Towards Any-Where Any-Time Greener 5G

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Joint work with Dr J. Zhang, University of Southampton, Dr Y. Li, Tsinghua University

Keynote speak at 2019 International Conference on Communication Technology, Xian, China

5G Reality Check

1. **5G** service requirements
   - **Massive rate**, 1 to 10 Gbps end to end
   - **Massive connections**, IoTs – every device connected
   - **Ultra low latency** for autonomous driving, intelligent transport system, etc

Ck: Our current technology capable of support 5G service requirements

2. **5G** should be anywhere anytime

Ck: We are instantaneously connected **anywhere anytime**, except some black holes
   - Step on jumbo jet, we disappear into a non-G **black hole**
   - Holiday on cruise ship, we disappear into a non-G **black hole**

3. **5G** should be greener, consuming less energy

Ck: 5G will consume **much more** energy – this is physics
   - Only way to make it 'greener' is to use **green** energy

Motivations

- Move 5G on to sky to complete interconnected world
  - When we travel by aeroplane, we disappear into connection **black hole**
  - Existing **satellite-based** and **ground-to-air**/air-to-ground techniques are very **expensive** and **incapable** of supporting **Internet above the Cloud**
  - Impossible to build ground stations to cover whole continent or over ocean

- Harvest traffic jam wasted energy for green computing to support 5G
  - 5G relies heavily on **signal processing**, consuming huge **computing resource**
  - Uneconomic to maintain dedicated computing facility at BS, RSU or AP to meet **peak** processing **demand**
  - C-RAN implementation to **outsource** baseband processing to **cloud**

This talk contains two parts, covering

1. How to **move 5G to sky** to realize Internet above the cloud
2. How to **harvest traffic jam's computing power** to support 5G signal processing

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

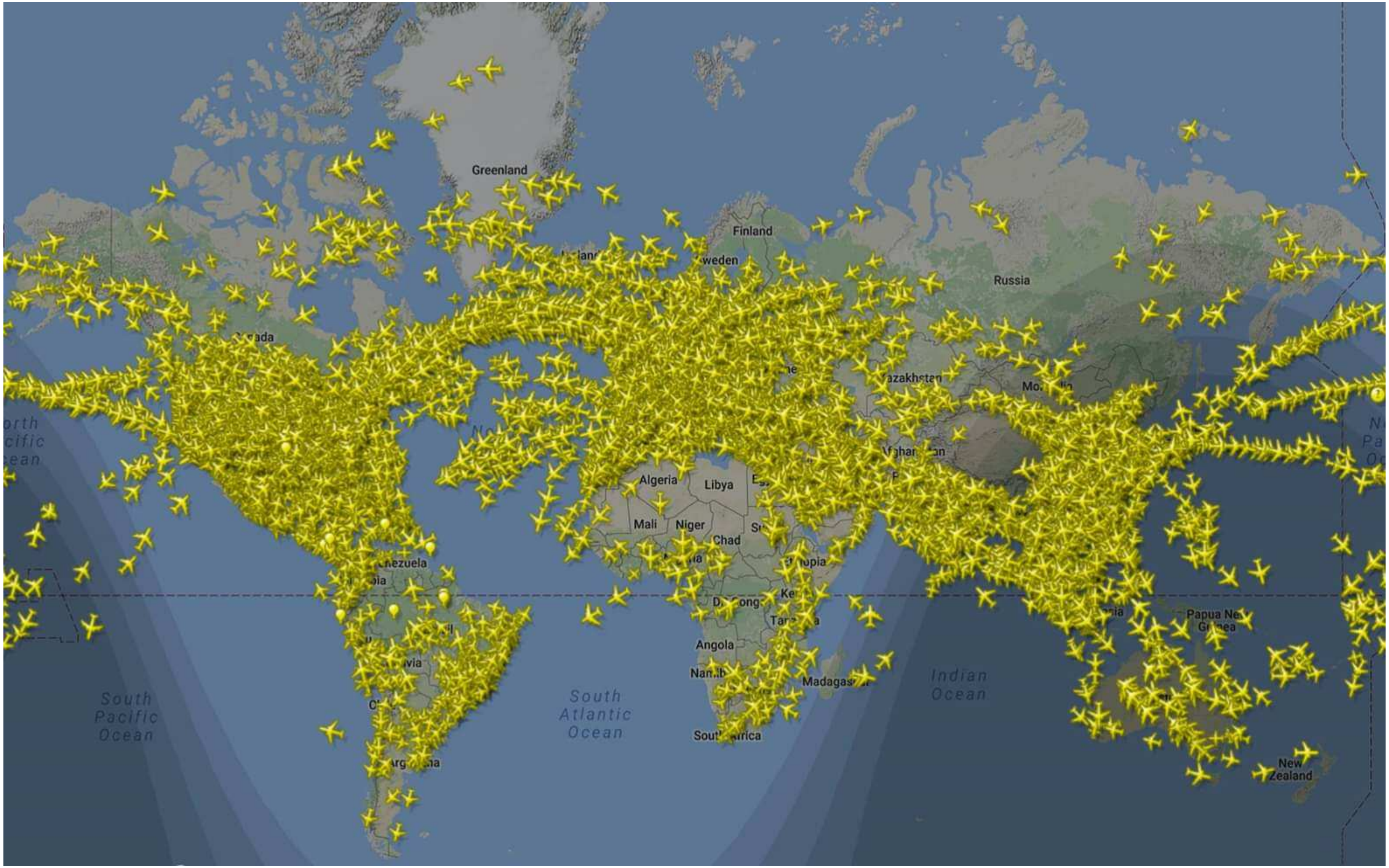
Joint work with Dr J. Zhang, University of Southampton

- Zhang, Chen, Maunder, Zhang, Hanzo, "Regularized zero-forcing precoding-aided adaptive coding and modulation for large-scale antenna array-based air-to-air communications," *IEEE J. Selected Areas Communications*, 36(9), 2087–2103, 2018

- Zhang, Chen, Maunder, Zhang, Hanzo, "Adaptive coding and modulation for large-scale antenna array-based aeronautical communications in the presence of co-channel interference," *IEEE Trans. Wireless Communications*, 17(2) 1343–1357, 2018

