MobiSys2012

A Close Examination of Performance and Power Characteristics of 4G LTE Networks

Junxian Huang[1] Feng Qian[1] Alexandre Gerber[2]
Z. Morley Mao[1] Subhabrata Sen[2] Oliver Spatscheck[2]

[1]University of Michigan [2]AT&T Labs - Research

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LTE is new, requires exploration

- 4G **LTE (Long Term Evolution)** is future trend
  - Initiated by 3GPP in 2004
    - **100**Mbps DL, **50**Mbps UL, **<5**ms latency
  - Entered commercial markets in 2009
- Lessons from 3G UMTS networks
  - Radio Resource Control (RRC) state machine is important
  - App traffic patterns trigger state transitions, different states determine UE power usage and user experience
  - State transitions incur energy, delay, signaling overhead

LTE state machine

LTE power model

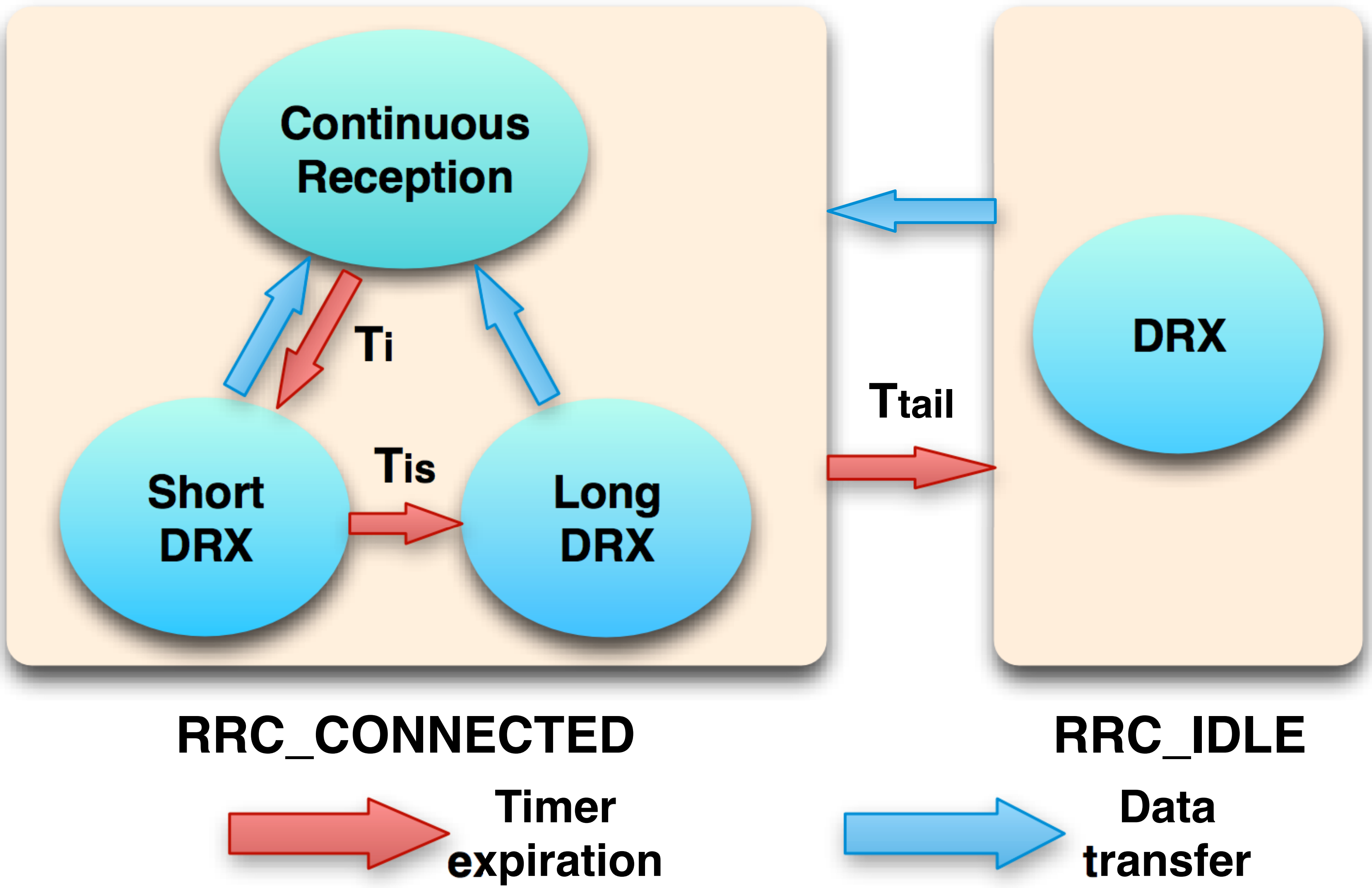
Network performance

Energy efficiency

Parameter configuration

Mobile application

RRC state transitions in LTE



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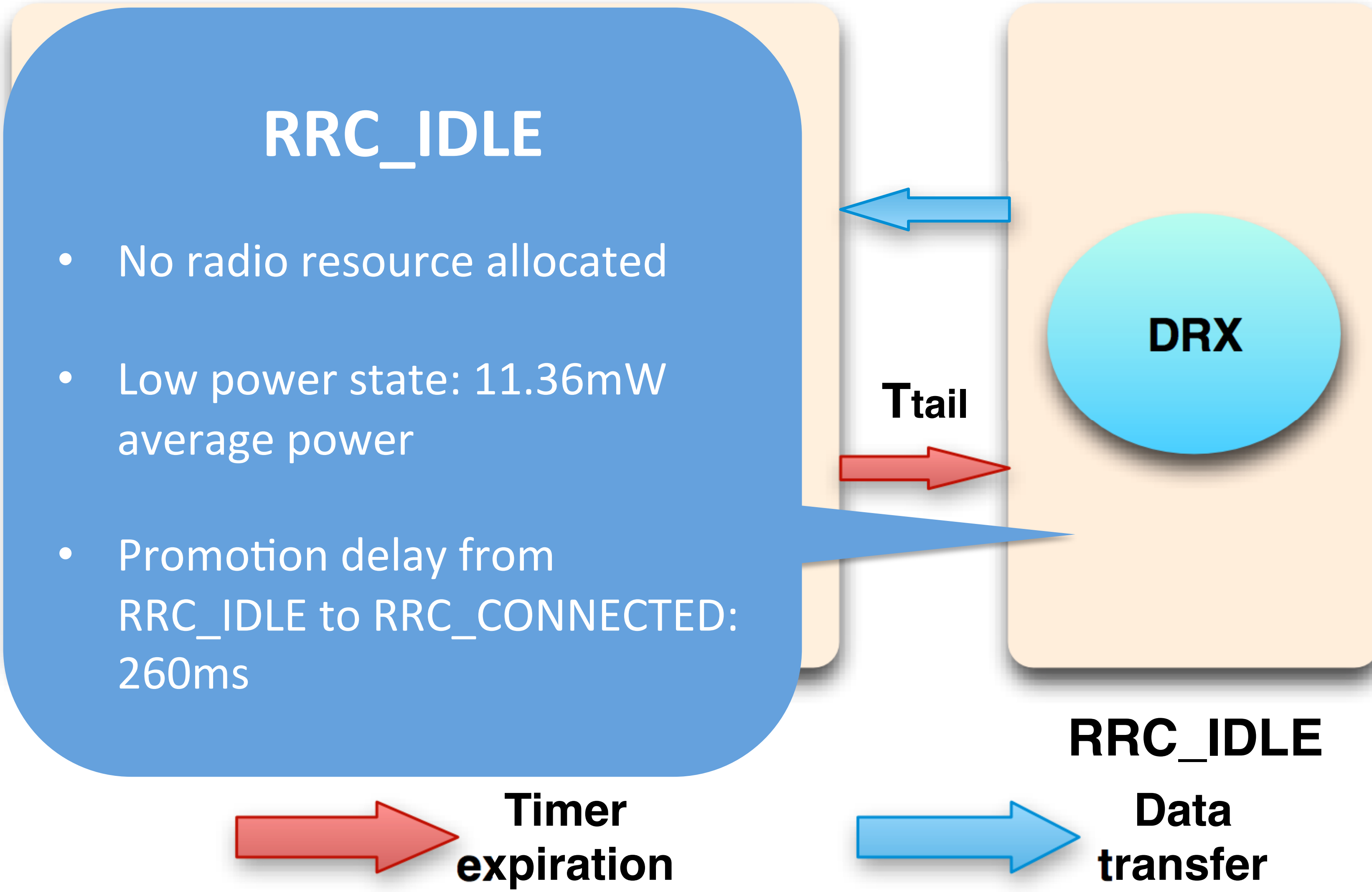

