Multi-agent situation awareness consistency analysis in ATM systems: a compositional hybrid system approach

Maria D. Di Benedetto

University of L'Aquila – Center of Excellence DEWS- L'Aquila (Italy)
mariadomenica.dibenedetto@univaq.it

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Berlin Hilton Hotel, June 13, 2011,

Outline

- **Modeling Multi-Agent ATM Systems: Compositional Hybrid Systems**
  - Model of each agent
  - Model of the interaction among the agents
  - Model of safety critical operations of the agents
- **Multi-Agent Situation Awareness Consistency Analysis**
  - Critical observability and hybrid observers
  - Complexity reduction techniques
- **Analysis of an A3 ConOps scenario**
- **Conclusions**

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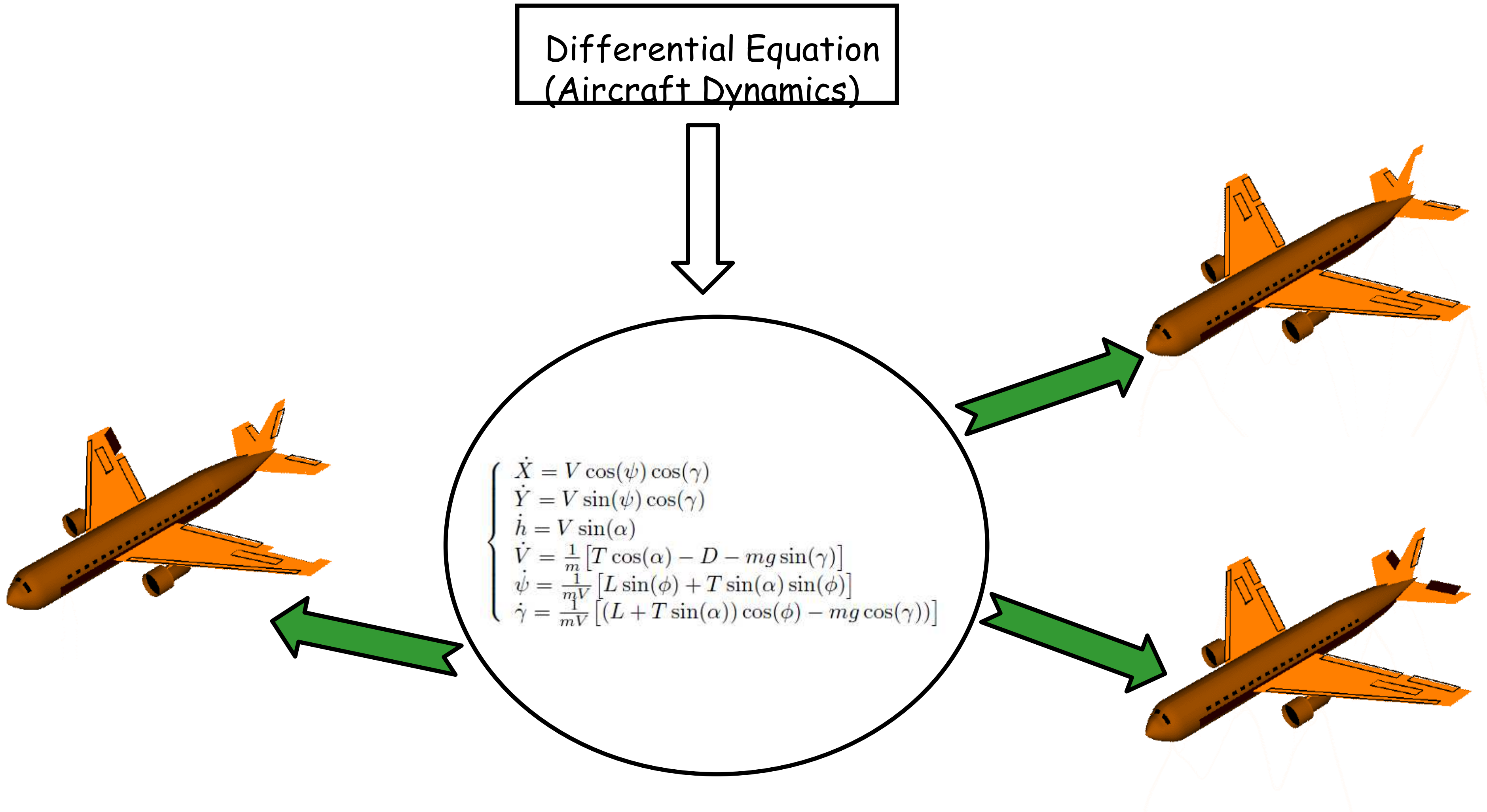
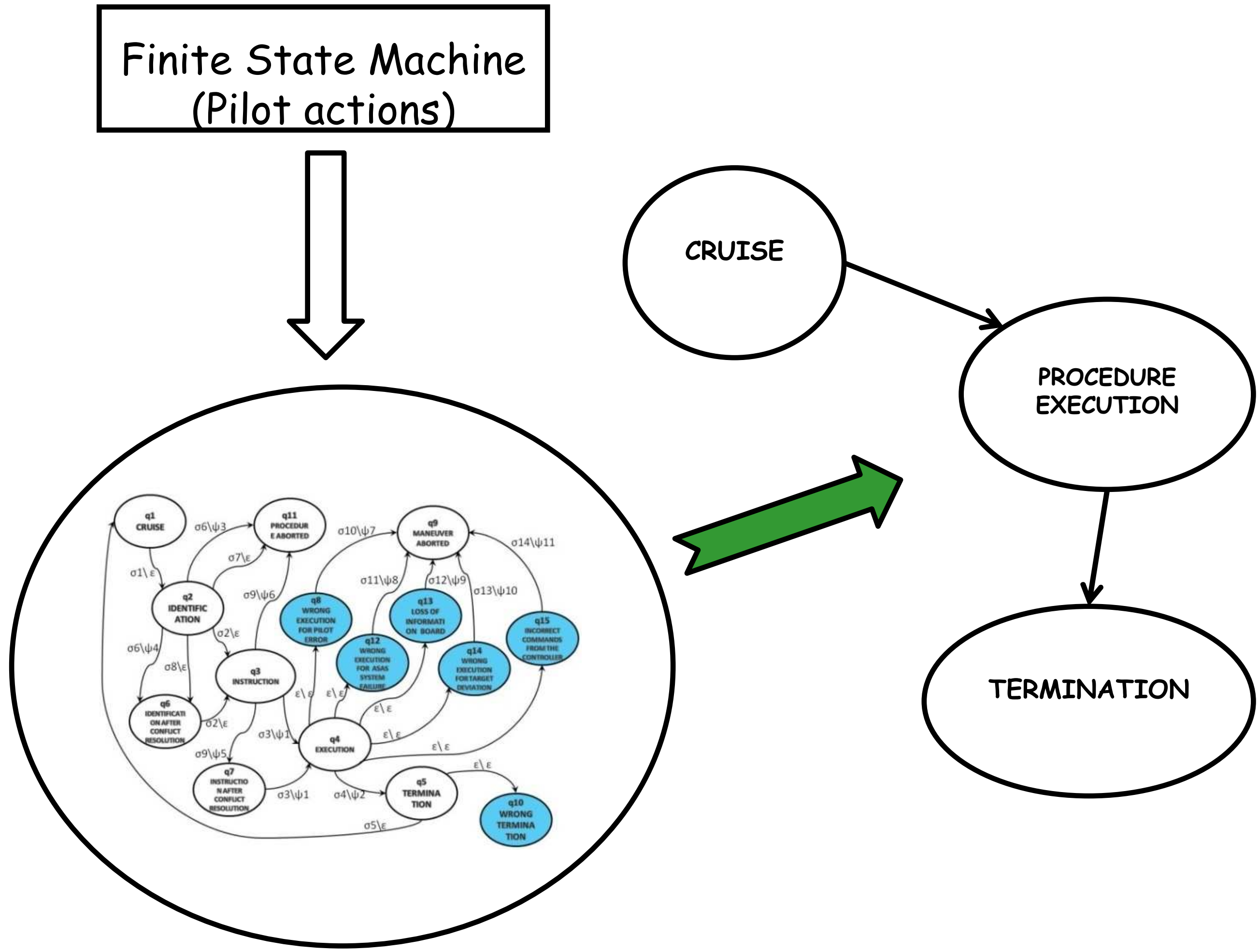
Hybrid Systems (1/3)



$$
\begin{cases}
\dot{X} = V\cos(\psi)\cos(\gamma) \\
\dot{Y} = V\sin(\psi)\cos(\gamma) \\
\dot{h} = V\sin(\alpha) \\
\dot{V} = \frac{1}{m}\left[T\cos(\alpha) - D - mg\sin(\gamma)\right] \\
\dot{\psi} = \frac{1}{mV}\left[L\sin(\phi) + T\sin(\alpha)\sin(\phi)\right] \\
\dot{\gamma} = \frac{1}{mV}\left[(L + T\sin(\alpha))\cos(\phi) - mg\cos(\gamma))\right]
\end{cases}
$$

