Modeling Cascading Failure in IoT-Based Drone Mission System

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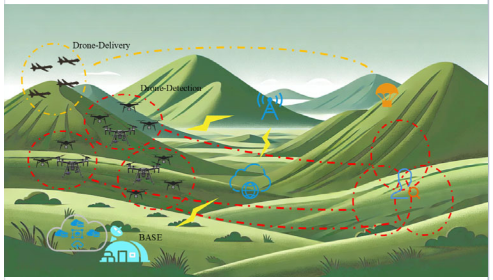
I. Overview

- Drone systems based on the Internet of Things (IoT) have been widely applied in modern applications such as disaster response and recovery, smart city management, and wireless communication relay. However, the growing scale and complexity of IoT-based drone networks increase their vulnerability to cascading failures. This poster presents how the failure of a critical node impacts system-wide performance by modeling failure propagation mechanisms. Based on the identified cascading sequences, a binary decision diagram-based analytical method is developed to assess the mission system reliability (R_{sys}) incorporating the effects of cascading failures (CFs). A detailed case study of a drone-based rescue mission system is performed to demonstrate the proposed CF modeling and evaluation method. The case study also demonstrates how failure propagation extends beyond individual drone malfunctions, causing extensive damage to the entire system. This work emphasizes the need for developing effective strategies to enhance resilience against CFs in IoT-based drone systems.

II. Illustrative Example

- Mission scenario:



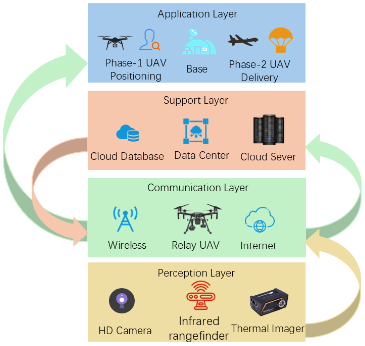
Phase 1: Detection drones $U_{i,j}$ Duration: $T_1 = 30$ minutes

Relay drones R_i $T_2 = 20$ minutes

Phase 2: Delivery drones $U_{D,j}$

where i and j represent the group number and serial number, respectively.

- IoT four-layer architecture:



III. Drone Failure Probability

- Failure probabilities

$$q_{R_i} = \mathrm{P}(GPS \cup Battery) = q_{GPS} + q_{Battery} - q_{GPS} * q_{Battery}$$

$$q_{U_{i,j}} = \mathrm{P}(GPS \cup Battery \cup Rotate) = q_{GPS} + q_{Battery} + q_{Rotate} - q_{GPS} * q_{Battery} - q_{GPS} * q_{Rotate} - q_{Battery} * q_{Rotate} + q_{GPS} * q_{Battery} * q_{Rotate}$$

- Weibull distribution

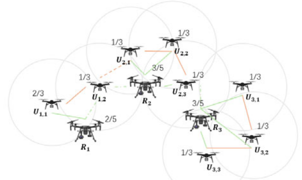
$$q_x = 1 - e^{-(\lambda * t)^{\beta}}$$

- Parameters (λ, β)

Component x	λ_x	β_x
GPS	7.53e-09	1.7187
$Battery$	7.43e-09	1.7046
$Rotate$	7.51e-09	1.6349
$U_{D,1\ or\ 2}$	8.00e-08	2.2
$U_{D,3\ or\ 4}$	7.00e-08	2.0

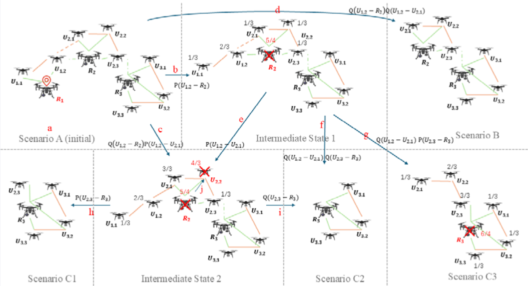
IV. Cascading Failure Mechanism

- Phase 1 of the example drone mission system



- Data load capacity:
  $U_{i,j}$: 3 MB per second
  R_i: 5 MB per second
- Data generation rate:
  $U_{i,j}$: 1 MB per second
  R_i: 0 MB per second

- Scenario transition diagram of cascading failure



a. **Under the initial scenario (Scenario A):**
R_1 experiences GPS failure with a certain probability:
GPS failure did not occur → R_{sys} is evaluated based on Scenario A.
GPS failure occurs → $U_{1,2}$ first attempts to connect to R_2:
Success → b.
Failure → $U_{1,2}$ attempts to connect with $U_{2,1}$:
Success → c.
Failure → d.

b. **$U_{1,2}$ Successfully Connects to R_2 (Intermediate State 1):**
R_2 fails due to data overload. Subsequently, $U_{1,2}$ attempts to connect to $U_{2,1}$:
Success → e.
Failure → $U_{2,3}$ attempts to connect with R_3:
Success → g.
Failure → f.

c. **$U_{1,2}$ fails to connect with R_2, but successfully connects to $U_{2,1}$ (Intermediate State 2):**
R_2 fails first due to data overload, causing the data transmission path to switch to the detection drones in Sw_1 and Sw_2. This subsequently results in the failure of $U_{2,2}$ (j). $U_{2,3}$ attempts to connect to R_3:
Success → h.
Failure → i.

d. **$U_{1,2}$ fails to connect with R_2 and $U_{2,1}$ (Scenario B):**
R_{sys} is evaluated based on Scenario B.

e. **$U_{1,2}$ successfully connects to $U_{2,1}$ (Intermediate State 2):**
$U_{2,2}$ fails due to data overload. $U_{2,3}$ attempts to connect to R_3:
Success → h.
Failure → i.

f. **$U_{2,3}$ fails to connect to R_3 (Scenario C2 from Intermediate State 1)**
R_{sys} is evaluated based on Scenario C2.

