Realizing Internet above the Cloud: An Enabling Air-to-Air Transmission Technique

Jiankang Zhang and Sheng Chen

Southampton Wireless Group

School of Electronics and Computer Science

University of Southampton

Southampton SO17 1BJ, UK

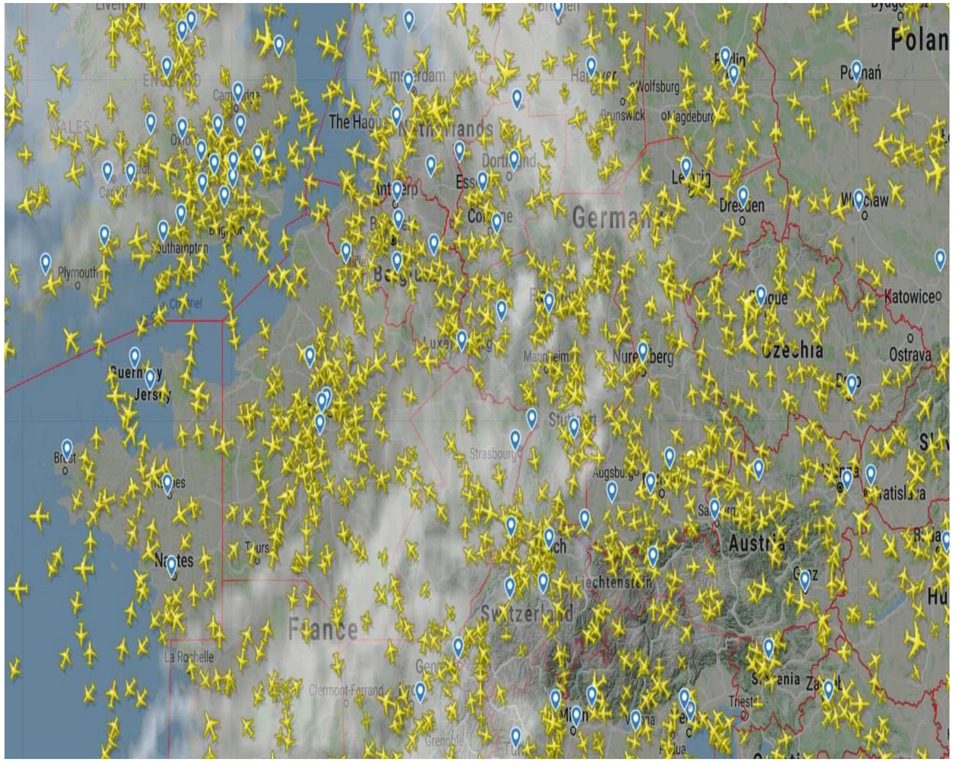
E-mail: sqc@ecs.soton.ac.uk

Dreams

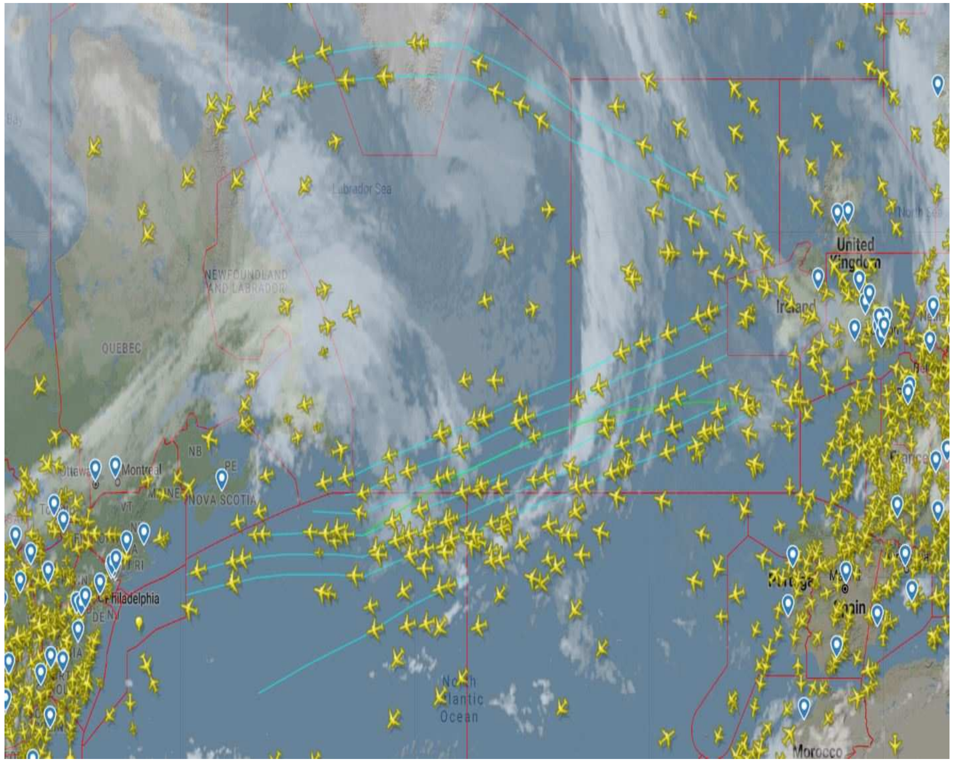
- We are **almost** instantaneously connected **anywhere anytime**
  - With coming 5G, our world is supposed to be 'completely' interconnected
- There is **black hole** in our interconnected world – when we travel by aeroplane
  - Step on jumbo jet, we disappear into this **black hole**
- Existing **satellite-based** and **ground-to-air**/air-to-ground techniques are very **expensive** and **incapable** of supporting Internet above the Cloud
  - Even future L-band digital aeronautical communications system L-DACS1 only offers 273 kbps net user rate for direct aircraft-to-aircraft communication
  - Impossible to build ground stations to cover whole continent or over ocean
- But we have been dreaming to realize **Internet above the Cloud**
  - How can we 'move' 5G on to the sky to complete interconnected world?

Our Sky

- 'Normal' snapshots of (a) **European airspace**, and (b) **North Atlantic airspace**



(a)



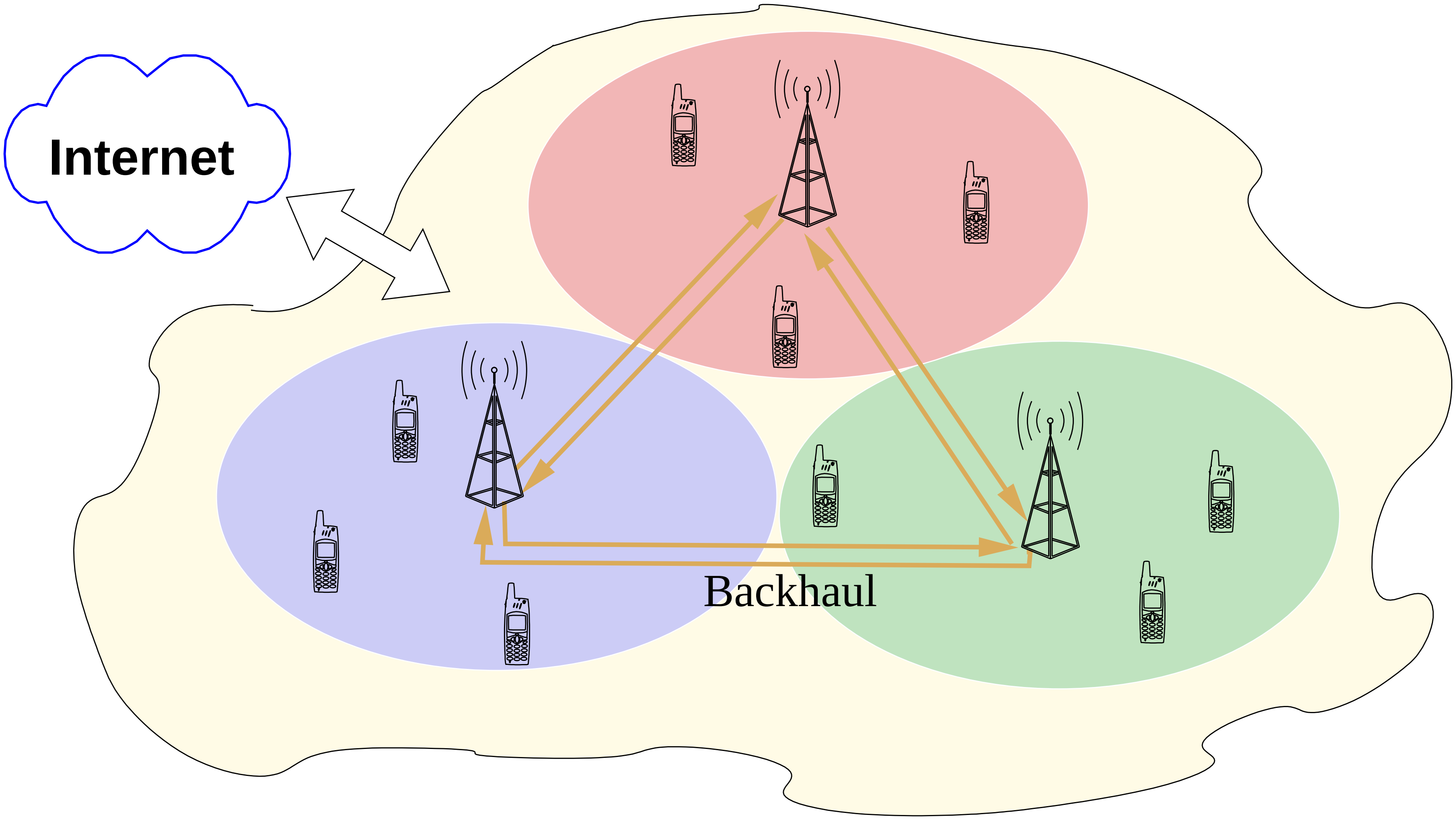
(b)

- **China's airspace** must be very similar
- **American airspace**: thousands of jumbo jets over American sky any time

Internet above the Cloud

- Huge number of **people** are travelling by **aeroplane**, and sky is full of jumbo jets
  - we all dream '**Internet above the Cloud**'
- **Vey important** point: we are not talking aeronautical systems for air traffic control, surveillance, safety monitoring, etc
  - We **CANNOT** do anything even **near** to these systems!
- We are thinking commercial **aeronautical ad hoc network** (AANET)
  - which enables us to do usual things at home, at work or travelling on land
- In this globally interconnected AANET, apart from huge amount of **higher-layer** protocols to be defined,
  - we need to define **physical layer** enabling transmission protocol: which is the main theme of this talk