Hybrid Systems (2/3)



Hybrid Systems (3/3)

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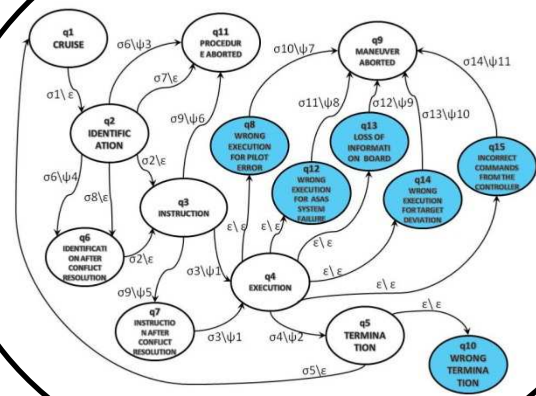
\end{cases}
$$

+



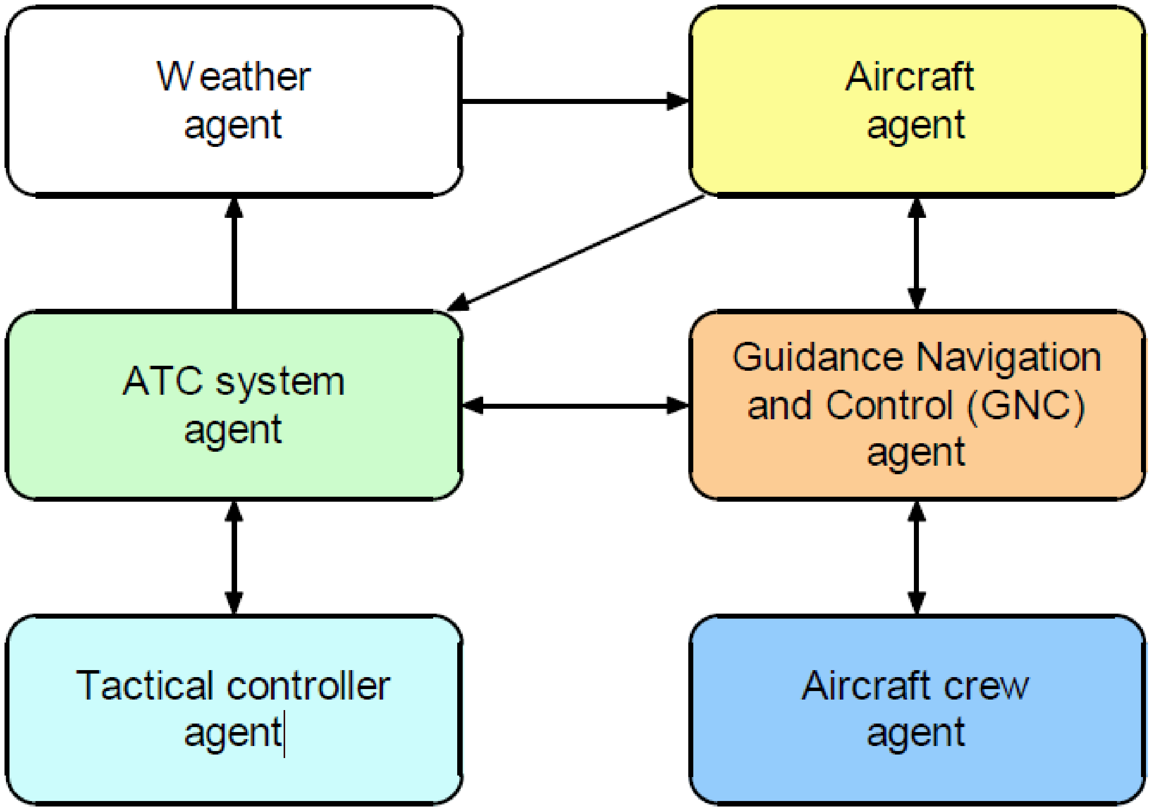
Differential Equation

Finite State Machine

Mathematical model: Continuous + Discrete Variables = Hybrid System

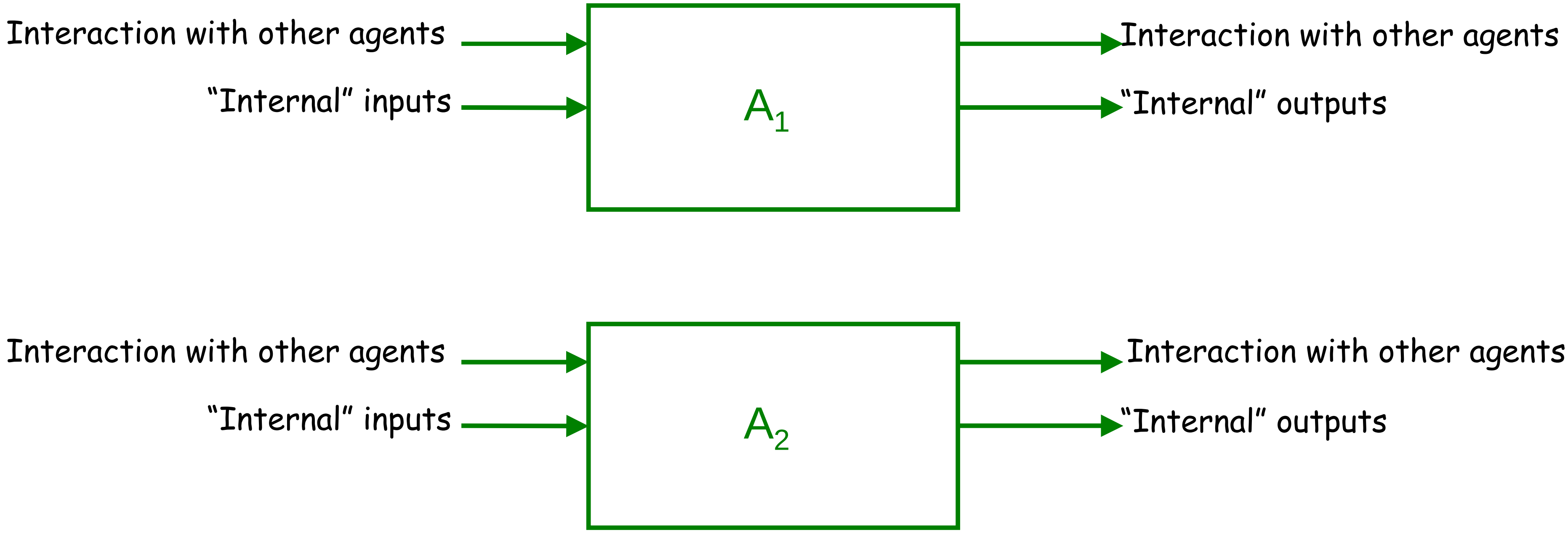
Modeling interaction among agents

Agents interact through exchange of information



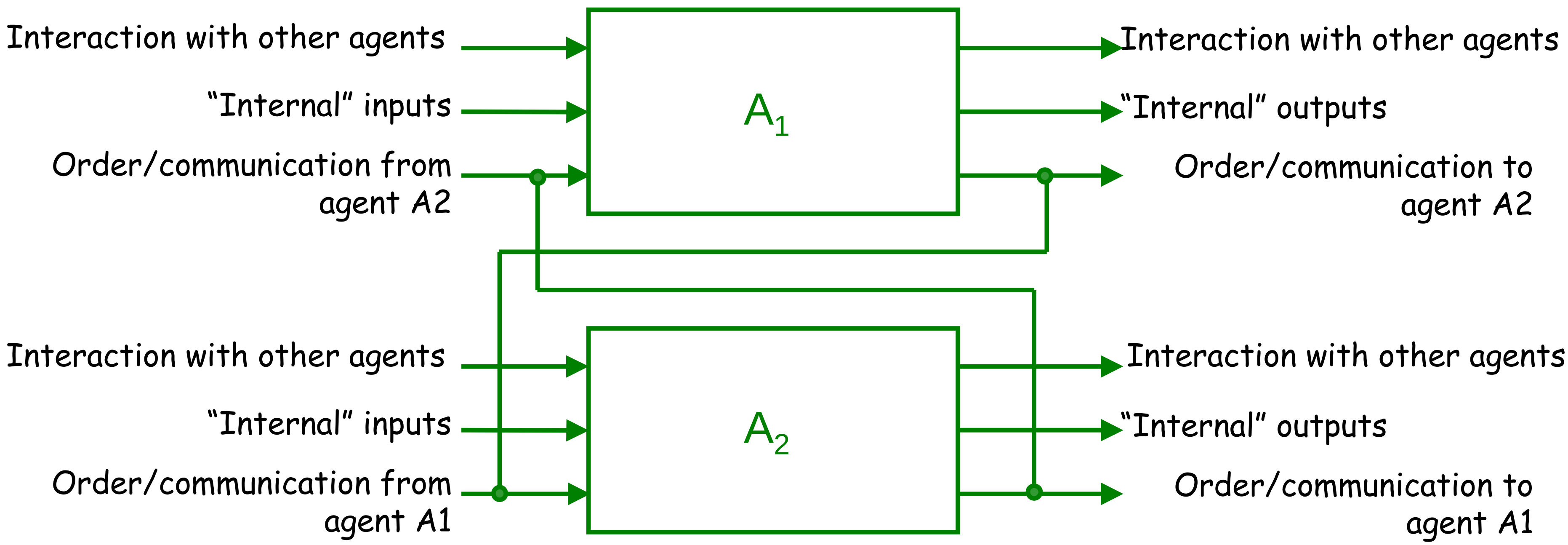
Modeling interaction among agents

Composition of Agents A_1 and A_2



Modeling interaction among agents

Composition of Agents A_1 and A_2



Given N agents A_i, each one modeled by a hybrid system H_i, one can model their interaction as an overall hybrid system H

