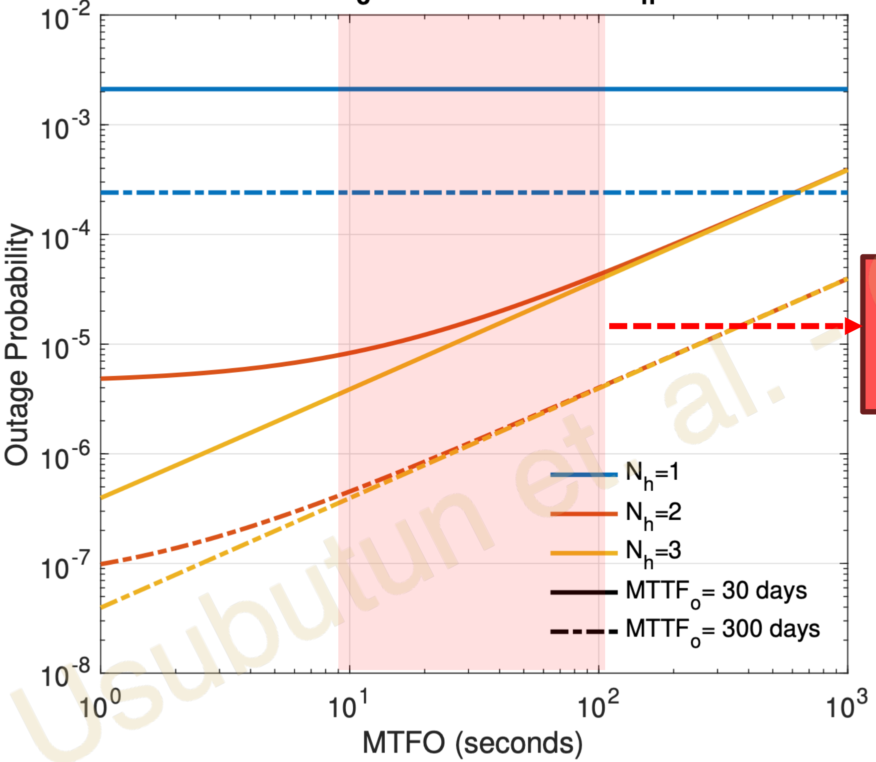
   $\gamma_h = 1/MTFO$

2. **Failover from OS/CaaS (*temporary*) failures**

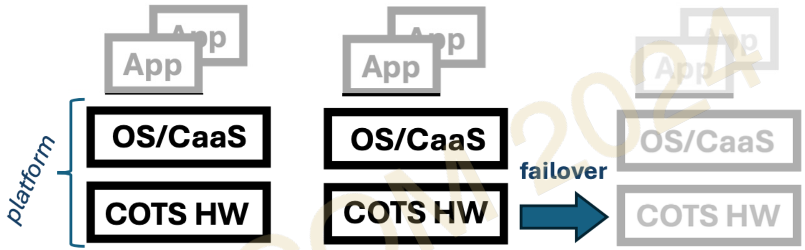
   $\gamma_o = 1/MTFO$

Active-passive platforms

Outage - MTTR$_o$ = 1.5 hours, MTTF$_h$ =35 years



MTFO: Mean time to fail-over



(a) *A cluster without platform replication*

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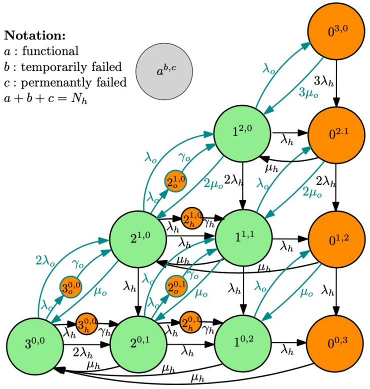
We can't fully exploit HW replication if we do not failover fast enough!

Result 3:

<u>Lines:</u> OS/CaaS MTTF
<u>x-axis:</u> **Failover time**



$\mathrm{MTTR}_h = 10$ hours

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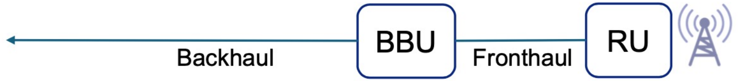

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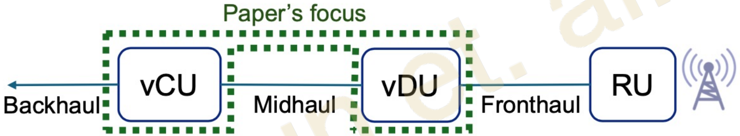


(b) Disaggregated dRAN Architecture with virtualized Distributed Unit (vDU) and virtualized Central Unit (vCU)

Vertical Disaggregation or Virtualization of RAN Functions

(c) Virtualized RAN Stack

Now focus on network elements – CU & DU (typically uses existing transport infrastructure)

Impact of centralizing the CU

X_d and X_c: # of unavailable cell sites for distributed and centralized CUs.