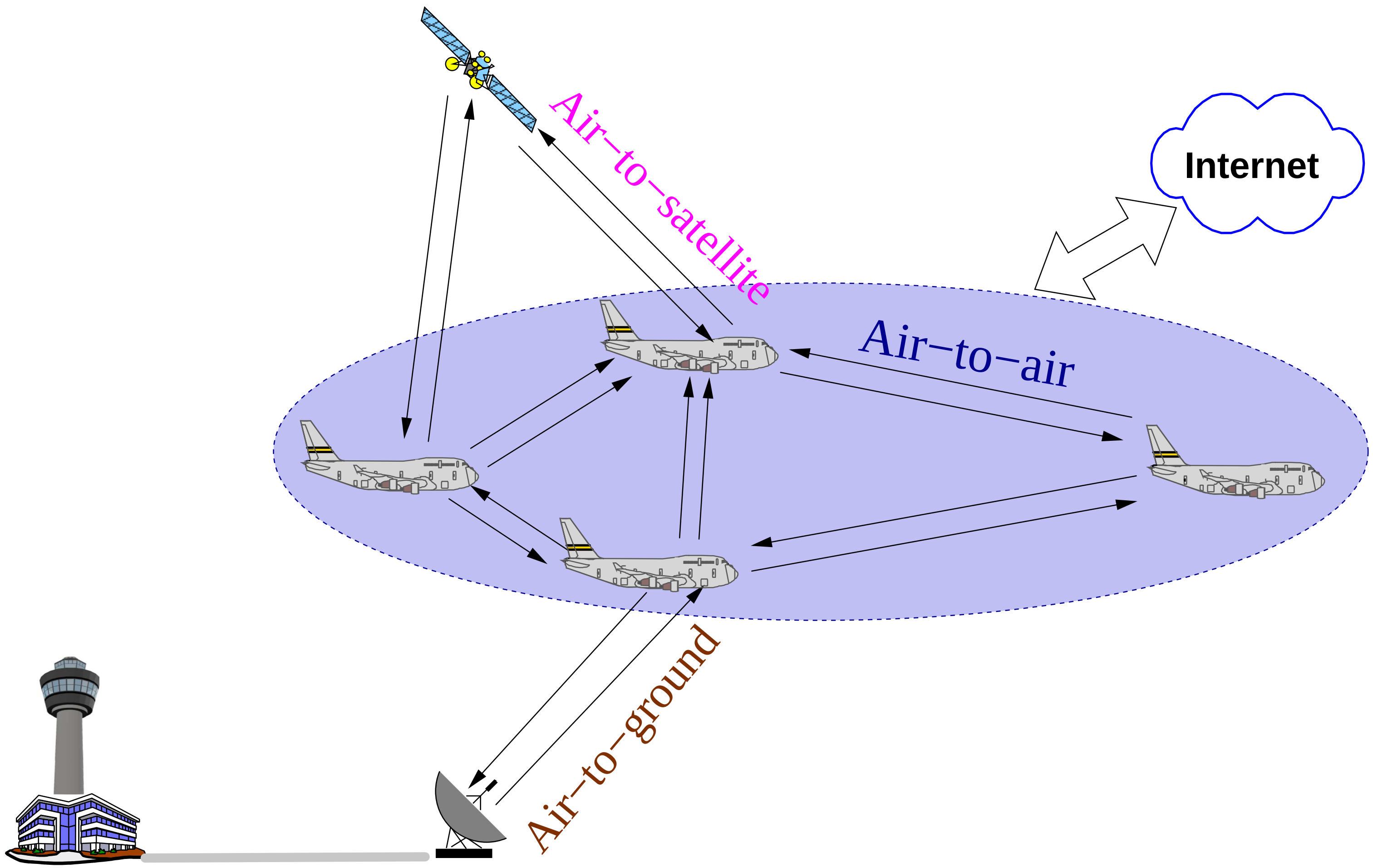
Terrestrial Mobile Network



- Hidden from us are **backhaul** transmissions, which really enable us to do our usual things, such as mobile **Internet access**

Aeronautical Ad Hoc Network

- Jumbo jet is a moving 'cell', where 'base station' and all its 'mobiles' or passengers move together
- 'Mobiles' or passengers can access to 'base station' via standard technique, such as WiFi
- **Air-to-air** transmissions, acting like **backhaul**, is really key to **Internet access**



Technical Considerations

- **Spectrum**: Better not use VHF and UHF bands, because
  - Existing air traffic systems mainly use VHF band of 118 MHz to 137 MHz
  - UHF band almost fully occupied by television broadcasting, mobile phones, and satellite communications, including GPS
  - No substantial idle frequency bands in VHF and UHF anyway
- **Potential solution**: Use super high frequency (SHF) band of 3 GHz to 30 GHz, e.g. 5 GHz carrier frequency for AANET application
  - **Need** international agreement
- **Massive MIMO**: To achieve high throughput and to maximize spectral efficiency, same bandwidth B_{total} **reused** by every jumbo jet $\Rightarrow$ to combate interference
  - New antenna technology **printing** antenna array on aeroplane surface
  - Every jumbo jet is equipped with **same** large-scale antenna array with N_t 'data-transmitting' antennas and $N_r (< N_t)$ 'data-receiving' antennas

Transmission Technique

- **Aeronautical channel** characteristics: bad and good
  - Very high **Doppler spread**, owing to very high flight speed
  - Channel is very **clean**: Rician with line-of-sign component dominant

- Unlike terrestrial mobile channel, **no local scatters** around aeroplane en route, due to enforced minimum flight separation distance
  - Spatial correlation matrices of transmit array and receive array remain **unchanged**
  - Make massive MIMO implementation much **easier**

- New **distance-based adaptive coding and modulation** transmission scheme
  - Existing ACM schemes unsuitable, because it is difficult to acquire accurate estimate of instantaneous SNR or other channel-quality measure
  - Achievable throughput of aeronautical channel mainly depends on distance
  - Aeroplane readily has distance information measured accurately

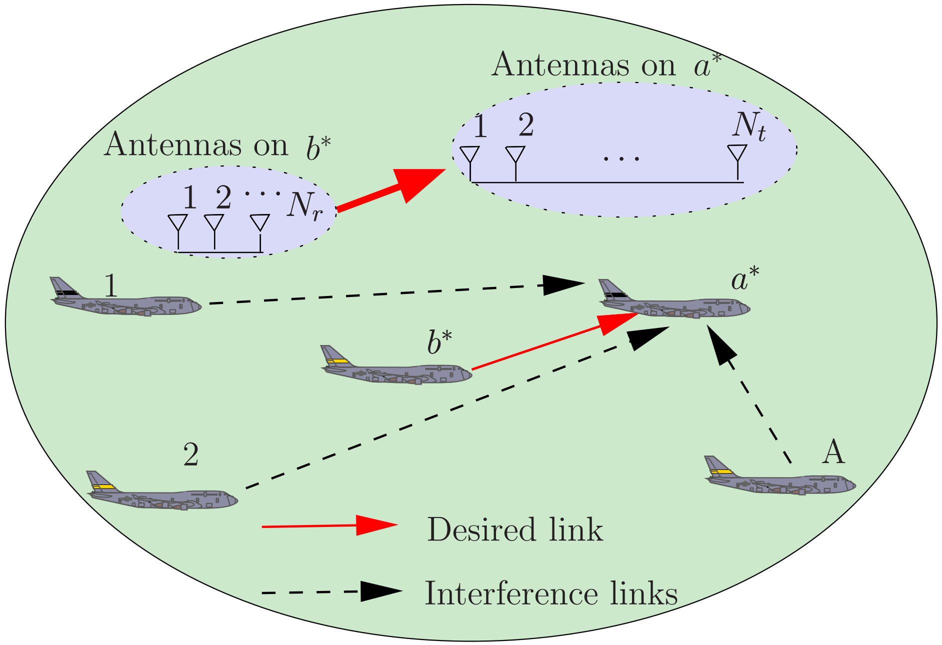
TDD Based System Model

- System adopts **TDD** protocol and OFDM: generically, aircraft a^* is transmitting data to aircraft b^*, in the presence of co-channel interference from other A aircraft

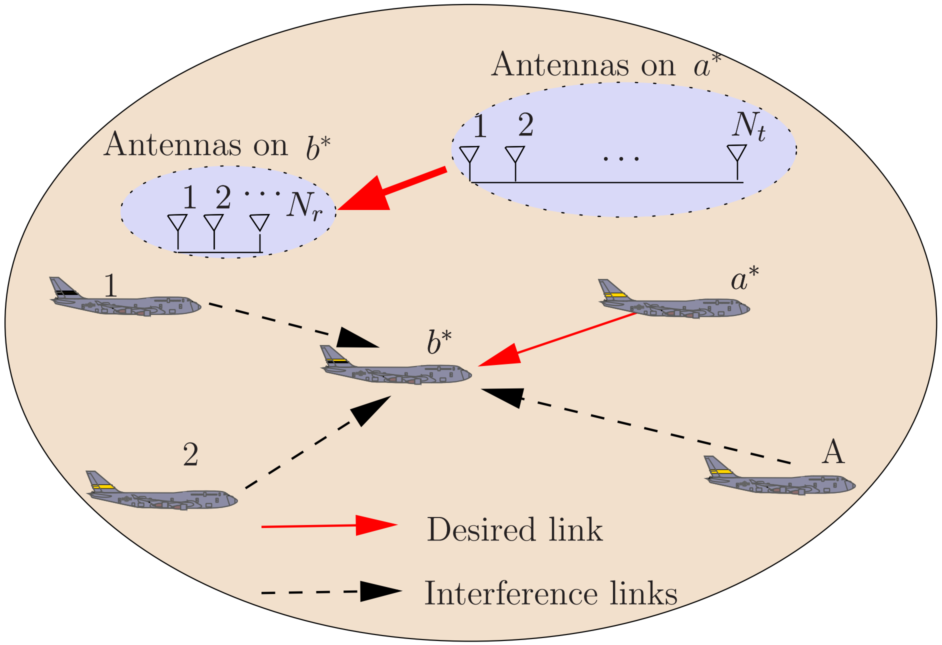
(a) **Pilot training**: b^* sends pilots from its N_r data-receiving antennas to a^*, which receives transmitted pilots using its N_t data-transmitting antennas

- To acquire MIMO channel matrix from b^*'s N_r antennas to a^*'s N_t antennas
- which is reciprocal to MIMO channel matrix from a^*'s N_t antennas to b^*'s N_r antennas

(b) **Data transmission**: With precoding based on acquired CSI, a^* transmits data using its N_t data-transmitting antennas to b^*, who receives data using its N_r data-receiving antennas



(a) Pilot training (b^* to a^*)



(b) Data transmission ($a^*$to b^*)

Pilot Training

- **Channel covariance matrix** is Kronecker product of spatial correlation matrix of a^*'s N_t antennas and spatial correlation matrix of b^*'s N_r antennas
  - **Assumption**: every jumbo jet is equipped with same antenna array
  - a^* knows spatial correlation matrix of its N_r antennas, which is the same as spatial correlation matrix of b^*'s N_r antennas
  - Consequently, a^* **has** channel covariance matrix

- We can apply optimal MMSE or **Bayesian estimator**
  - MSE of channel estimate attains **Cramér-Rao lower bound**
  - **Pilot contamination free**, even other aircraft are interfering