Modeling safety critical operations (1/3)

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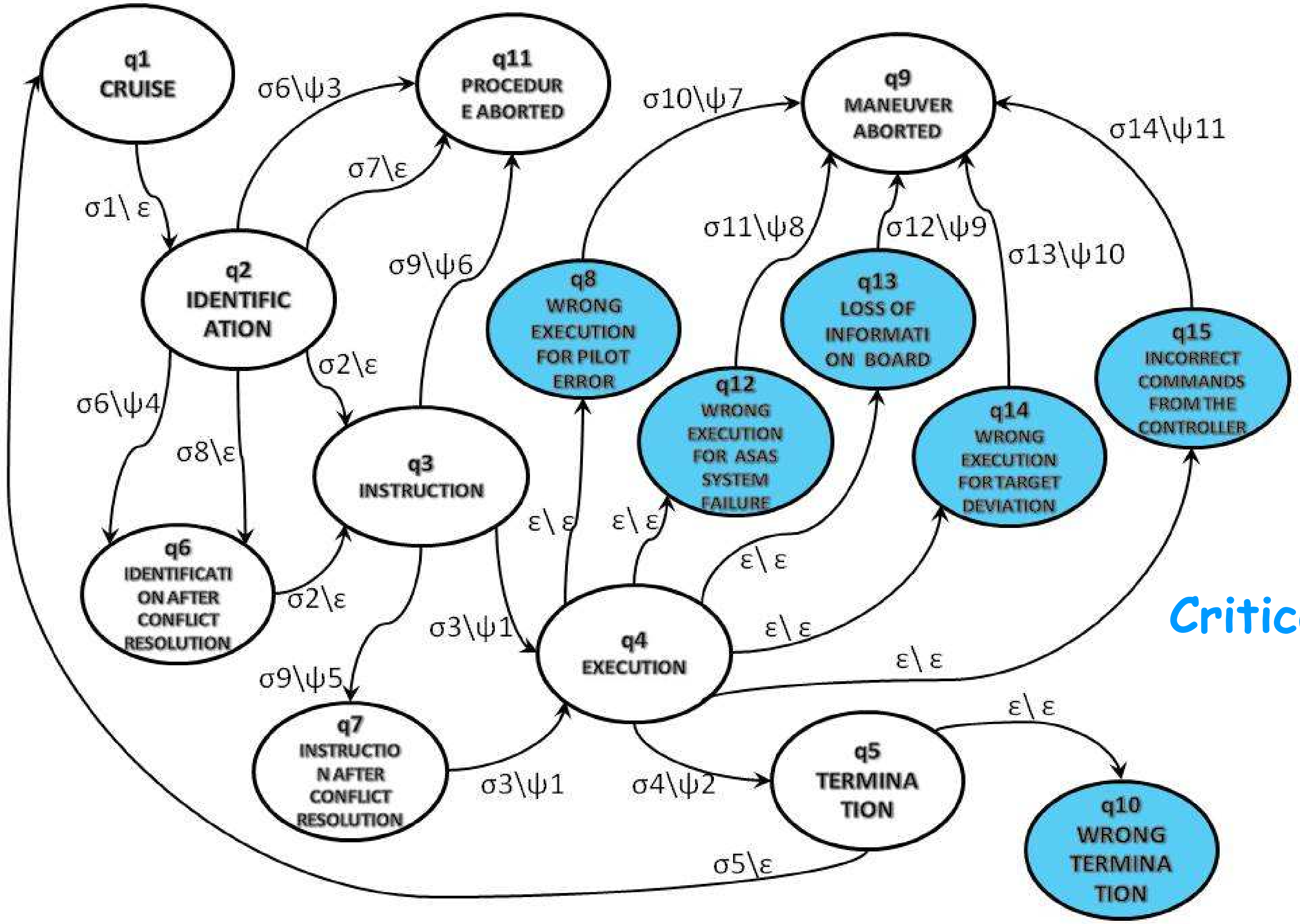

Hybrid model of clearance aircraft in ASAS lateral crossing

Modeling safety critical operations (2/3)

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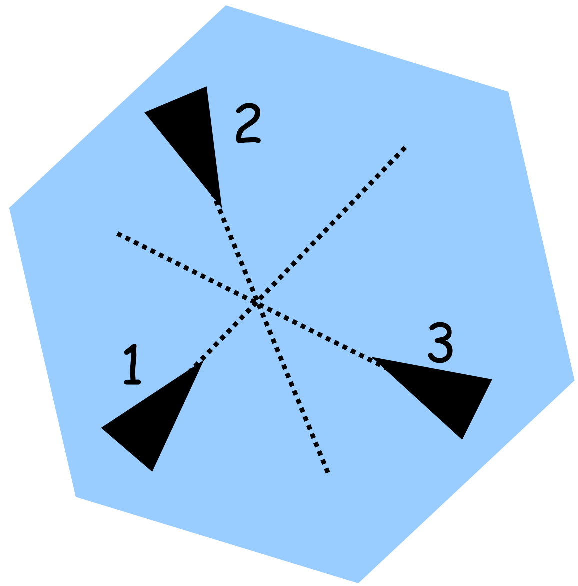
Non-critical states of isolated agents H_1,H_2 can turn into critical states in the composed system $H_1||H_2$; e.g.

1. Two aircraft following a path have no critical states considered individually: in the composition, a critical state arises when paths intersect
2. Two aircraft are following correct steps of an ATM procedure, which are not allowed simultaneously (e.g. manoeuvre initiation)

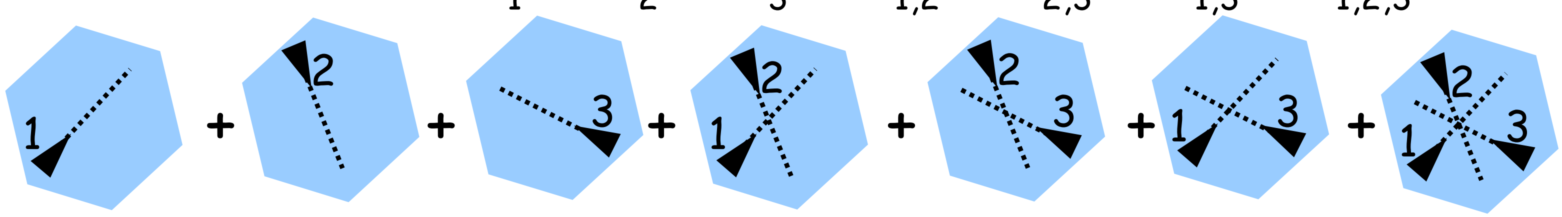
Let $R \subset Q_1 \times Q_2 \times \ldots \times Q_N$ be the critical relation capturing all critical states of the overall system H

Modeling safety critical operations (3/3)

Consider a scenario in which 3 aircraft operate:



Critical Relation: $R = R_1 \cup R_2 \cup R_3 \cup R_{1,2} \cup R_{2,3} \cup R_{1,3} \cup R_{1,2,3}$



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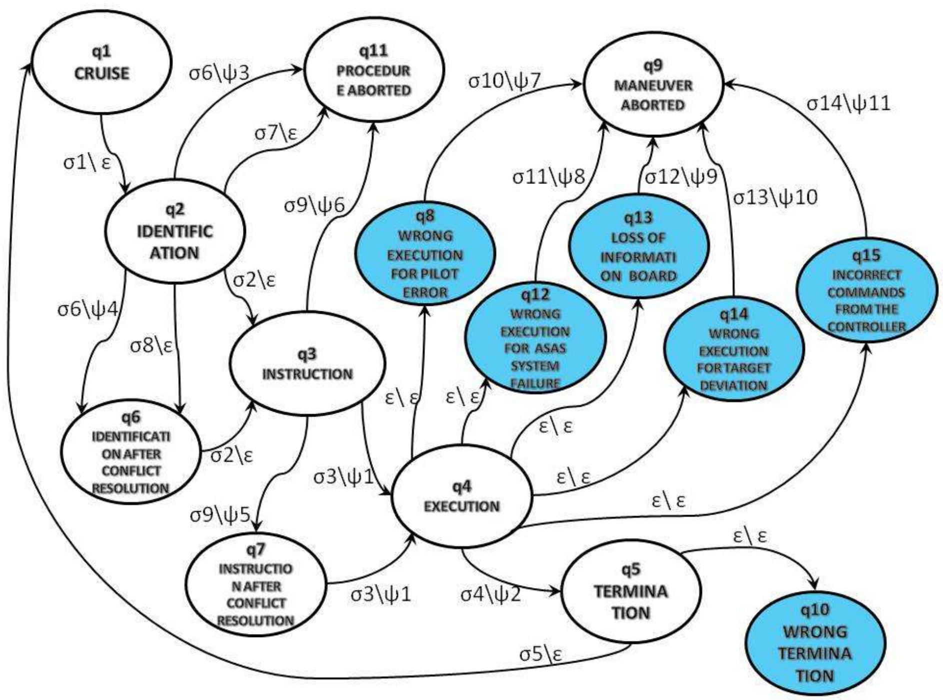
Analysis of safety critical operations