Our Sky

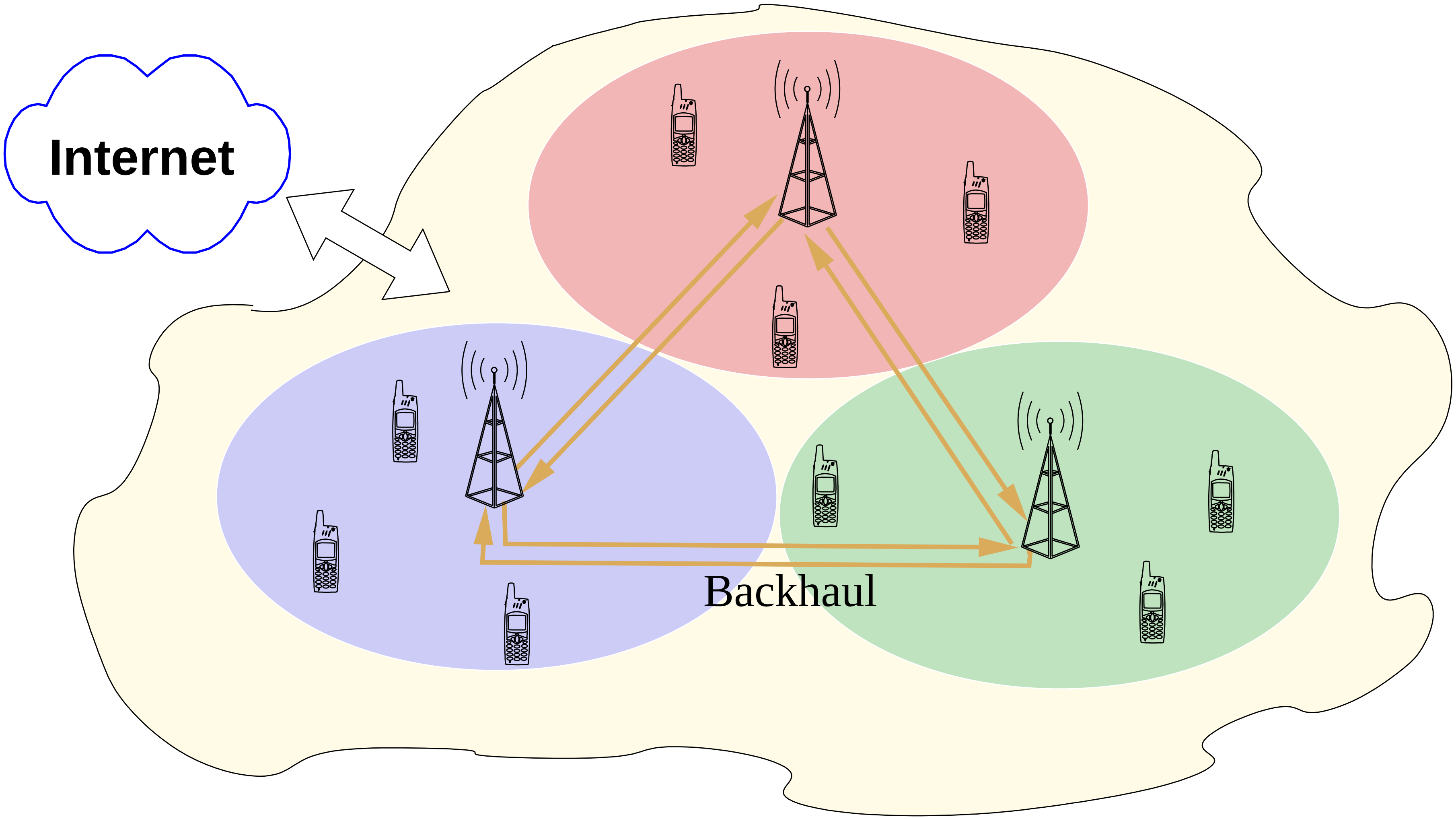
- Normal snapshot of world's commercial **airspace**



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 **NEW** 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, including Internet gateway, cache policy, etc
  - we need to define **physical layer** enabling transmission protocol: which is the key to realize **5G in sky**

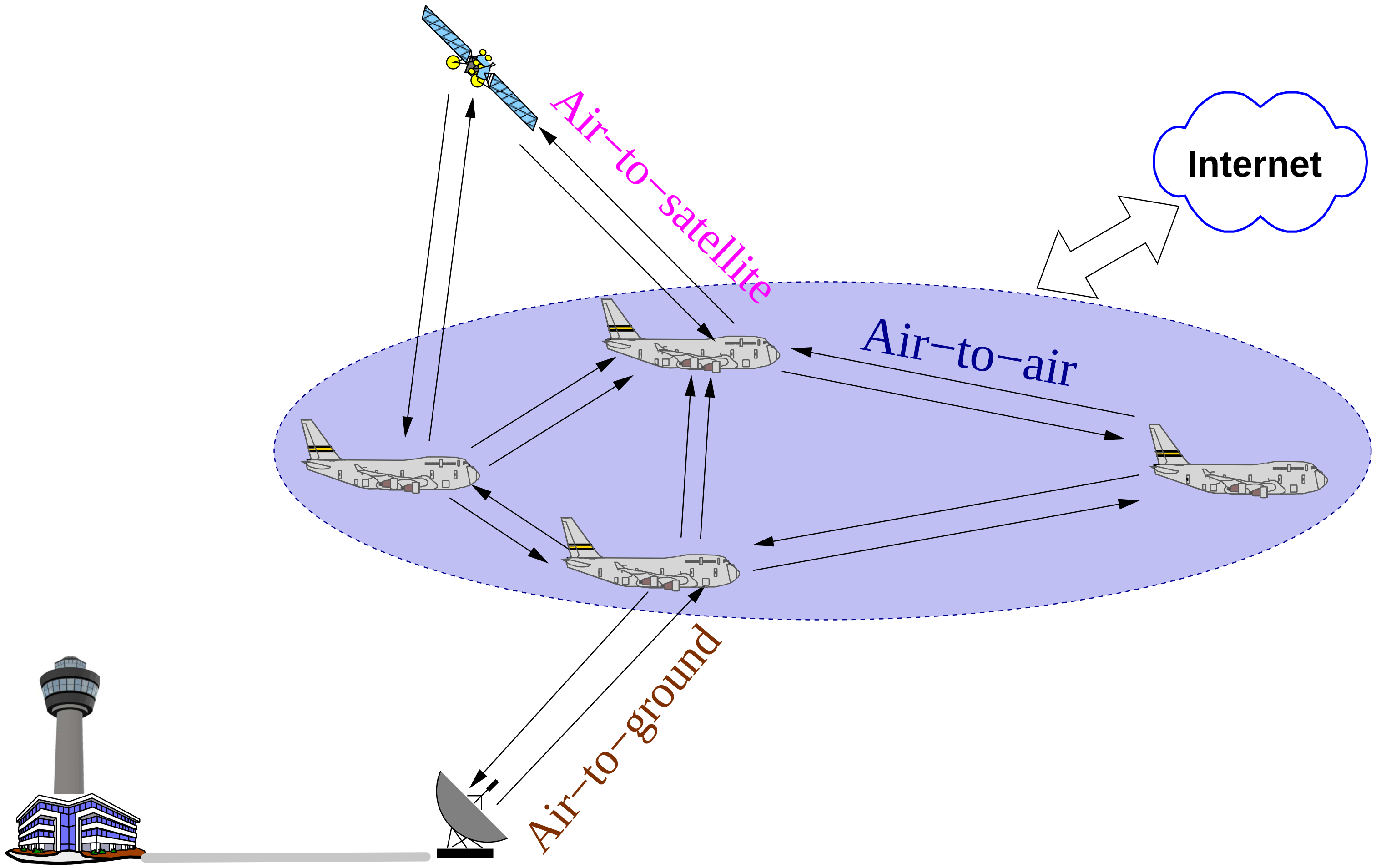
Terrestrial Mobile Network



- 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
  - Consider how large world's commercial jumbo jet fleet, price will come down