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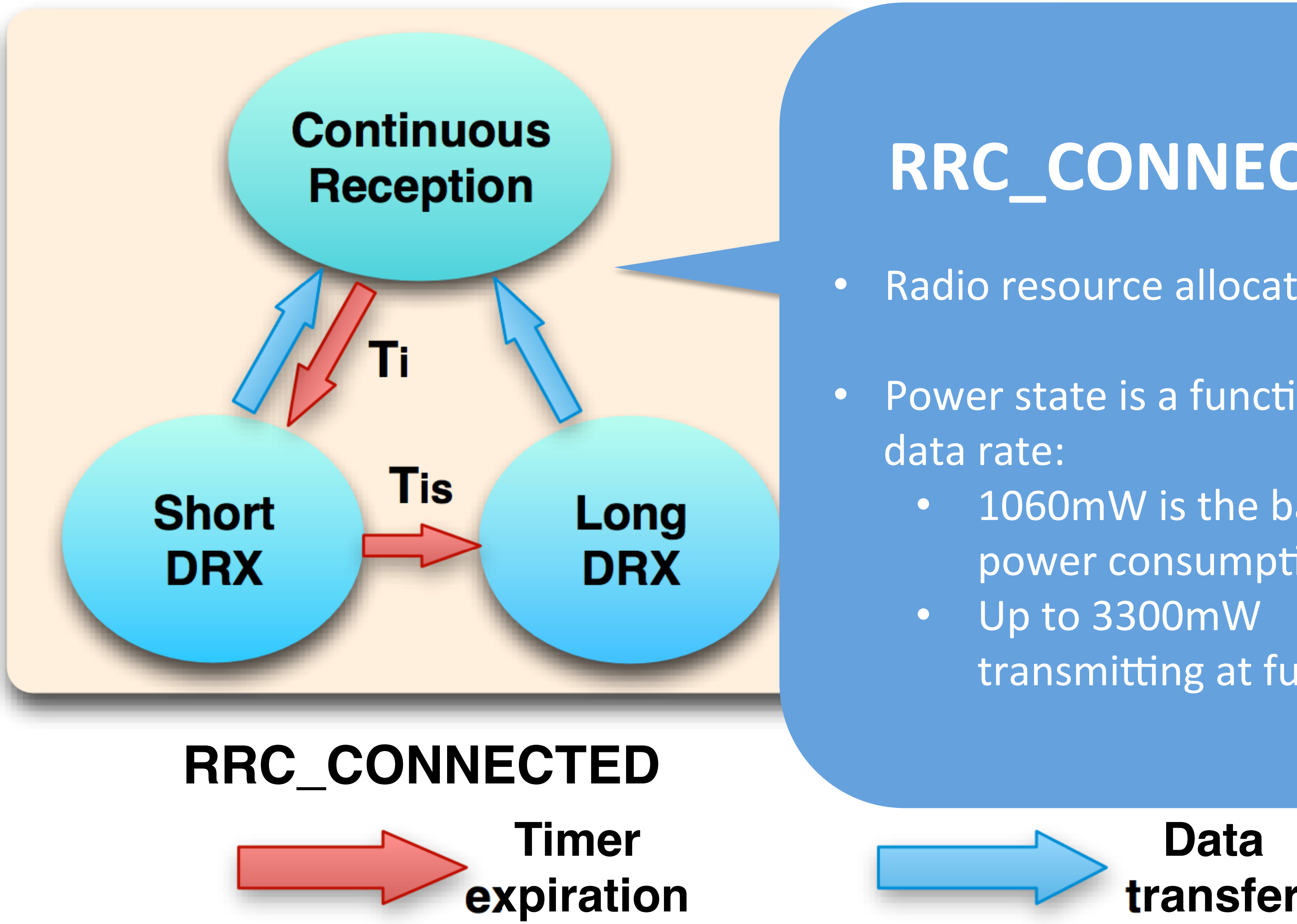
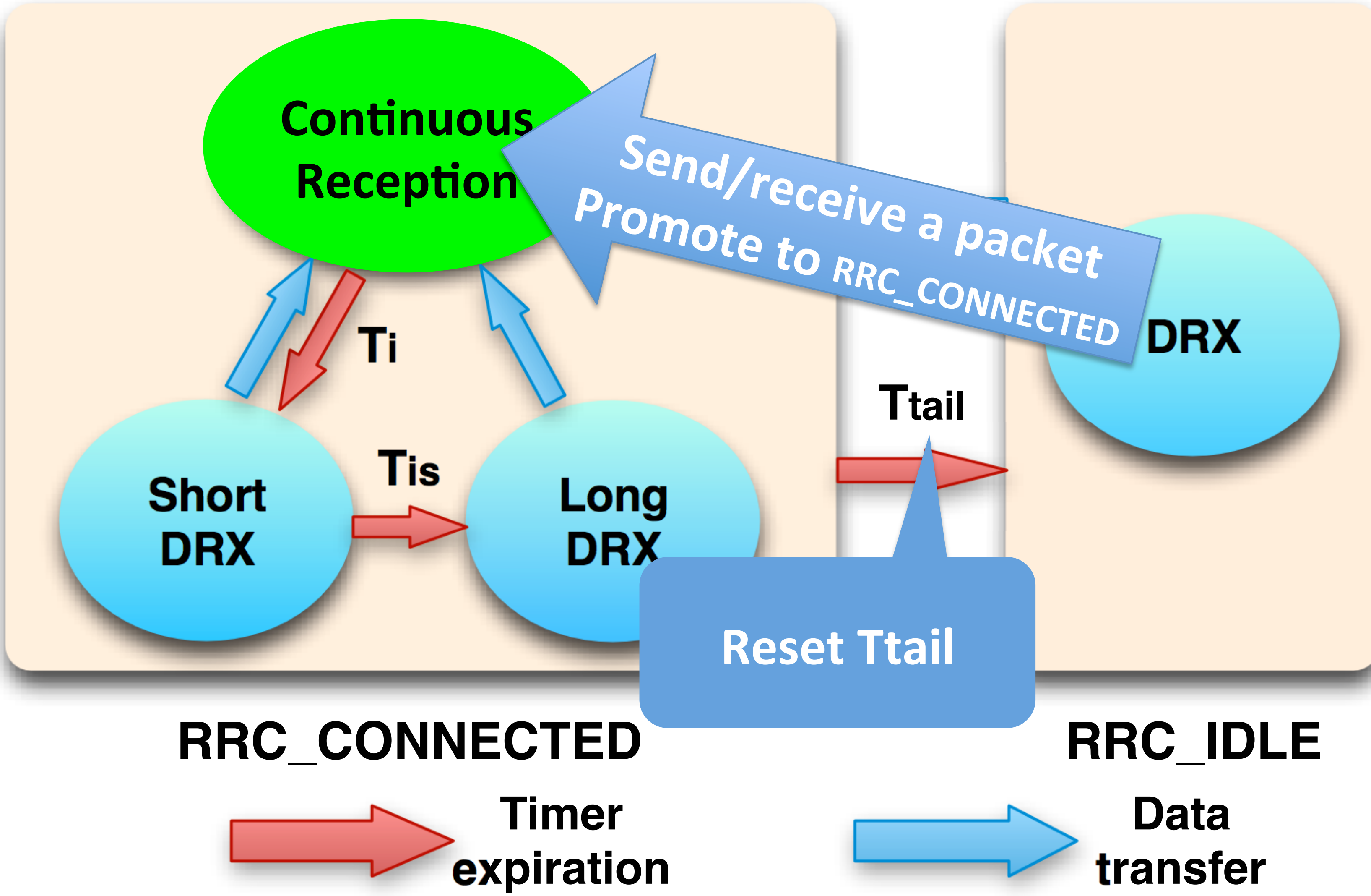


RRC_CONNECTED

- Radio resource allocated
- Power state is a function of data rate:
  - 1060mW is the base power consumption
  - Up to 3300mW transmitting at full speed

RRC state transitions in LTE



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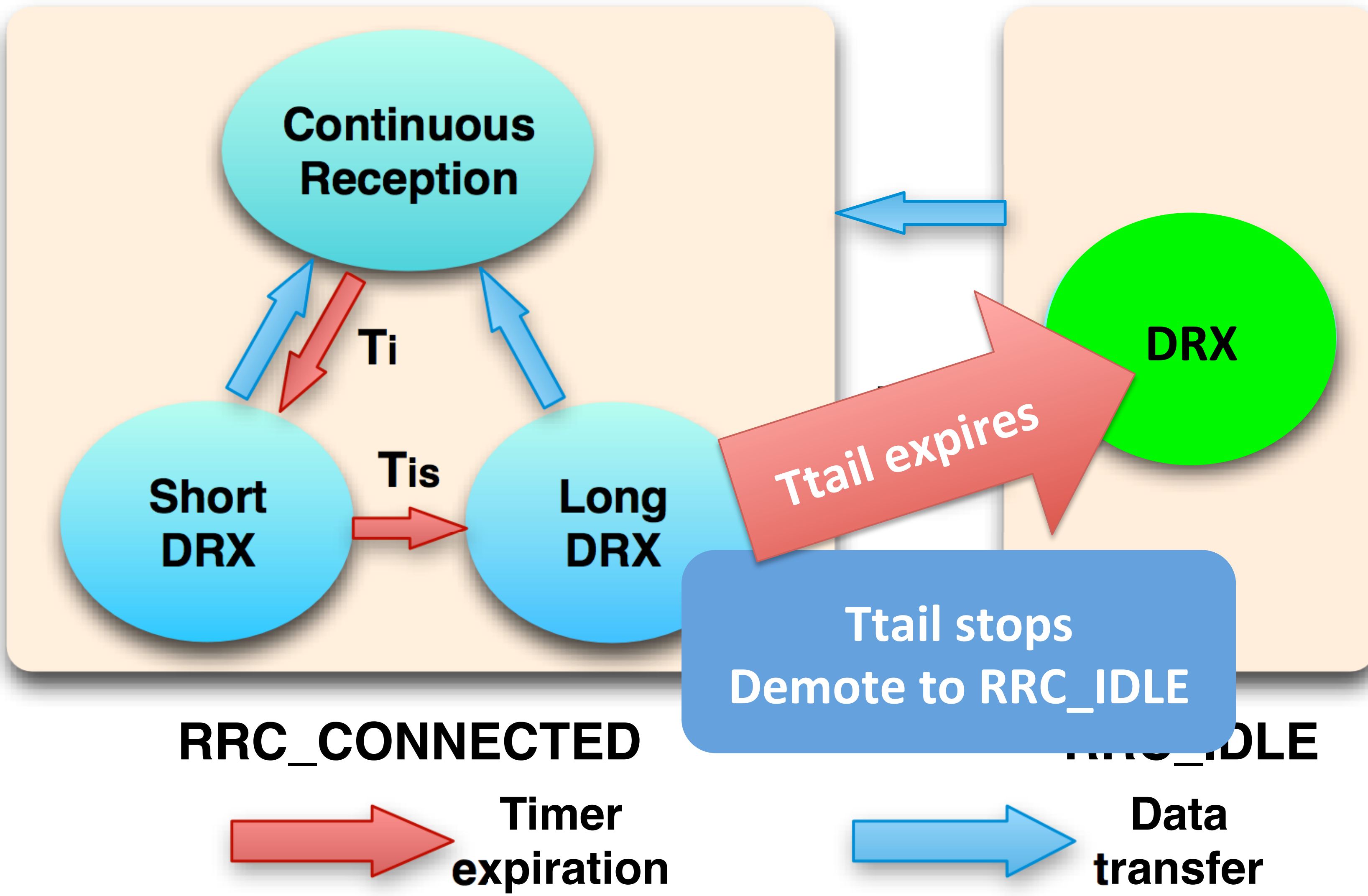
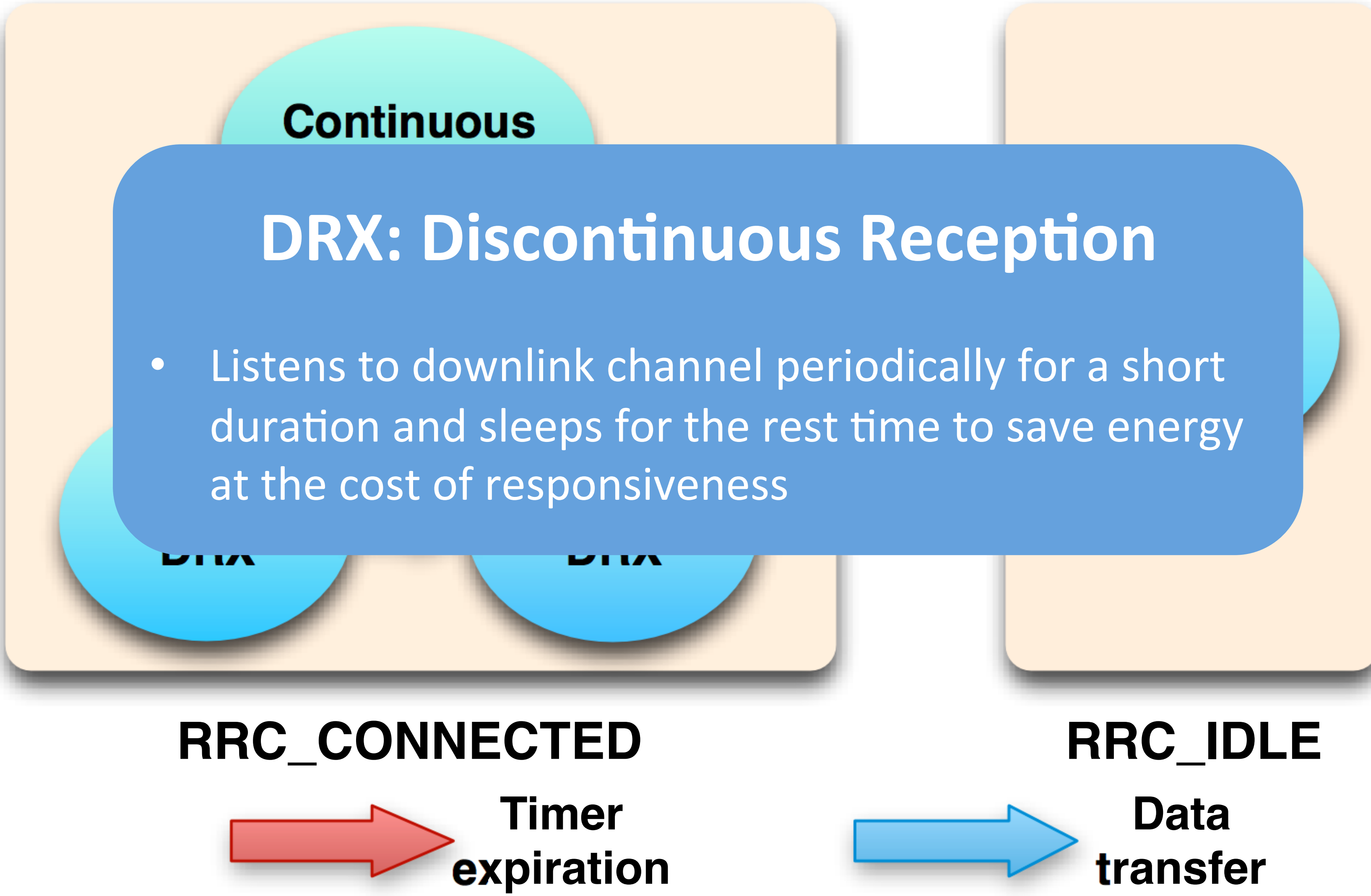