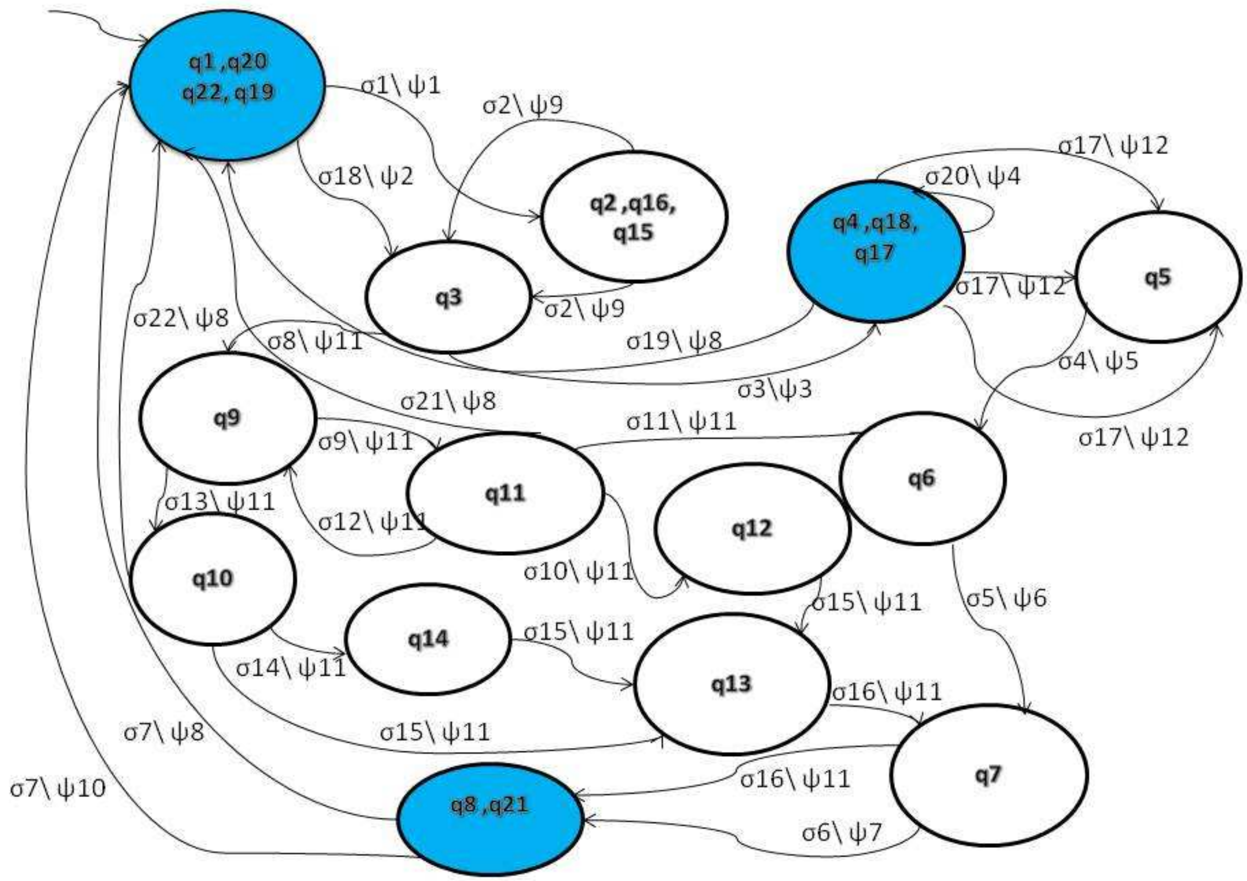
- **Can a safety critical situation arise in the evolution of the multi-agent system?** (Are critical states reachable?)
- **If so, can we detect the occurrence of such situations?**

  (Are critical states observable?)

- ...



Analysis of safety critical operations



Hybrid observer of the clearance aircraft

Analysis of safety critical operations

- Can a safety critical situation arise in the evolution of the multi-agent system? (Are critical states reachable?)
- If so, can we detect occurrence of such situations?

  (Are critical states observable?)

Our approach to such analysis basically consists of:

1. Constructing the mathematical model of each agent H_i
2. Constructing the composition H of the agents H_i
3. Analyzing critical observability of the overall system H

Analysis: the multi-agent case

- Can a safety critical situation arise in the evolution of the multi-agent system? (Are critical states reachable?)
- If so, can we detect occurrence of such situations?

  (Are critical states observable?)

Straightforward implementation of our approach is computationally demanding

Solution through mathematics-based complexity reduction

E. De Santis, M.D. Di Benedetto, A. Petriccone, G.Pola, EUROCONTROL Innovative ATM Research Workshop & Exhibition, December 1-3 2009

A. Petriccone, G. Pola, M.D. Di Benedetto, E. De Santis, 49th IEEE Conference on Decision and Control, Atlanta, USA, December, 2010

G. Pola, E. De Santis, M.D. Di Benedetto, 18th IFAC World Congress, Milan, Italy.

Airborne SEParation In-Trail Procedure

- We considered a scenario in which 4 aircraft operate
- The resulting mathematical model consists of 980 discrete states
- The corresponding hybrid observer would consist of 2^{980} discrete states
- By applying the proposed complexity reduction algorithms we reduced the observer model from 2^{980} to 16416 states

