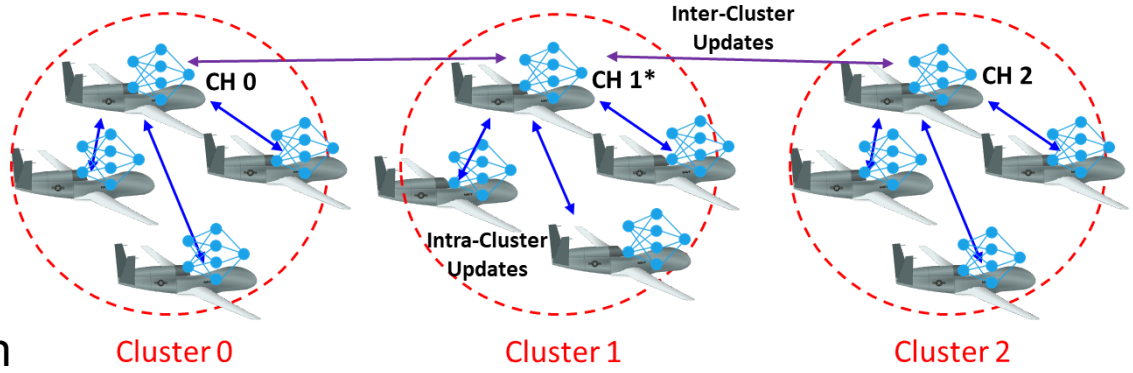
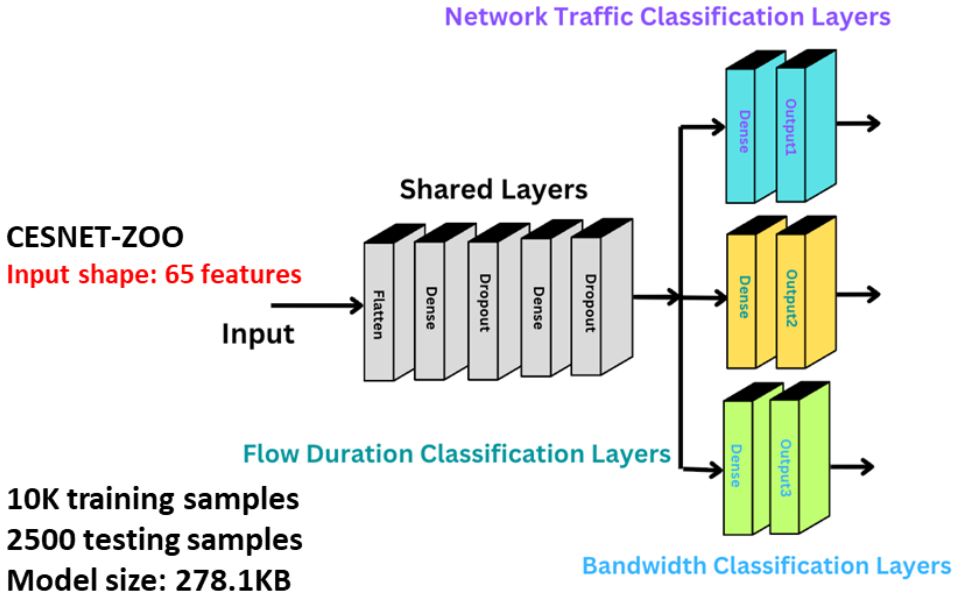
Swarm Coherence in DDIL Environments- A Scalability Feasibility Study

- Adopt hierarchal federated structure to enable large-scale UAV swarm operations
  - Instead of exchanging raw data, processed info (i.e., NN parameters) are exchanged
  - Multiple correlated missions/tasks can be achieved via a single-round UAV dispatch and data collection

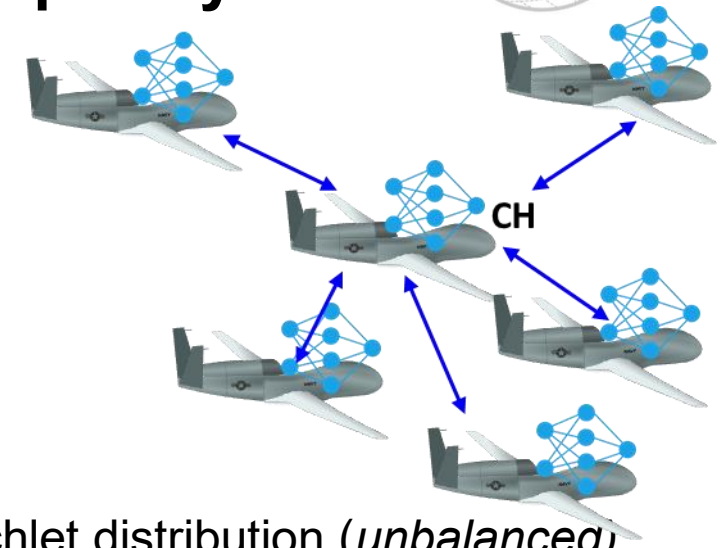


- Scalability study:
  - A. Intra-cluster updating
    - Performance improvement per updating frequency
  - B. Inter-cluster updating
    - Clustering versus flat baseline
    - CH compromised and recovery



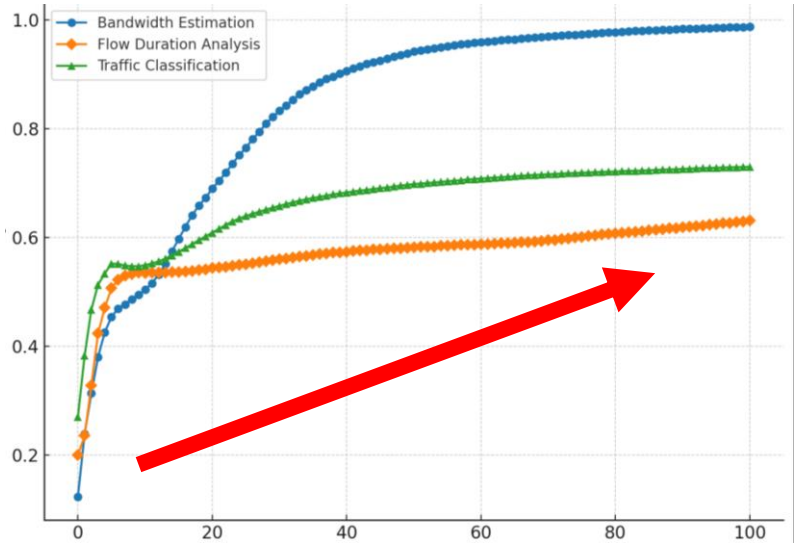
A. Federated UAV Swarm Operation and Updating Frequency

- Leverage/synergize local UAV computation capabilities while retaining data privacy-preserving using federation
  1. Local UAVs execute their (same) NNs with on-board sensory data
  2. UAVs send NN parameters to the CH for aggregation (FedAvg)
  3. UAVs receive the global aggregated NN from the CH



- Evaluation metrics:
  - Consider 200 nodes with 10K training samples distributed using Dirichlet distribution (*unbalanced*)