▼ In **terrestrial** massive MIMO, coordinated channel estimation with optimal Bayesian estimator is pilot contamination free but impractical
  - Acquisition of channel covariance matrices at BSs is extremely **time consuming**
  - Sharing them among BSs requires **huge** amount of **back-haul** transmissions

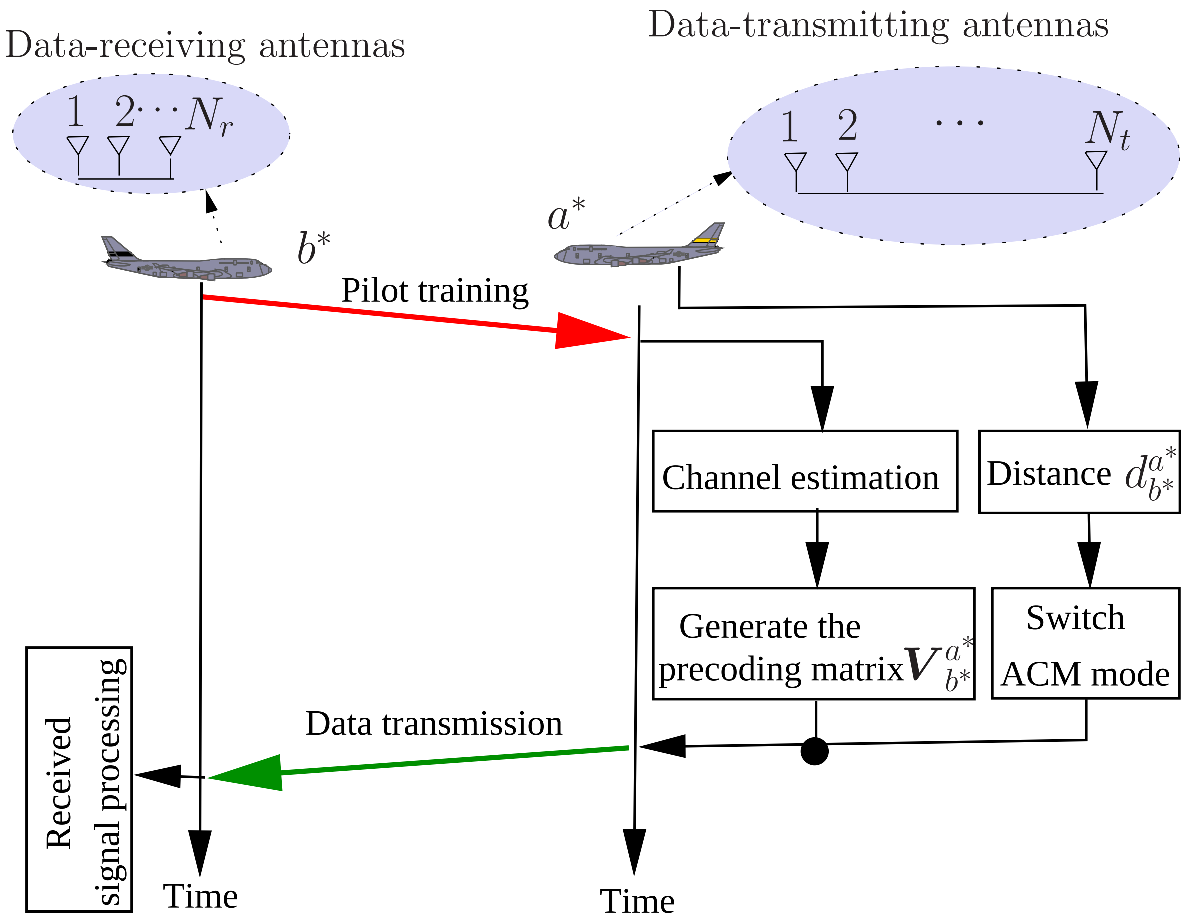
▲ By contrast, our application of optimal Bayesian estimator is **completely practical and effective**

Air-to-Air Transmission

- Aircraft a^* calculates transmit precoding matrix based on channel estimate
- Aircraft a^* selects an ACM mode to transmit data according to its distance $d_{b^*}^{a^*}$ to b^*

$$\text{If } d_k \leq d_{b^*}^{a^*} < d_{k-1}: \text{ choose mode } k; \quad k \in \{1, 2, \cdots, K\}$$

$d_0 = D_{\max}$, **maximum** communication rage, and $d_{b^*}^{a^*} \geq D_{\min}$ for safety **minimum** separation



References

- J. Zhang, S. Chen, R.G. Maunder, R. Zhang, and L. Hanzo, "Adaptive coding and modulation for large-scale antenna array based aeronautical communications in the presence of co-channel interference," *IEEE Transactions on Wireless Communications*, vol. 17, no. 2, pp. 1343–1357, Feb. 2018

- J. Zhang, S. Chen, R.G. Maunder, R. Zhang, and L. Hanzo, "Regularized zero-forcing precoding aided adaptive coding and modulation for large-scale antenna array based air-to-air communications," *IEEE Journal on Selected Areas in Communications*, to appear, 2018

System Parameters

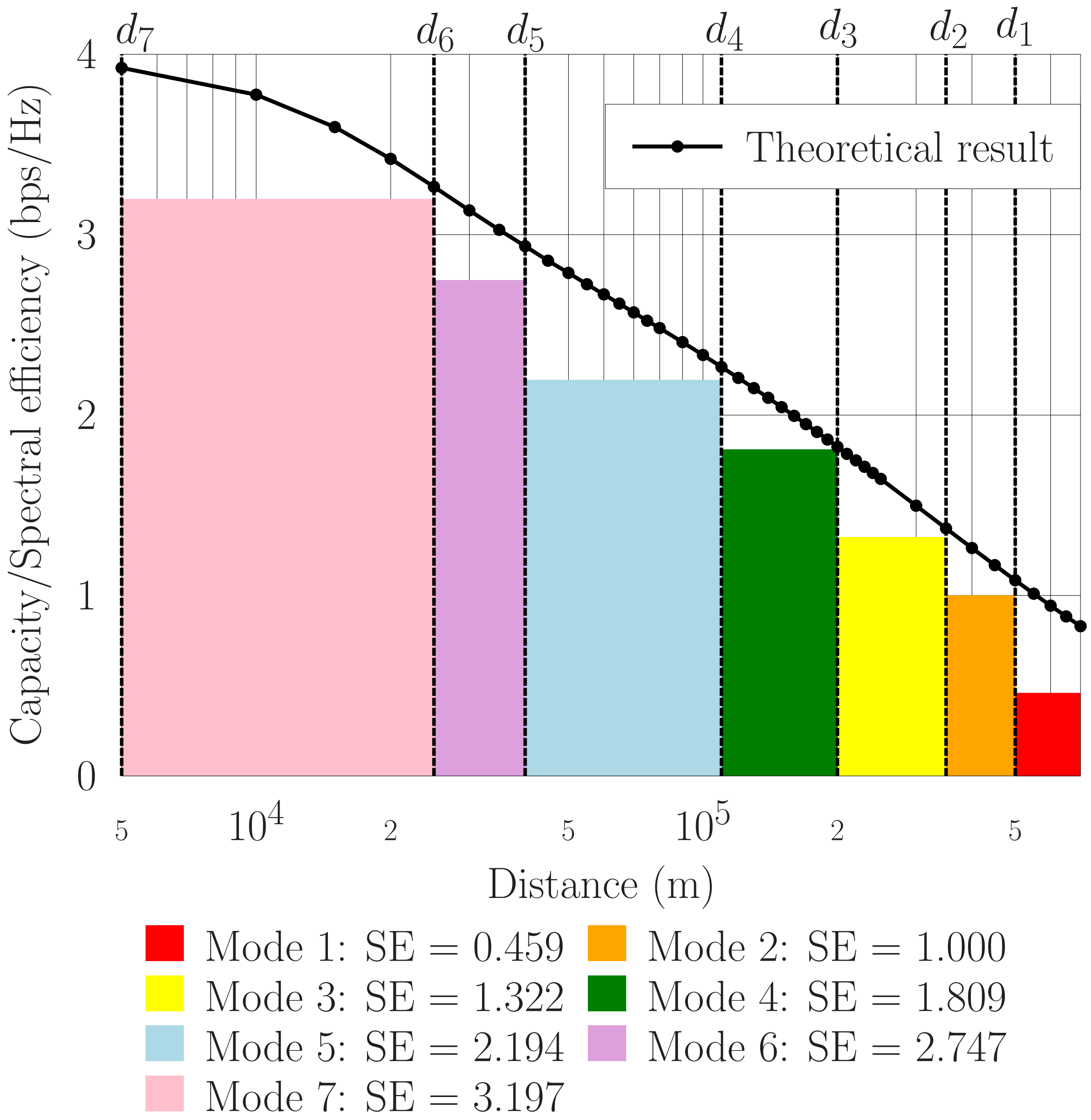
Table 1: Default parameters used in simulated aeronautical communication system

System parameters for ACM	
Number of interference aircraft A	4
Number of data-receiving antennas N_r	4
Number of data-transmitting antennas N_t	32
Transmit power per antennas P_t	1 watt
Number of total OFDM subcarriers N	512
Number of CPs N_{cp}	32
Rician factor K_{Rice}	5
Bandwidth B_{total}	6 MHz
Frequency of centre subcarrier	5 GHz
Other system parameters	
Correlation factor between antennas ρ	0.1
Noise figure at receiver F	4 dB
Distance between communicating aircraft a^* and b^* $d_{b^*}^{a^*}$	10 km
Maximum communication distance $D_{\max}$	740 km

Distance-Based ACM

- **Distance** information is readily available
  - Every jumbo jet has a radar and is equipped with GPS
- $K = 7$, $D_{\max} = 740$ km, $D_{\min} = 5$ km
  - System parameters listed in Table 1
  - Design listed in Table 2
- If $d_k \leq d_{b*}^{a^*} < d_{k-1}$: choose mode k
  - Mode 1: $d_1 \leq d_{b*}^{a^*} < d_0 = D_{\max}$
  - Mode 2: $d_2 \leq d_{b*}^{a^*} < d_1$
  - Mode 3: $d_3 \leq d_{b*}^{a^*} < d_2$
  - Mode 4: $d_4 \leq d_{b*}^{a^*} < d_3$
  - Mode 5: $d_5 \leq d_{b*}^{a^*} < d_4$
  - Mode 6: $d_6 \leq d_{b*}^{a^*} < d_5$
  - Mode 7: $D_{\min} = d_7 \leq d_{b*}^{a^*} < d_6$

Most of time ACM will operate in modes 7 or 6



ACM Design Example

Table 2: **Adaptive coding and modulation**: system parameters listed in Table 1.