They have different distributions.

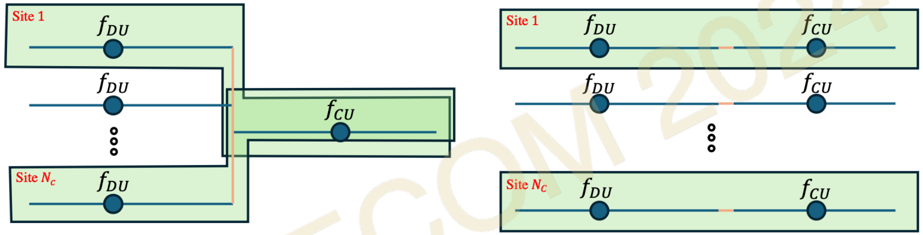
Yet interestingly:

$$E[X_d] = E[X_c] = N_c(1 - f_{DU} f_{CU})$$

With the same availability, the two schemes perform the same on average!

Cell site outage:

$$E[X_d]/N_c = E[X_c]/N_c = (1 - f_{DU} f_{CU})$$



(a) *Centralized vCU* (b) *Distributed vCU*

DU Outage $1 - f_{DU}$	CU Outage $1 - f_{CU}$	Cell Outage $1 - f_{DU} f_{CU}$
10^{-5}	10^{-5}	$\sim 1.99 \cdot 10^{-5}$
10^{-5}	10^{-6}	$\sim 1.10 \cdot 10^{-5}$
10^{-5}	10^{-7}	$\sim 1.01 \cdot 10^{-5}$

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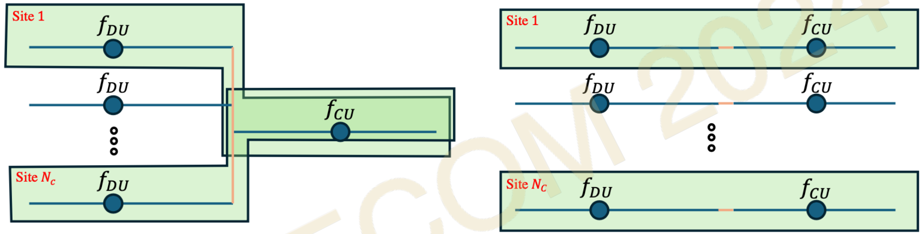

(a) *Centralized vCU* (b) *Distributed vCU*

DU Outage $1 - f_{DU}$	CU Outage $1 - f_{CU}$	Cell Outage $1 - f_{DU} f_{CU}$	All Cells Unavailable $\Pr(X_c = N_c)$
10^{-5}	10^{-5}	$\sim 1.99 \cdot 10^{-5}$	$\sim 10^{-5}$
10^{-5}	10^{-6}	$\sim 1.10 \cdot 10^{-5}$	$\sim 10^{-6}$
10^{-5}	10^{-7}	$\sim 1.01 \cdot 10^{-5}$	$\sim 10^{-7}$

Improving CU resiliency is key to avoiding an “all cells” outage

Fewer vCU locations in centralized vCU model !

Conclusions

Find our paper here →

- Hardware replication necessary to go beyond 5-nines availability.
- OS/CaaS reliability can significantly alter the availability (1 to 3 nines!).
- In active-passive systems, failover times, if slow, can hinder the gain from replicating hardware.
- Centralized CU deployments have a single point of failure. This weakness can be mitigated by making them more reliable. This is justifiable due to fewer quantity.

Questions?

References – for MTTFs and MTTRs

[1] J. Scaramella, M. Marden, J. Daly, and R. Perry, “The cost of retaining aging it infrastructure,” Technical report, International Data Corporation (IDC), Framingham, MA, Tech. Rep., 2014.

[2] K. V. Vishwanath and N. Nagappan, “Characterizing cloud computing hardware reliability,” in *ACM SoCC*, 2010.

[3] G. Wang, L. Zhang, and W. Xu, “What can we learn from four years of data center hardware failures?” in *IEEE/IFIP DSN 2017*, 2017.