Tradeoffs of *Ttail* settings

Ttail setting	Energy Consumption	# of state transitions	Responsiveness
Long	High	Small	Fast
Short	Low	Large	Slow

RRC state transitions in LTE



DRX: Discontinuous Reception

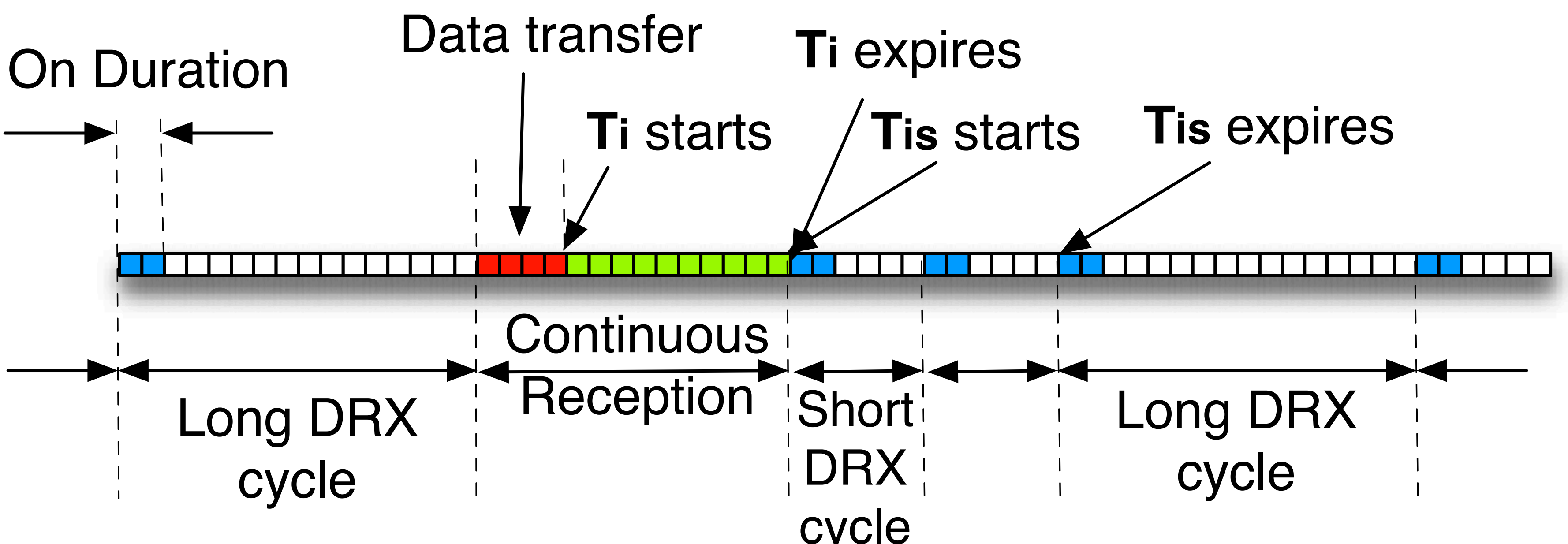
- Listens to downlink channel periodically for a short duration and sleeps for the rest time to save energy at the cost of responsiveness

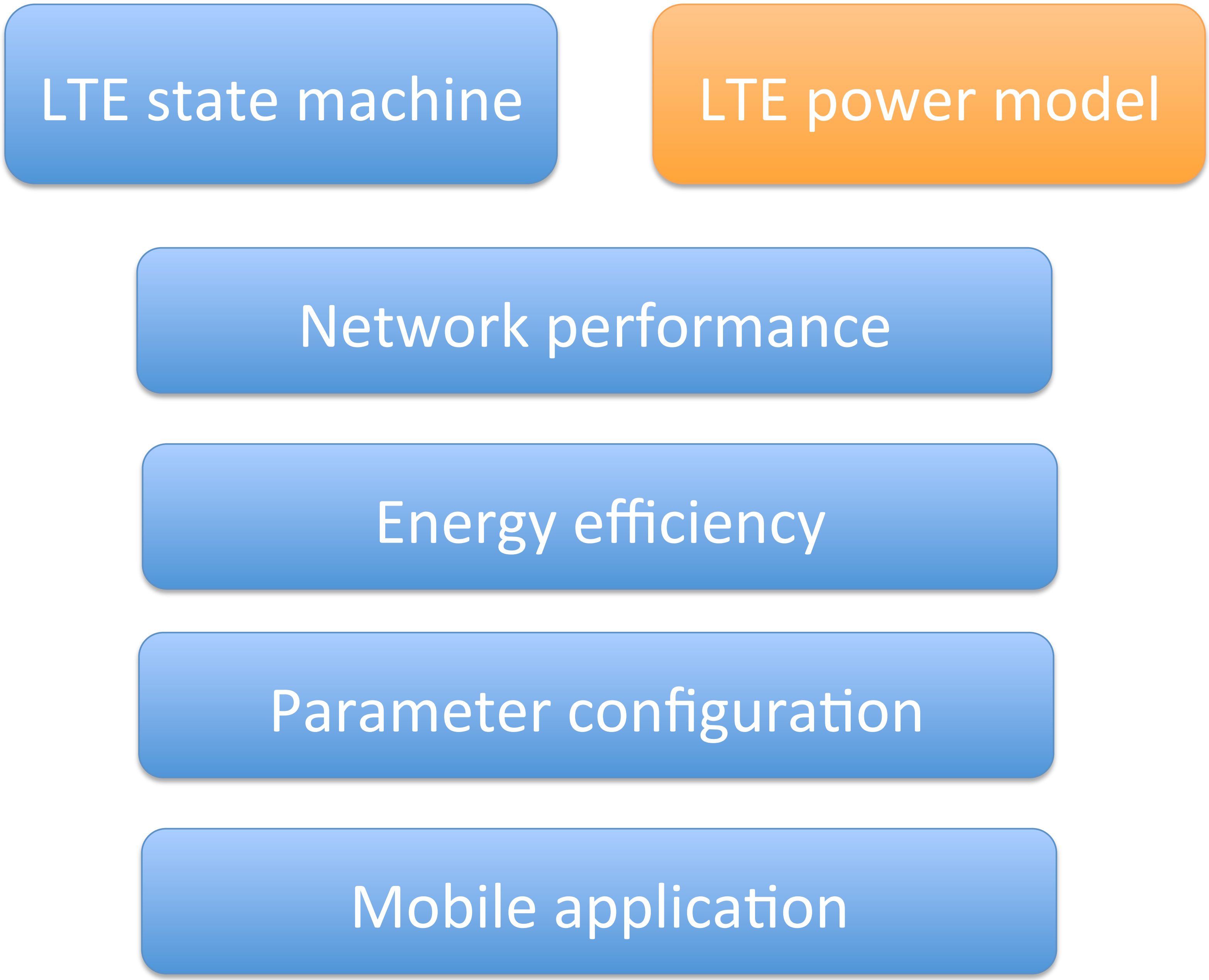
Discontinuous Reception (DRX): micro-sleeps for energy saving

- In LTE 4G, DRX makes UE ***micro-sleep periodically*** in the RRC_CONNECTED state
  - Short DRX
  - Long DRX
- DRX incurs tradeoffs between energy usage and latency
  - Short DRX – *sleep less and respond faster*
  - Long DRX – *sleep more and respond slower*
- In contrast, in UMTS 3G, UE is always listening to the downlink control channel in the data transmission states

DRX in LTE

- A DRX cycle consists of
  - 'On Duration' - UE monitors the downlink control channel (PDCCH)
  - 'Off Duration' - skip reception of downlink channel
- T_i: Continuous reception inactivity timer
  - When to start Short DRX
- T_{is}: Short DRX inactivity timer
  - When to start Long DRX

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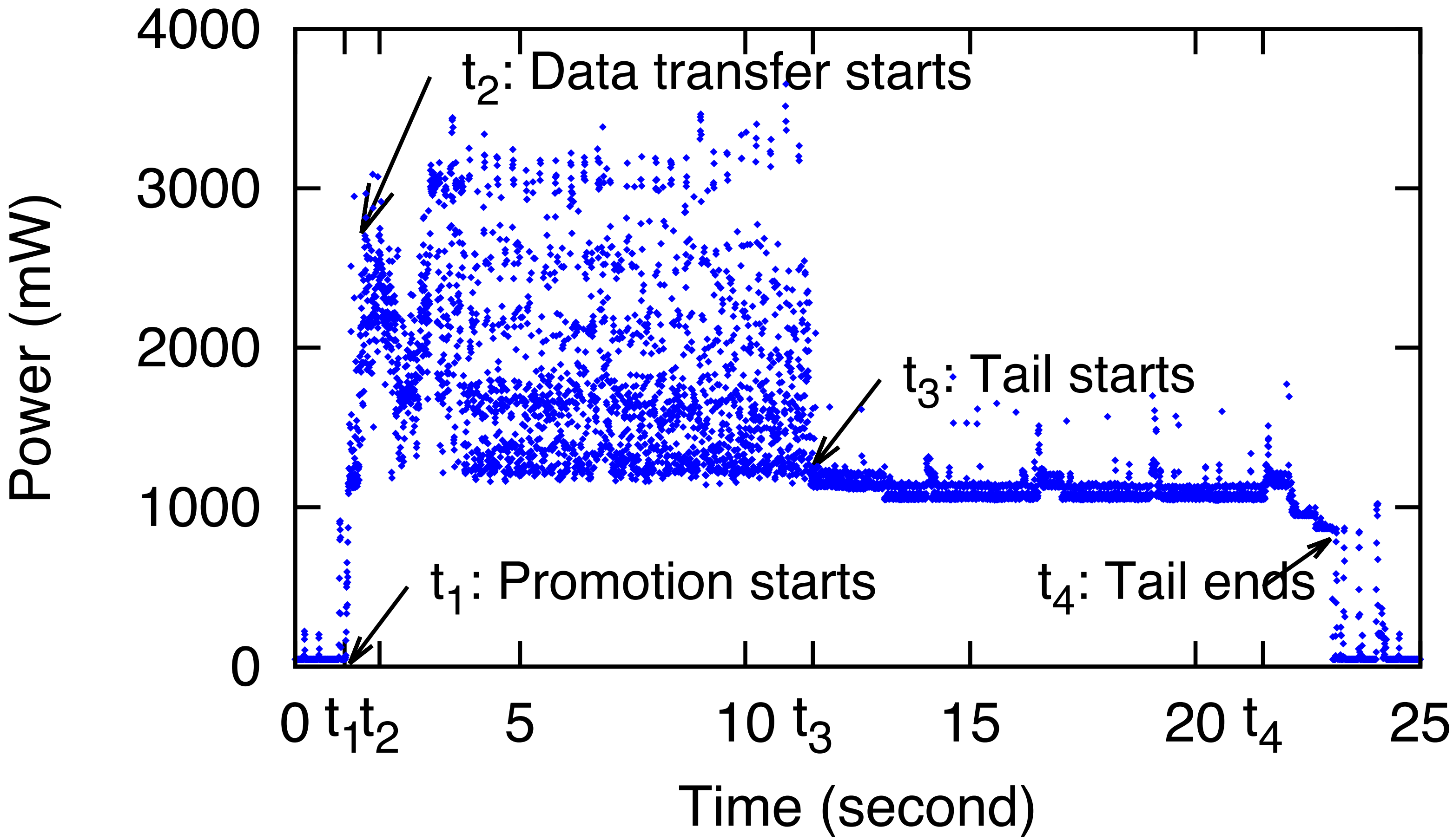
Power trace of RRC state transitions