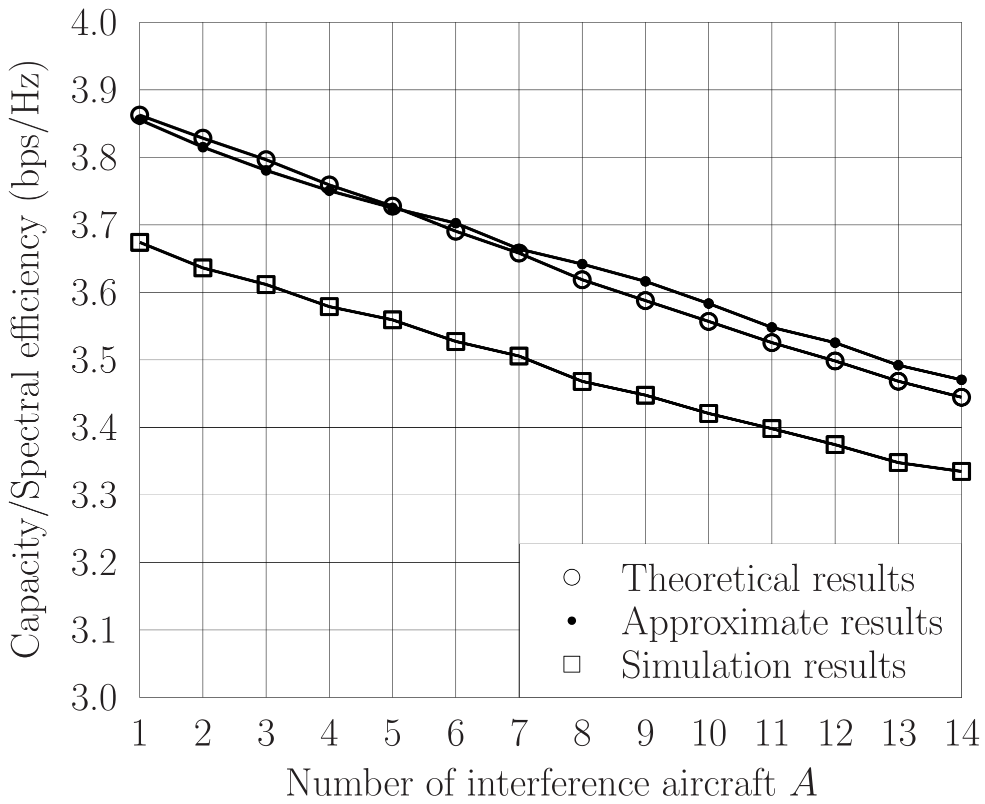
Mode k	Modulation	Code rate	Spectral efficiency (bps/Hz)	Switching threshold d_k (km)	Data rate per antenna (Mbps)	Total data rate (Mbps)
1	BPSK	0.488	0.459	500	2.754	11.016
2	QPSK	0.533	1.000	350	6.000	24.000
3	QPSK	0.706	1.322	200	7.932	31.728
4	8-QAM	0.642	1.809	110	10.854	43.416
5	8-QAM	0.780	2.194	40	13.164	52.656
6	16-QAM	0.731	2.747	25	16.482	65.928
7	16-QAM	0.853	3.197	5.56	19.182	76.728

- To ensure successful transmission, distance **thresholds** $\{d_k\}_{k=1}^{K}$ are chosen so that
  - **Spectrum efficiency** of mode k is lower than theoretically achievable rate per data-receiving antenna in distance range of $[d_k, \ d_{k-1}]$
- In following simulation study
  - **Theoretical**: asymptotic theoretical derivation for large $N_t \rightarrow \infty$
  - **Approximate**: with approximations in asymptotic theoretical result
  - **Simulation**: result obtained by simulation

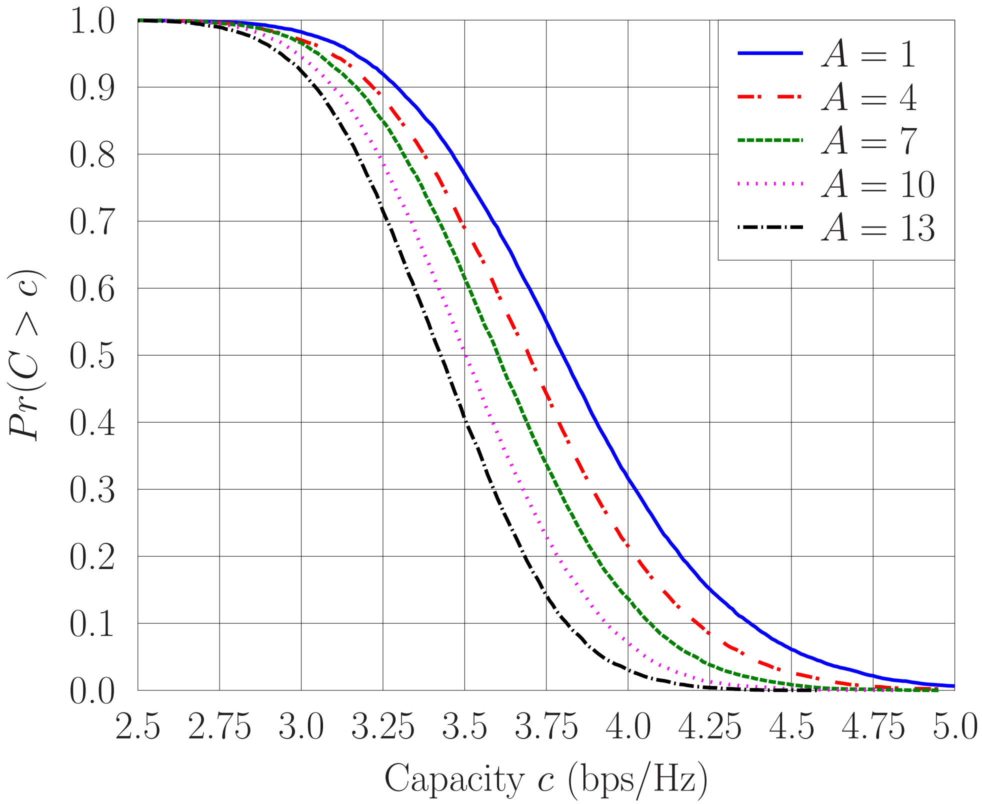
(a) **Achievable throughput** per data-receiving antenna as function of **interfering aircraft** number A

- Distances between interfering aircraft and b^* are uniformly distributed in $\left[d_{b^*}^{a^*},\ D_{\max}\right]$
- **Approximate** result very closed to **theoretical** result (approximation is accurate)
- **Simulation** result ($N_t = 32$) is 0.2 bps/Hz lower than theoretical result ($N_t \rightarrow \infty$)

(b) **Complementary cumulative distribution functions** of simulated throughputs per data-receiving antenna for different numbers of interfering aircraft



(a)

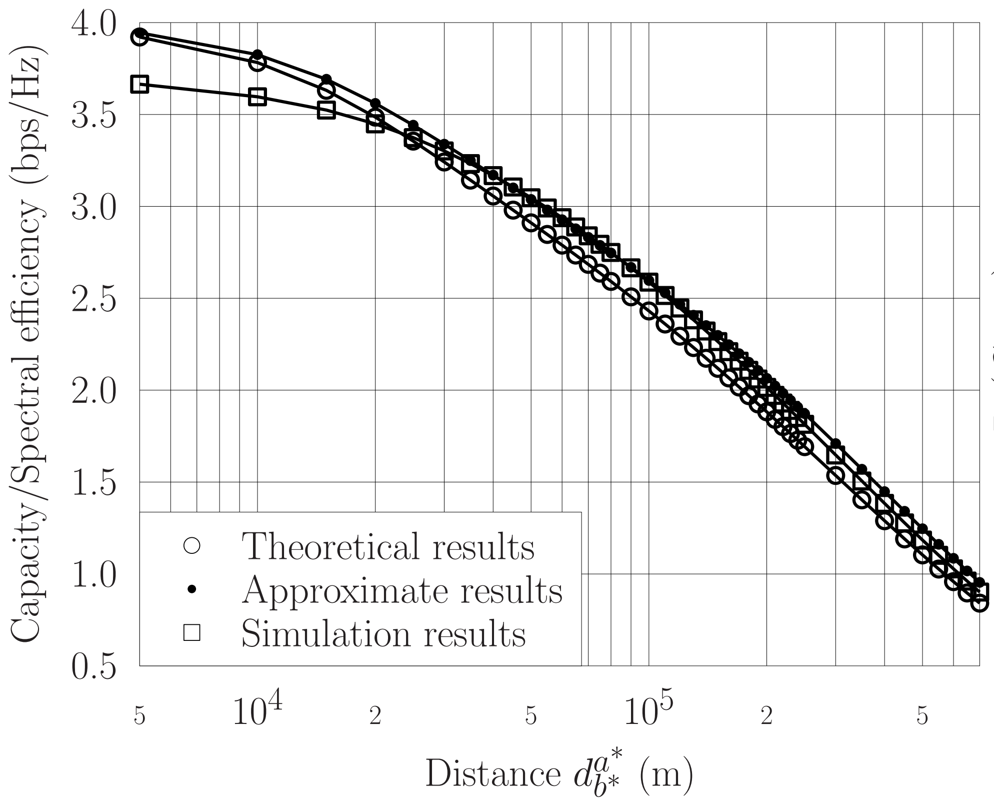


(b)

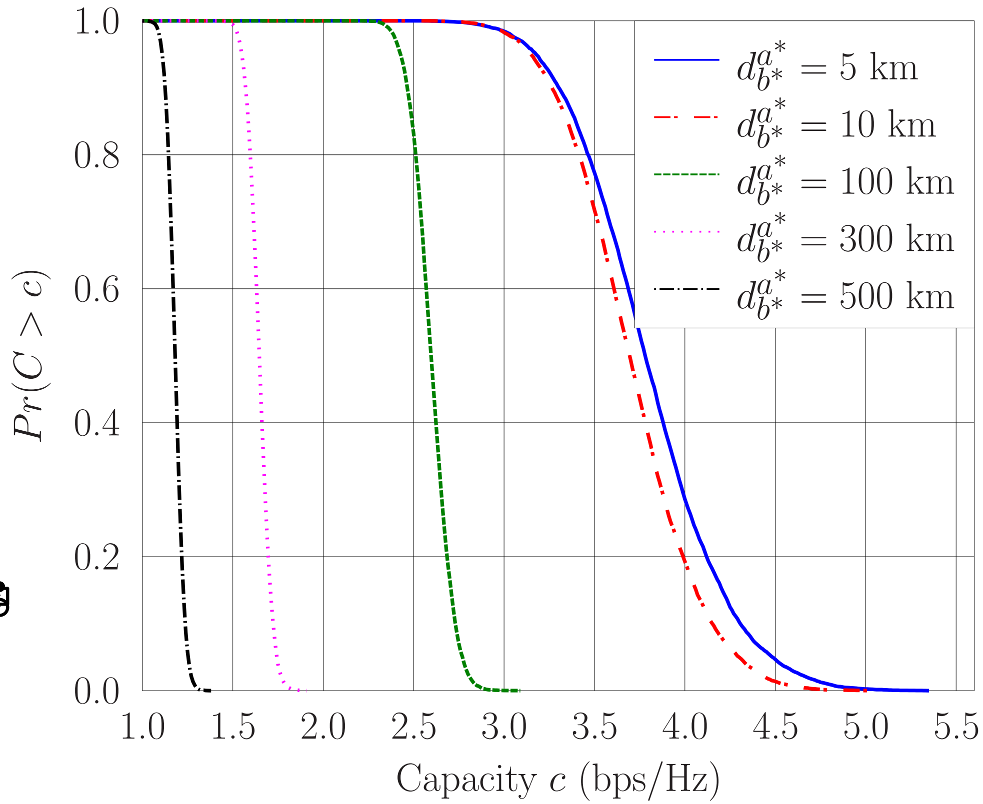
(a) **Achievable throughput** per data-receiving antenna as function of **distance** $d_{b^*}^{a^*}$