[4] R. Matias, M. Prince, L. Borges, C. Sousa, and L. Henrique, “An empirical exploratory study on operating system reliability,” in *Proc. ACM Symp. Appl. Comput.*, 2014, pp. 1523–1528.

[5] S. I. Abrita, M. Sarker, F. Abrar, and M. A. Adnan, “Benchmarking VM startup time in the cloud,” in *Benchmarking, Measuring, and Optimizing*, C. Zheng and J. Zhan, Eds. Cham: Springer, 2019, pp. 53–64.

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[7] E. F. Boza, C. L. Abad, S. P. Narayanan, B. Balasubramanian, and M. Jang, “A case for performance-aware deployment of containers,” in *WOC*, 2019, pp. 25–30.

[8] T. K. Authors, “Configure liveness, readiness and startup probes,” www.kubernetes.io/docs/tasks/configure- pod-container/configure-liveness-readiness-startup-probes, accessed: 2024-03-17.

[9] R.-S. Schmoll, T. Fischer, H. Salah, and F. H. P. Fitzek, “Comparing and evaluating application-specific boot times of virtualized instances,” in *IEEE 5GWF*, 2019, pp. 602–606.

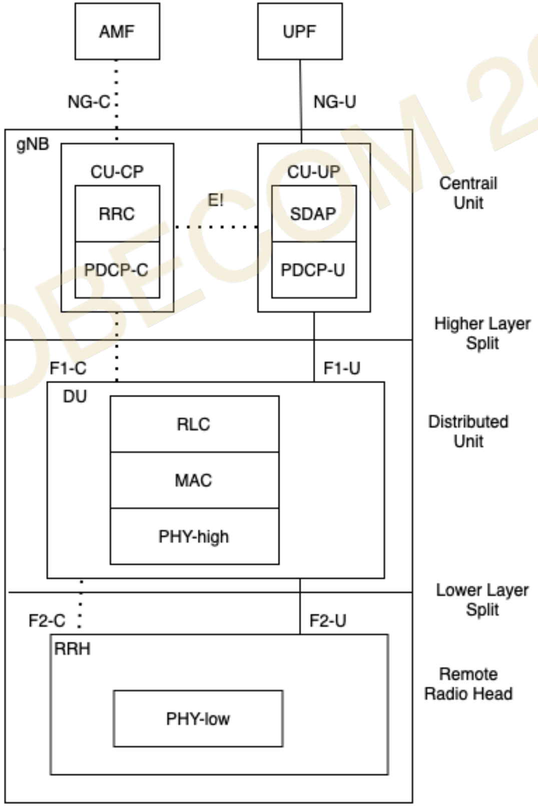
Backup Slides

5G Radio Access Networks

gNB is a logical name.

3GPP further defines functional blocks

All the layers/functional blocks need not be implemented in the same physical location.

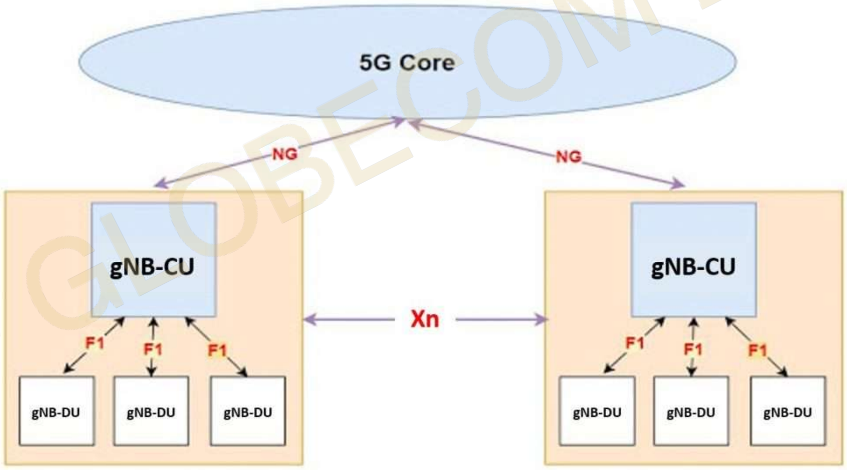


https://www.prodevelopertutorial.com/5g-nr-ran-functional-splits/

5G Radio Access Networks

A gNB-CU (Centralized Unit) can handle multiple gnb-DUs (Distributed Unit)