Achieved Task Accuracy



Communication rounds T

$$\widetilde{W} = 2T(N \cdot \omega)$$

Communication Cost = 2*100*200*278.1KB = 11.124GB

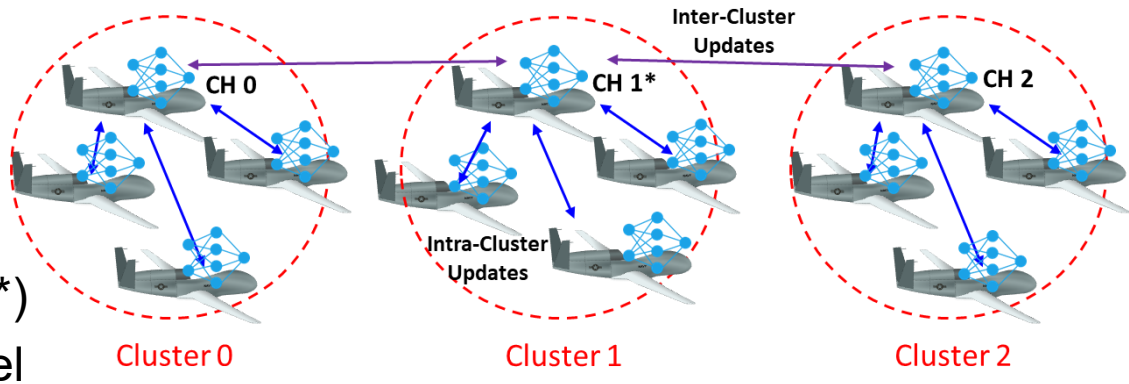
(*upper bound*)

T = # of communication/federation rounds
N = # of nodes
ω = NN model size

[1] S. Liu et al. "FedCPF: An Efficient-Communication Federated Learning Approach for Vehicular Edge Computing in 6G Communication Networks," *IEEE Trans. Intell. Transp. Syst.*, 2022.

B.1 Clustering-Enhanced Federation Scalability

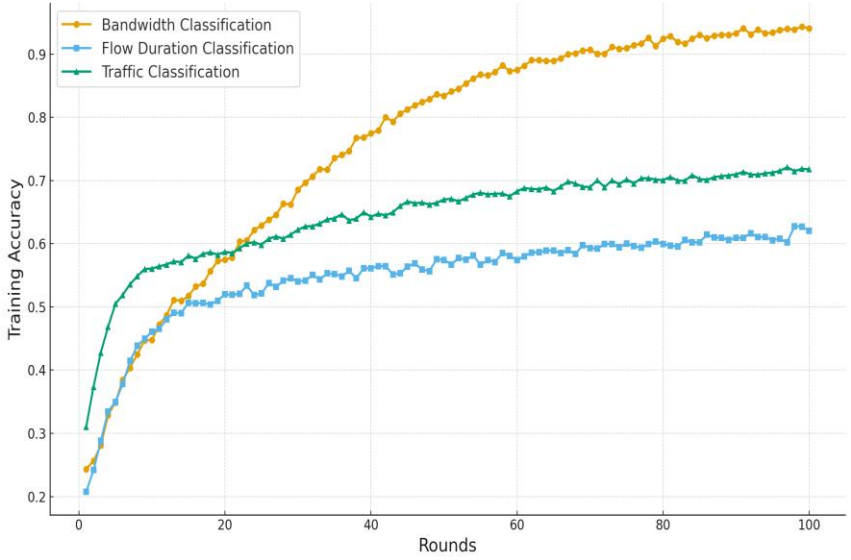
- Form cluster systems for large-scale swarms giving fast response, less signaling, robustness, fault tolerance, and effective management
  1. Beyond intra-cluster operations, CHs send aggregated local models to a representative CH (CH*)
  2. CH* aggregate local NNs (FedAvg) for a global model and broadcast it back to CHs
  3. Each CHs use this new global NN for next-round intra-cluster operations



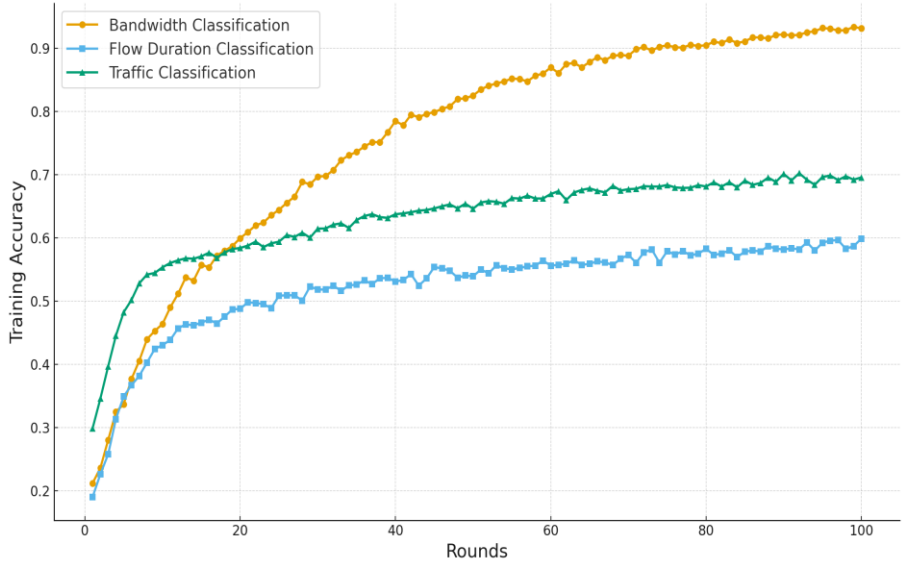
- Validation plan:
  - Confirm our cluster structure can support similar collaborative performance as flat structure: examine training/testing phases and different testing data setups
  - Evaluate CH compromised scenario: examine the timeline/steps for reselecting a new CH and recovering normal operations

Training Performance Comparisons for Cluster Formation

- A single cluster: contain 10K training samples, distributed among 600 UAVs via Dirichlet dist.
- Three clusters: contain (3334, 3333, 3333) training samples, respectively; each cluster distributes its samples among its 200 UAVs using Dirichlet dist.