– Distances between interfering aircraft and b^* are uniformly distributed in $\left[d_{b^*}^{a^*},\ D_{\text{max}}\right]$, and rest parameters listed in Table 1

(b) **Complementary cumulative distribution functions** of simulated throughputs per data-receiving antenna for different $d_{b^*}^{a^*}$



(a)

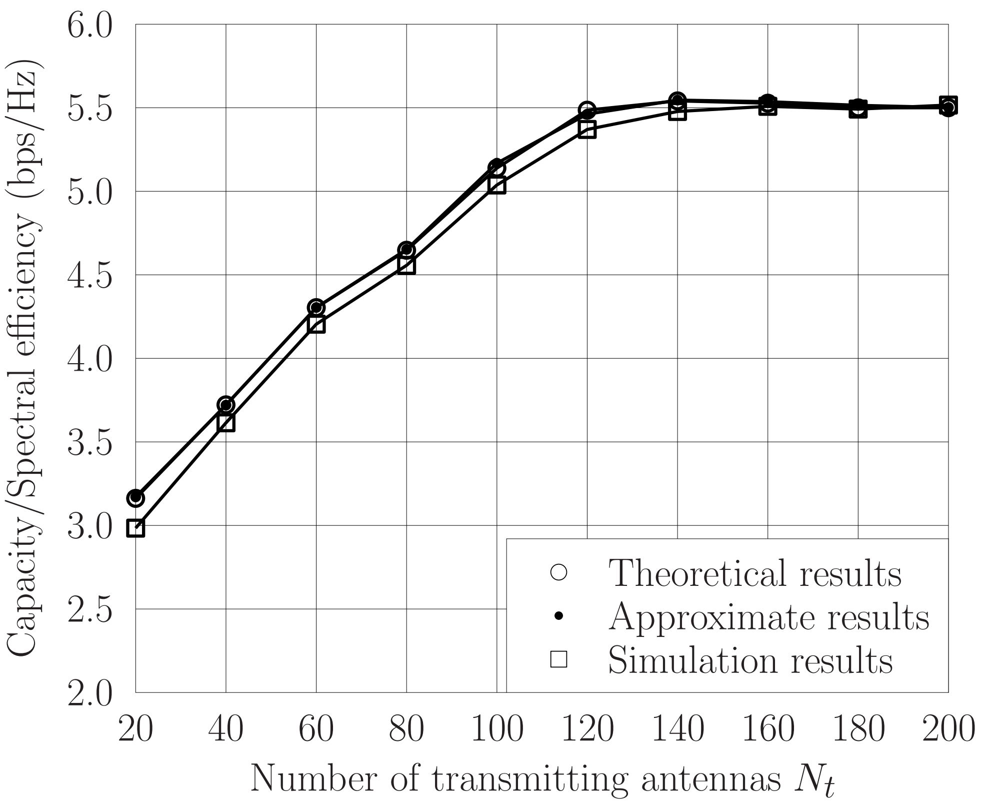


(b)

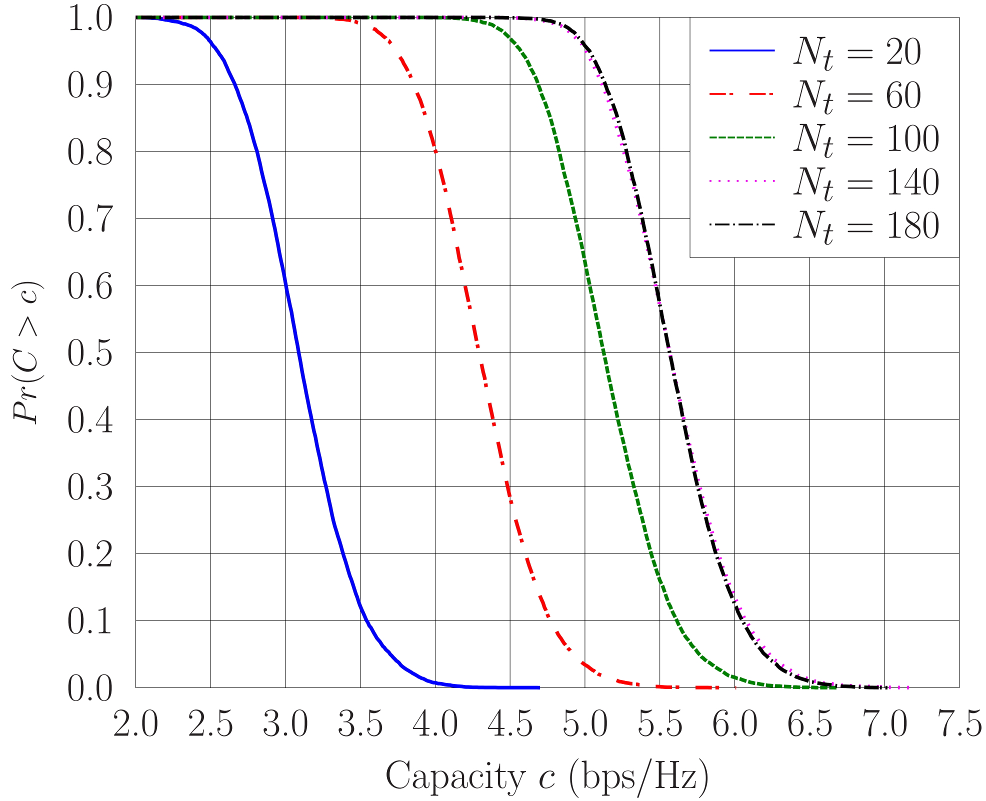
(a) **Achievable throughput** per data-receiving antenna as function of N_t

– Distances between interfering aircraft and b^* are uniformly distributed in $\left[d_{b^*}^{a^*},\ D_{\text{max}}\right]$, rest parameters listed in Table 1, and for large number of **data-transmitting antennas** ($N_t \geq 140$), simulation result agrees with theoretical one

(b) **Complementary cumulative distribution functions** of simulated throughputs per data-receiving antenna for different N_t



(a)

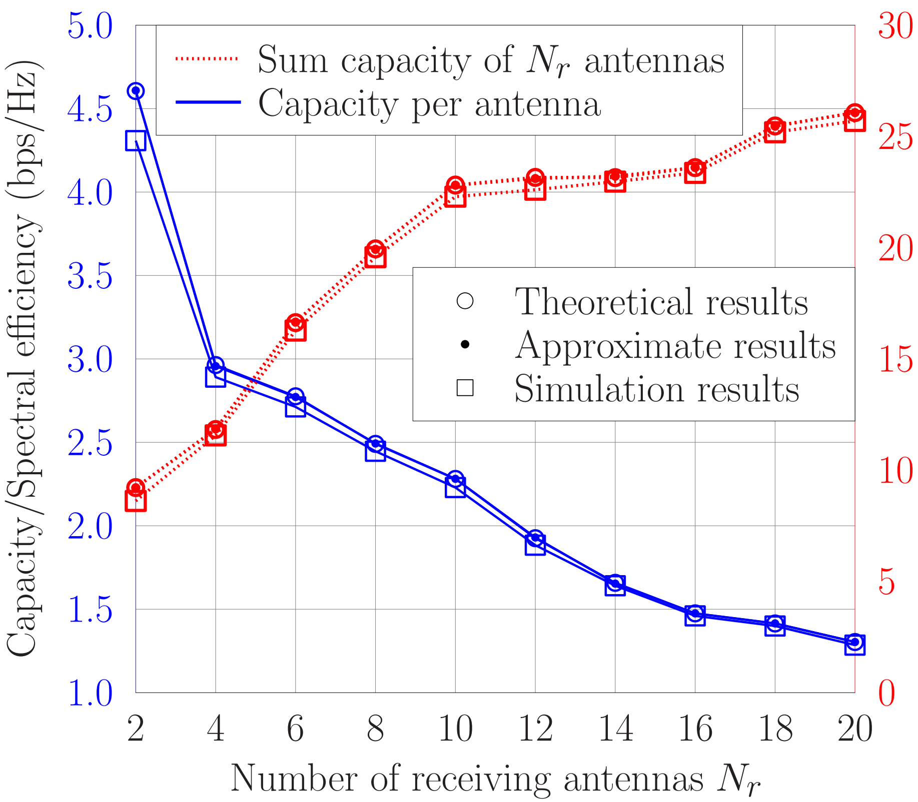


(b)

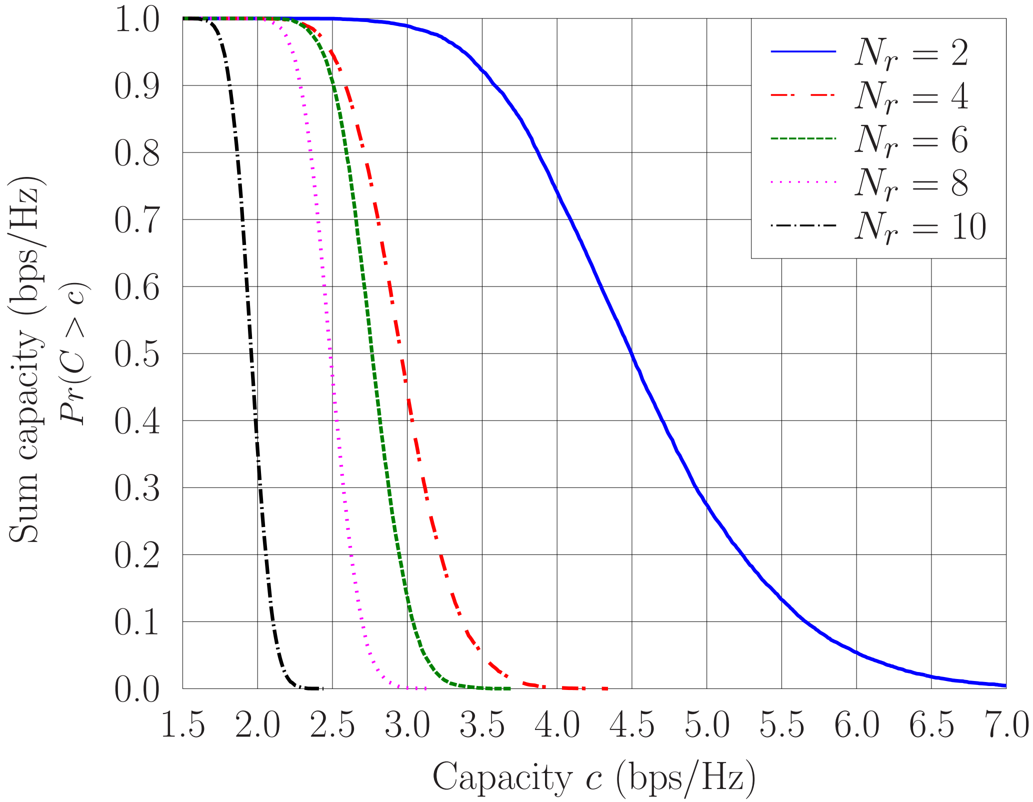
(a) **Achievable throughput** per data-receiving antenna is reduced as N_r increases, because of increase in inter-antenna interference, while **achievable sum rate** increases as N_r increases