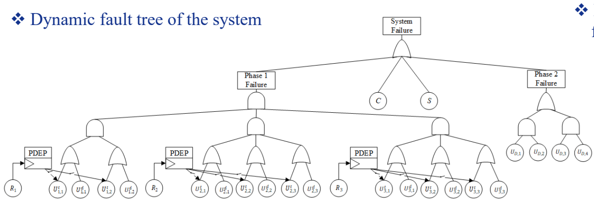
g. **$U_{2,3}$ successfully connects to R_3 (Scenario C3):**
R_3 fails due to data overload. In this case, the entire Phase 1 system loses relay drone support, and signal transmission cannot proceed normally. R_{sys} is evaluated based on Scenario C3.

h. **$U_{2,3}$ successfully connects to R_3 (Scenario C1):**
R_{sys} is evaluated based on Scenario C1.

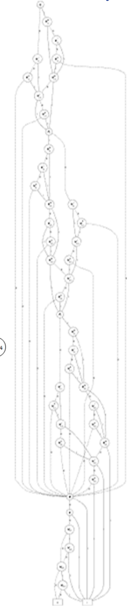
i. **$U_{2,3}$ fails to connect with R_3 (Scenario C2 from Intermediate State 2):**
R_{sys} is evaluated based on Scenario C2.

V. Reliability Modeling and Evaluation

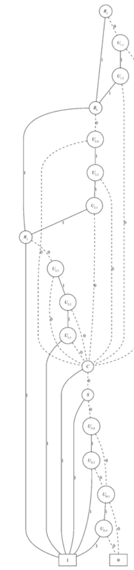
- Dynamic fault tree of the system



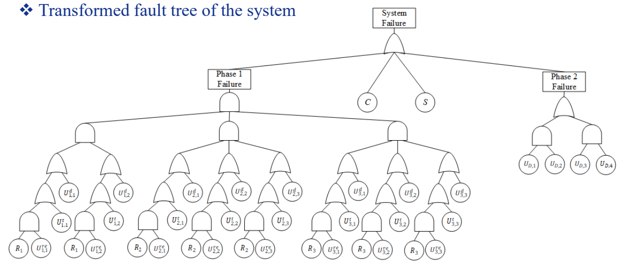
- BDD for transformed fault tree of the system



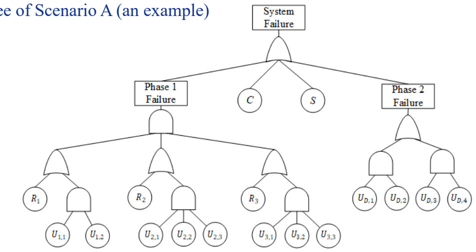
- BDD of Scenario A (an example)



- Transformed fault tree of the system



- Fault tree of Scenario A (an example)



$U_{i,j}^d$, $U_{i,j}^t$: detection, transmission component of drone $U_{i,j}$
$U_{i,j}^{re}$ (or $U_{i,j}$- R_i): reconnection between drones
C: communication layer
S: support layer

- Failure probability of components

Component	q_x
R_i	q_{R_i}
$U_{i,j}^d$	$q_{U_{i,j}}$
$U_{i,j}^t$	0.01
$U_{i,j}^{re}(U_{i,j} - R_i)$	0.05
C	0.01
S	0.01
$U_{D,j}$	$q_{U_{D,j}}$

- Ordering of component variables:

$$R_1 < R_2 < R_3 < U_{1,1} < U_{1,2} < U_{2,1} < U_{2,2} < U_{2,3} < U_{3,1} < U_{3,2} < U_{3,3} < C < S < U_{D,1} < U_{D,2} < U_{D,3} < U_{D,4}$$

- System reliability analysis based on total probability law

$$R_{sys} = \sum_i P(\text{Scenario } k) R(\text{Scenario } k),\ k \in \{A, B, C1, C2, C3\}$$

where $P(\text{Scenario } k)$: occurrence probability of Scenario k
$R(\text{Scenario } k)$: system reliability under Scenario k

- System reliability results

Without CF	With CF
0.960381	0.632907

VI. Conclusion

- Cascading failures can have a substantial impact on the success of a drone mission system.
- Modeling the impact of cascading failures is essential for accurate reliability analysis and robust design of IoT-based drone mission systems.
- It is pivotal to develop effective mitigation strategies to enhance the system's resilience against cascading failures.

Acknowledgement: National Science Foundation Grant No. 2302094.