Single cluster

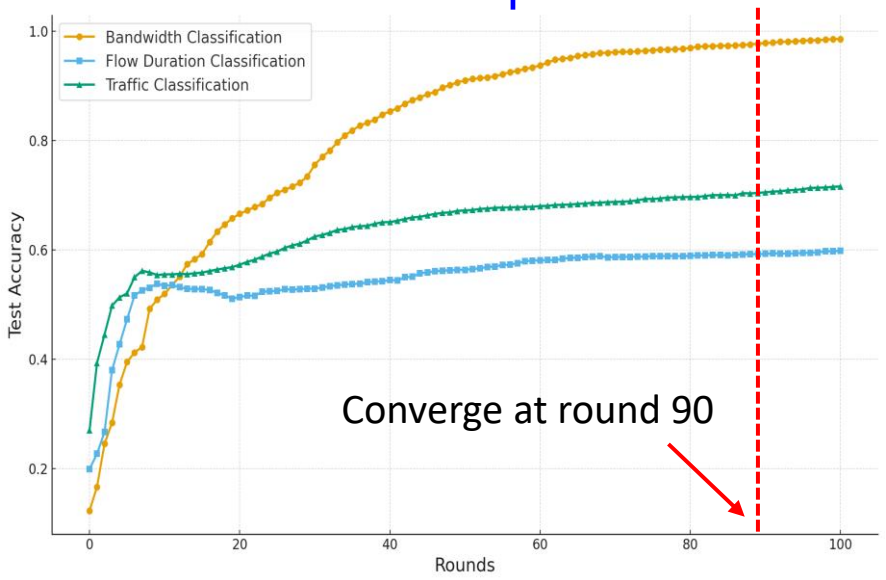


Three cluster average

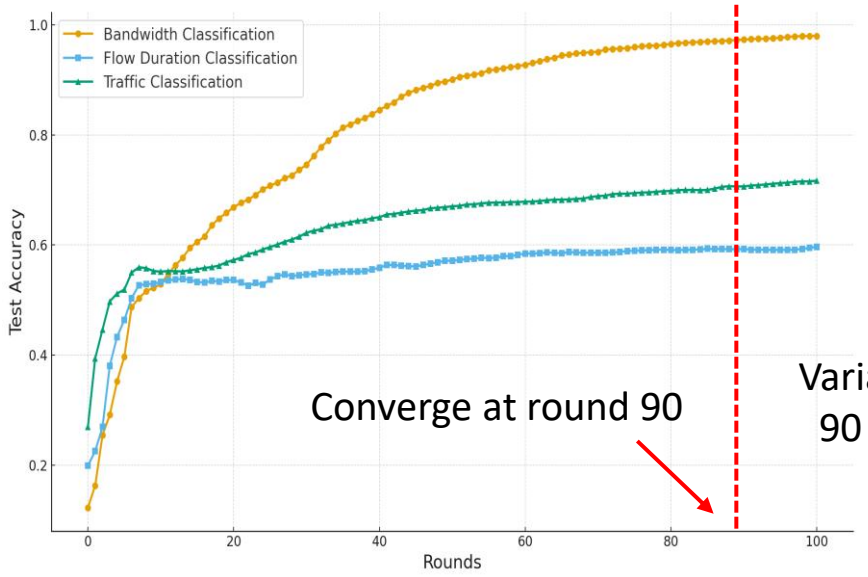
⇒ Single-cluster (flat) and multi-cluster yields similar performance for all three tasks

Testing Performance Comparisons for Cluster Formation

- A 2500 samples used for testing: single-cluster utilizes all samples; three-cluster, each uses approximate 2500/3 samples



Single cluster



Three cluster average

Variance btw rounds 90 and 100 stayed below 1%

⇒ Single-cluster (flat) and multi-cluster yields similar values and convergence

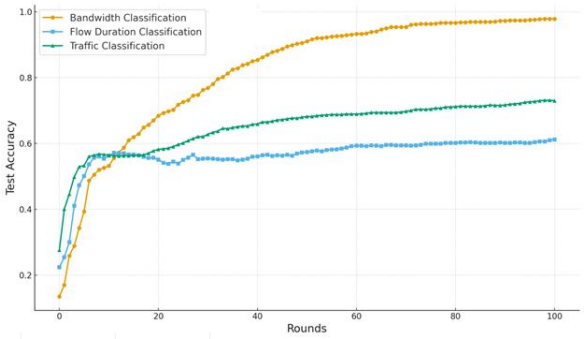
⇒ It confirms that our clustering implementation is an effective realization that supports close to optimal performance by flat structure; but ours gives speed, efficiency, manageability, and resilience— crucial in large-scale UAV swarm operations

More Testing Results for our Clustering Scheme

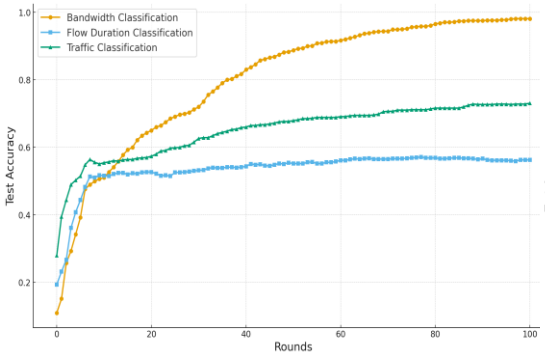
- We distribute 2500 testing samples following two cases
  - Equal Split: each of three clusters get approximate 2500/3 samples
  - Dirichlet Split: 2500 samples distributed among clusters (600 UAVs) via Dirichlet distribution (i.e., *data unbalance among clusters*)

Equal Split

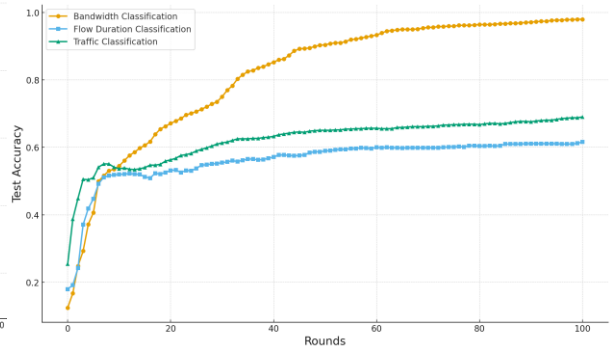
Cluster 0



Cluster 1

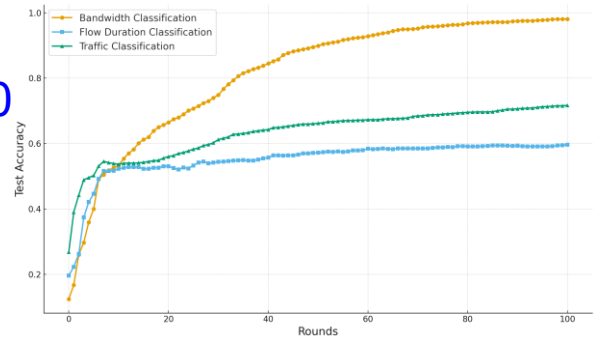


Cluster 2

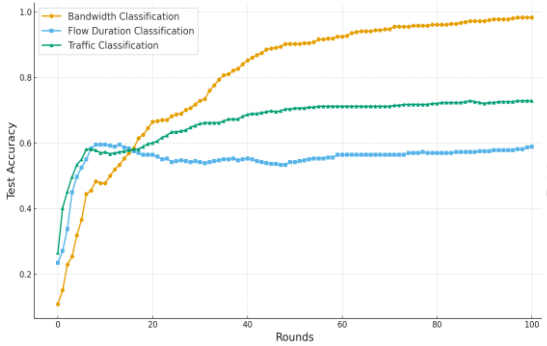


Dirichlet Split

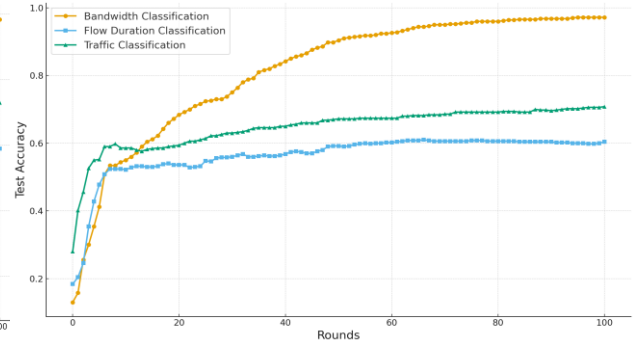
Cluster 0



Cluster 1



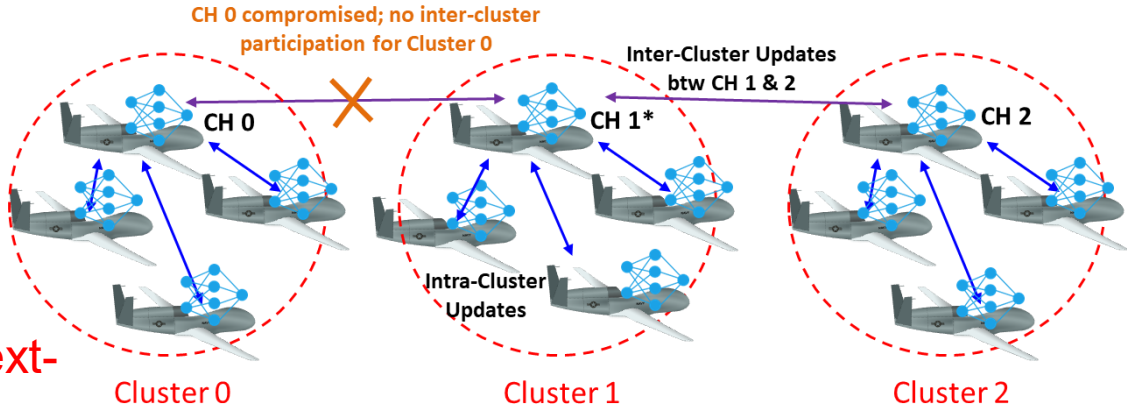
Cluster 2



⇒ Our clustered federation effectively combats massively distributed, unbalanced, non-IID data input, which often occur in DDIL environments