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**

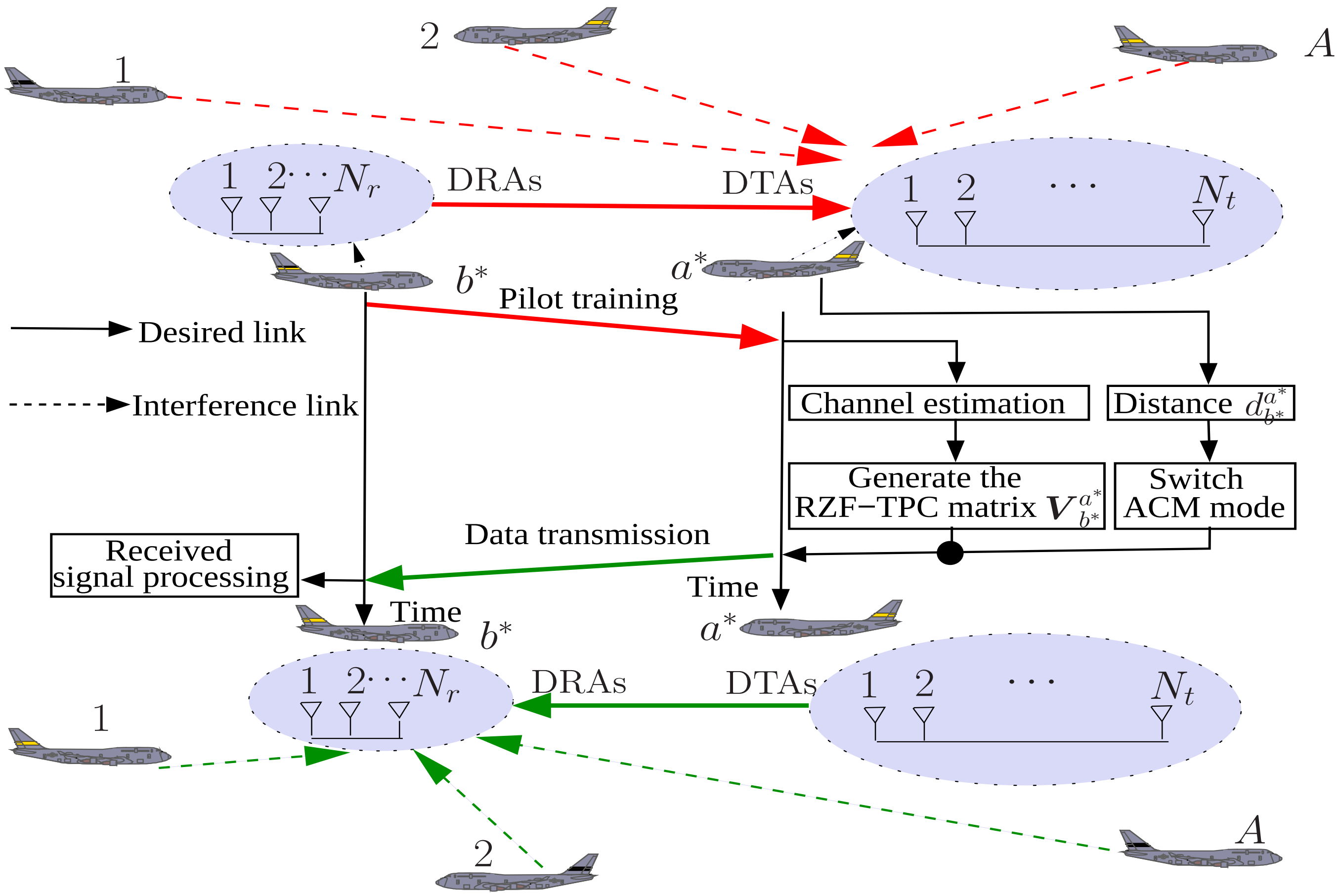
- New **distance-based adaptive coding and modulation** transmission scheme
  - Existing ACM schemes unsuitable, because it is difficult to acquire accurate estimate of instantaneous SNR or other channel-quality measure
  - Achievable throughput of aeronautical channel mainly depends on distance
  -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

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^*

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

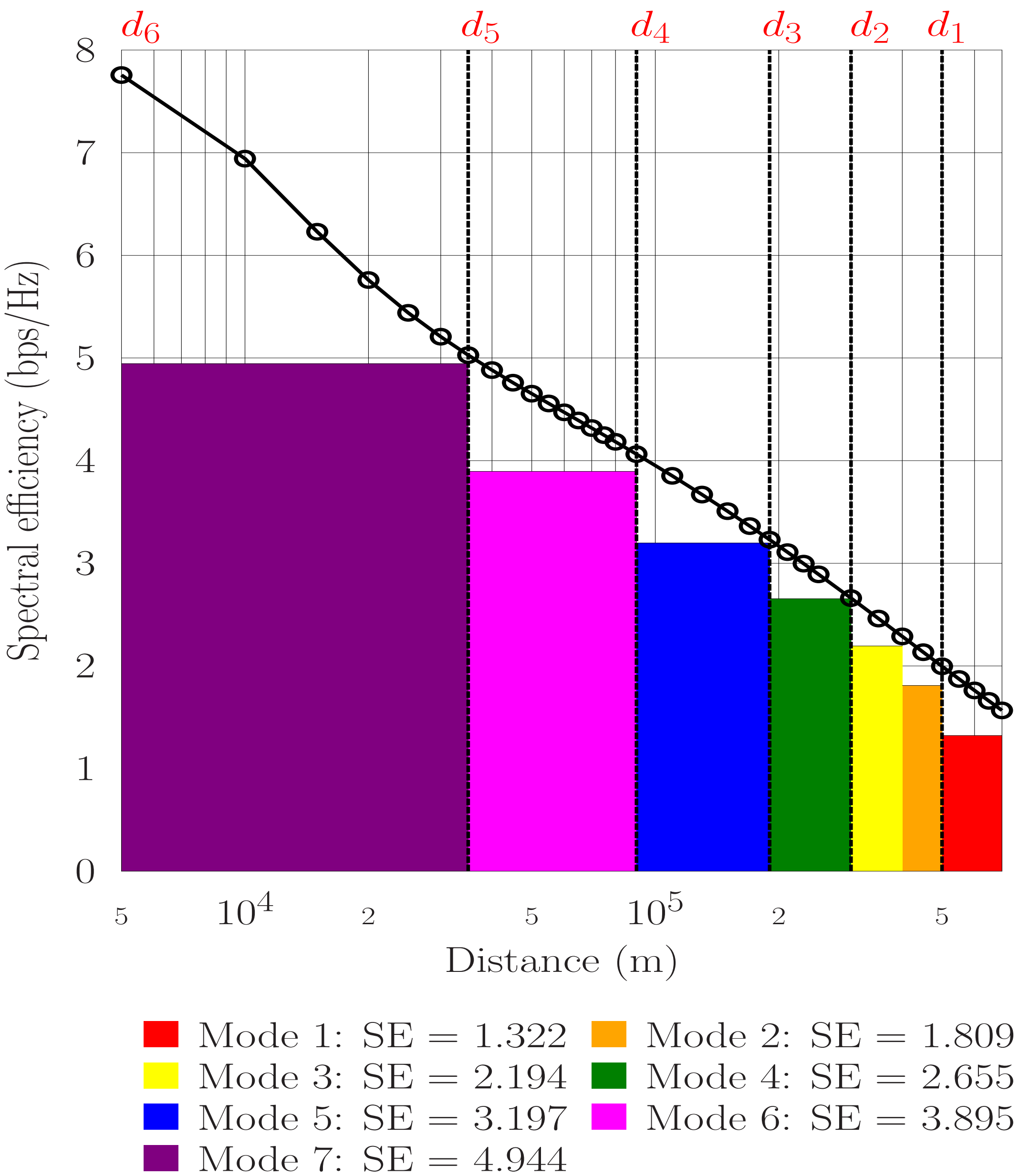
$d_0 = D_{\max}$, **maximum** communication rage, and $d_{b^*}^{a^*} \geq D_{\min}$ for safety **minimum** separation