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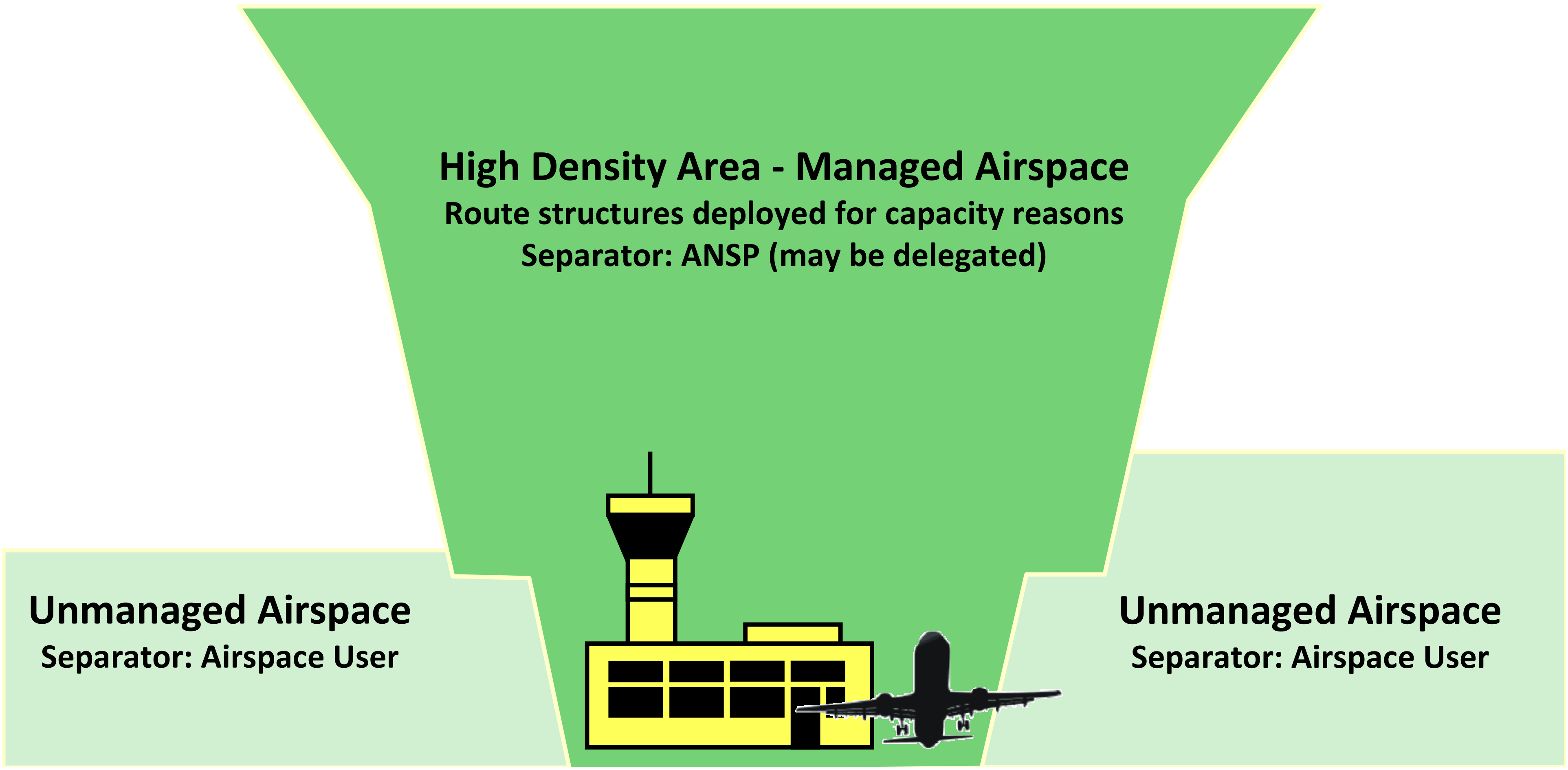
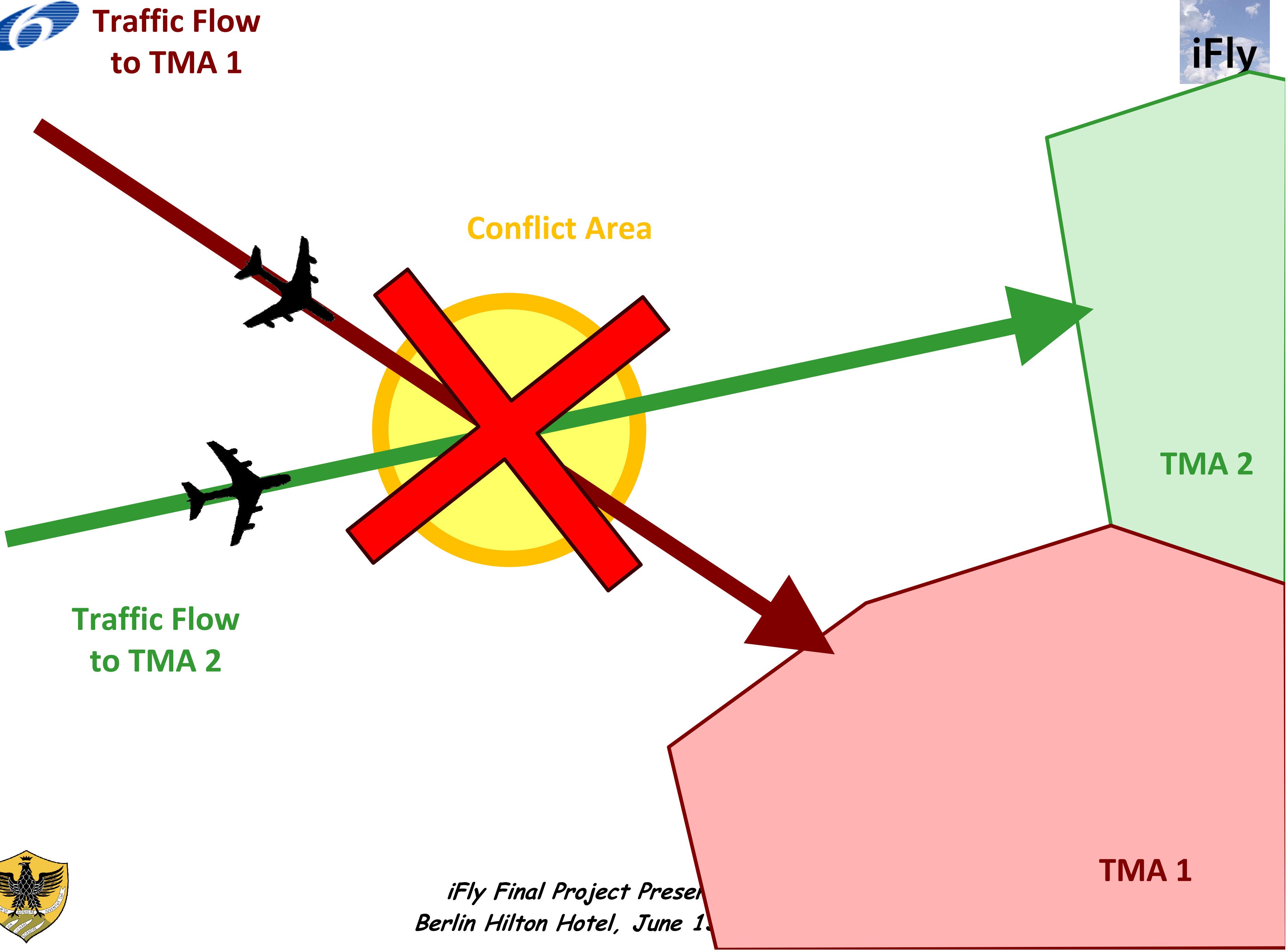
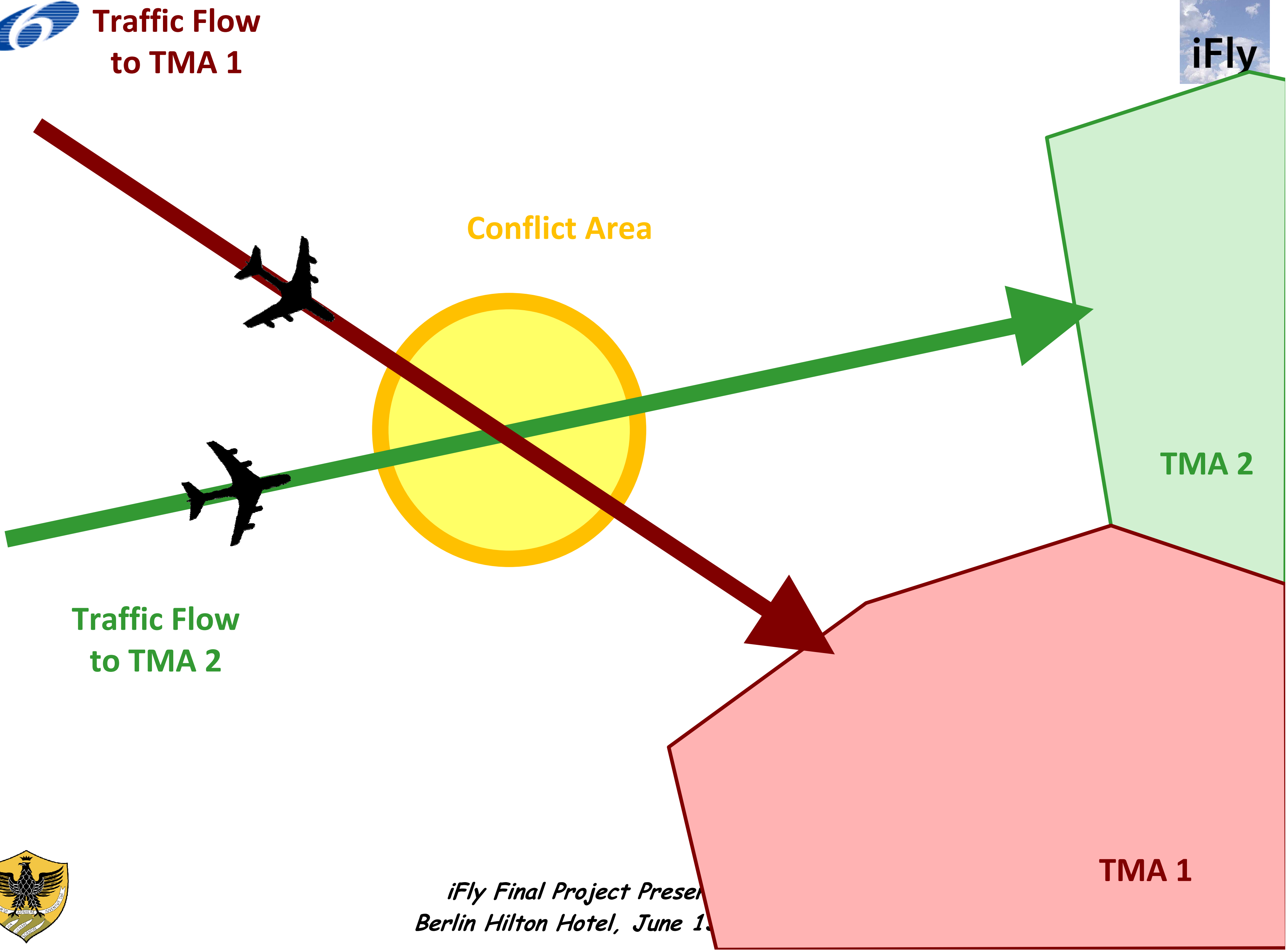
A^3 ConOps