– Distances between interfering aircraft and b^* are uniformly distributed in $\left[d_{b^*}^{a^*},\ D_{\text{max}}\right]$, and rest parameters listed in Table 1

(b) **Complementary cumulative distribution functions** of simulated throughputs per data-receiving antenna for different N_r



(a)

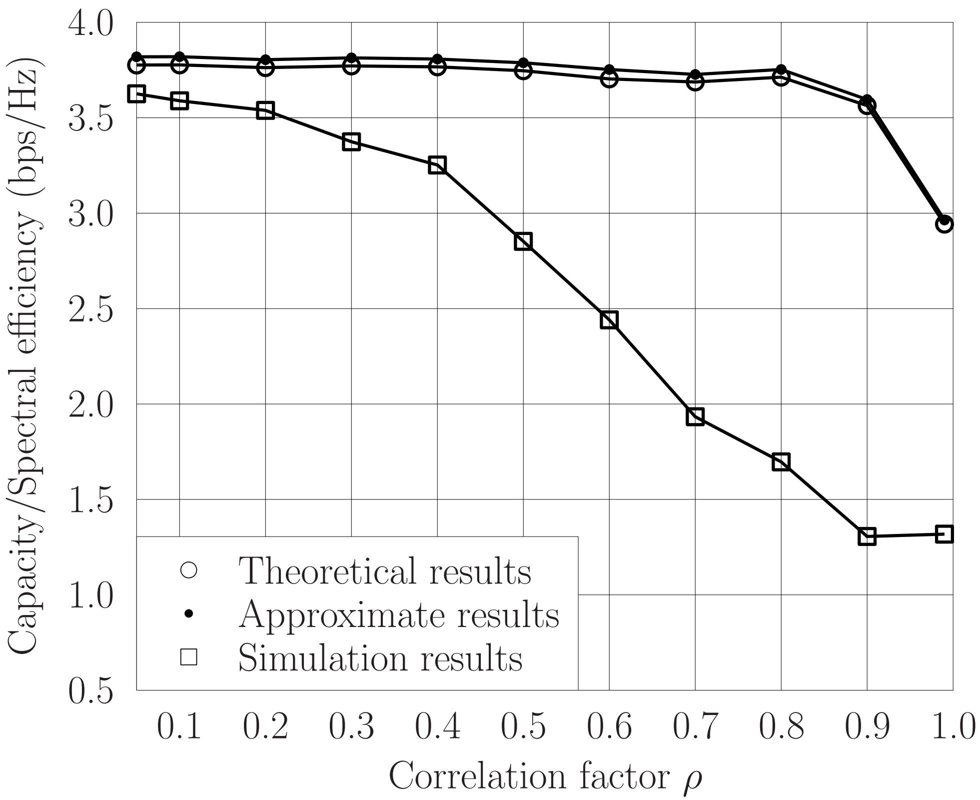


(b)

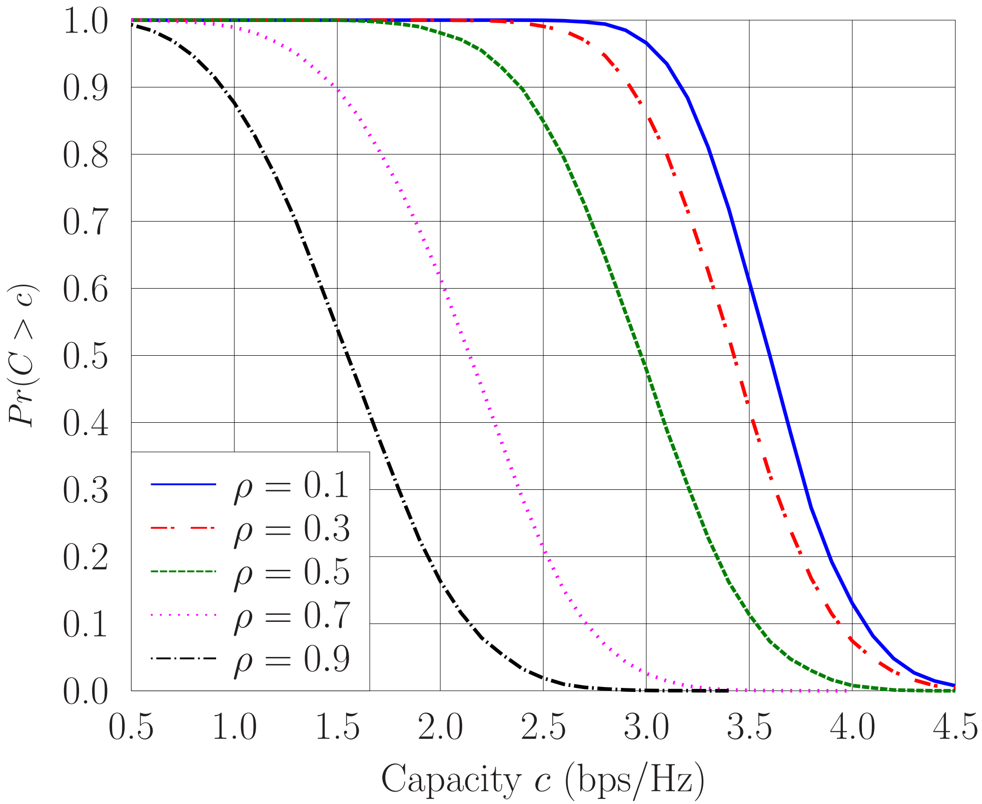
(a) **Achievable throughput** per data-receiving antenna as function of antenna **correlation factor** ρ

- Distances between interfering aircraft and b^* are uniformly distributed in $\left[d_{b^*}^{a^*},\ D_{\max}\right]$, and rest parameters listed in Table 1
- Large gap between theoretical upper bound and simulation result when $\rho \geq 0.4$

(b) **Complementary cumulative distribution functions** of simulated throughputs per data-receiving antenna for different values of ρ



(a)

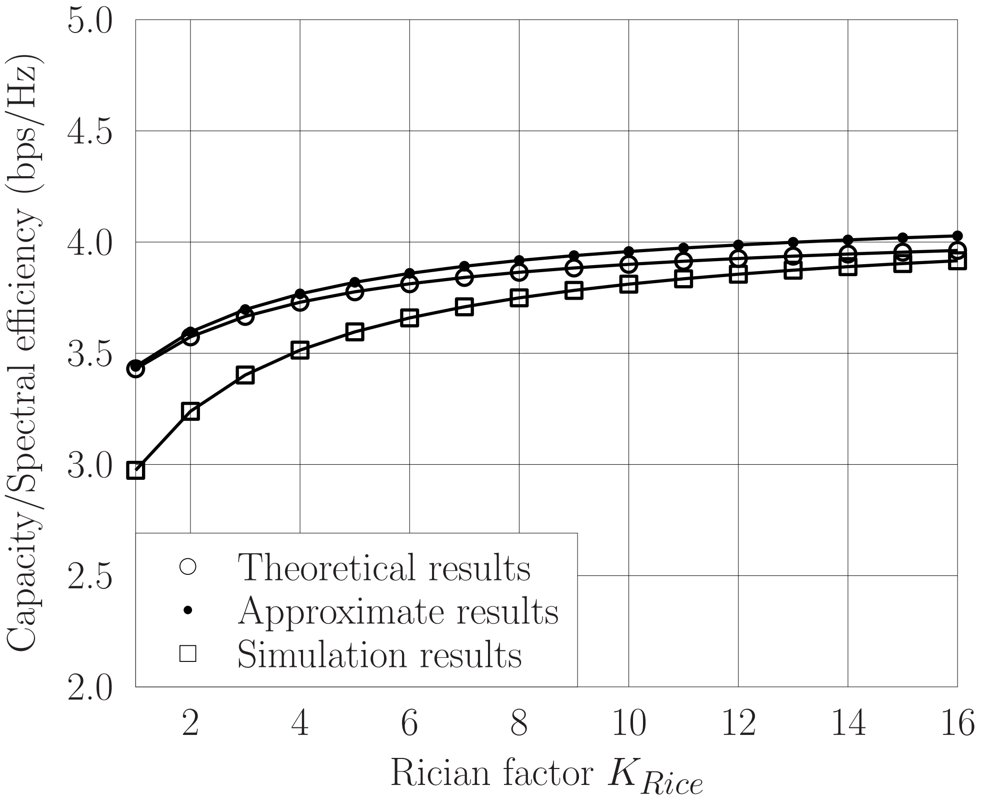


(b)

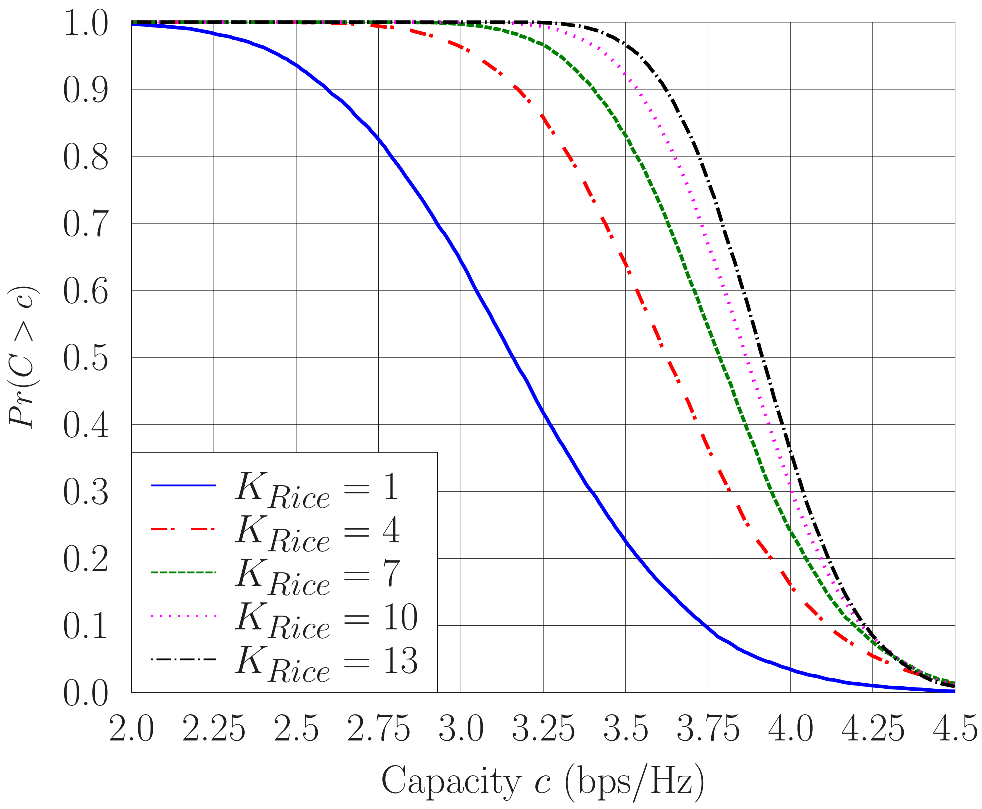
(a) **Achievable throughput** per data-receiving antenna as function of **Rician factor** K_{Rice}