The data points are sampled and DRX in RRC_CONNECTED tail is not obvious due to the low sampling rate

LTE power model

- Measured with a LTE phone and Monsoon power meter, averaged with repeated samples

	Power* (mW)	Duration (ms)	Periodicity (ms)
Screen off (base)	11.4±0.4	N/A	N/A
Screen 100% on	847.2±2.7	N/A	N/A
LTE promotion	1210.7±85.6	T_{pro}: 260.1±15.8	N/A
LTE Short DRX On in **RRC_CONNECTED**	1680.2±15.7	T_{on}: 1.0±0.1	T_{ps}: 20.0±0.1
LTE Long DRX On in **RRC_CONNECTED**	1680.1±14.3	T_{on}: 1.0±0.1	T_{pl}: 40.1±0.1
LTE Off Duration in **RRC_CONNECTED**	1060.0±3.3	T_{tail}: 11576.0±26.1	N/A
LTE DRX On in **RRC_IDLE**	594.3±8.7	T_{oni}: 43.2±1.5	T_{pi}: 1280.2±7.1

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LTE power model

- Measured with a LTE phone and Monsoon power meter, averaged with repeated samples

	Power*	Duration	Periodicity (ms)
Scre[illegible]	[illegible]	[illegible]	N/A
Scre[illegible]	[illegible]	[illegible]	N/A
LTE[illegible]	[illegible]	[illegible]	N/A
LTE S[illegible] in RRC[illegible]	[illegible]	[illegible]	T_{ps}: [illegible]0±0.1
LTE L[illegible] in RRC[illegible]	[illegible]	[illegible]	T_{pl}: [illegible]1±0.1
LTE C[illegible] in RRC_CONNECTED	[illegible]	11576.0±26.1	N/A
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- **P(on) – P(off) = 620mW, DRX saves 36% energy in RRC_CONNECTED**
- **High power levels in *both* On and Off durations in the DRX cycle of RRC_CONNECTED**

LTE consumes more instant power than 3G/WiFi in the high-power tail

- Average power for WiFi tail
  - **120** mW
- Average power for 3G tail
  - **800** mW
- Average power for LTE tail
  - **1080** mW

Power model for data transfer

- A linear model is used to quantify instant power level:
  - Downlink throughput t_d Mbps
  - Uplink throughput t_u Mbps

$$P = \alpha_u t_u + \alpha_d t_d + \beta$$

Data transfer power model

< 6% error rate in evaluations with real applications

Energy per bit comparison

- LTE's high throughput compensates for the promotion energy and tail energy

Transfer Size	LTE μ J / bit	WiFi μ J / bit	3G μ J / bit
10KB	**170**	6	100
10MB	**0.3**	0.1	4

Total energy per bit for downlink bulk data transfer

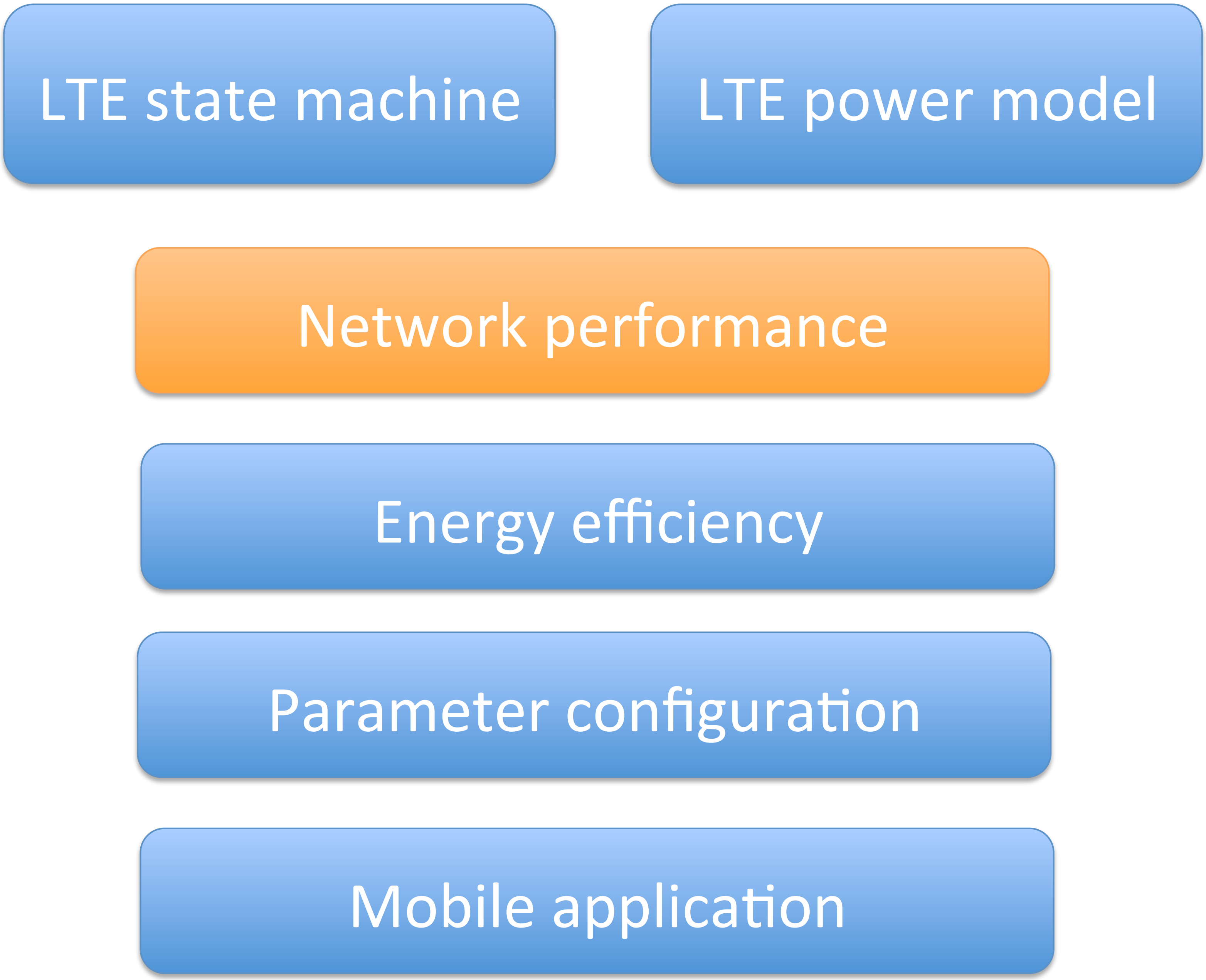
Energy per bit comparison

- LTE's high throughput compensates for the promotion energy and tail energy

Small data transfer, LTE wastes energy
Large data transfer, LTE is energy efficient

10MB	**0.3**	0.1	4

Total energy per bit for downlink bulk data transfer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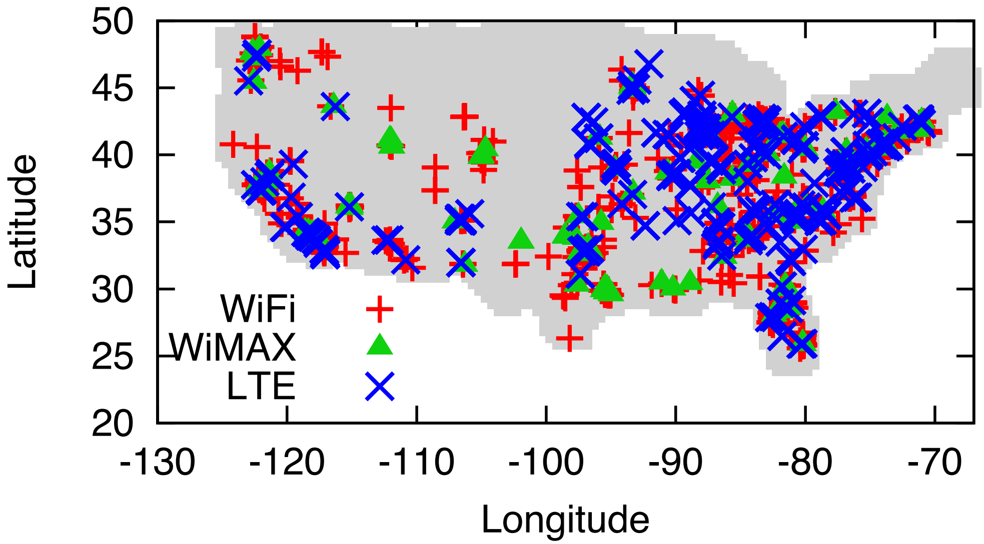
Network characteristics

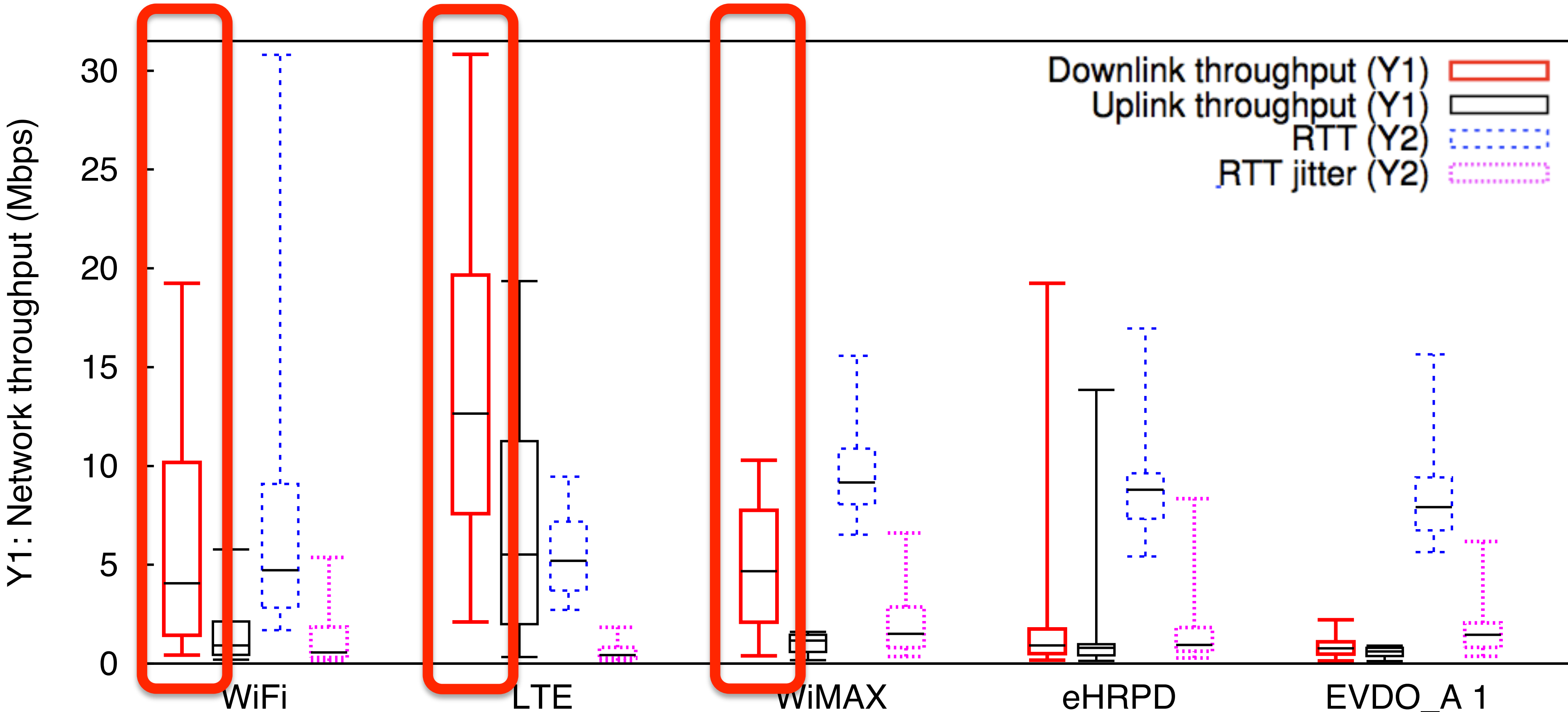
- ***4GTest*** on Android
  - *http://mobiperf.com/4g.html*
  - Measures network performance with the help of 46 **M-Lab** nodes across the world
  - **3,300** users and **14,000** runs in 2 months 10/15/2011 ~ 12/15/2011



4GTest user coverage in the U.S.