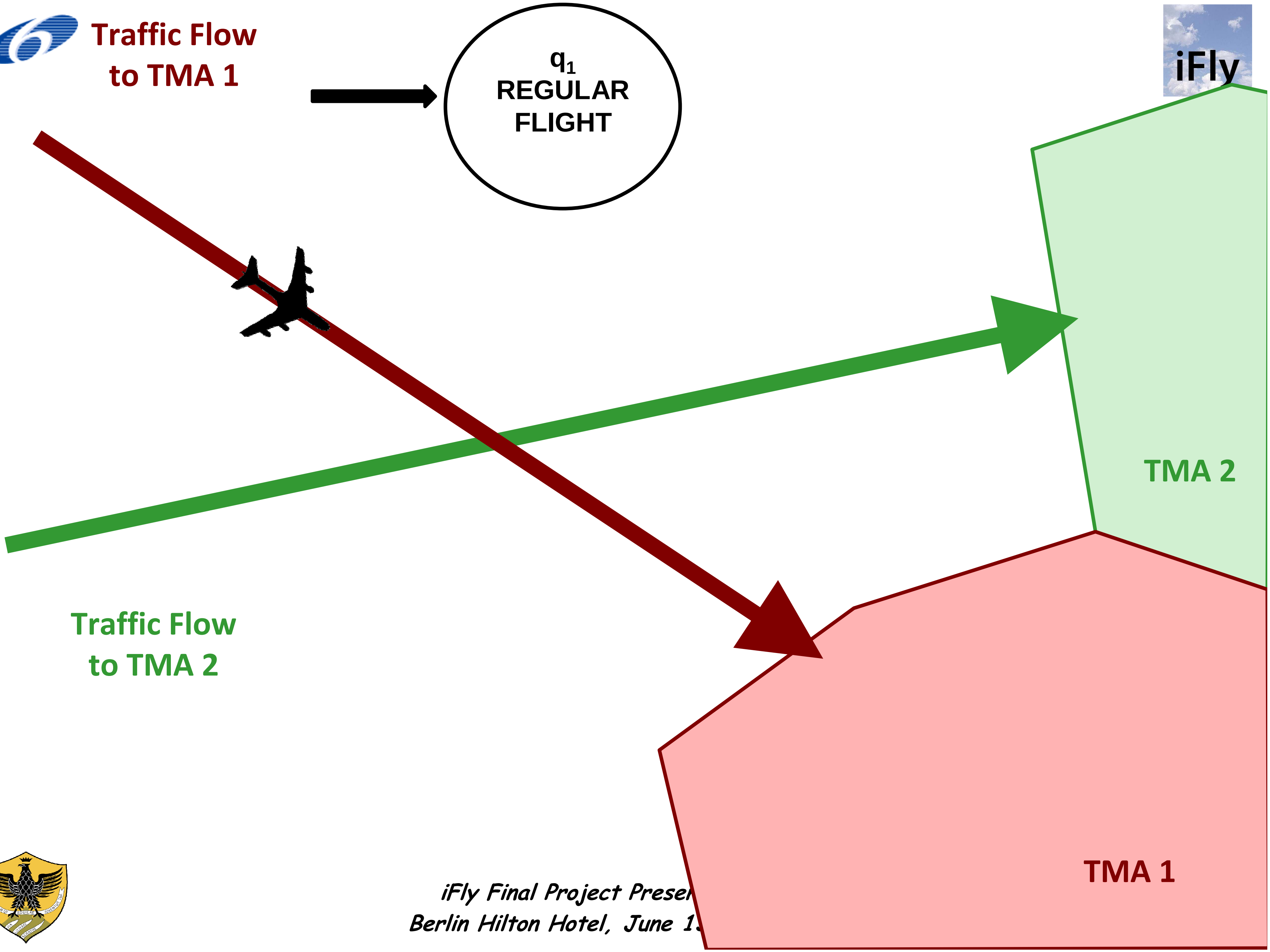

High Density Area - Managed Airspace
Route structures deployed for capacity reasons
Separator: ANSP (may be delegated)
Unmanaged Airspace
Separator: Airspace User
Unmanaged Airspace
Separator: Airspace User