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
  - $D_{\max}$: maximum distance for communication
  - $D_{\min}$: enforced safety separation
- If $d_k \le d_{b*}^{a*} < d_{k-1}$: choose mode k
  - Mode 1: $d_1 \le d_{b*}^{a*} < d_0 = D_{\max}$
  - Mode 2: $d_2 \le d_{b*}^{a*} < d_1$
  - Mode 3: $d_3 \le d_{b*}^{a*} < d_2$
  - Mode 4: $d_4 \le d_{b*}^{a*} < d_3$
  - Mode 5: $d_5 \le d_{b*}^{a*} < d_4$
  - Mode 6: $d_6 \le d_{b*}^{a*} < d_5$
  - Mode 7: $D_{\min} = d_7 \le d_{b*}^{a*} < d_6$

Most of time ACM will operate in modes 7 or 6



ACM Design Example

Data **Tx antennas** $N_t = 64$, data **Rx antennas** $N_r = 4$, other parameters as in paper (*IEEE J. Selected Areas Communications*, 36(9), 2087–2103, 2018)

Mode k	Modulation	Code rate	Spectral efficiency (bps/Hz)	Switching threshold d_k (km)	Data rate per Rx antenna (Mbps)	Total data rate (Mbps)
1	QPSK	0.706	1.323	500	7.974	31.895
2	8-QAM	0.642	1.813	400	10.876	43.505
3	8-QAM	0.780	2.202	300	13.214	52.857
4	16-QAM	0.708	2.665	190	15.993	63.970
5	16-QAM	0.853	3.211	90	19.268	77.071
6	32-QAM	0.831	3.911	35	23.464	93.853
7	64-QAM	0.879	4.964	5.56	29.783	119.130

- 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 $[d_k,\ d_{k-1}]$
- Even in **worst scenario**, $d_{b^*}^{a^*}$ in 500 km to 740 km, **31 Mbps** is achieved
  - Future L-band digital aeronautical communications system **L-DACS1** only offers **273 kbps** net user rate for direct aircraft-to-aircraft communication

Capability of AANET

- Two aircraft fly at cruising speed of 920 km/h, heading in opposite direction
  - For first **1 min flight**, **7 Gbits** of data transmitted: average data rate **117 Mbps** (not surprisingly as most time at Mode 7)
  - For first **10 min** flight, **48 to 49 Gbits** of data transmitted: average data rate **81 Mbps**
  - Over distance up to 740 km about **24 min** flight (worst senario), **77 Gbits** of data transmitted: average rate **53 Mbps**

- This is with 5 MHz bandwidth, considering 50 MHz to 100 Hz bandwidth for 5G,
  - capable of **connecting** '**City in the Sky**' and realizing '**Internet above the Cloud**'

- **Comment**: It is easier to develop similar oceanic ad hoc network (OANET)
  - To **connect** '**City on the Ocean**' and realizing '**Internet above the Wave**'

Part II: JamCloud: Turning Traffic Jams into Computation Opportunities

Joint work with Dr Y. Li, Tsinghua University

- Xiao, Hou, Wang, Li, Hui, Chen, "JamCloud: Turning traffic jams into computation opportunities – whose time has come," *IEEE Access*, 7, 115797–115815, 2019

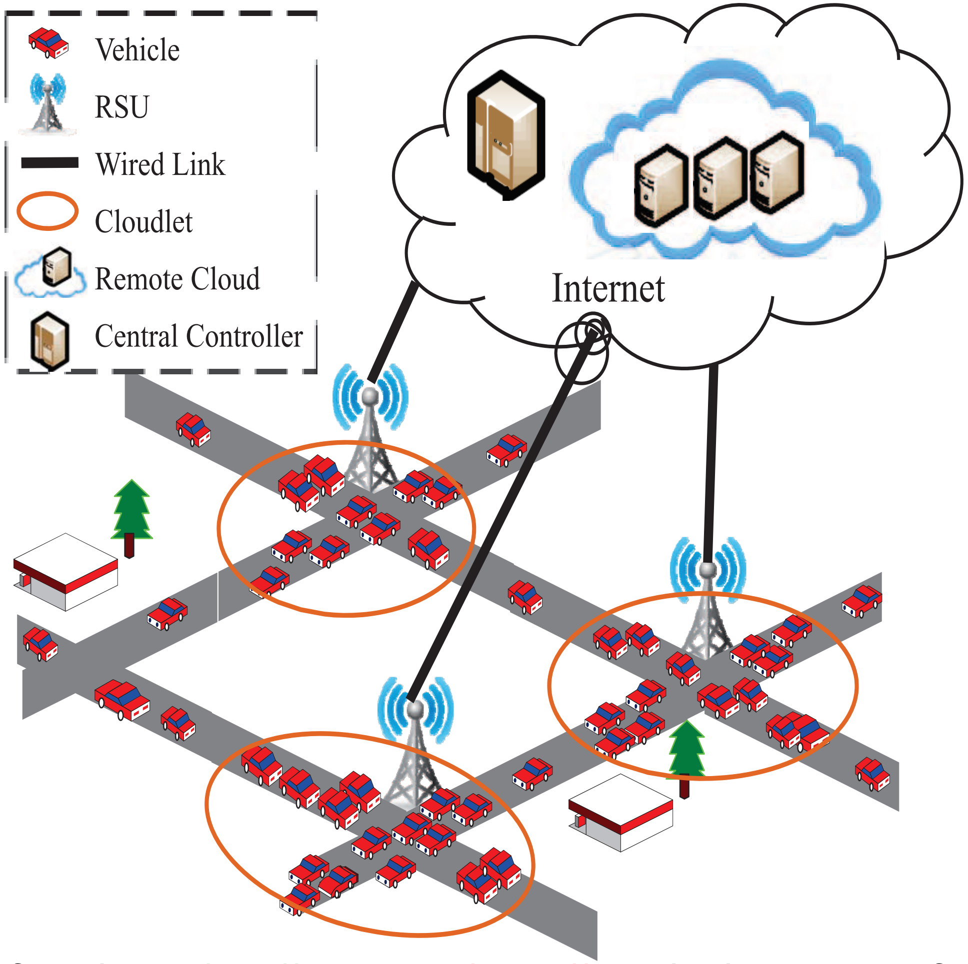
- Hou, Li, Chen, Wu, Jin, Chen, "Vehicular fog computing: A viewpoint of vehicles as the infrastructures," *IEEE Trans. Vehicular Technology*, 65(6) 3860–3873, 2016 (received IEEE Vehicular Technology Society **2019 Jack Neubauer Memorial Award**)

Traffic Jam


- **Traffic jam** don't we hate it
  - In 2018, average London driver lost **227 hours** due to congestion and the cost of congestion per driver was £**1,680**
  - **Beijing could be worst**
- Can't we do something about it
  - How about turning traffic jams into **computation** opportunities

JamCloud

- **Vehicles** equipped with embedded computers **jammed** around **intersections**
  - With **5G**, come **intelligent** city
  - Vehicles linked to BSs/RSUs/APs via V2I
  - Vehicles linked to each other via V2V (D2D)
- Vehicles congested around an intersection form **mobile** or vehicular **cloudlet**
  - BS/RSU/AP can collect computing resource offered by each congested vehicle
  - Aggregate computing resources of vehicles in area to form mobile cloudlet
- BS/RSU/AP can **harvest** computation capacity of mobile cloudlet, which otherwise is wasted
  - Send baseband **processing jobs** to cloudlet
  - Handy cloudlet is nearby for **low latency**