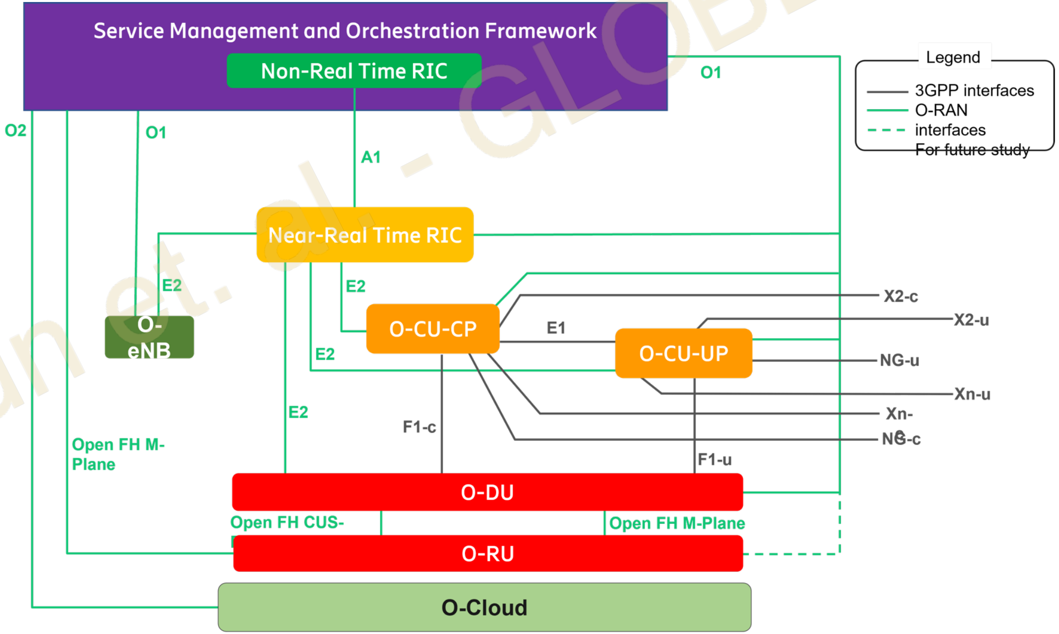
And a DU can handle multiple Radio Units (RU)



https://www.5gworldpro.com/5g-knowledge/what-is-cu-and-du-in-5g.html

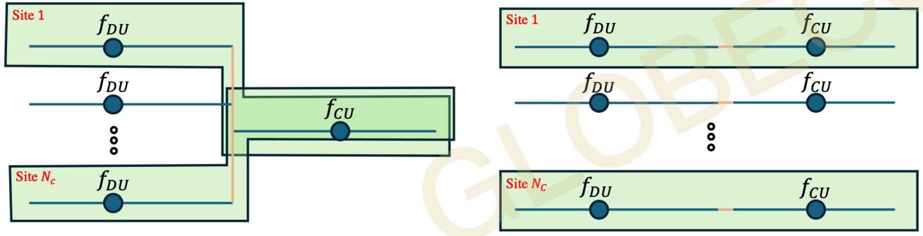
Let me briefly revisit the O-RAN diagram