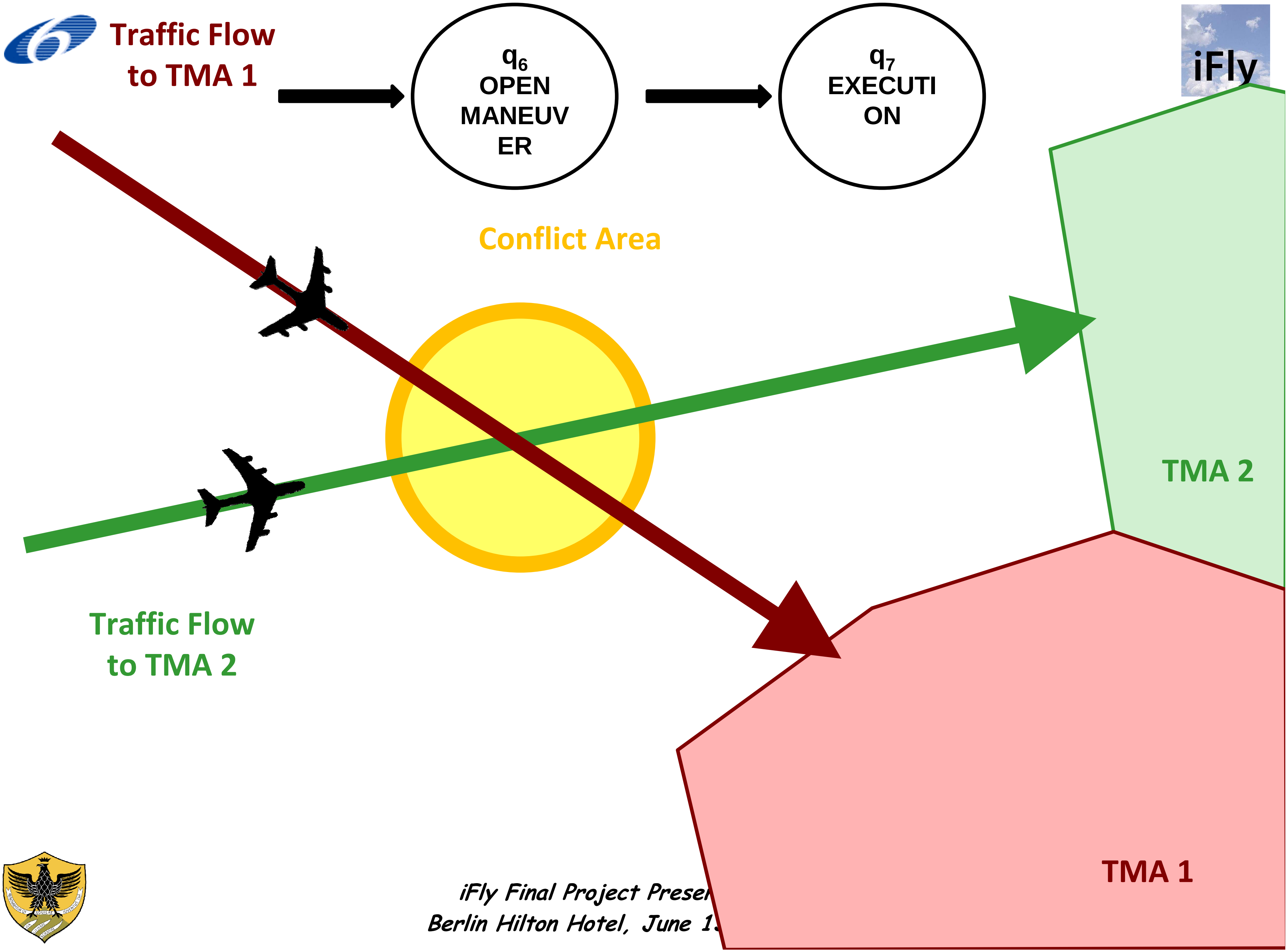

Traffic Flow
to TMA 1
Conflict Area
Traffic Flow
to TMA 2
TMA 2
TMA 1


Traffic Flow
to TMA 1
Conflict Area
Traffic Flow
to TMA 2
TMA 2
TMA 1

A^3 ConOps Scenario – Non-nominal conditions

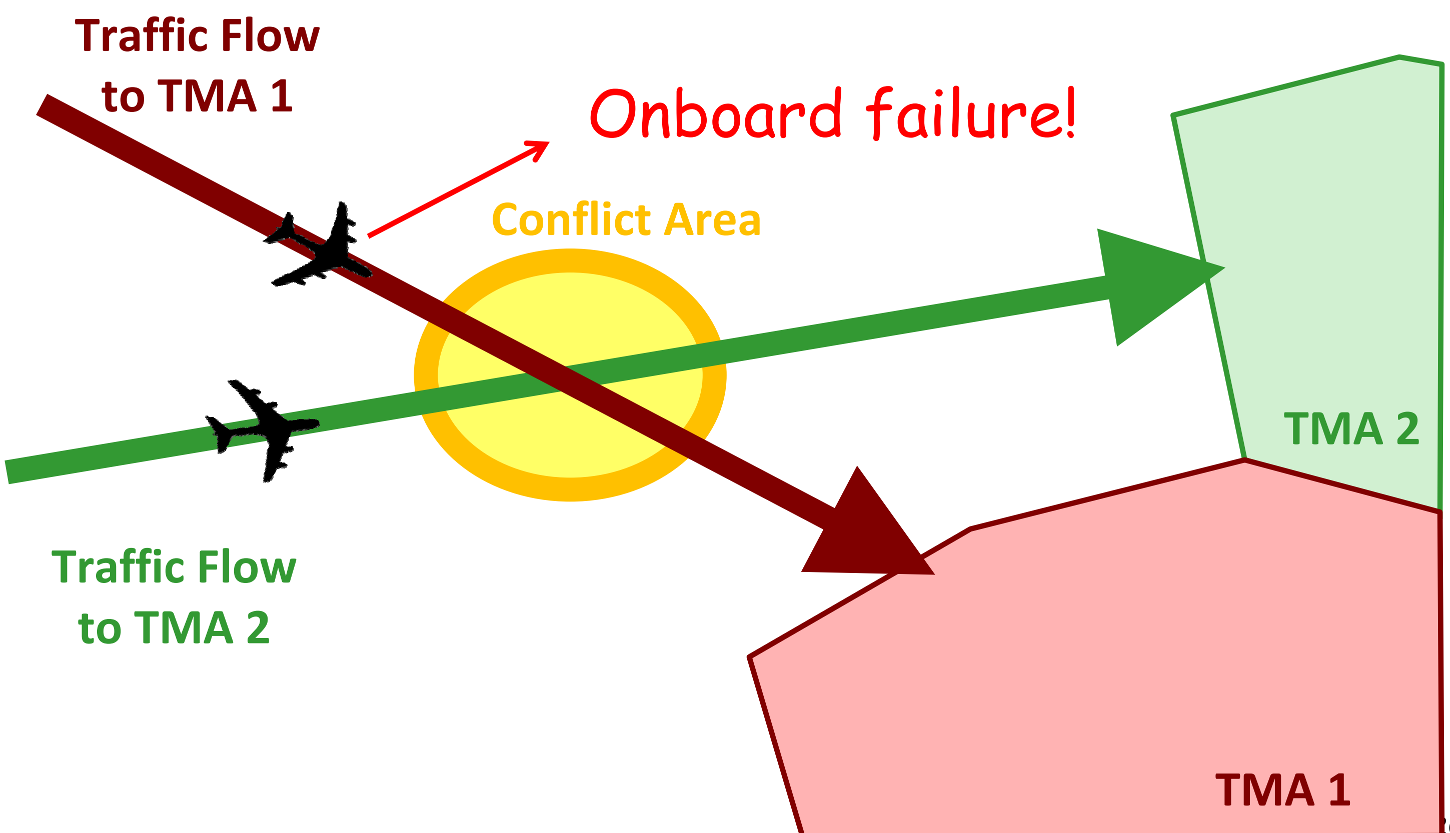
- Ten intent related (non-nominal) conditions, eight of which are caused by situation awareness inconsistencies of the agents involved:
  - C1. Own aircraft intent is not conflict free and nobody is aware.
  - C2. Another aircraft intent is not conflict free and nobody is aware.
  - C3. Another aircraft intent is intentionally not conflict free; others are not aware.
  - C4. Own aircraft intent intentionally is not conflict free; others are not aware.
  - C5. Intent of own aircraft is not broadcasted.
  - C6. Intent of one other aircraft is not received.
  - C7. New intents of multiple aircraft are not received and crew does not know.
  - C8. Own crew has situation awareness difference for another aircraft.
  - C9. Own state/intent is not properly perceived by encountering crew.
  - C10. Intent exchange does not work well and nobody is aware.


Traffic Flow
to TMA 1
q_1
REGULAR
FLIGHT
Traffic Flow
to TMA 2
TMA 2
TMA 1


Traffic Flow
to TMA 1
q6
OPEN
MANEUV
ER
q7
EXECUTI
ON
Conflict Area
Traffic Flow
to TMA 2
TMA 2
TMA 1

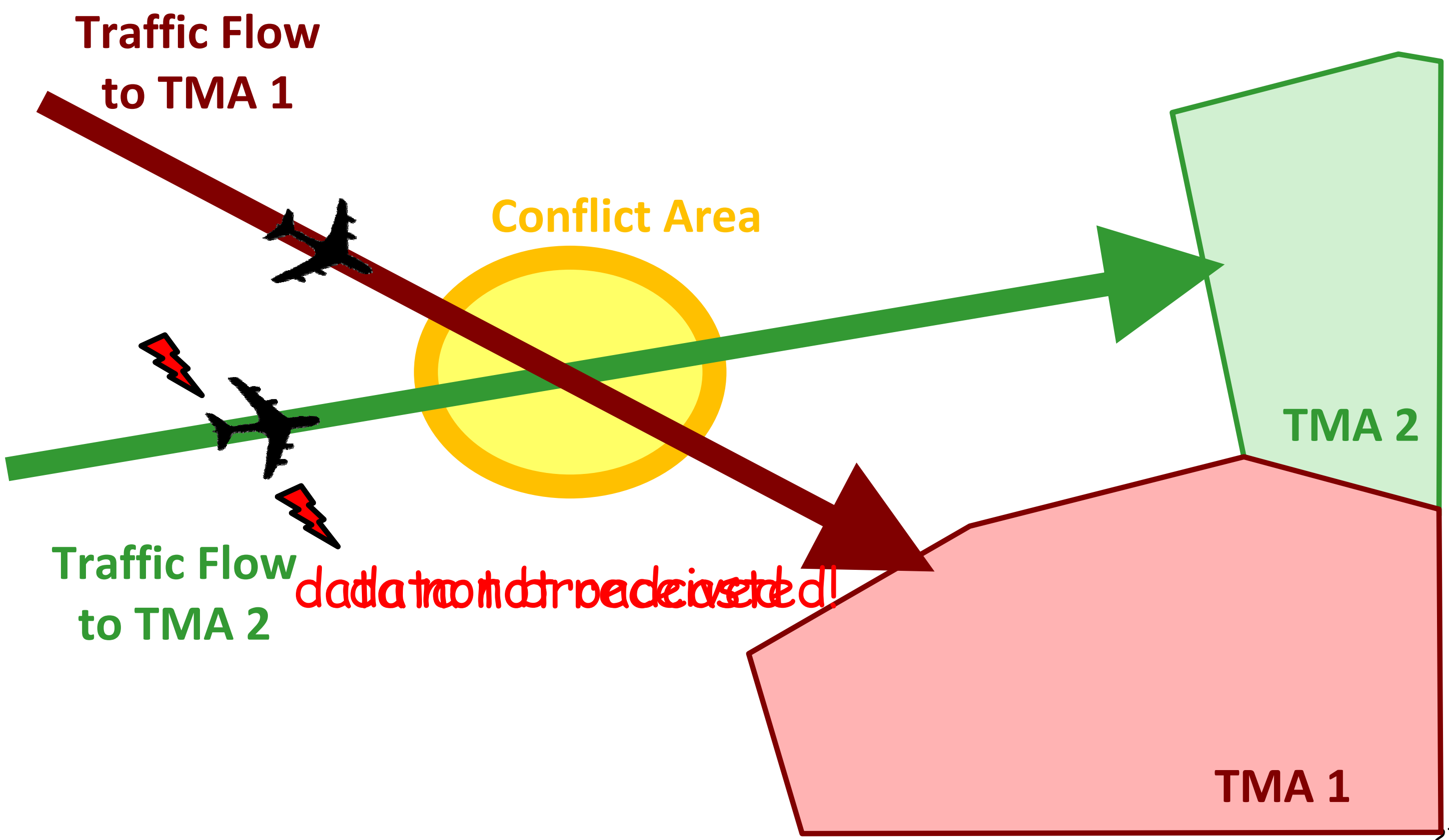
Mathematical Model of the Scenario

- Some discrete states are included in the hybrid mathematical model to represent non-nominal conditions C1-C10:
  - q_{19} represents the situation of no detection of a conflict, due to onboard system failure.