- Heuristically, dynamics of computation capacity of mobile **cloudlet match well** with dynamics of **BS** baseband processing demands
  - Peak communication demand corresponds to cloudlet's peak computing capacity
  - Early morning, very little computing capacity but also very little communication demand

Fundamental Issues

- 5G will enable **intelligent** transport system and intelligent city
  - Collecting resources and allocating computing jobs can be done
- What is **computation capacity** of a vehicular mobile cloudlet?
  - Statistics of vehicles' mobility patterns are fundamental to answer this question
  - From vehicular (taxi) mobility traces, we collect statistics on mobility patterns of vehicles, to model and estimate computation capacity of mobile cloudlet.
- What is overall **achievable performance** of JamCloud consisting of local cloudlets?
  - **Computation capacity** of mobile cloudlet defined as aggregate floating point operation speed (Gflops/s)
  - Satisfying probability of cloudlet: **Computation demands** met by its **computation resources**
  - Probability of cloud-wide satisfaction: If all **cloudlets** are in computationally satisfactory state, **JamCloud** in **computationally satisfactory state**

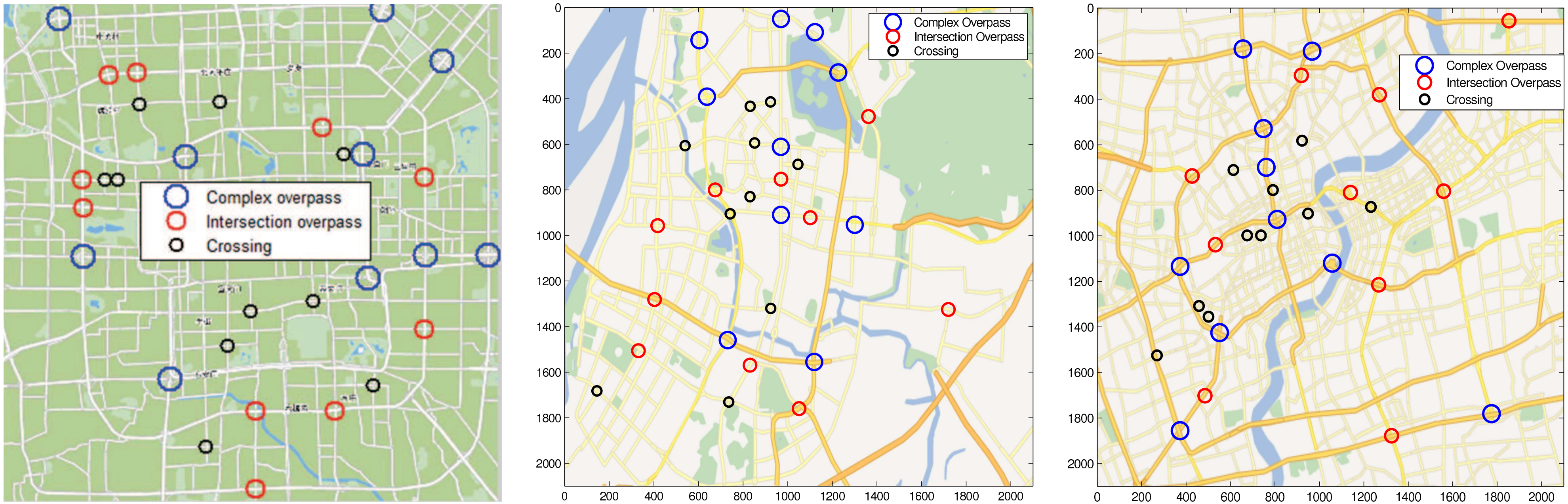
Statistic Model

- Mobile cloudlet: vehicles enter cloudlet, congest or queue at intersection, and leave cloudlet – **incoming** vehicles, staying (**resident**) time, **outgoing** vehicles
  - **Poisson** distributions for numbers of incoming, outgoing and resident vehicles
  - Means of incoming, outgoing and resident numbers fitted from vehicular traces
- **JamCloud** consists of N vehicular cloudlets: $\{A_1, \cdots, A_N\}$
  - **Queueing network** model: $\mathcal{N} = \{A_1, \cdots, A_N\}$ N server nodes with infinite queue size
  - Exogenous arrival to each server follows Poisson process, hence an **open Jackson network**
- We use large scale **taxi** mobility traces to model vehicular mobility patterns, and fit model parameters
  - Readily available, sufficiently large, spatially and temporally well distributed
  - To include **all vechicle**, such as buses and private cars, we only need to '**scale up**' by a factor

Parameter Fitting

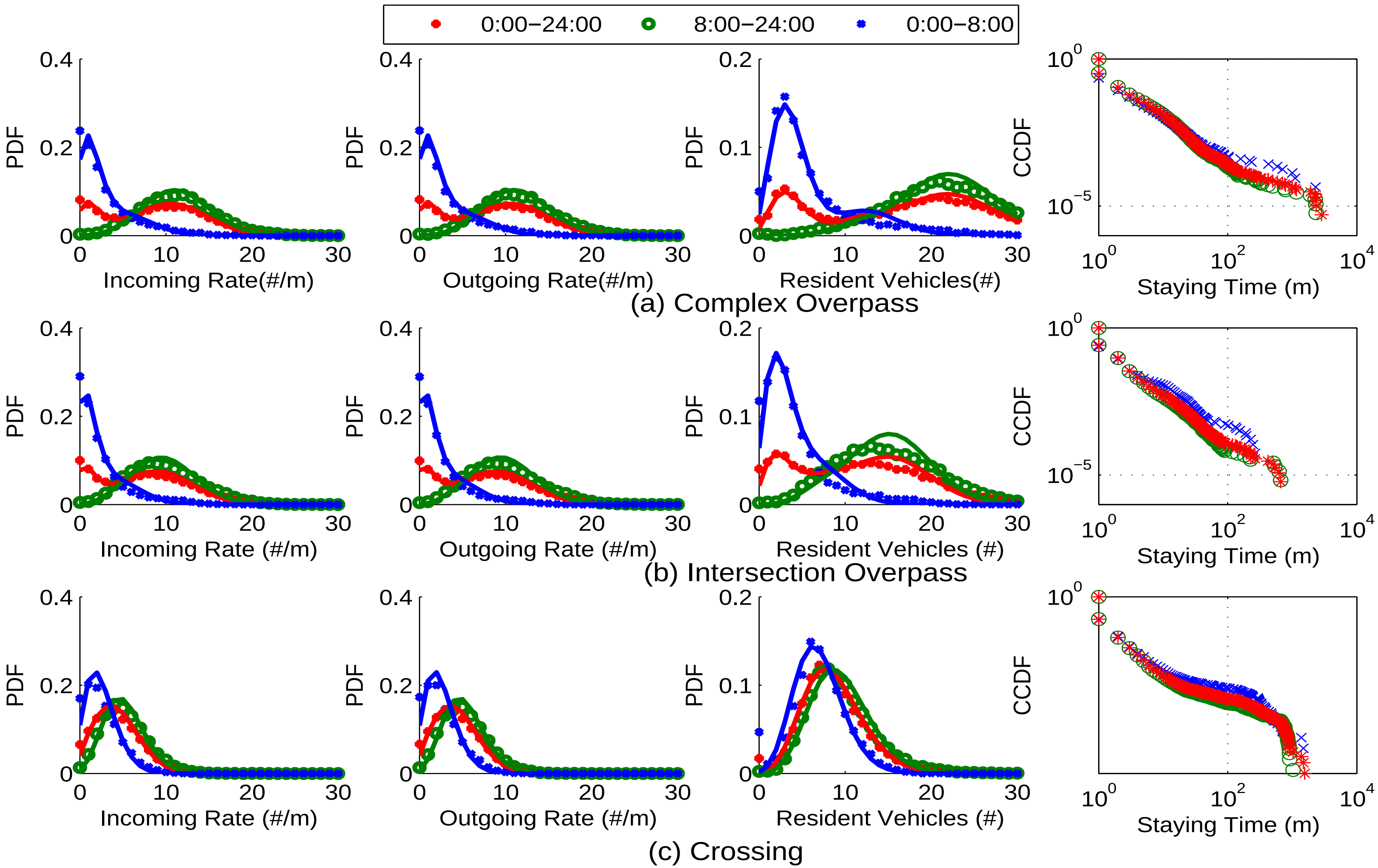
- Taxi mobility traces of Beijing, Nanjing and Shanghai are used to collect statistics