B.2 Robustness Provisioning: CH Compromised Study

- Examine one CH fails (e.g., CH 0), how the entire system reacts quickly to normal operations
- Our proposed recovery steps:
  1. **Detection:** anomaly detection from link/net-level
  2. **Intra-Cluster Re-Election:** re-elect a new CH (context-aware CH selection)
  3. **Inter-Cluster Continuity:** healthy clusters continue global aggregation
  4. **Re-Stabilization:** synchronize federation across clusters



Context-Aware CH Selection

$$\text{New CH 0} = \max_{UAV\ i \in Cluster\ 0} \left(\alpha \cdot E_i^{residual} + \beta \cdot RSSI_i^{ave\ to\ other\ UAVs\ in\ Cluster\ 0} \right)$$

- Expand famous LEACH protocol ([2] from MIT) with both energy and network geometry concerns

- Validation plan:
  - Evaluate CH compromised occurs when our clustered federation in (i) convergence or (ii) non-convergence (*transient*) stage

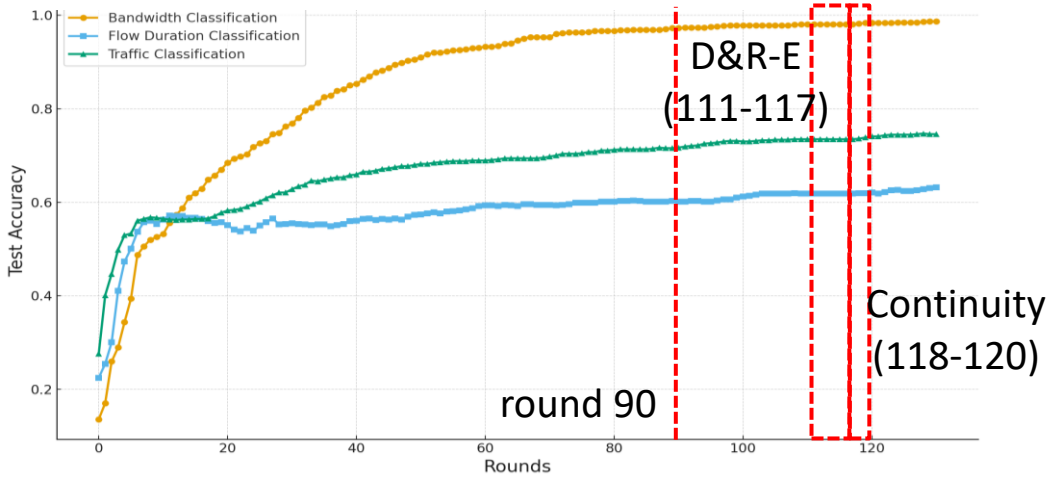
[2] W. B. Heinzelman et al. “An Application-Specific Protocol Architecture for Wireless Microsensor Networks,” *IEEE Trans. Wirel. Commun.*, 2022.

Convergence Case when CH Compromised Occurs

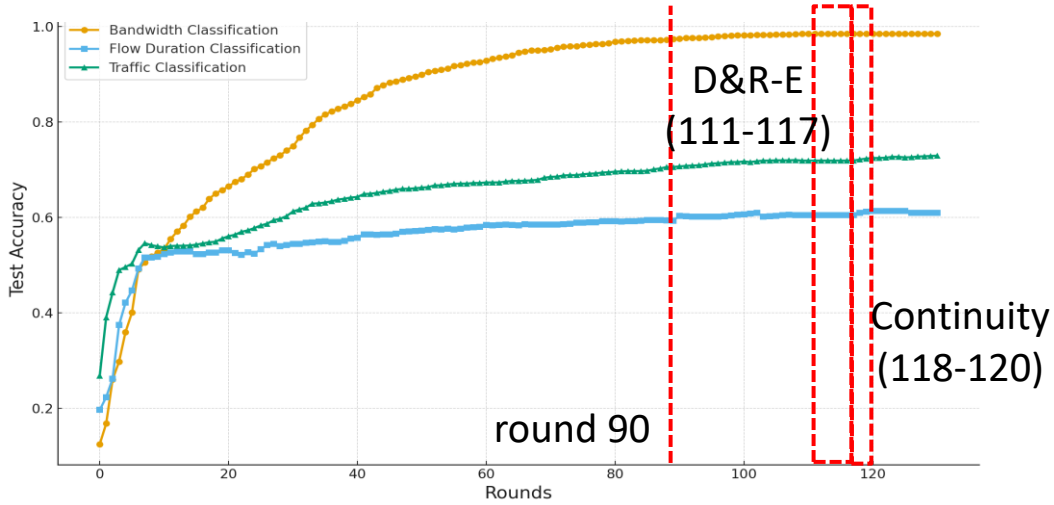
- From previous testing: our design converges at round 90th; assume recovery steps (Detection, Intra-Cluster Recovery, Inter-Cluster Continuity, Re-Stabilization) starts at round 111
  - Detection & Re-Election: 7 rounds (round 111-117)— CH 0 offline; remaining UAVs no federation
  - Continuity (Inter-Cluster Sync): 3 rounds (round 118-120)— UAVs gradually participate in new CH 0 aggregation, round 118- 30% UAV participate, round 119- 70%, round 120- 100%

Cluster 0

Equal Split (each cluster has 2500/3 samples)



Dirichlet Split (2500 samples distributed among clusters)



⇒ **D&R-E:** Cluster 0's use outdated model, leading to flat test accuracy per earlier convergence

Continuity: no noticeable improvement with new CH 0, further training in vain due to convergence

Zoom-In Results for Cluster 0 with CH 0 Compromised

- Assume recovery starts at round 111
  - Detection & Re-Election: 7 rounds (round 111-117)— CH 0 offline; remaining UAVs no federation
  - Continuity (Inter-Cluster Sync): 3 rounds (round 118-120)— UAVs gradually participate in new CH 0 aggregation, round 118- 30% UAV participate, round 119- 70%, round 120- 100%