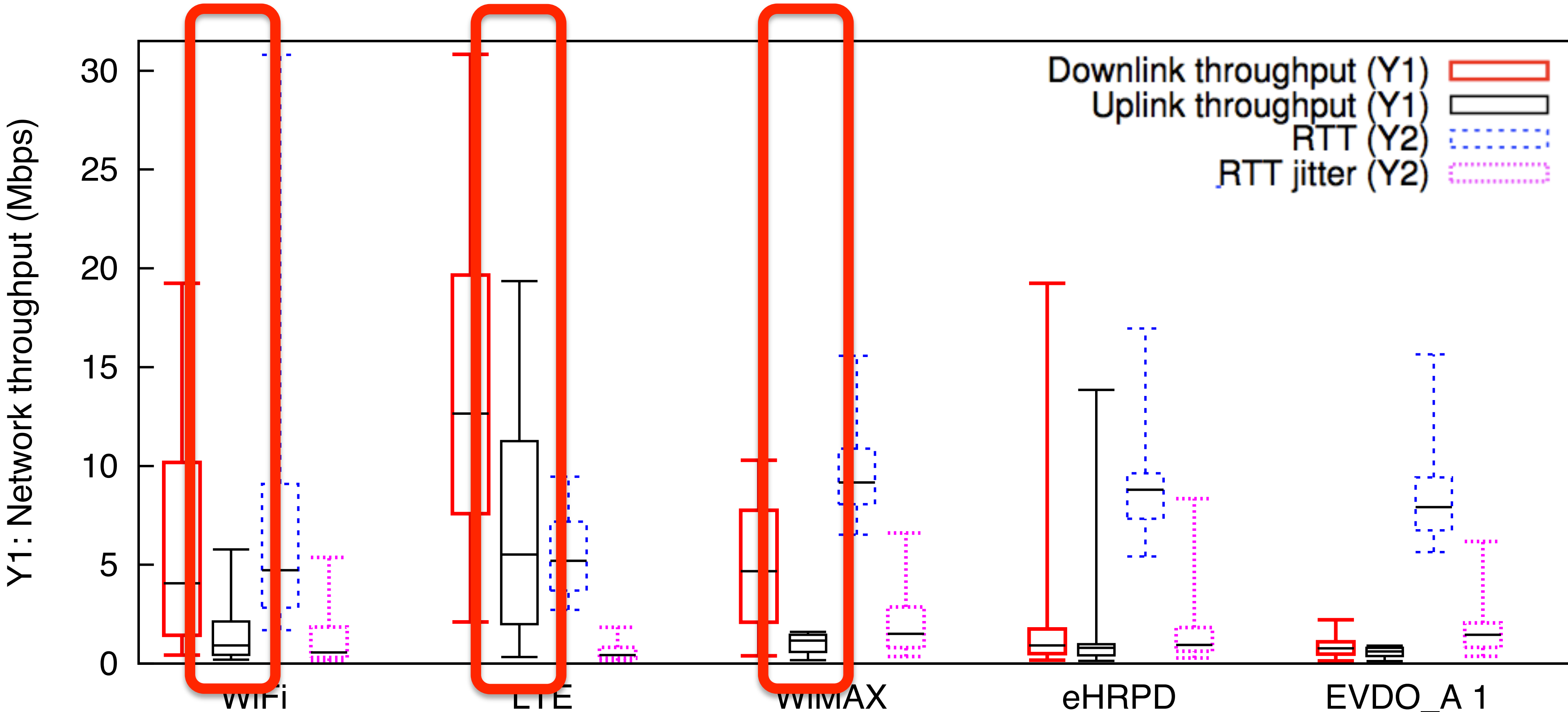
Downlink throughput

- LTE median is **13**Mbps, up to **30**Mbps
  - The LTE network is relatively unloaded
- WiFi, WiMAX **< 5**Mbps median



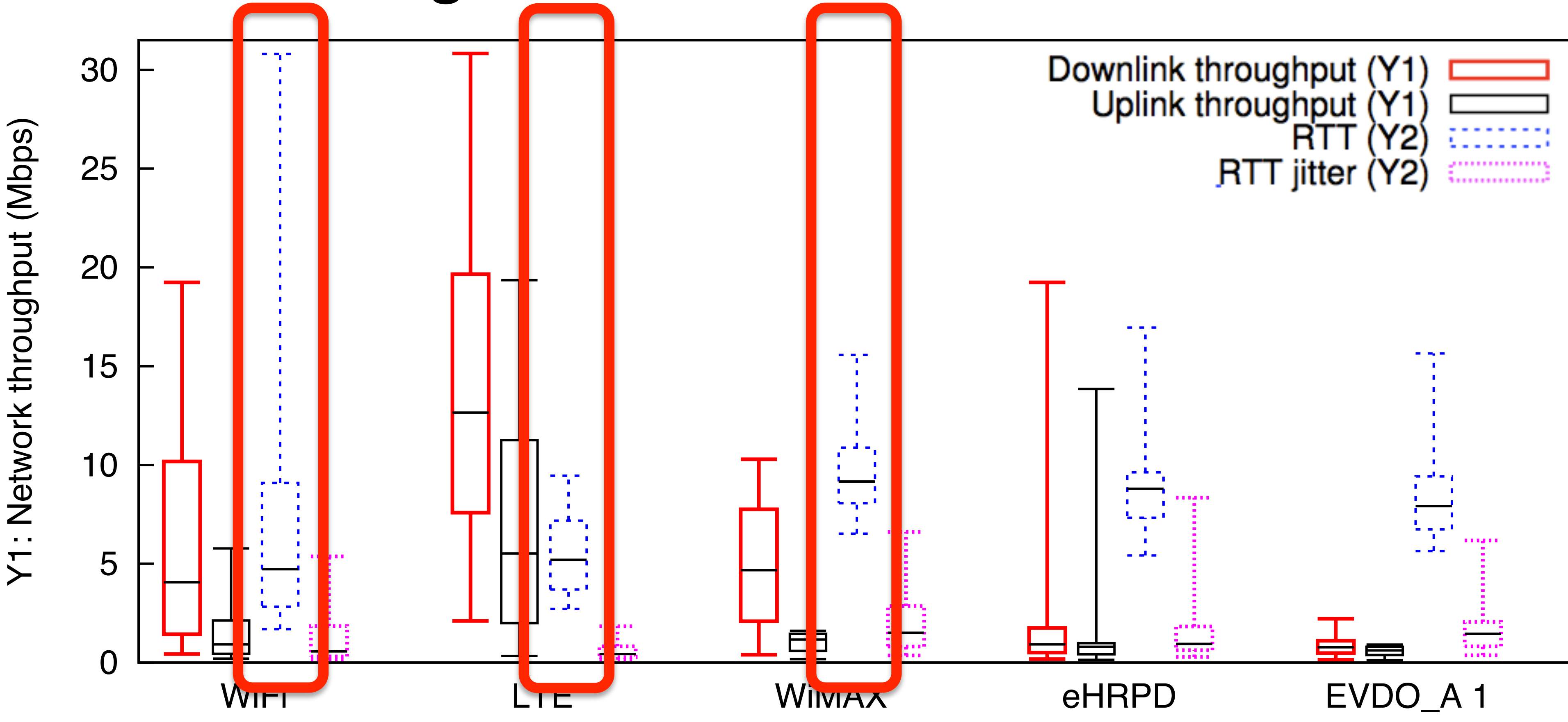
Uplink throughput

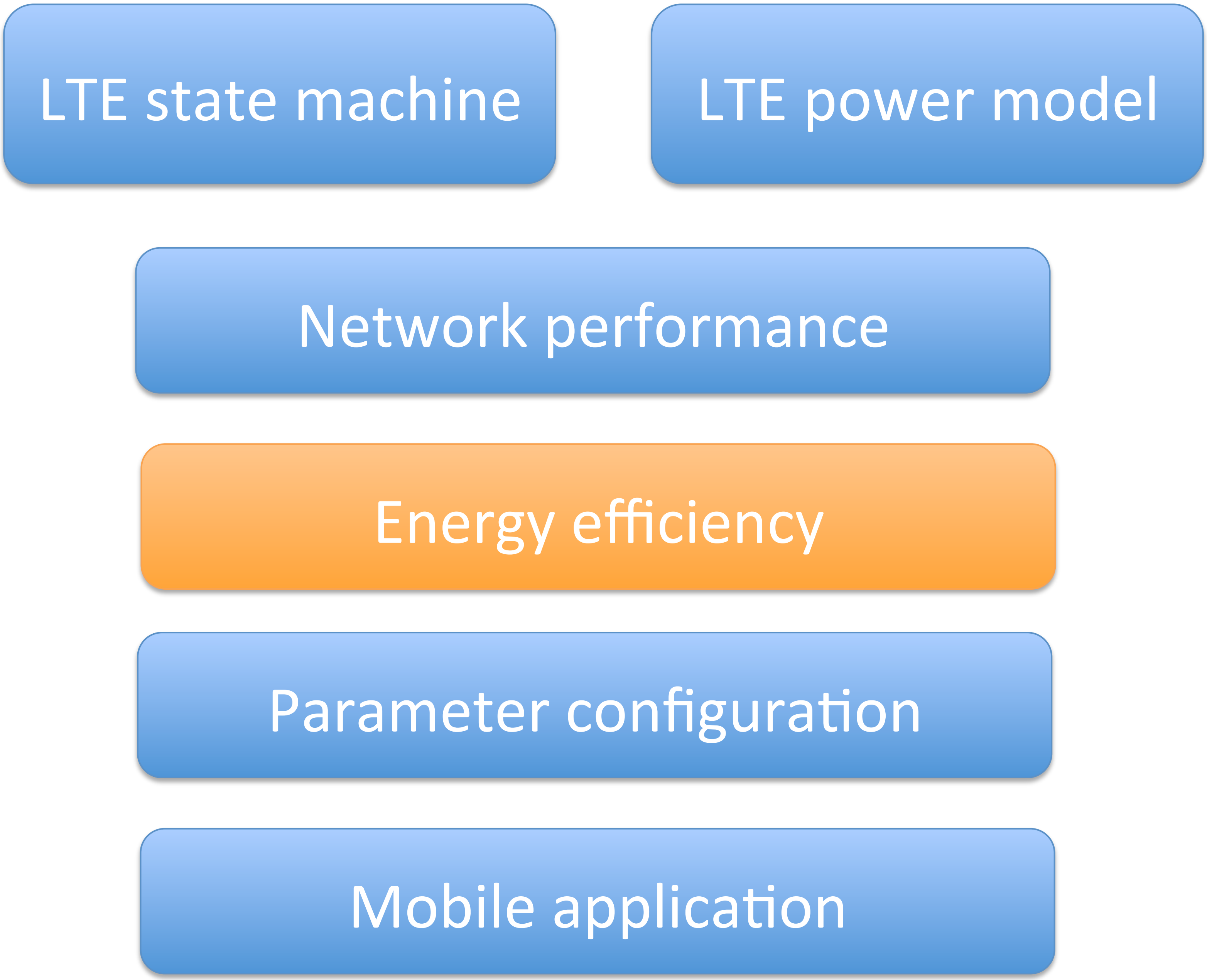
- LTE median is **5.6**Mbps, up to **20**Mbps
- WiFi, WiMAX **< 2**Mbps median