- O-CU-CP, O-CU-UP, O-DU etc. are all SOFTWARE!
- Running on the O-Cloud

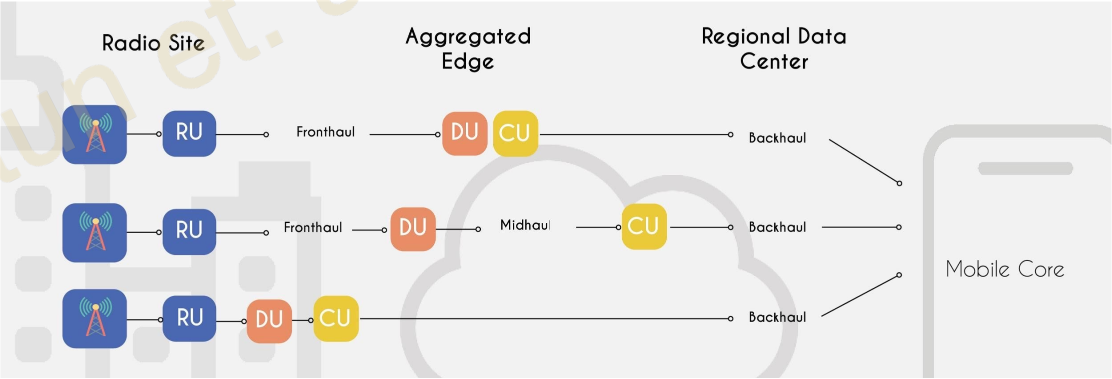


Resilience Modeling – Centralized vs Distributed Deployment

- How should Cell Sites be built?
  - Centralized or Distributed

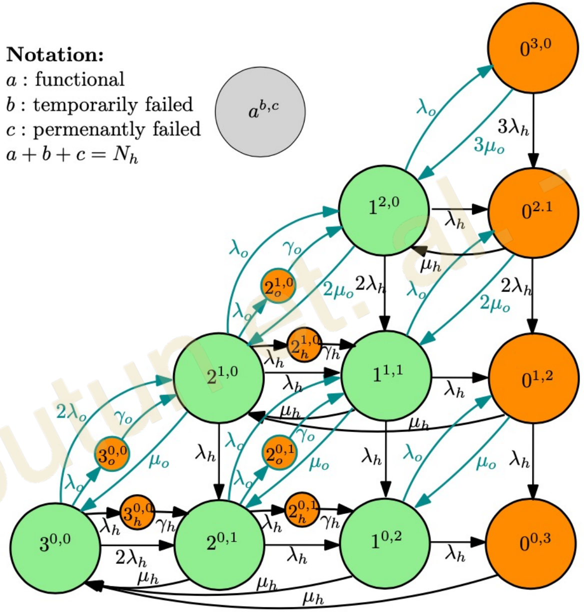


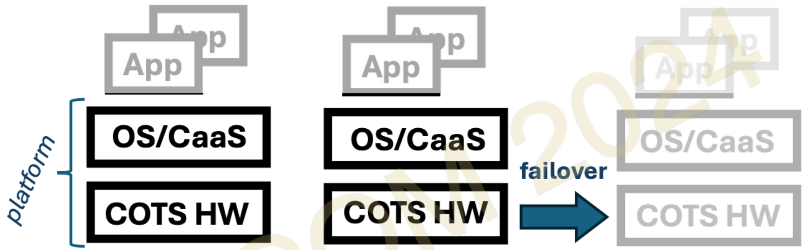
(a) *Centralized vCU* (b) *Distributed vCU*



Modeling the platform (2)

Active-passive platform model





(a) *A cluster without platform replication* (c) A cluster with *active-passive platform* replication

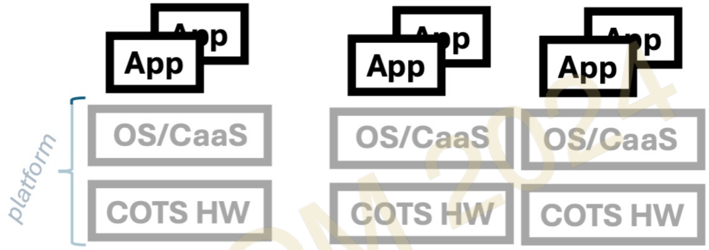
1. **Failover from hardware (*permanent*) failures**

   $\gamma_h = 1/MTFO$

2. **Failover from OS/CaaS (*temporary*) failures**

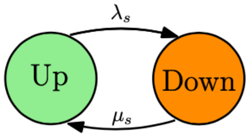
   $\gamma_o = 1/MTFO$

Modeling the RAN Applications

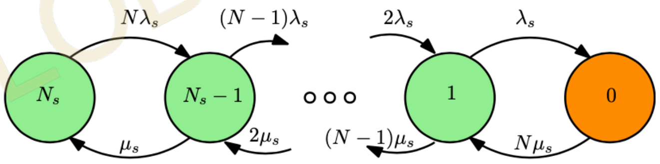


(a) *A cluster without platform replication* (b) A cluster with *active-active platform* replication

Modeled in cascade to the *platform*



(a) Single



(b) Replicated

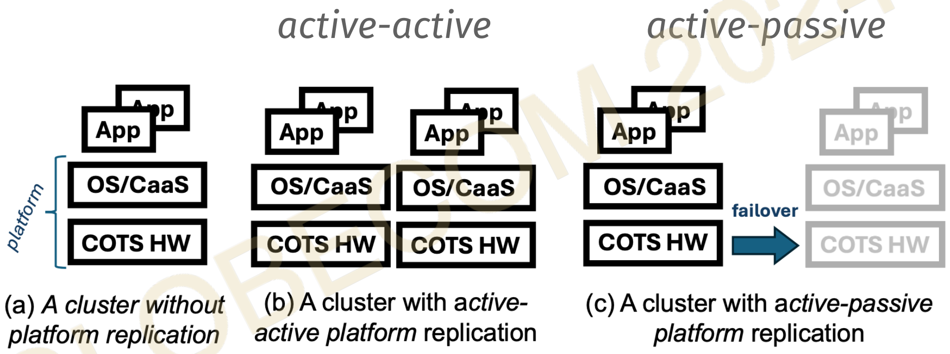
$$\Pr(\mathrm{Up}) = {}^{\mu_s}/_{\lambda_s+\mu_s}, \quad \Pr(\mathrm{Down}) = {}^{\lambda_s}/_{\lambda_s+\mu_s}$$

$$p_i = \binom{N_s}{i}\left(\frac{\mu_s}{\lambda_s+\mu_s}\right)^i\left(\frac{\lambda_s}{\lambda_s+\mu_s}\right)^{N_s-i}$$