Cluster 0

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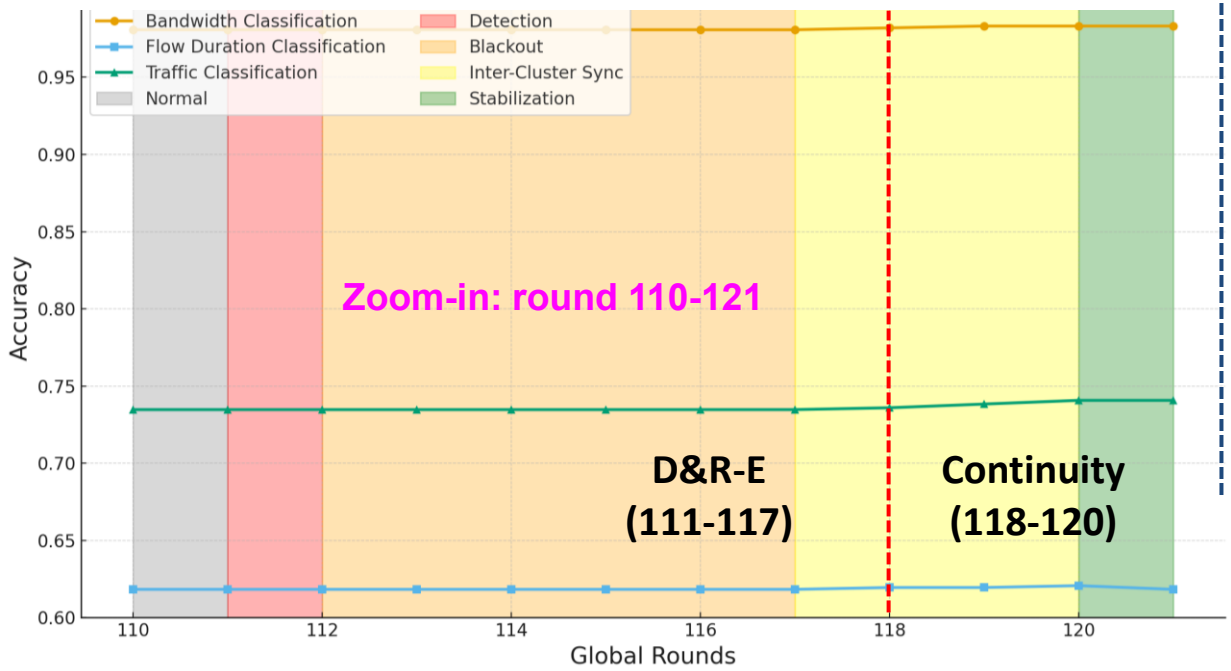
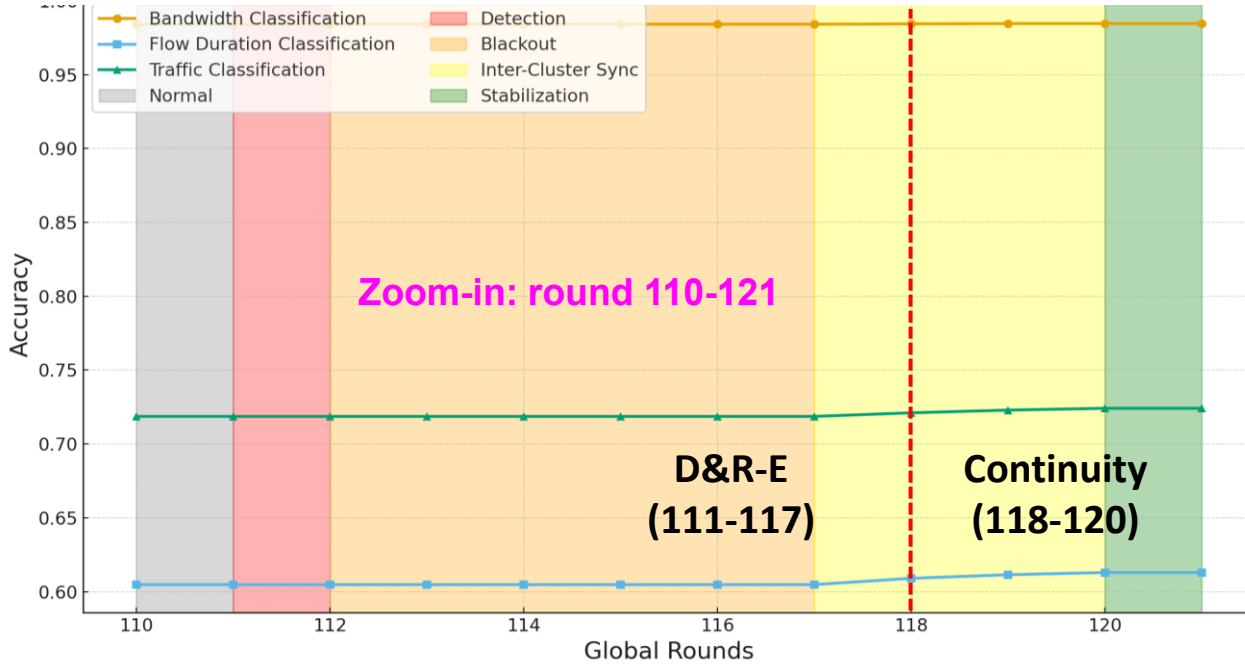


Dirichlet Split (2500 samples distributed among clusters)



⇒ **D&R-E:** Cluster 0's use outdated model, leading to flat test accuracy per earlier convergence

Continuity: no noticeable improvement with new CH 0, further training in vain due to convergence

Convergence Case for Cluster 1 with CH 0-Compromised

- From previous testing: our design converges at round 90th; assume recovery steps (Detection, Intra-Cluster Recovery, Inter-Cluster Continuity, Re-Stabilization) starts at round 111
  - Detection & Re-Election: 7 rounds (round 111-117)— CH 0 offline; remaining UAVs no federation
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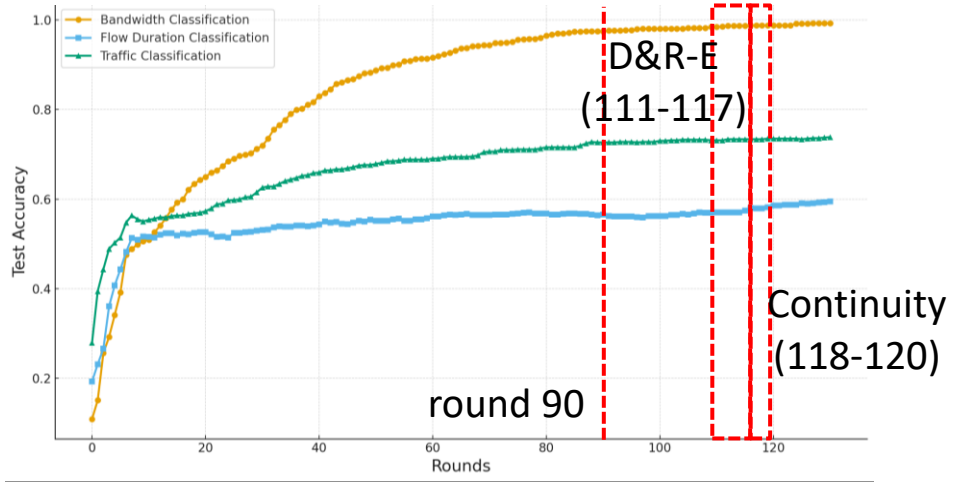
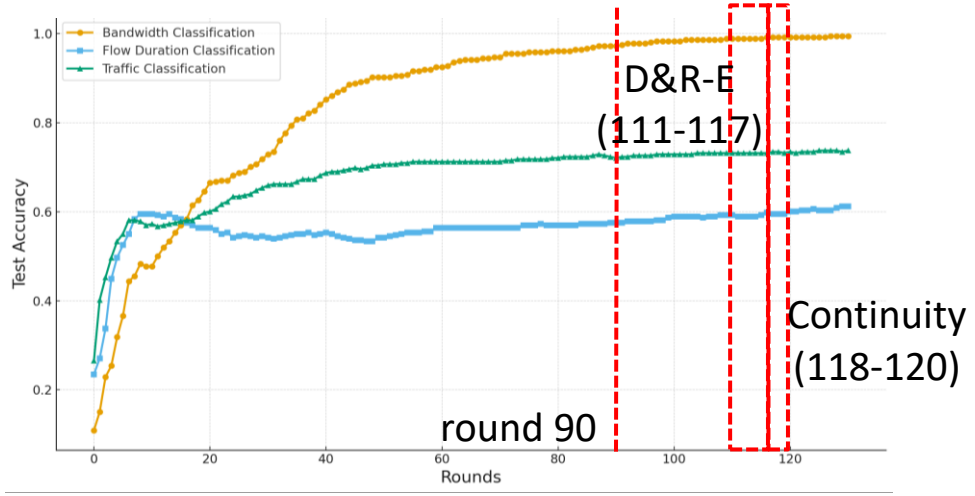
Cluster 1