- Locations of the selected regions (complex overpass, intersection overpass, crossing)in: (a) Beijing, (b) Nanjing, and (c) Shanghai.



(a) (b) (c)

Beijing: Cloudlet Modeling

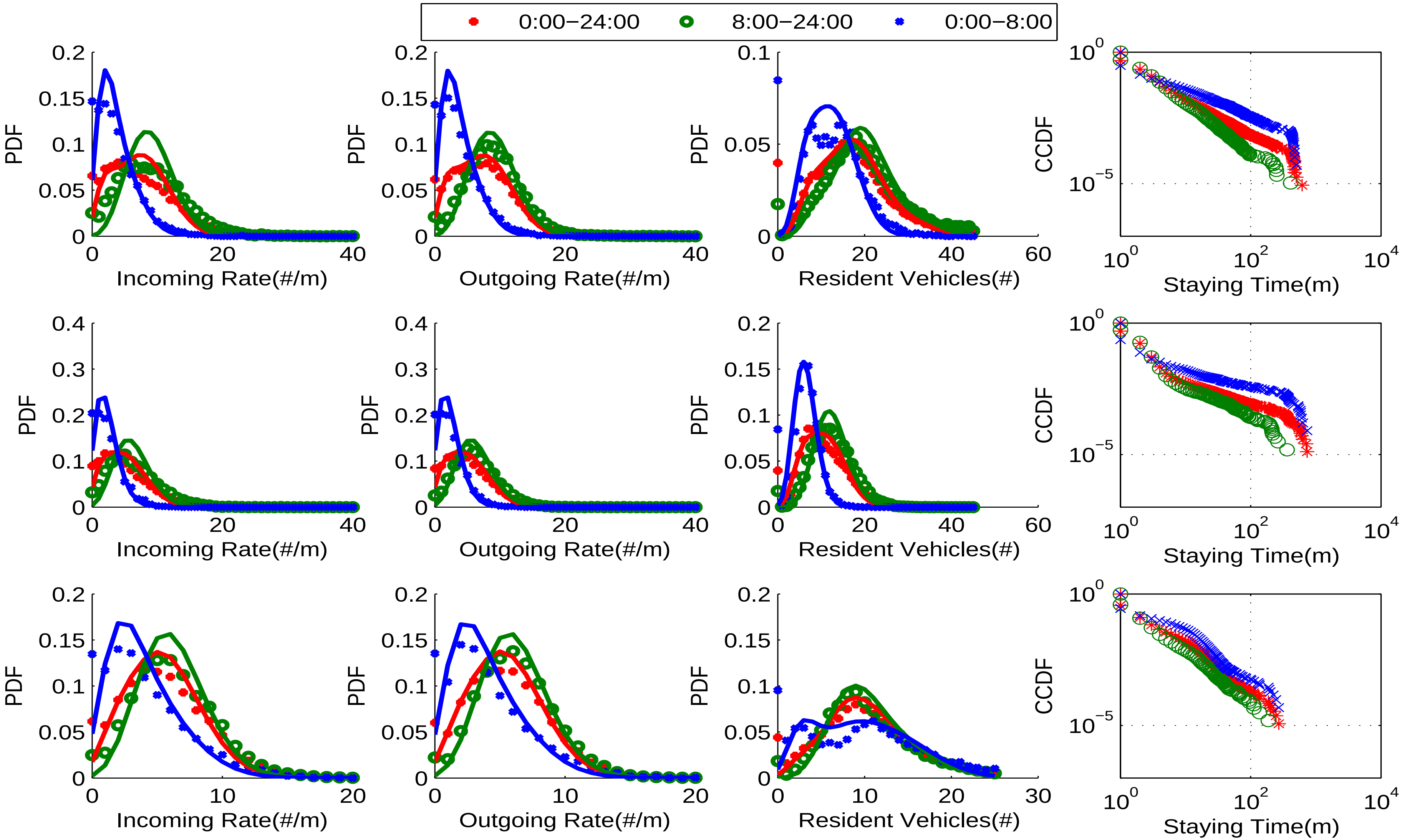


(a) Complex Overpass

(b) Intersection Overpass

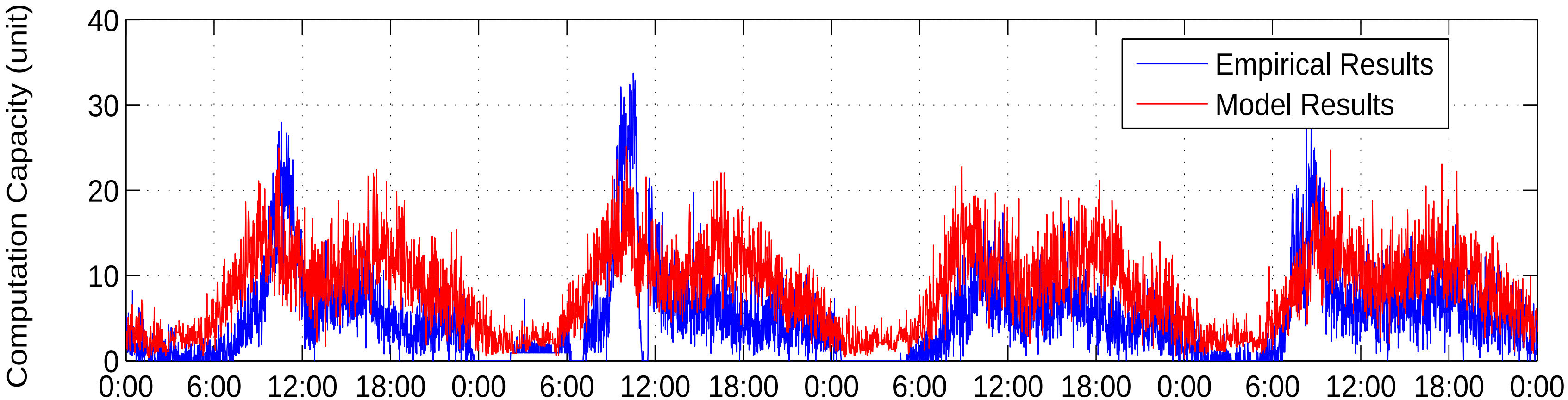
(c) Crossing

Nanjing: Cloudlet Modeling

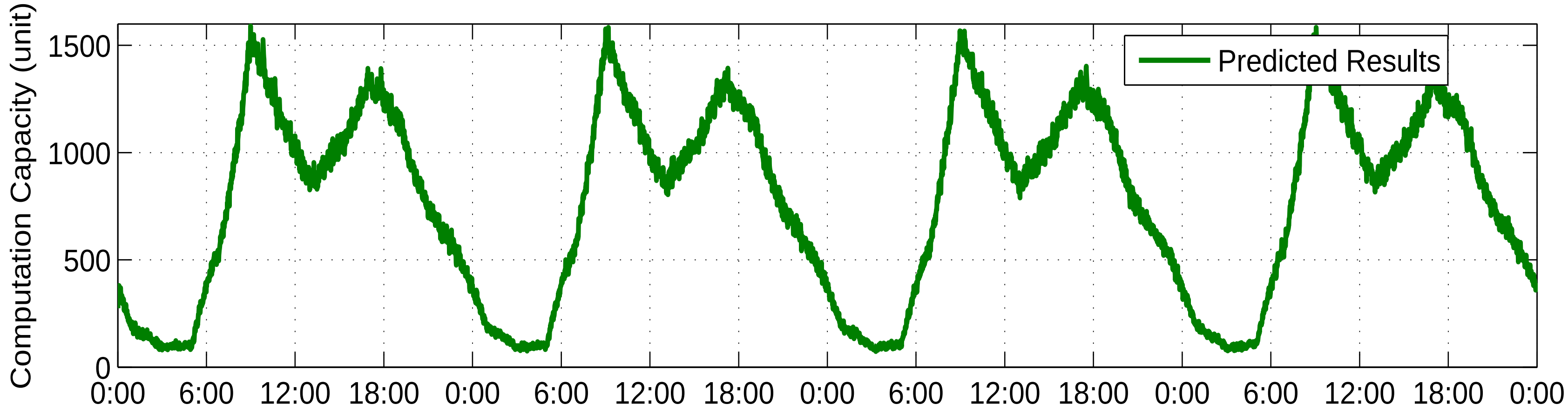


Beijing: Cloudlet Computing Capacity

- Predicted Results: assume total number of vehicles on road in Beijing is 3 million
- **Two** capacity peaks correspond to two **rush hours**, and low capacity at earily morning