3. **CU/DU Application failures**
   $\lambda_h = 1/MTTF_h$ and $\mu_h = 1/MTTR_h$

Modeling Cluster Availability

Modeled in cascade



Active-active cluster availability

f_a = **Active-active platform avail.(** N_h **) * App. avail.(** $N_h * N_s$ **)**

Active-passive cluster availability

f_p = **Active-active platform avail.(** N_h **) * App. avail.(** N_s **)**

What is needed for 6-nines overall availability?

Active-active

#9s	$\#9s_p$	$\#9s_s$	N_h	$MTTF_h$	$MTTF_o$	$MTTR_o$	N_s	$MTTR_s$
6	6	6	2	10 years	10 months	90 min	1	30 min
6	6	6	2	10 years, 100 years	1 months	15 min	1	30 min
6	6	8	2	10 years	10 months	90 min	1	5 min
6	6	8	2	10 years, 100 years	1 months	15 min	1	5 min
7	7	8	2	10 years	10 months	15 min	1	5 min
7	7	8	2	100 years	10 months	90 min	1	5 min

Active-passive

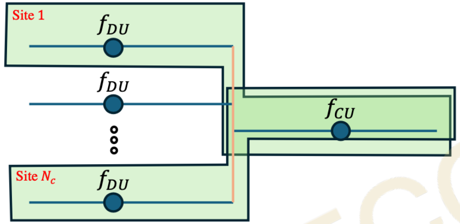
#9s	$\#9s_p$	$\#9s_s$	N_h	$MTTF_h$	$MTTF_o$	$MTTR_o$	MTFO	N_s	$MTTR_s$
5	5	5	2, 3	10 years, 100 years	10 months	1 min, 15 min, 90 min	100 sec	2	30 min
5	5	7	2, 3	10 years, 100 years	10 months	1 min, 15 min, 90 min	100 sec	2	5 min
6	6	7	2, 3	10 years, 100 years	10 months	1 min, 15 min, 90 min	10 sec	2	5 min
6	6	8	2, 3	10 years, 100 years	10 months	1 min, 15 min, 90 min	10 sec	3	30 min

$MTTR_h = 10$ hours, $MTTF_s = 2$ months

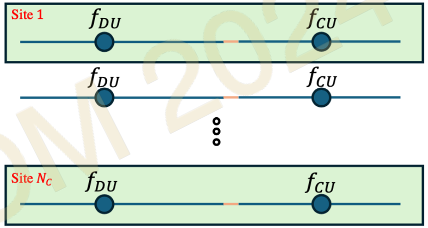
All possible combinations of parameters in a given row result in the same number of nines for the cluster, platform and application respectively.

Impact of centralizing the CU

X_d and X_c: # of unavailable cell sites for distributed and centralized CUs.



(a) *Centralized vCU*



(b) *Distributed vCU*

$$\Pr(X_d = k) = \binom{N_c}{k} (1 - f_{DU} f_{CU})^k \, (f_{DU} f_{CU})^{N_c - k}$$

All independent (Binomial Dist.)

$$\Pr(X_c = k) = \begin{cases} f_{CU} \binom{N_c}{k} (\overline{f_{DU}})^k (f_{DU})^{N_c - k} & \text{, else} \\ \overline{f_{CU}} + f_{CU} (\overline{f_{DU}})^{N_c} & \text{, if } k = N_c \end{cases}$$

Some sites down

All sites down

Interestingly:

$$E[X_d] = E[X_c] = N_c(1 - f_{DU} f_{CU})$$

With the same availability, the two schemes perform the same on average!

Site outage:

$$E[X_d]/N_c = E[X_c]/N_c = (1 - f_{DU} f_{CU})$$

Impact of centralizing the CU

X_d and X_c: # of unavailable cell sites for distributed and centralized CUs.