Equal Split (each cluster has 2500/3 samples)



Dirichlet Split (2500 samples distributed among clusters)



⇒ **D&R-E:** Cluster 1 continues global federation with Cluster 2, flat test accuracy per earlier convergence

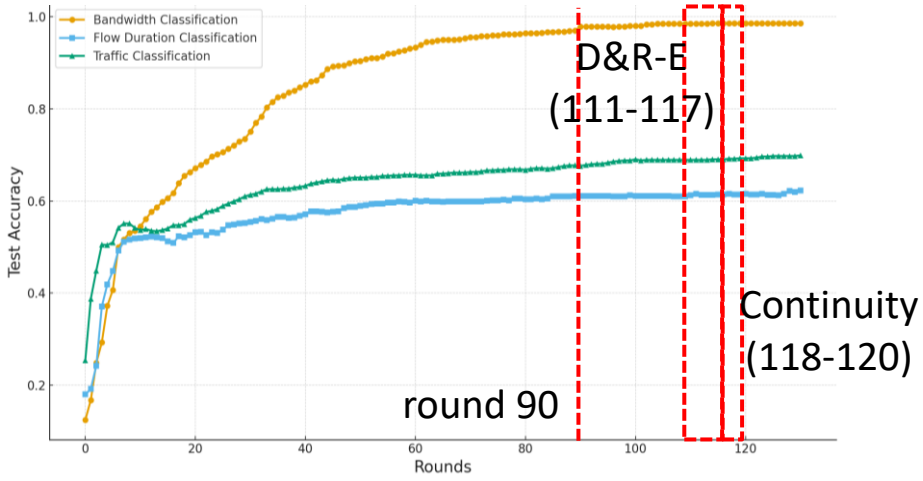
Continuity: new CH 0 doesn't bring noticeable improvement due to earlier convergence

Convergence Case for Cluster 2 with CH 0-Compromised

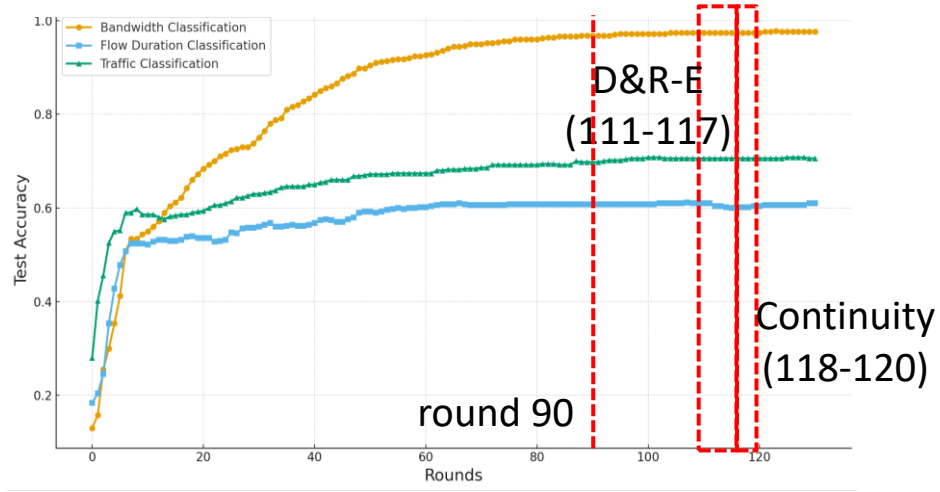
- From previous testing: our design converges at round 90th; assume recovery steps (Detection, Intra-Cluster Recovery, Inter-Cluster Continuity, Re-Stabilization) starts at round 111
  - Detection & Re-Election: 7 rounds (round 111-117)— CH 0 offline; remaining UAVs no federation
  - Continuity (Inter-Cluster Sync): 3 rounds (round 118-120)— UAVs gradually participate in new CH 0 aggregation, round 118- 30% UAV participate, round 119- 70%, round 120- 100%

Cluster 2

Equal Split (each cluster has 2500/3 samples)



Dirichlet Split (2500 samples distributed among clusters)

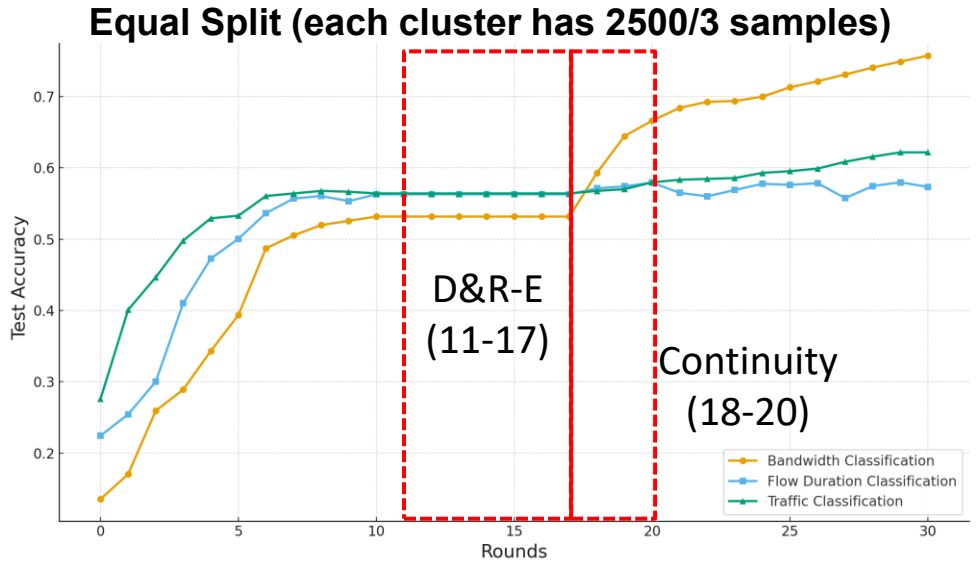


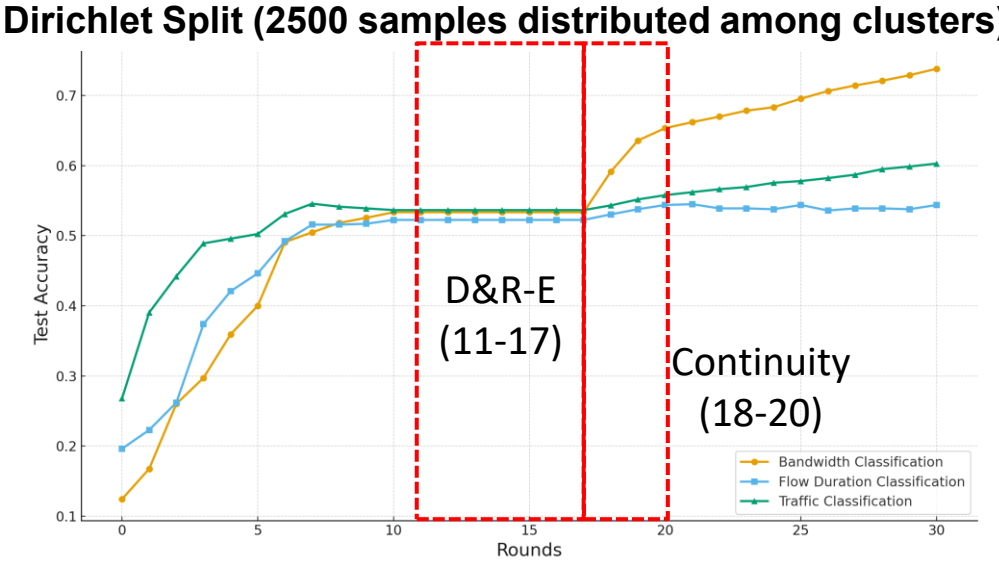
⇒ **D&R-E** and **Continuity:** Cluster 2 acts similar as Cluster 1 to continue global federation with negligible performance improvement due to earlier convergence