RTT

- LTE median **70**ms
- WiFi similar to LTE
- WiMAX higher

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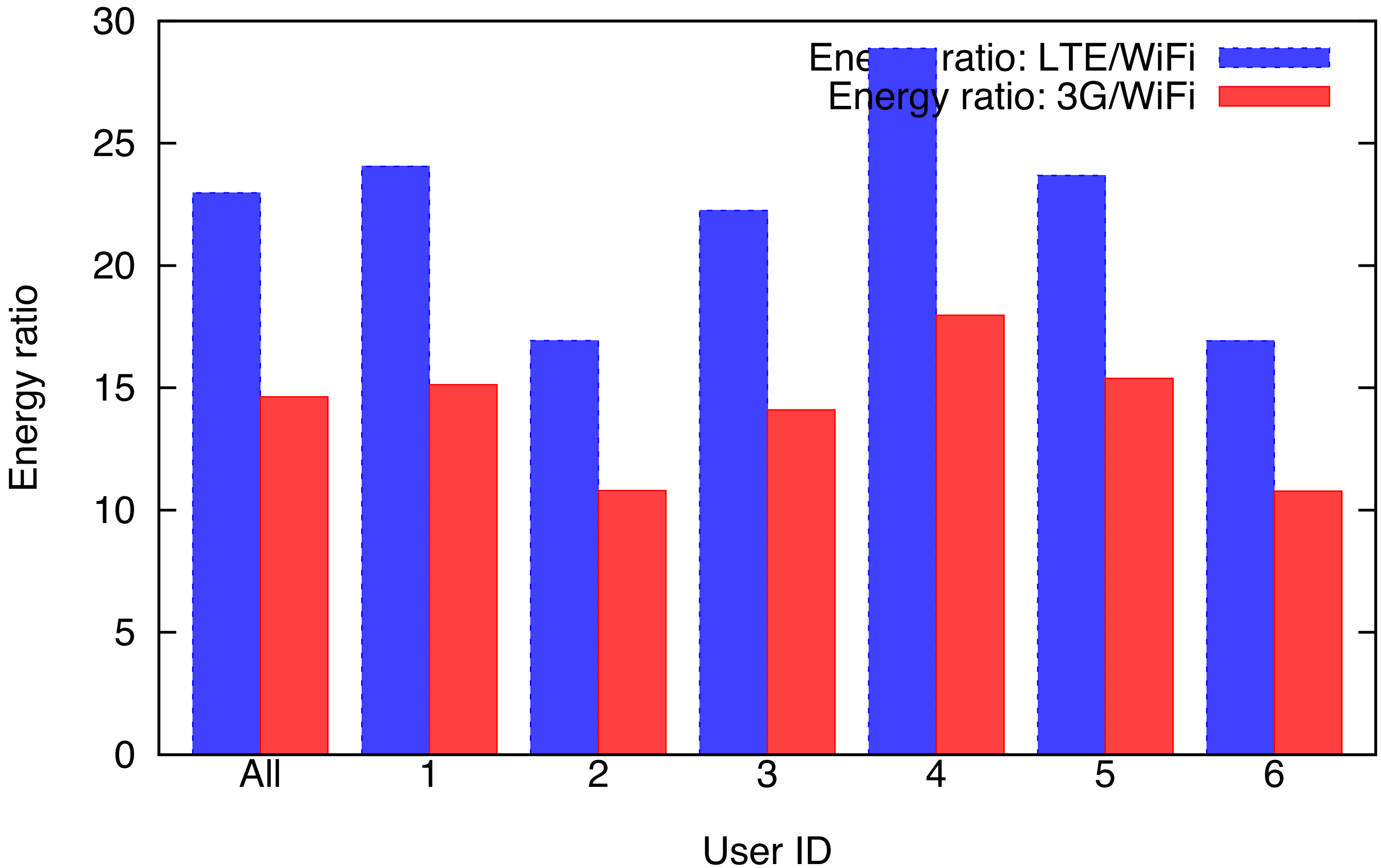
User trace based analysis

- UMICH data set
  - Collected from 20 volunteer smartphone users for five months, totaling 118GB
  - Contains packet traces including full payload
- Trace-driven modeling methodology
  - Network model simulator
    - Simulates network states, such as RRC state transitions
  - Power model simulator
    - Calculates power usage based on the network states

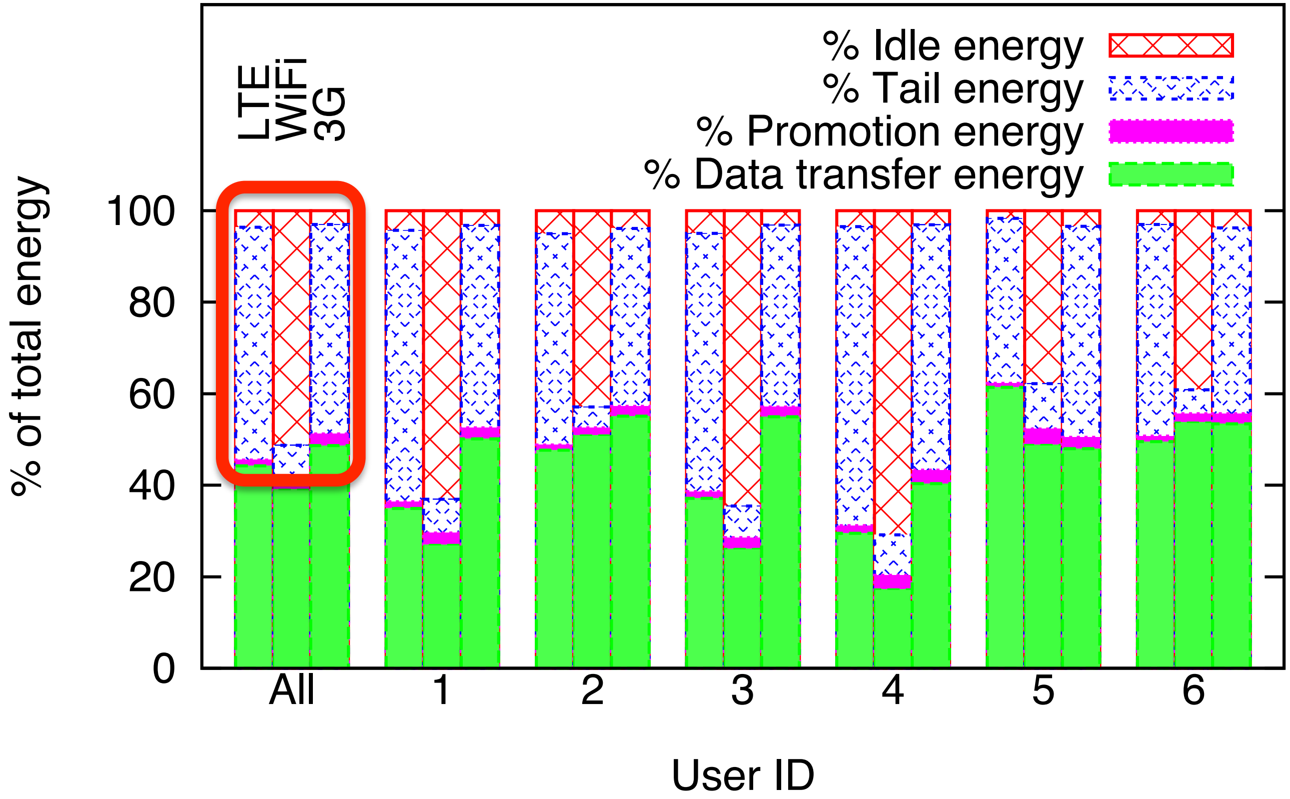
Comparing total energy of all user traces via simulation in LTE/3G/WiFi