- Distances between interfering aircraft and b^* are uniformly distributed in $\left[d_{b^*}^{a^*},\ D_{\text{max}}\right]$, and rest parameters listed in Table 1
- Higher K_{Rice} leads to higher achievable throughput

(b) **Complementary cumulative distribution functions** of simulated throughputs per data-receiving antenna for different values of K_{Rice}



(a)

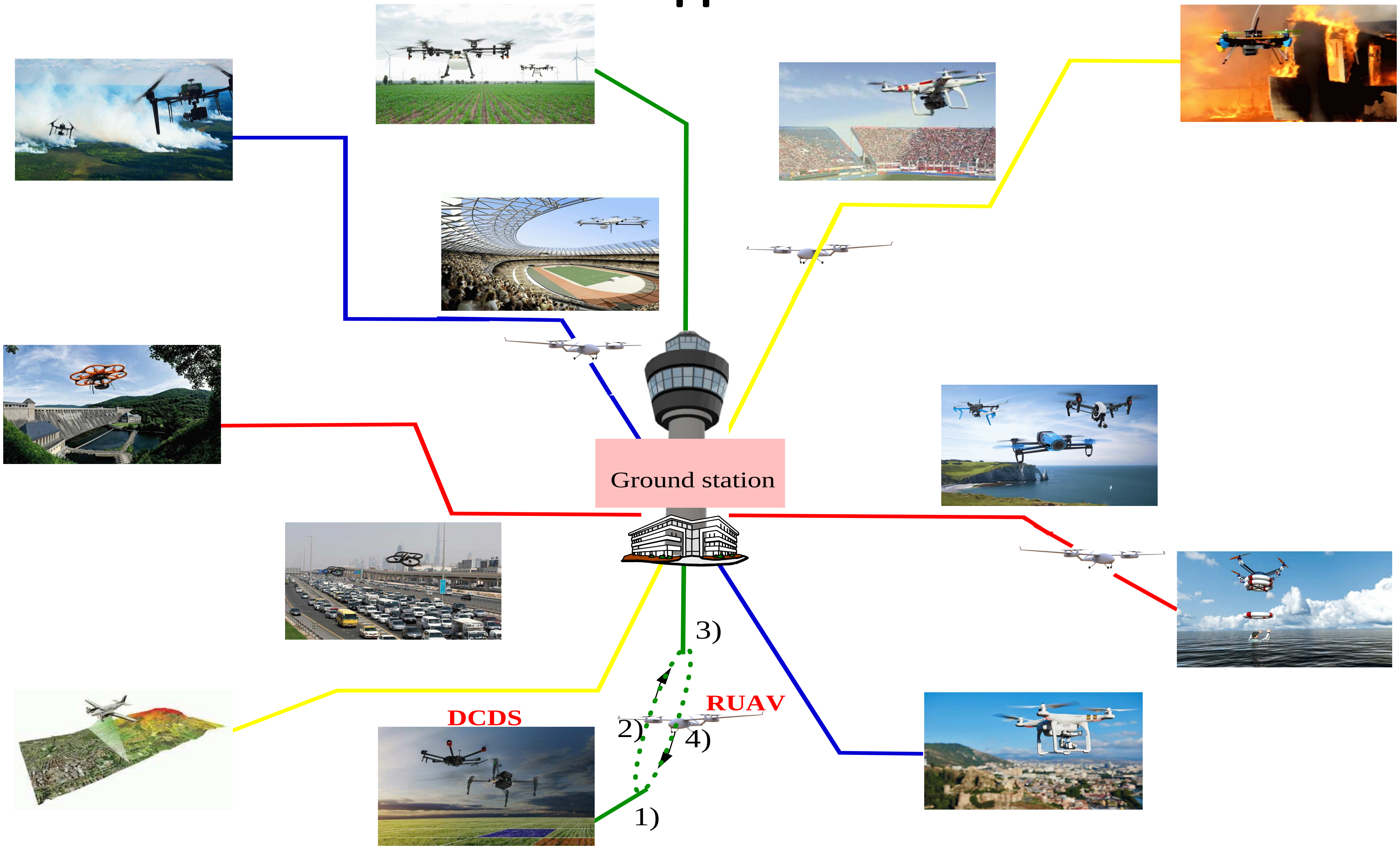


(b)

Discussions

- Our **massive MIMO** aided **adaptive coding and modulation** scheme capable of supporting future '**Internet above Cloud**'
  - ■ 5 GHz carrier and 6 MHz system bandwidth spatially shared by all aircraft:
  - – Interfering aircraft $A = 14$ and distance between desired pair of communicating aircraft $d_{b*}^{a^*} = 10$ km, our design capable of offering total data rate of 79 Mbps
  - – Interfering aircraft $A = 4$ and distance between desired pair of communicating aircraft $d_{b*}^{a^*} = 70$ km, our design capable of offering total data rate of 60 Mbps
- Our two key assumptions are **practical**:
  1. Each jumbo jet can acquire the distance to its nearest aircraft with aid of airborne radar or GPS
  2. Each jumbo jet is equipped with same large-scale antenna array of $N_{\text{total}} = N_t + N_r$ antennas, e.g. $N_{\text{total}} = 36$ or higher
- Our **physical-layer** scheme particular suitable for aeronautical applications
  - – Owing to high velocity of aircraft, no transmission scheme can guarantee successful transmission for every transmission slot
  - – Adopt suitable higher-layer measures for enhancing reliable communication
  - – Discussing **higher-layer** protocols is beyond scope of this talk

Other Applications



Phases: 1) Data loading 2) Heading to GS 3) Data offloading 4) Heading to DCDS

Relay-Assisted Drone Swarm

- Proposed **air-to-air transmission** technique has many other applications
- Relay-assisted drone swarm communications
  - Swarm of drones over a remote area **collecting data** with cameras and sensors, termed data collecting drone swarm (DCDS)
  - Direct transmissions of huge volume of data from DCDS to ground station (GS) impossible, no direct DCDS-to-GS link
  - A powerful unmanned aerial vehicle (UAV) acts a relay to **ferry data** from DCDS to GS, termed as relay-UAV (RUAV)
- This application generates **huge volume** of data, requires **very high air-to-air transmission rate** and large buffer at RUAV
- Proposed large antenna-array assisted and distance-based ACM scheme very **suitable** for this task

Protocol

1. DCDS-to-RUAV **data loading**: RUAV stationary at target-area, DCDS transmit collected data to RUAV until its buffer full or all data have loaded

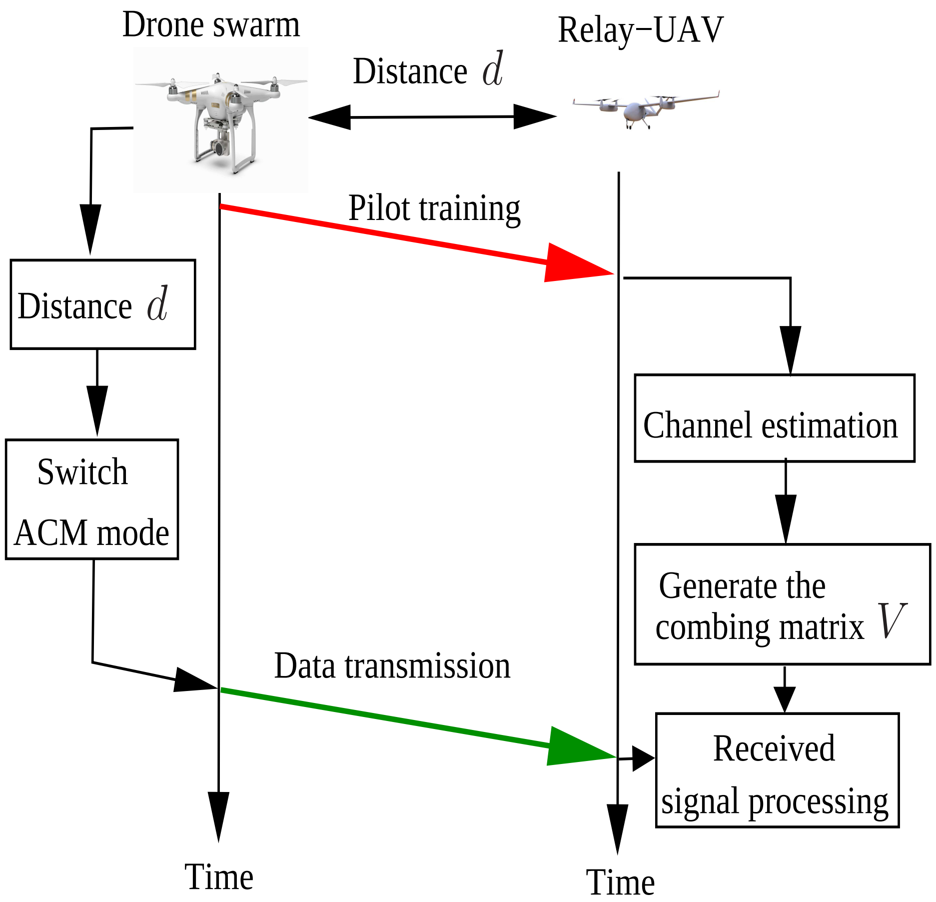
2. **Heading to GS**: RUAV ferries data from target-area to GS, DCDS may transmit new data to RUAV if it is within communication range and its buffer is not full

3. RUAV-to-GS **data offloading**: RUAV may start offloading data to GS when in range, and then stays stationary close to GS for offloading until its buffer empty