Non-Convergence (Transient) when CH Compromised Occurs

- From previous testing: our design converges at round 90th; assume recovery steps (Detection, Intra-Cluster Recovery, Inter-Cluster Continuity, Re-Stabilization) starts at round 11
  - Detection & Re-Election: 7 rounds (round 11-17)— CH 0 offline; remaining UAVs no federation
  - Continuity (Inter-Cluster Sync): 3 rounds (round 18-20)— UAVs gradually participate in new CH 0 aggregation, round 18- 30% UAV participate, round 19- 70%, round 20- 100%

Cluster 0





⇒ **D&R-E:** Cluster 0's use outdated model at round 10 locally, leading to flat test accuracy

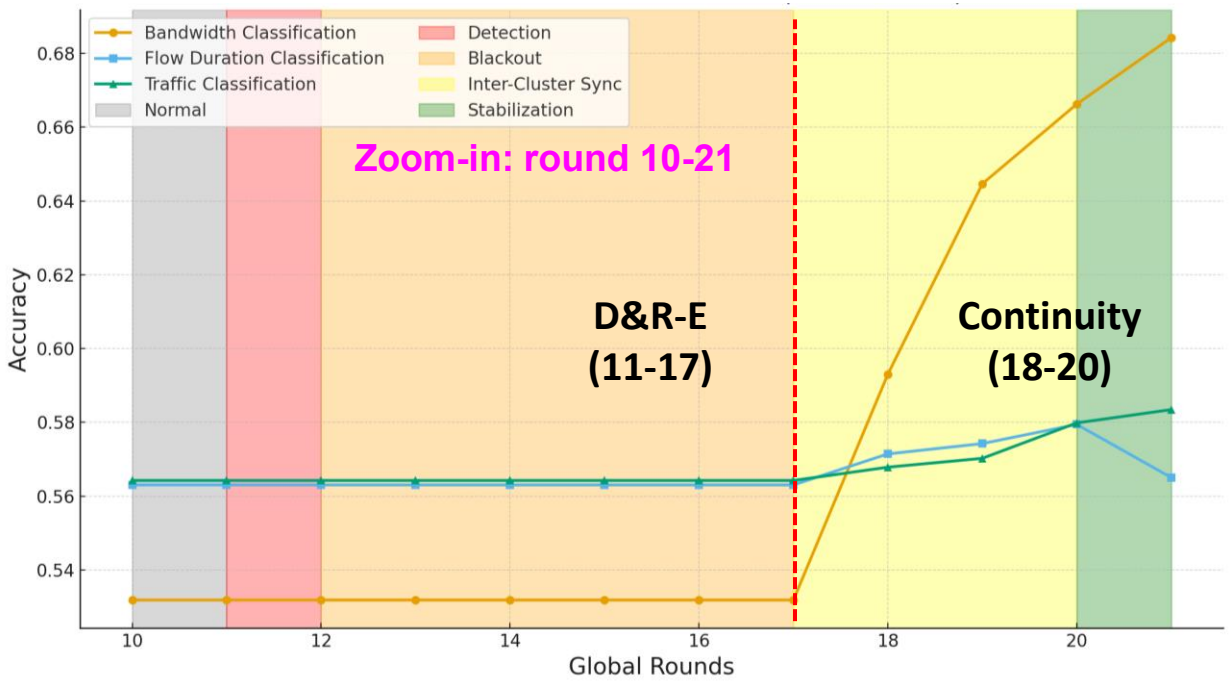
Continuity: better accuracies due to new CH 0 and increasing participations of Cluster 0's UAVs; continue to stabilization with increasing performance up to later convergence round

Zoom-In (Transient) Results for Cluster 0 with CH 0 Compromised

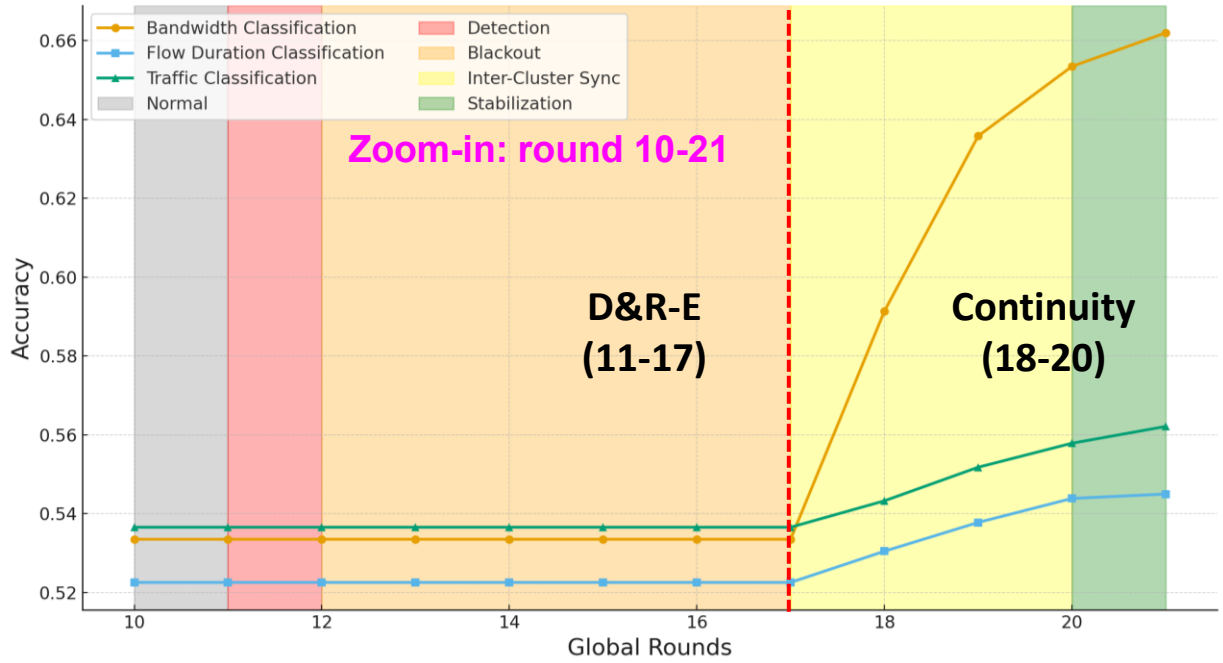
- Assume recovery starts at round 11
  - Detection & Re-Election: 7 rounds (round 11-17)— CH 0 offline; remaining UAVs no federation
  - Continuity (Inter-Cluster Sync): 3 rounds (round 18-20)— UAVs gradually participate in new CH 0 aggregation, round 18- 30% UAV participate, round 19- 70%, round 20- 100%

Cluster 0

Equal Split (each cluster has 2500/3 samples)



Dirichlet Split (2500 samples distributed among clusters)



⇒ **D&R-E:** Cluster 0's use outdated model at round 10, leading to flat test accuracy