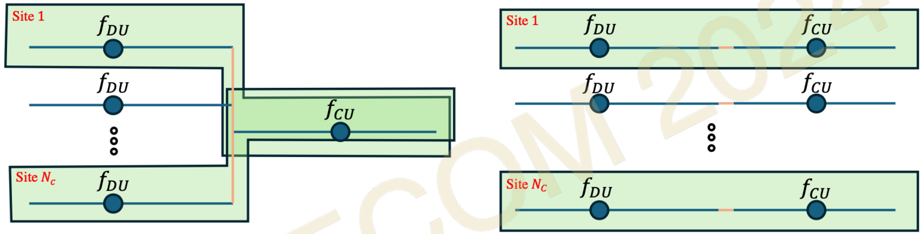
$$\Pr(X_d = k) = \binom{N_c}{k} (1 - f_{DU} f_{CU})^k (f_{DU} f_{CU})^{N_c - k}$$

$$\Pr(X_c = k) = \begin{cases} f_{CU} \binom{N_c}{k} (\overline{f_{DU}})^k (f_{DU})^{N_c - k} & \text{, else} \\ \overline{f_{CU}} + f_{CU} (\overline{f_{DU}})^{N_c} & \text{, if } k = N_c \end{cases}$$

Interestingly:

$$E[X_d] = E[X_c] = N_c(1 - f_{DU} f_{CU})$$

With the same availability, the two schemes perform the same on average!



(a) *Centralized vCU* (b) *Distributed vCU*

DU Outage $1 - f_{DU}$	CU Outage $1 - f_{CU}$	Cell Outage $1 - f_{DU} f_{CU}$
10^{-5}	10^{-5}	$\sim 1.99 \cdot 10^{-5}$
10^{-5}	10^{-6}	$\sim 1.10 \cdot 10^{-5}$
10^{-5}	10^{-7}	$\sim 1.01 \cdot 10^{-5}$

Improving vCU resiliency is key to minimizing outage impact

Site outage:

$$E[X_d]/N_c = E[X_c]/N_c = (1 - f_{DU} f_{CU})$$

Impact of centralizing the CU

X_d and X_c: # of unavailable cell sites for distributed and centralized CUs.

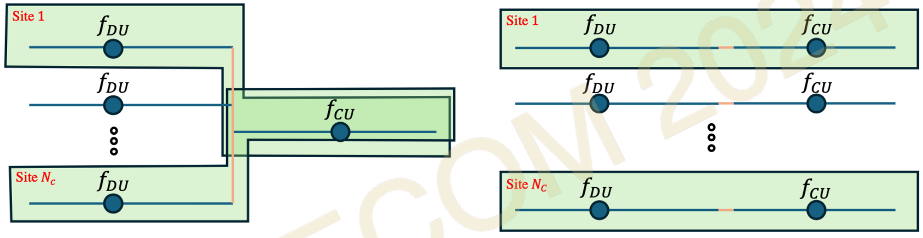
$$\Pr(X_d = k) = \binom{N_c}{k} (1 - f_{DU} f_{CU})^k \, (f_{DU} f_{CU})^{N_c - k}$$

$$\Pr(X_c = k) = \begin{cases} \overline{f_{CU}} \binom{N_c}{k} (\overline{f_{DU}})^k (f_{DU})^{N_c - k} & \text{, else} \\ \overline{f_{CU}} + f_{CU} (\overline{f_{DU}})^{N_c} & \text{, if } k = N_c \end{cases}$$

Interestingly:

$$E[X_d] = E[X_c] = N_c(1 - f_{DU} f_{CU})$$

With the same availability, the two schemes perform the same on average!



(a) *Centralized vCU* (b) *Distributed vCU*

DU Outage $1 - f_{DU}$	CU Outage $1 - f_{CU}$	Cell Outage $1 - f_{DU} f_{CU}$	All Cells Unavailable $\Pr(X_c = N_c)$
10^{-5}	10^{-5}	$\sim 1.99 \cdot 10^{-5}$	$\sim 10^{-5}$
10^{-5}	10^{-6}	$\sim 1.10 \cdot 10^{-5}$	$\sim 10^{-6}$
10^{-5}	10^{-7}	$\sim 1.01 \cdot 10^{-5}$	$\sim 10^{-7}$