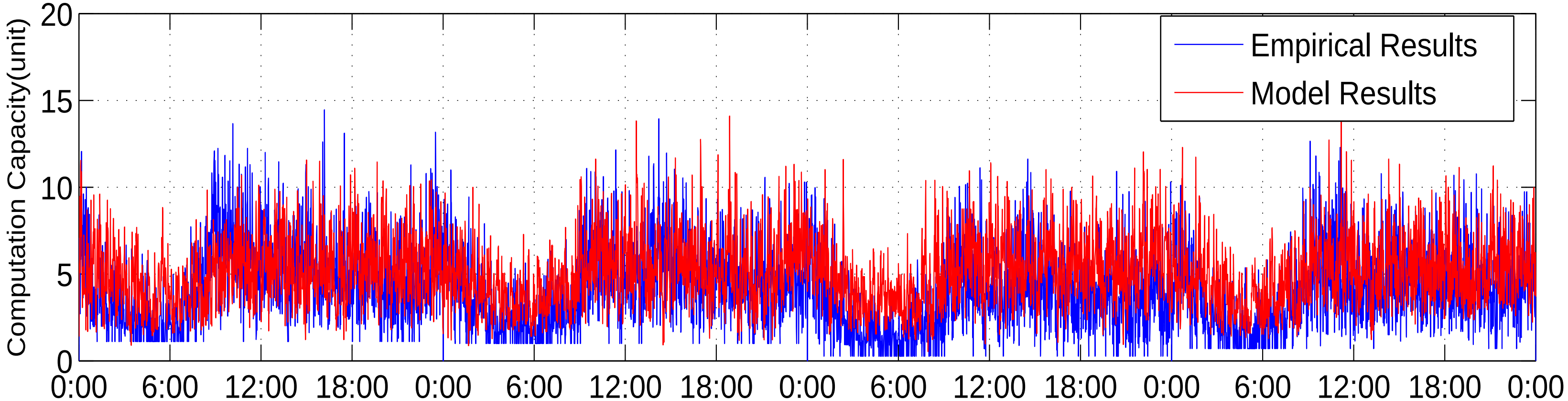
(a) Comparing of empirical results obtained from the trace with theoretical results calculated by our proposed model



(b) Predicted results calculated by the proposed model

Shanghai: Cloudlet Computing Capacity

- Predicted Results: assume total number of vehicles on road in Shanghai is 2,470,000
- Capacity peak **all day to midnight**, and low capacity at earily morning



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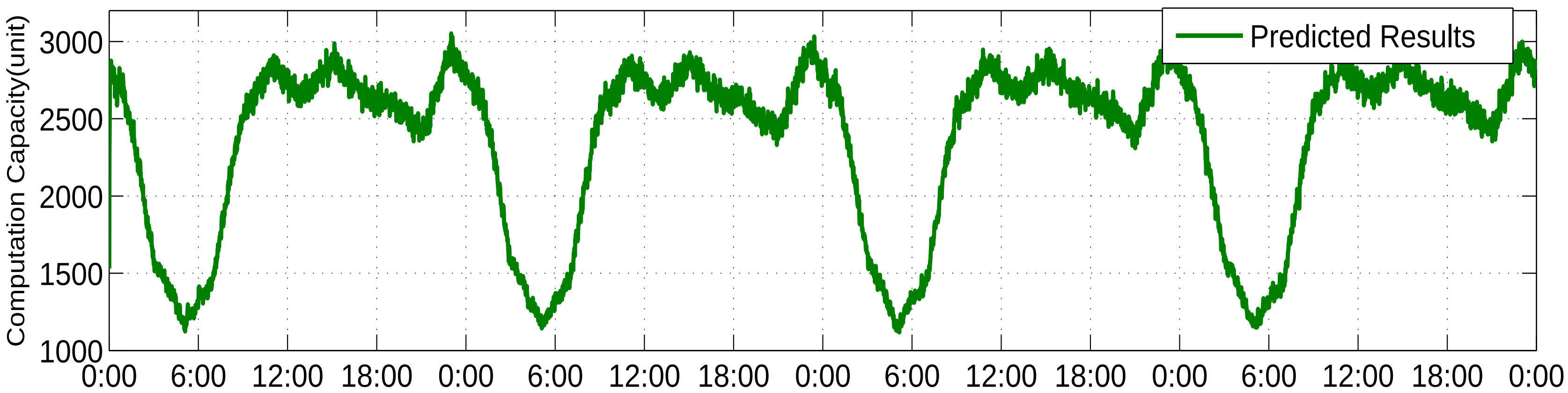
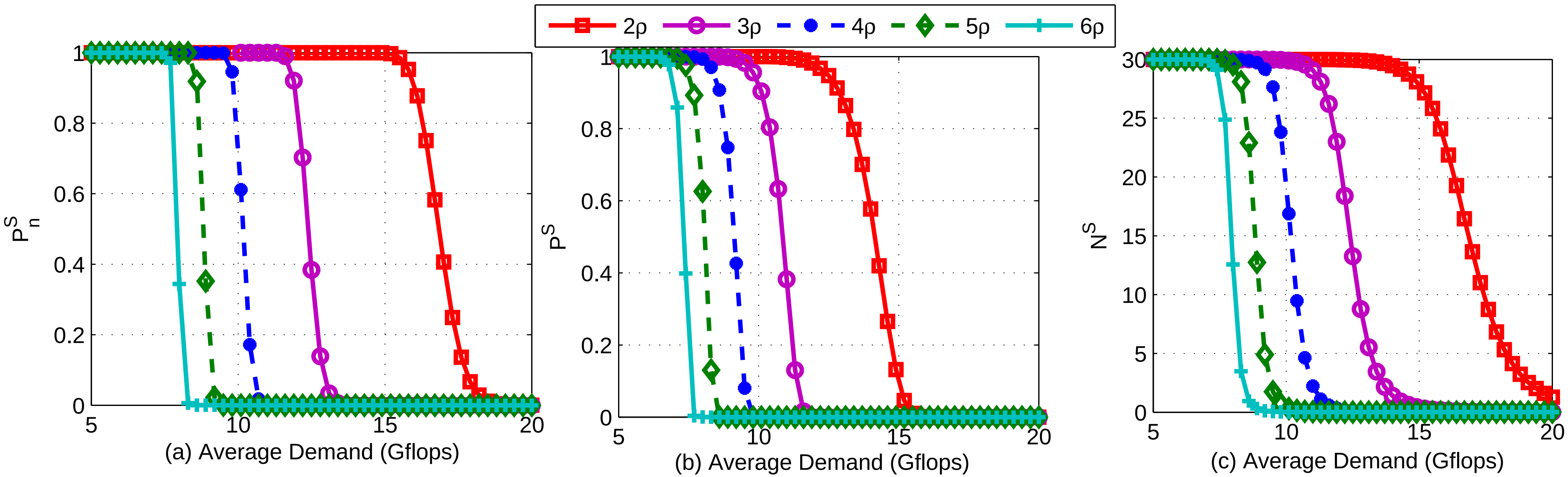