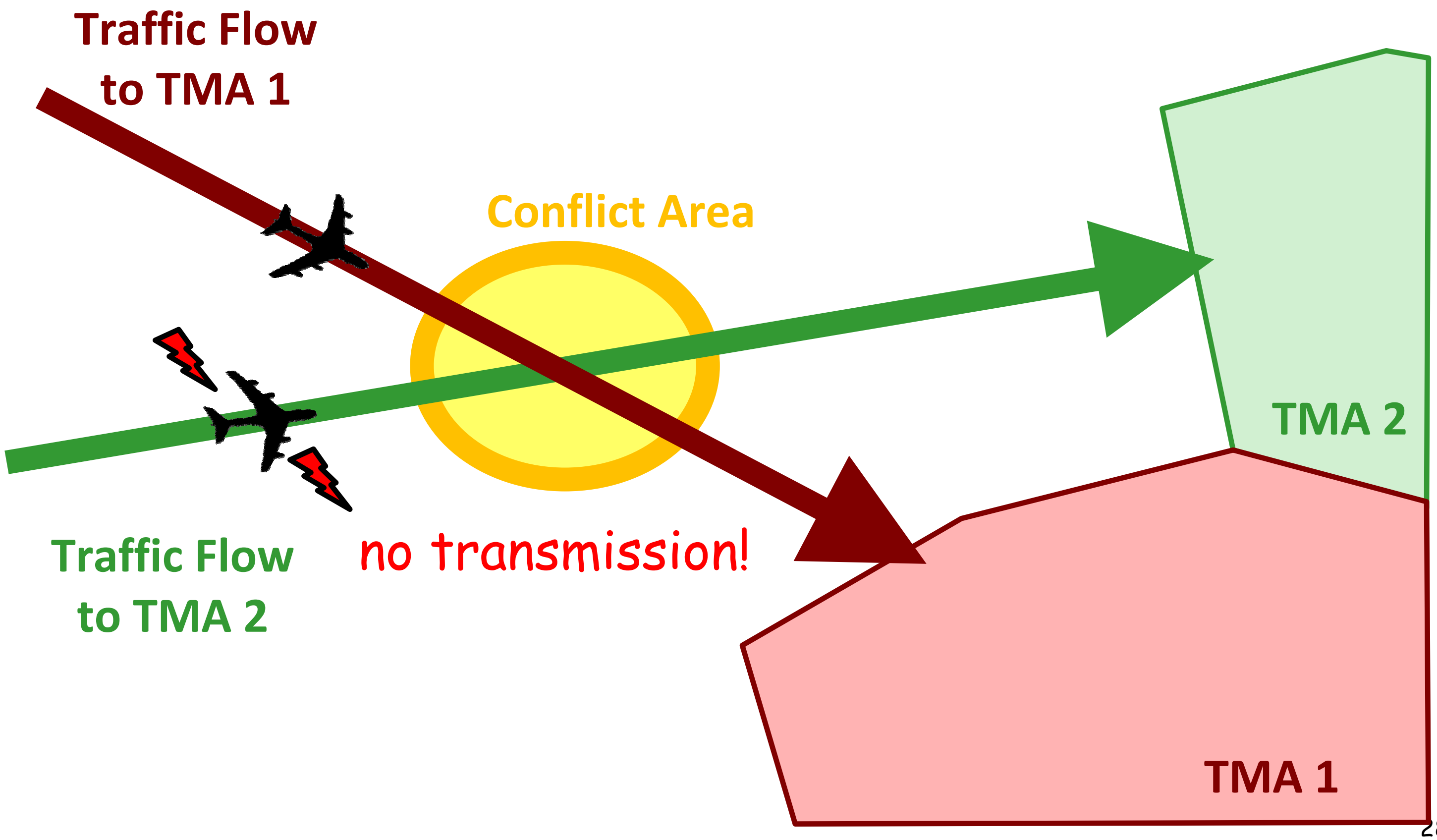
Mathematical Model of the Scenario

- Some discrete states are included in the hybrid mathematical model to represent non-nominal conditions C1-C10:
  - q_{21} represents the situation of data not broadcasted.
  - q_{22} represents the situation of intent not received.



Mathematical Model of the Scenario

- Some discrete states are included in the hybrid mathematical model to represent non-nominal conditions C1-C10:
  - q_{20} represents the situation of no detection of a conflict, due to lack of transmission.



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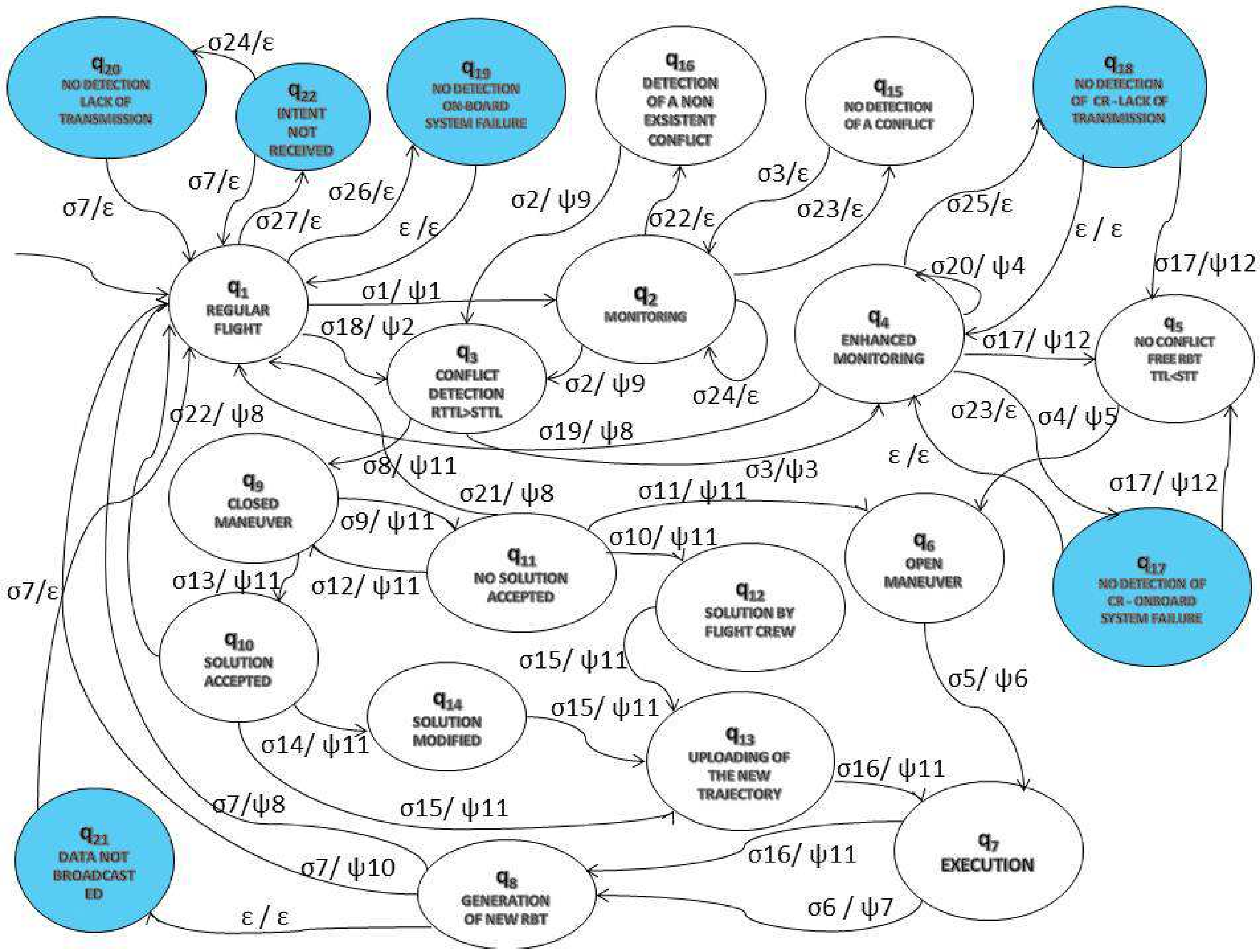

Safety Criticality Analysis and Mitigation Means

- Mitigation means of potential unsafe events due to non-detectable critical states
  - Three critical states (q20, q18, q22) are related to the absence of transmission. This type of failure is detectable for onboard system.
  - Two critical states (q17, q19) are related to the failure of onboard (ASAS) equipment. The main mitigation mean for this type of failure are built–in test functions which inform flight crew about a failure of the system.
  - Two critical states (q15, q16) are related to the general failure of CD function. The main mitigation of the impact for this type of problems is the short-term CR with implicit coordination ensuring that the other conflicting aircraft will solve potential conflict even without the manoeuvering of own aircraft.
  - One critical state q21 is not affecting own onboard functions. Hence, this failure is difficult to detect onboard own aircraft. Mitigation requires coordination between crews, possibly with support of the Airline Operational Centres.

Conclusions (1/2)

- A3ConOps defines a complex socio-technical system where Situation Awareness is shared among many (humans and technical) agents
- Significant potential for multi-agent SA confusion sneaking into the A3 socio-technical system
- Analysis of A3ConOps on safety critical conditions, including those of multi-agent SA confusion (recently developed powerful theory and tools from hybrid systems safety verification)

Conclusions (2/2)

- Four types of potential non-nominal conditions are safety critical.
- Mitigating measures have been developed for three types of these conditions, which can be applied on-board aircraft.
- For one type of safety critical condition, mitigation asks for coordination between crews, possibly with support of the Airline Operational Centres. Appropriate protocol remains to be developed.

Follow-up research

- Our approach is general enough to be applied to other advanced ATM ConOps developments
- MAREA project: application of this approach to SESAR2020 in the TMA
- Ongoing research on hybrid systems safety verification
  - Compositional bisimulation
  - Complexity reduction

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ank you!

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