Improving vCU resiliency is key to minimizing outage impact

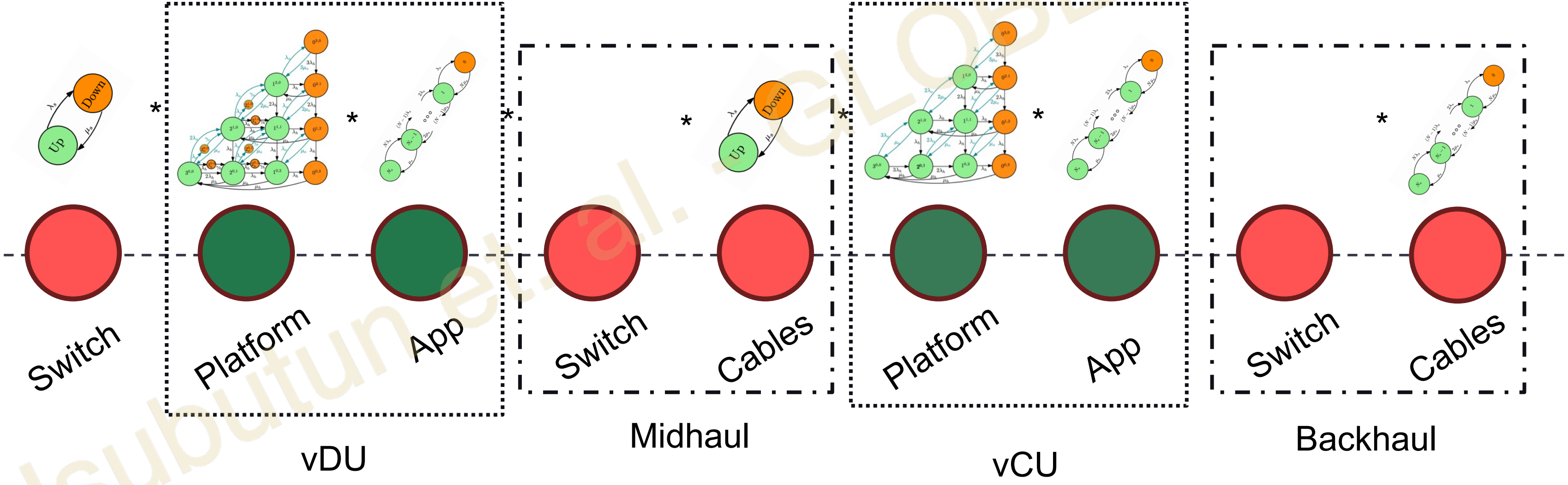
Fewer vCU locations in centralized vCU model !

Site out

$$E[X_d]/N_c = E[X_c]/N_c = (1 - f_{DU} f_{CU})$$

We provided a model for vDU and vCU

However, this approach can be expanded to the transport and beyond!



Proof: Centralized-Distributed Expected Outage Equivalence

The random variable X_d: number of cell sites out in the distributed setting

$$\Pr(X_d = k) = \binom{N_c}{k} (1 - f_{DU} f_{CU})^k (f_{DU} f_{CU})^{N_c - k}$$

By definition of binomial distribution

$$\mathbb{E}[X_d] = N_c(1 - f_{DU} f_{CU})$$

Cont'd in the next page

Proof: Centralized-Distributed Expected Outage Equivalence

The random variable X_c: number of cell sites out in the centralized setting

$$\Pr(X_c = k) = \begin{cases} f_{CU}\binom{N_c}{k}(\overline{f_{DU}})^k(f_{DU})^{N_c-k}, & \text{else} \\ \overline{f_{CU}} + f_{CU}(\overline{f_{DU}})^{N_c}, & \text{if } k = N_c \end{cases}$$

For simplicity define

$$f_{CU} = \alpha, \qquad \overline{f_{CU}} = 1 - f_{CU} = \beta$$
$$f_{DU} = p, \qquad \overline{f_{DU}} = 1 - f_{DU} = q$$

Substituting these

$$\Pr(X_c = k) = \begin{cases} \alpha\binom{N_c}{k}q^k p^{N_c-k}, & \text{else} \\ \beta + \alpha q^{N_c}, & \text{if } k = N_c \end{cases}$$

Now define dummy variable X' such that,

$$\Pr(X' = k) = \binom{N_c}{k}(q)^k(p)^{N_c-k}$$
$$\mathbb{E}[X'] = N_c q$$

Therefore,

$$\begin{aligned} \mathbb{E}[X_c] &= \alpha\big[\mathbb{E}[X'] - N_c \cdot \Pr(X' = N_c)\big] + N_c \cdot \Pr(X_c = N_c) \\ &= \alpha\big[N_c q - N_c q^{N_c}\big] + N_c \cdot (\beta + \alpha q^{N_c}) \\ &= N_c(\alpha q + \beta) \\ &= N_c(\alpha(1-p) + 1 - \alpha) \\ &= N_c(1 - p\alpha) \\ &= N_c(1 - f_{DU} f_{CU}) = \mathbb{E}[X_d] \end{aligned}$$