(b)Predicted results calculated by the proposed model

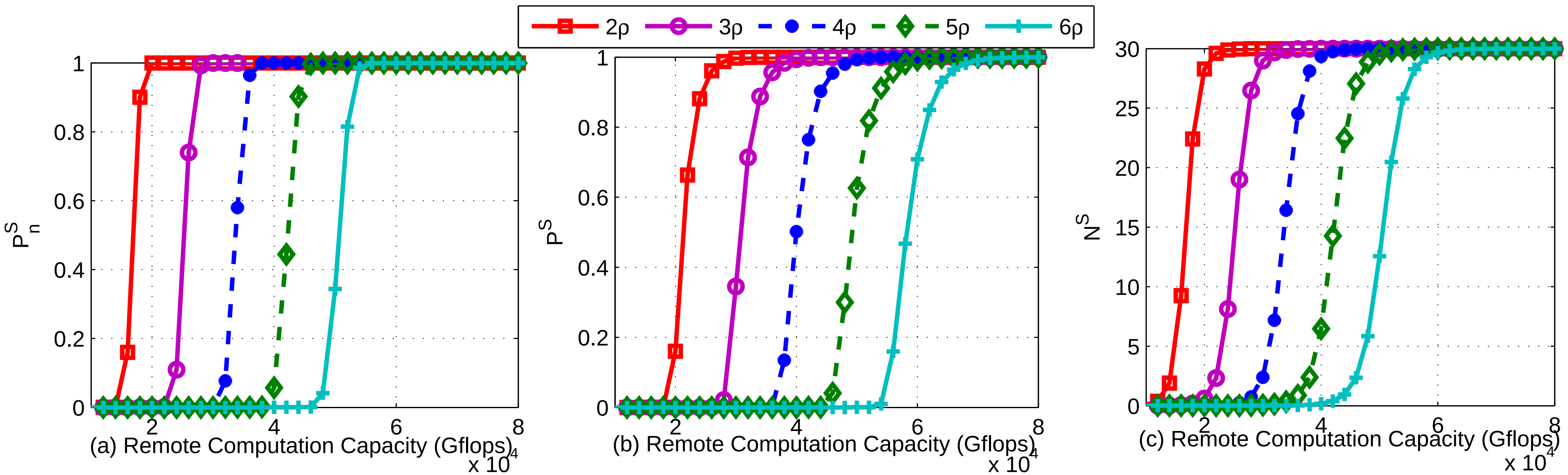
JamCloud Performance

- $N = 30$ selected intersections in Beijing, i.e., **30 cloudlets**
  - ρ: average taxi number of cloudlet, $m \times \rho$: average vehicle number of cloudlet
  - **Individual** vehicles capacity 2 Gflops
  - Total **remote cloud** capacity available: 50,000 Gflops
- (a) cloudlet satisfying probability, (b) cloudlet-wide satisfying probability, and (c) number of satisfied cloudlets
  - For 2ρ, when **average demand** per cloudlet is 10 Gflops, number of satisfied cloudlets is 30, cloudlet satisfying probability is 100%, and cloudlet-wide satisfying probability is 100%



JamCloud Performance (2)

- $N = 30$ selected intersections in Beijing, i.e., **30 cloudlets**
  - ρ: average taxi number of cloudlet, $m \times \rho$: average vehicle number of cloudlet
  - **Individual** vehicles capacity 2 Gflops
  - **Average computation demand** 10 Gflops
- (a) cloudlet satisfying probability, (b) cloudlet-wide satisfying probability, and (c) number of satisfied cloudlets
  - For 2ρ, **very little remote cloud** is needed, less than 4 Gflops, to achieve all 30 cloudlets satisfied, cloudlet satisfying probability 100%, and cloudlet-wide satisfying probability 100%



(a) Remote Computation Capacity (Gflops)

(b) Remote Computation Capacity (Gflops)

(c) Remote Computation Capacity (Gflops)

Discussions

- Dynamical capacity of JamCloud matches well network communication demand
  - **Peak computation capacity** of vehicular cloudlet **coincides** with **peak communication/computing demand** of BS/RSU/AP
  - Suitable for helping **5G** baseband signal processing **computation**
  - **JamCloud** turns energy otherwise wasted into computation opportunities, helping to realize **greener** communications
- **ParkingCloud**: vehicles parked at street or **car park** can be similarly turned into **cloud computing** capacity
  - With revolution of making vehicles electric, car park is also charging station, ParkingCloud will be particularly relevant
- 5G revolution brings **integrated intelligent communication and computing**
  - New concepts, such as JamCloud and ParkingCloud will contribute to make intelligent communication and computing system greener

Conclusions

- To truly realize **anywhere anytime** 5G, we need to connect **City in the Sky** and **City on the Ocean**, last frontier of **connection black holes**
  - Commercial aeronautical ad hoc network and oceanic ad hoc network to complete **connecting** world, realizing **Internet above Cloud** and **Internet above Wave**
  - In connecting City in the Sky, effective air-to-air transmission technology is key
- 5G will enable integrated **intelligent** communication and computing, and will **revolutionize** society
  - Vital to making intelligent communication and computing system **greener**, e.g., with **JamCloud** and **ParkingCloud**
  - JamCloud, turning traffic jams into computation opportunities, in particular, will help to make 5G greener