- Total energy usage
  - LTE/WiFi ≈ **23**   3G/WiFi ≈ **15**



Energy consumption break down

- Tail energy dominates LTE energy consumption, similar to 3G



The total energy for different networks and users is normalized to be 100%

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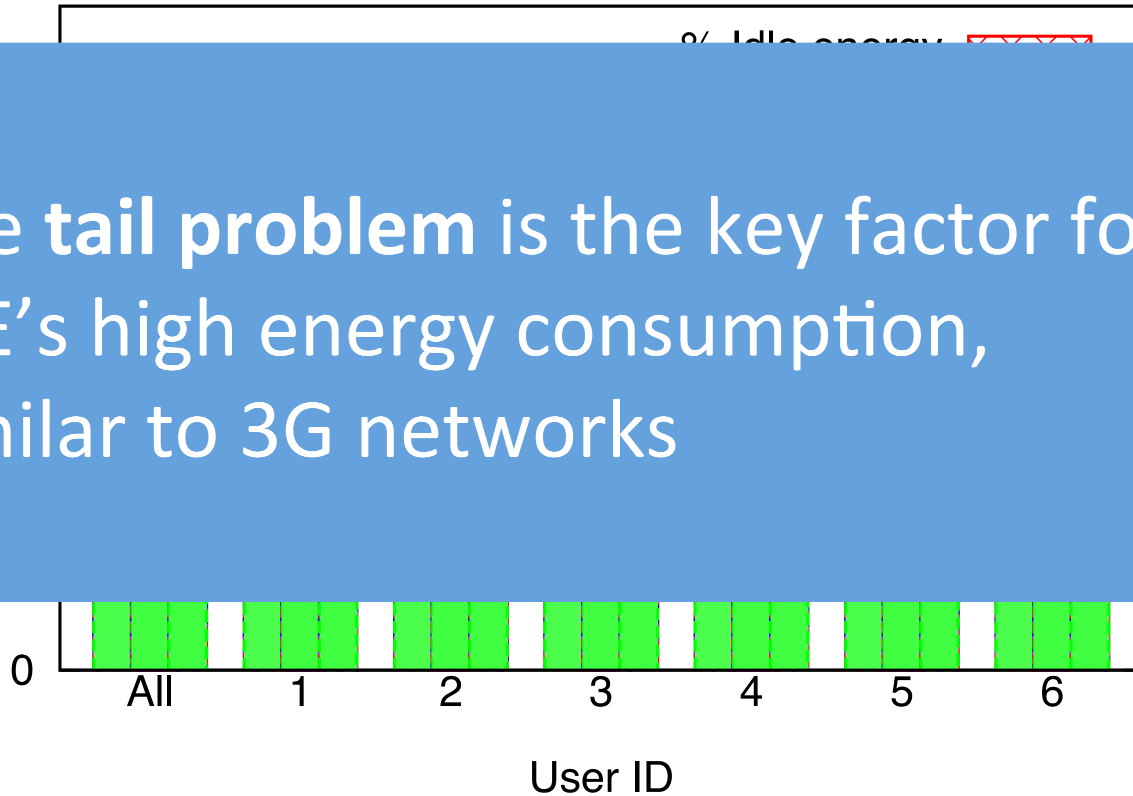
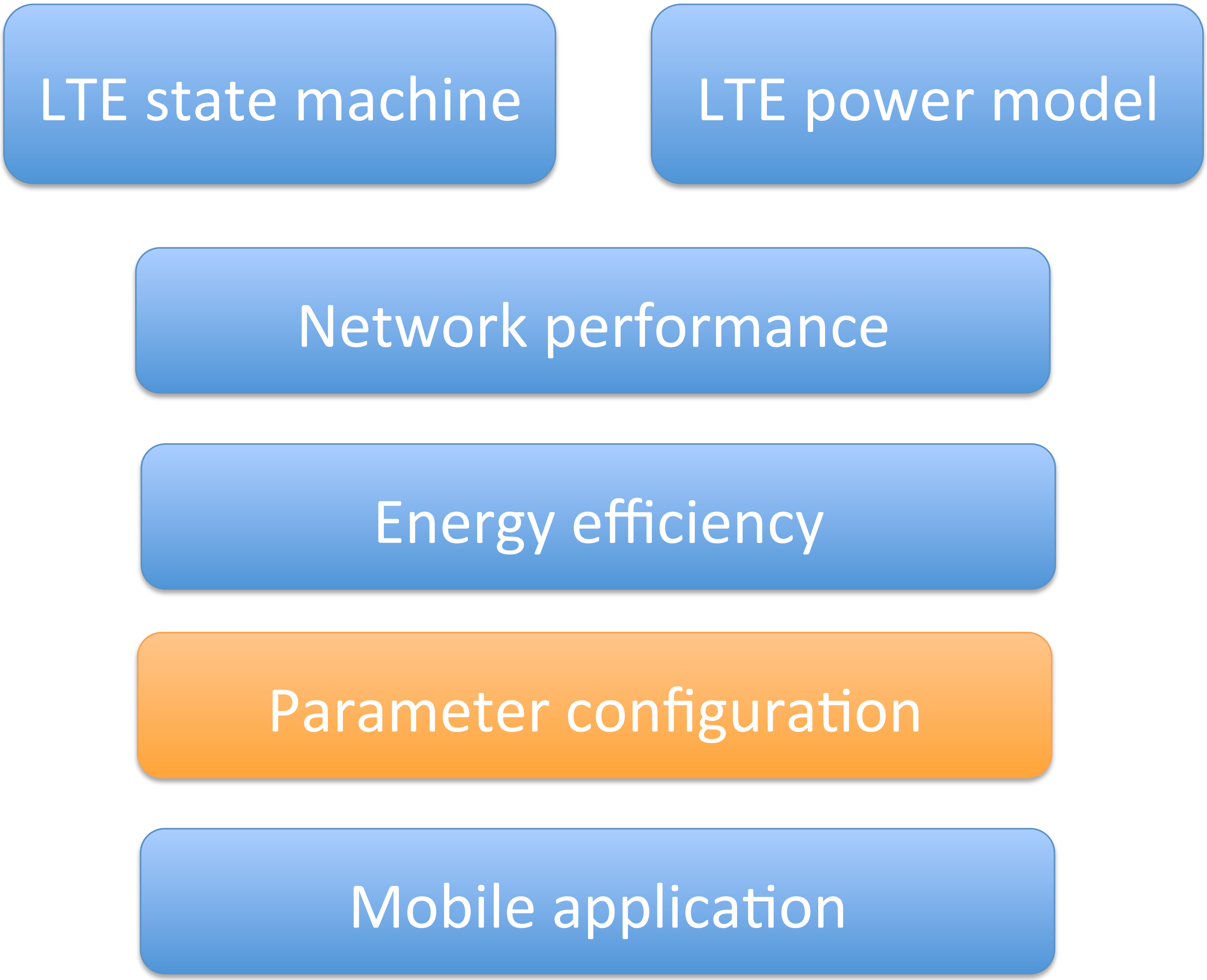


The **tail problem** is the key factor for LTE's high energy consumption, similar to 3G networks

The total energy for different networks and users is normalized to be 100%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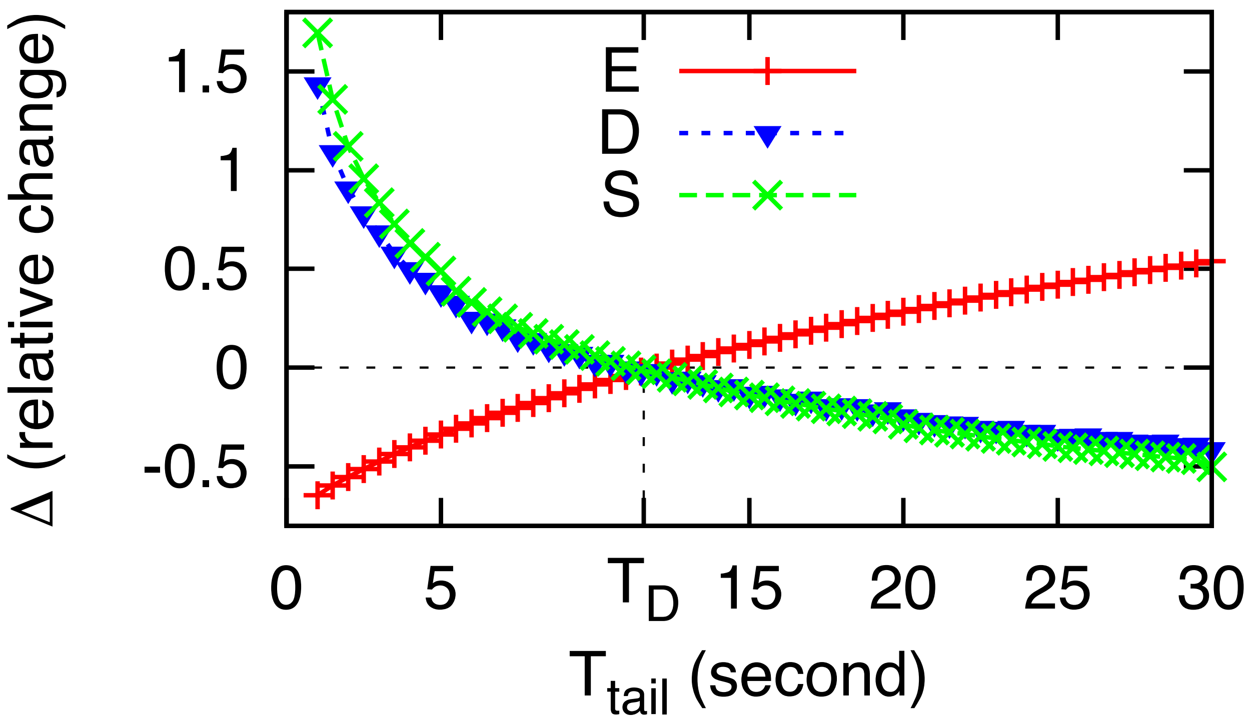
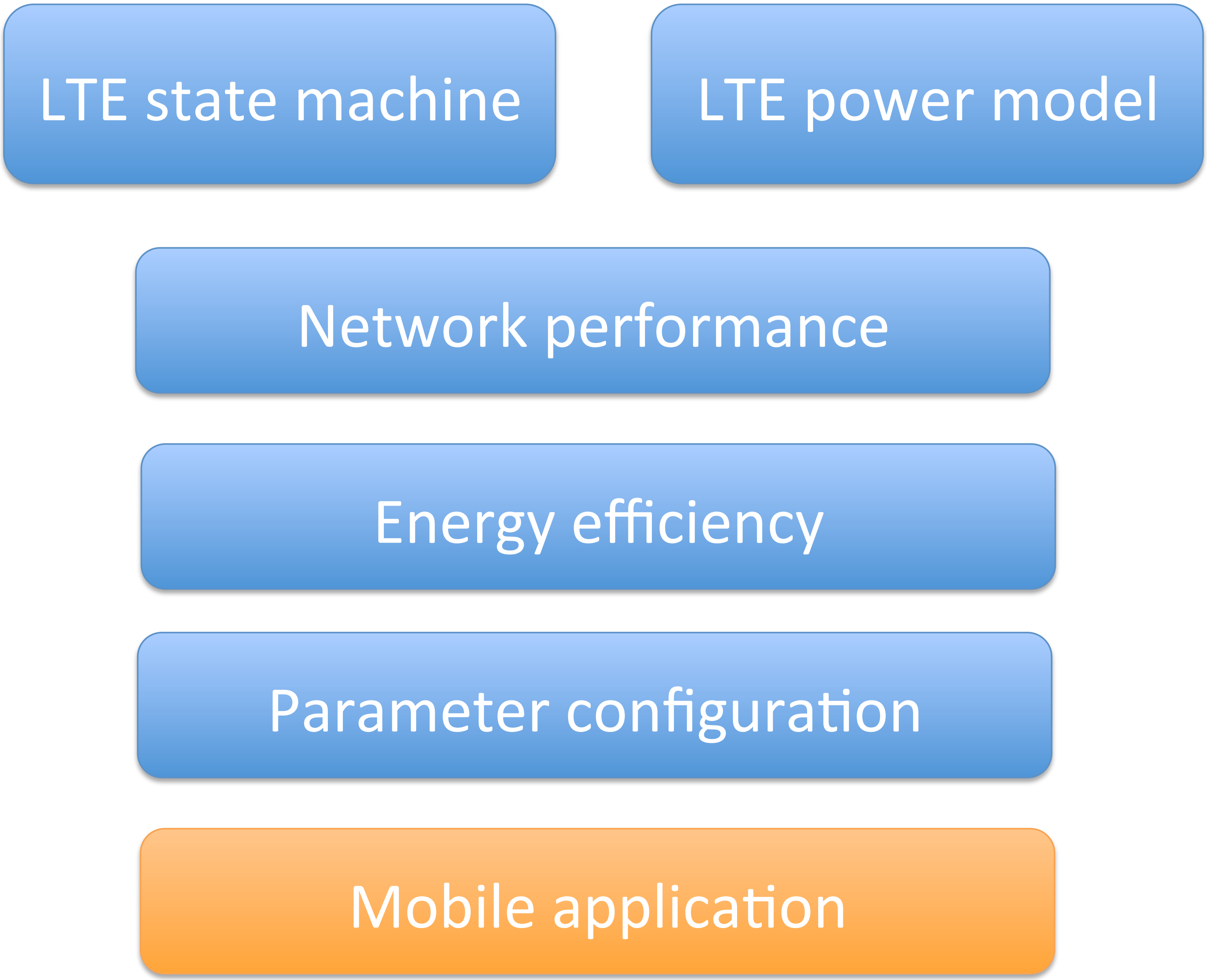
Impact of configuring LTE tail timer (T_{tail})

- S is defined to be the number of promotions
- T_{tail} has significant impact on radio energy E, channel scheduling delay D, and signaling overhead S



T_D is the default setting for T_{tail} in the measured network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App case study

- Studied 5 web-based apps
- LTE has comparable page loading time as WiFi, with 3G lagging behind
- CPU usage for LTE/WiFi is between 80% ~ 90% during page loading
  - Network does not appear to be the bottleneck
- Total energy consumption: LTE > 3G >> WiFi

App case study

- Stu
- LTE ... WiFi, wit
- CP ... 90% du
  - ... ck
- Tot ... iFi

In LTE network, applications should more aggressively burst traffic to make more efficient use of the bandwidth given the high energy overhead

Summary

- LTE has significantly higher speed, compared to 3G and WiFi
- LTE is much less power efficient than WiFi due to its tail energy for small data transfers
- Derived a power model of a commercial LTE network, with less than 6% error rate
- UE processing is the bottleneck for web-based applications in LTE networks
- Mobile app design should be LTE friendly