Continuity: increasing performance to stabilization and up to later convergence

Non-Convergence (Transient) for Cluster 1 with CH 0-Compromised

- From previous testing: our design converges at round 90th; assume recovery steps (Detection, Intra-Cluster Recovery, Inter-Cluster Continuity, Re-Stabilization) starts at round 11
  - Detection & Re-Election: 7 rounds (round 11-17)— CH 0 offline; remaining UAVs no federation
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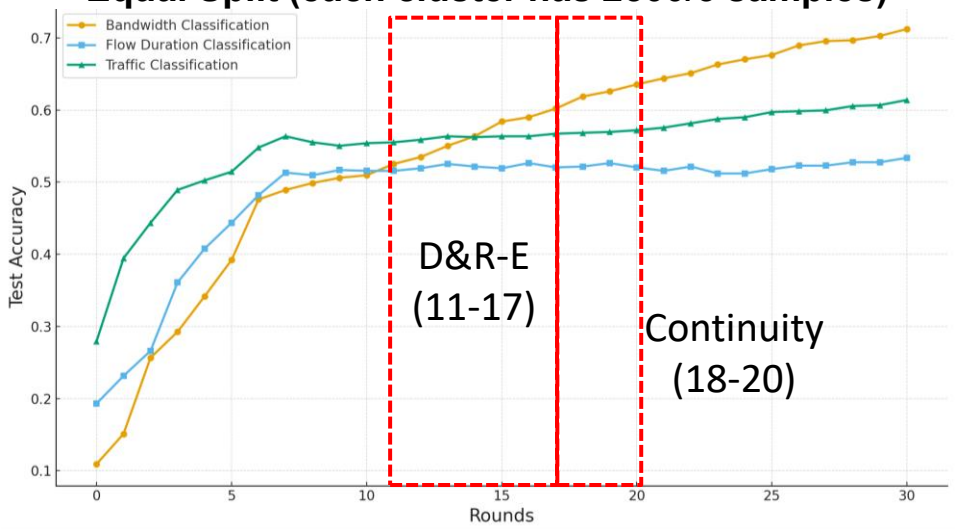
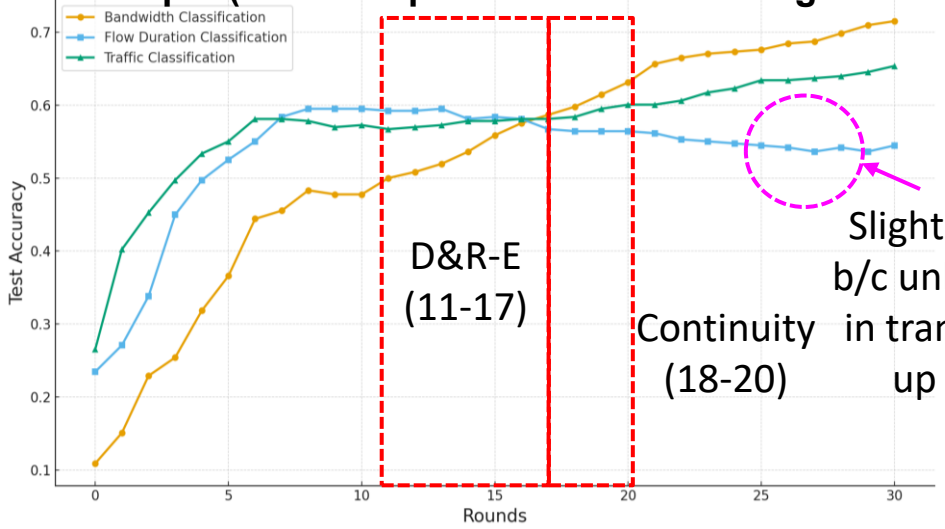
Cluster 1

Equal Split (each cluster has 2500/3 samples)



Dirichlet Split (2500 samples distributed among clusters)



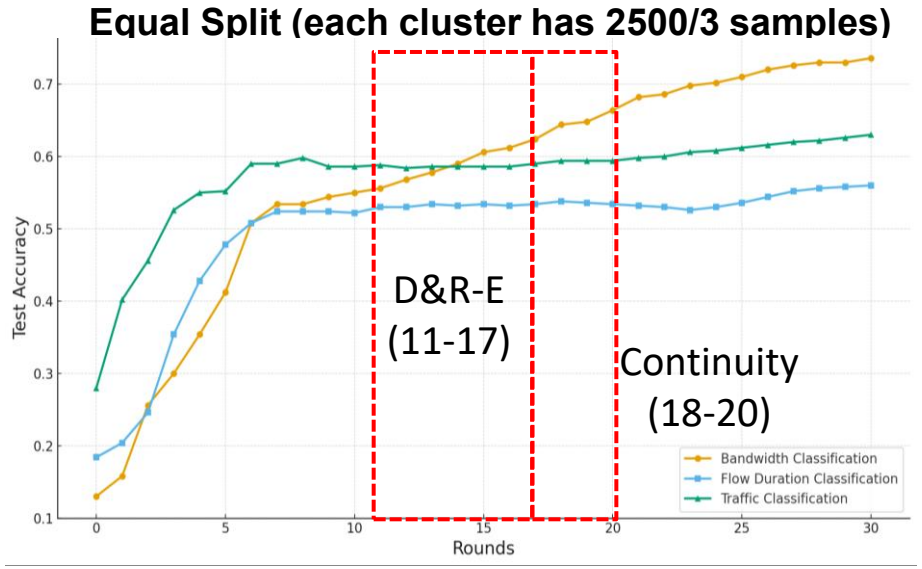
⇒ **D&R-E:** Cluster 1 federates with Cluster 2 for increasing accuracy with updated global model

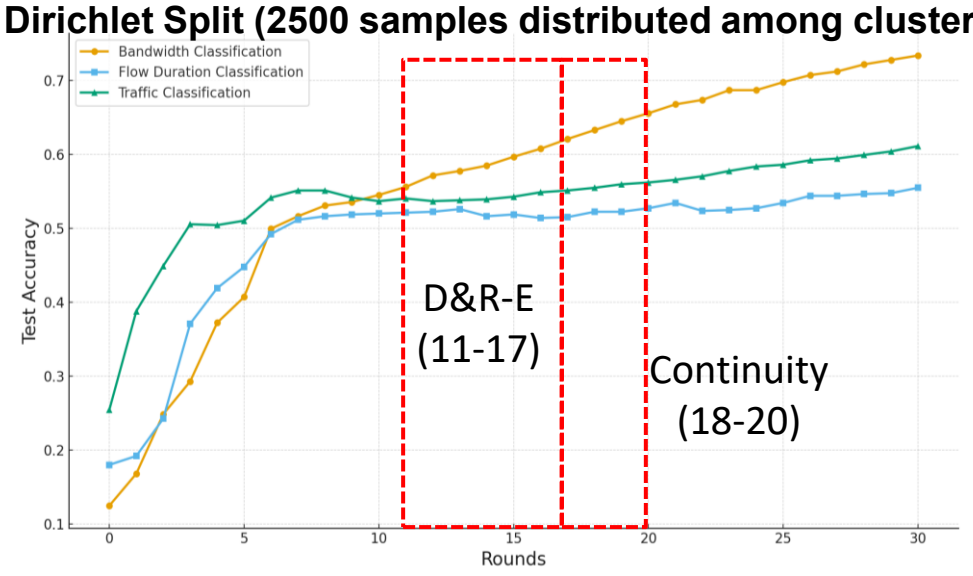
Continuity: new CH 0 participates for better performance improvement up to later convergence

Non-Convergence (Transient) for Cluster 2 with CH 0-Compromised

- From previous testing: our design converges at round 90th; assume recovery steps (Detection, Intra-Cluster Recovery, Inter-Cluster Continuity, Re-Stabilization) starts at round 11
  - Detection & Re-Election: 7 rounds (round 11-17)— CH 0 offline; remaining UAVs no federation
  - Continuity (Inter-Cluster Sync): 3 rounds (round 18-20)— UAVs gradually participate in new CH 0 aggregation, round 18- 30% UAV participate, round 19- 70%, round 20- 100%

Cluster 2





⇒ **D&R-E** and **Continuity:** Cluster 2 acts similar as Cluster 1 for increasing accuracy with updated global model, up to later convergence