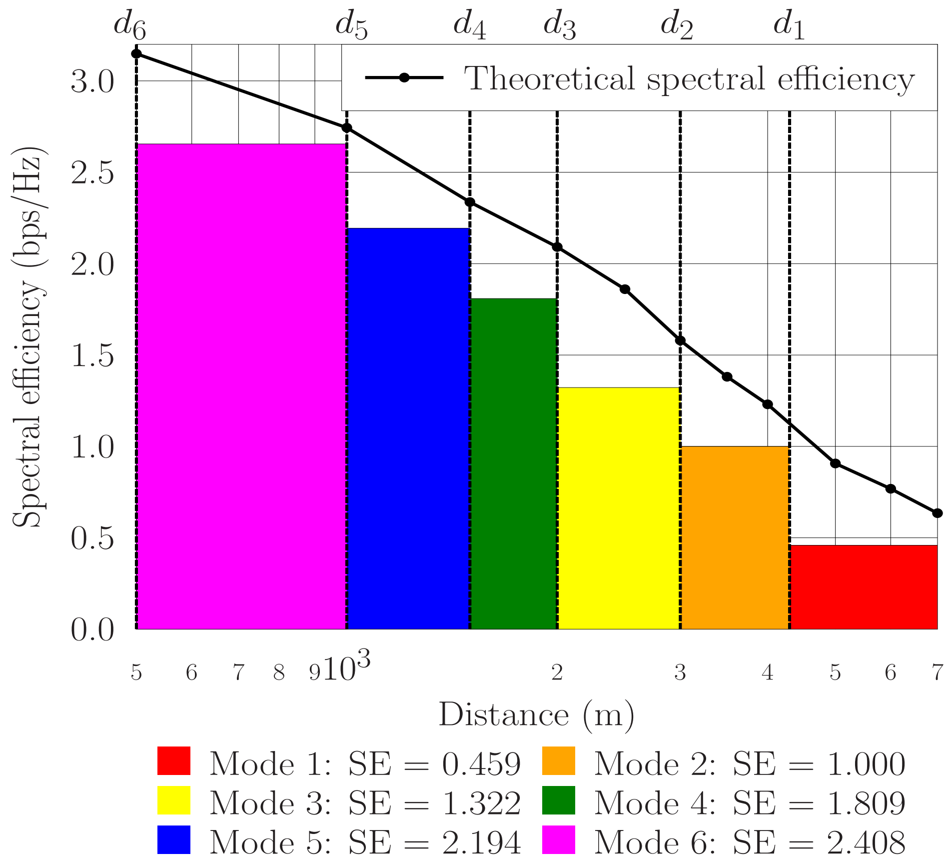
4. **Heading to DCDS**: RUAV flies back to target-area for new data, it may start receiving data from DCDS when in communication range

- Generally, end-to-end connectivity is **intermittent**
- If **end-to-end connectivity** always exists: When direct DCDS-to-RUAV and RUAV-to-GS links exist simultaneously, RUAV may stay stationary at an optimized position to serve as 'conveyor' for collecting data from DCDS and delivering them to GS
- A RUAV may serve **multiple DCDSs** around its route and the route can be optimized according to different requirements of different drone swarm communication tasks

Transmission Scheme



(a)



(b)

(a) DCDS-to-RUAV protocol: note **receiver combining** rather than transmitter precoding

(b) Example of distance-based ACM design

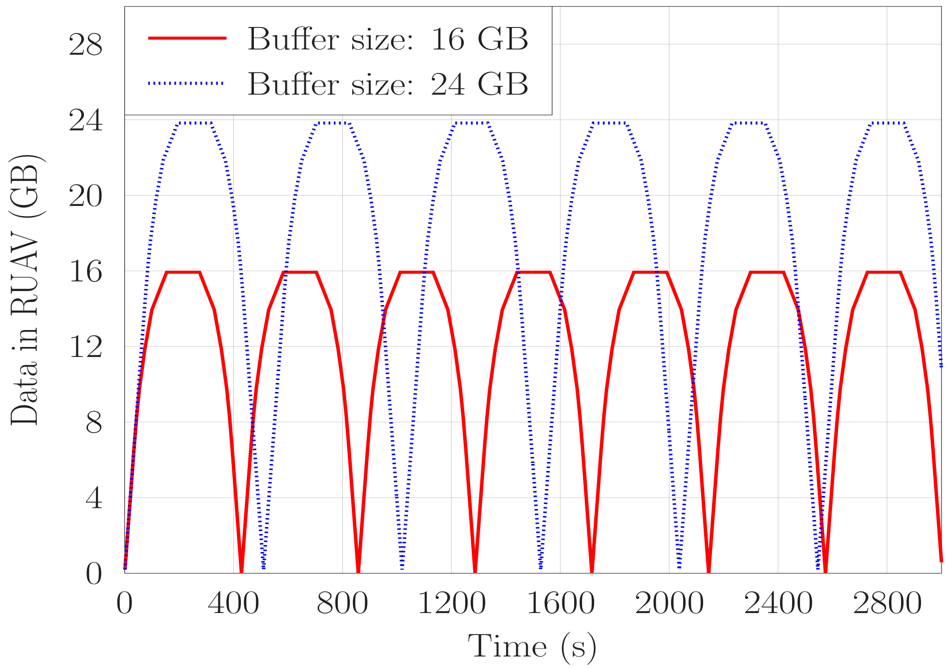
Simulation Experiment

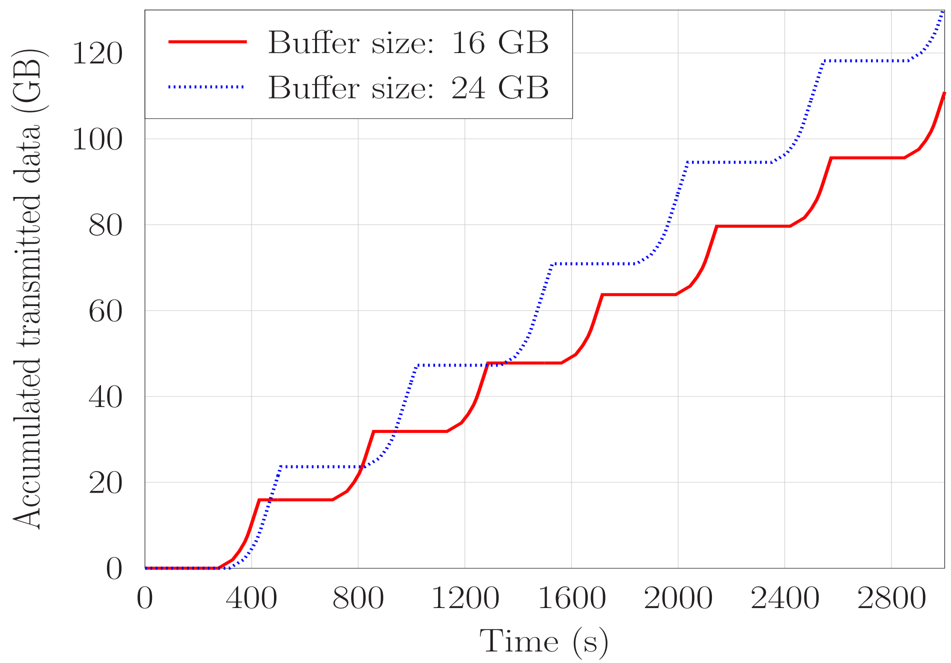
Receive antennas of GS and RUAV: both $N_r = 64$
Velocity of RUAV: 50 m/s, buffer size: 16 GB, 24 GB
8 single transmit-antenna drones, and hence transmit antennas: $N_t = 8$
System bandwidth: $B_{\text{total}} = 6$ MHz, carrier frequency: 60 GHz
Transmit power per transmit antenna: $P_t = 78$ mW
Channel: Rician with Rician factor $K_{\text{Rice}} = 5$
Maximum communication range: 7000 m
Minimum separation distance RUAV/DCDS , RUAV/GS: 500 m
Distance between GS and DCDS: 20,000 m

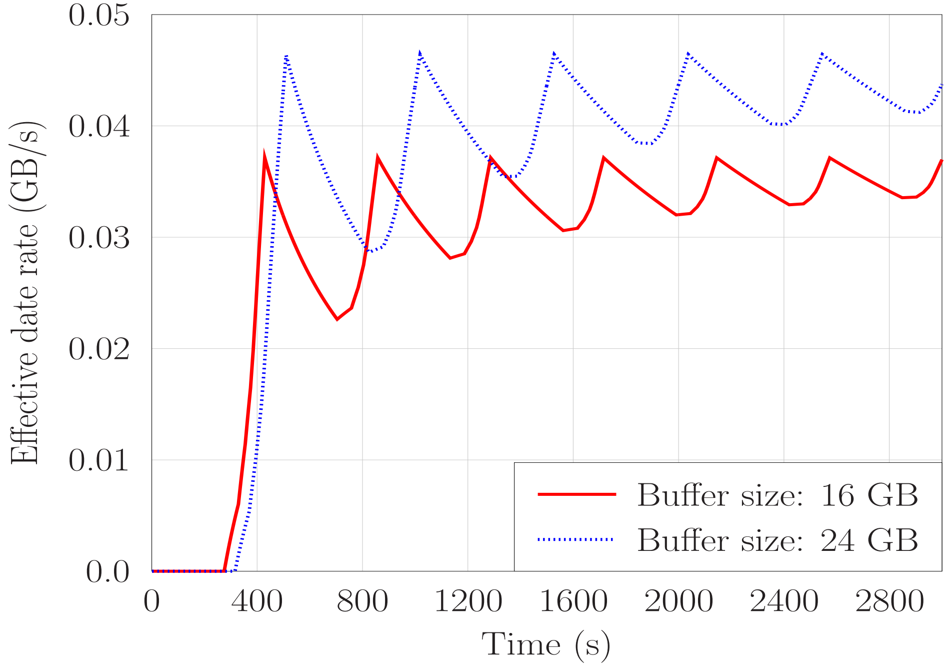
- Note that end-to-end connectivity is **intermittent**, even with aid of RUAV

- We define **effective data rate** as

$$\text{Effective data rate} = \frac{\text{Accumulated transmitted data volume}}{\text{Time}} \, [\text{GB/s}]$$







- RUAV stationary at 500 m to DCDS for loading data until buffer full
- Heads back to GS, when 7000 m to GS, offloading starts; when 500 m to GS, RUAV becomes stationary to continue offloading until buffer empty
- Head back to DCDS, when 7000 m to DCDS loading starts

Conclusions

- '**Extend terrestrial mobile network to sky**' by constructing **aeronautical ad hoc network** for '**Internet above the Cloud**' has been a dream of many
  - Existing physical-layer transmission techniques are incapable of supporting this high-throughput aeronautical communication application
- We have proposed practical **massive MIMO** assisted **adaptive coding and modulation** based physical-layer transmission scheme
  - Capable of offering sufficiently high throughput to support air-to-air transmission for realizing '**Internet above the Cloud**'
- **Challenges** remain how to construct reliable higher-layer protocols for enabling aeronautical ad hoc **networking** to realize dream of '**Internet above the Cloud**'
- Proposed air-to-air transmission technique has many **smaller** scale applications
  - e.g., **Relay** assisted **drone swarm** communications