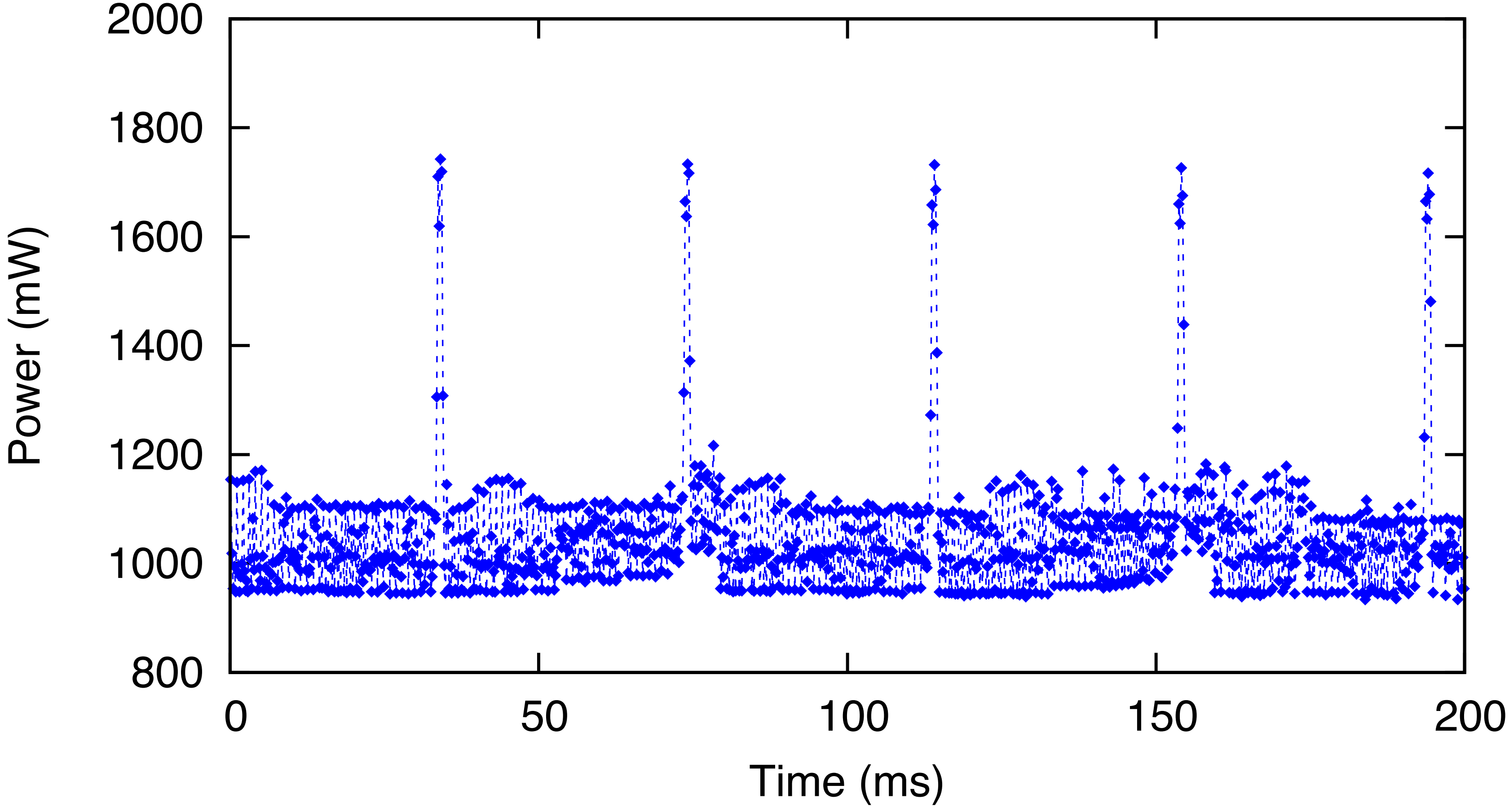
Thank you!

Q & A

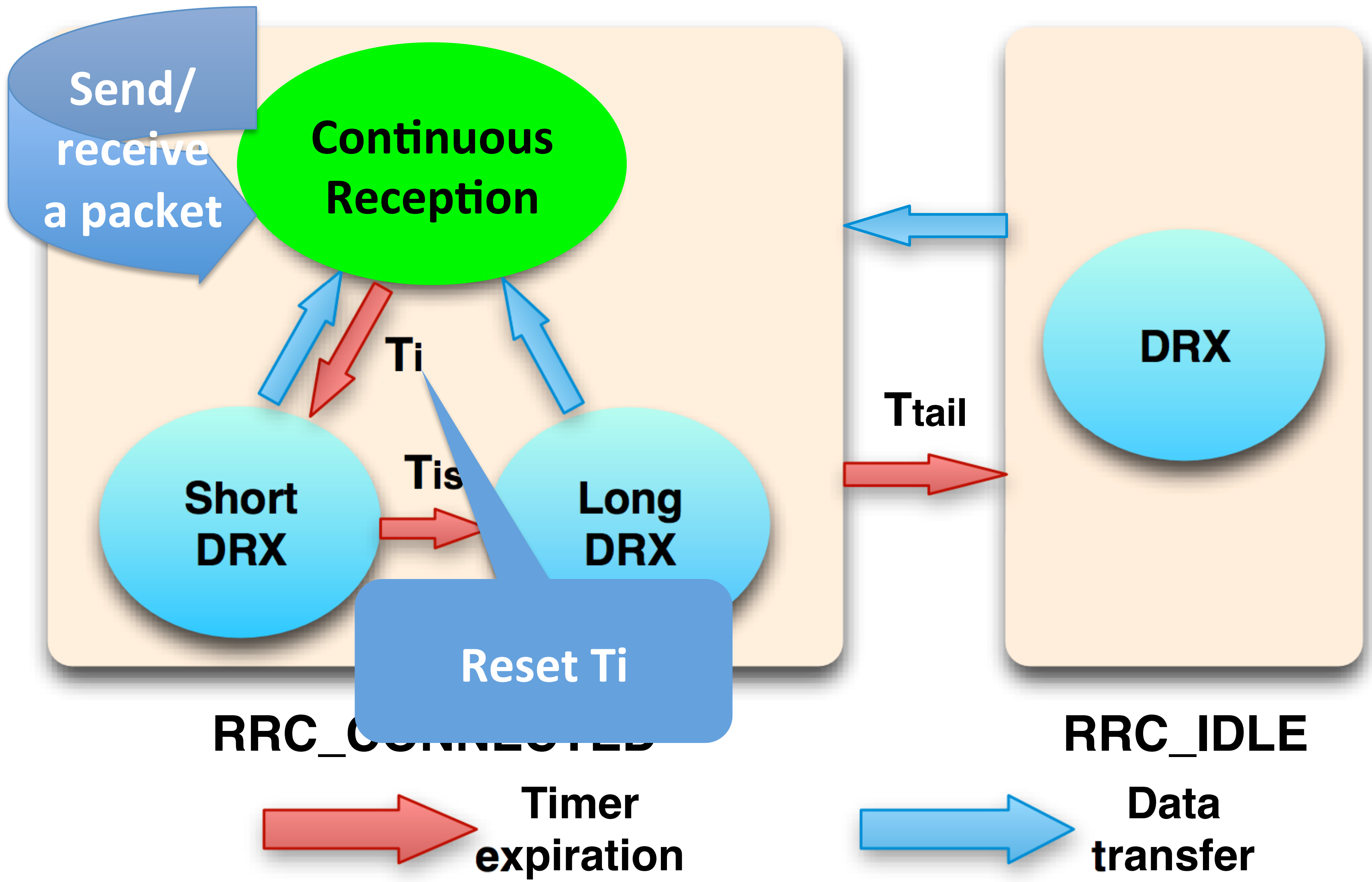
Contact: Junxian Huang (hjx@umich.edu)

Backup slides

Power trace of DRX in RRC_CONNECTED



RRC state transitions in LTE



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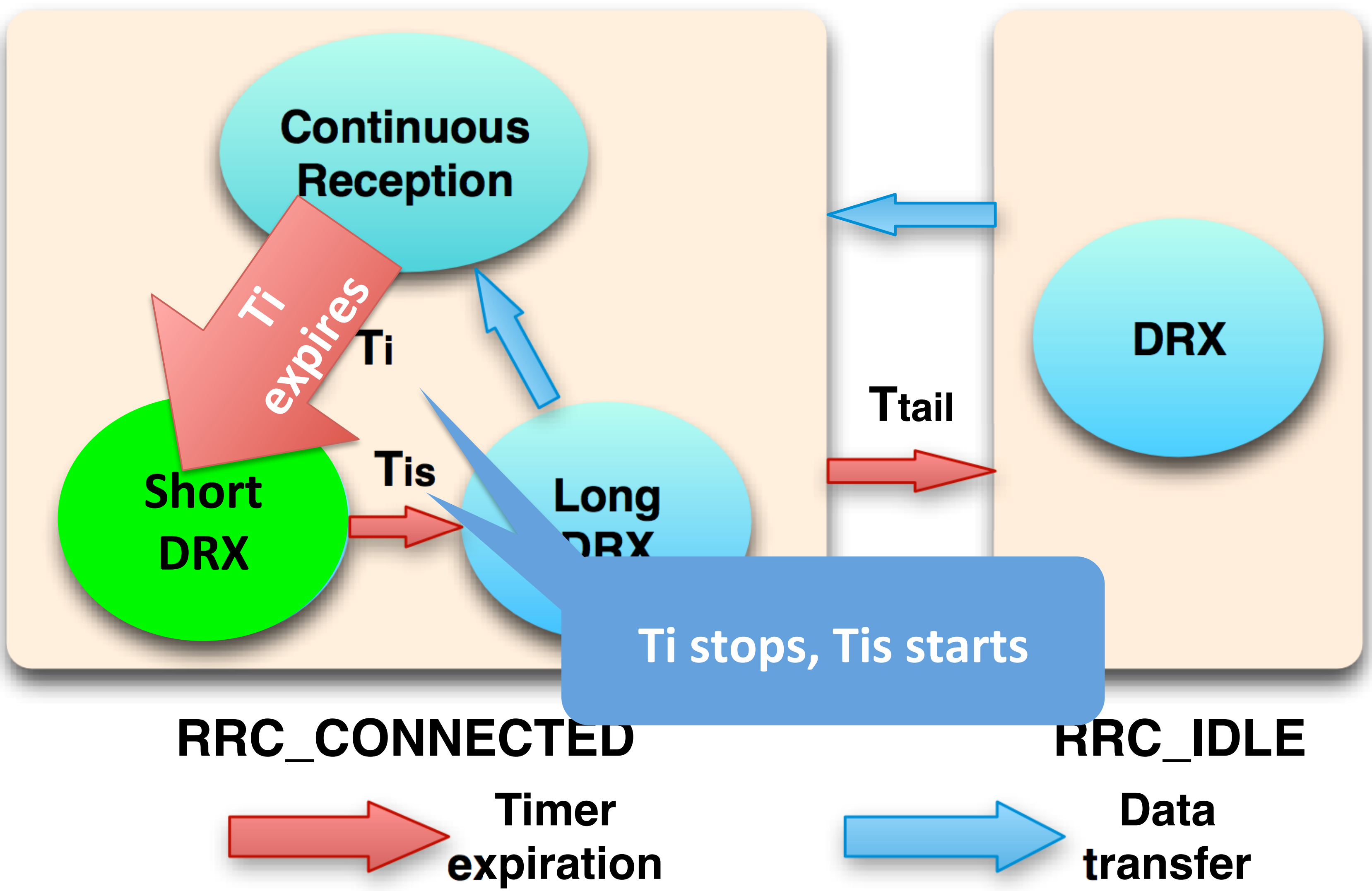

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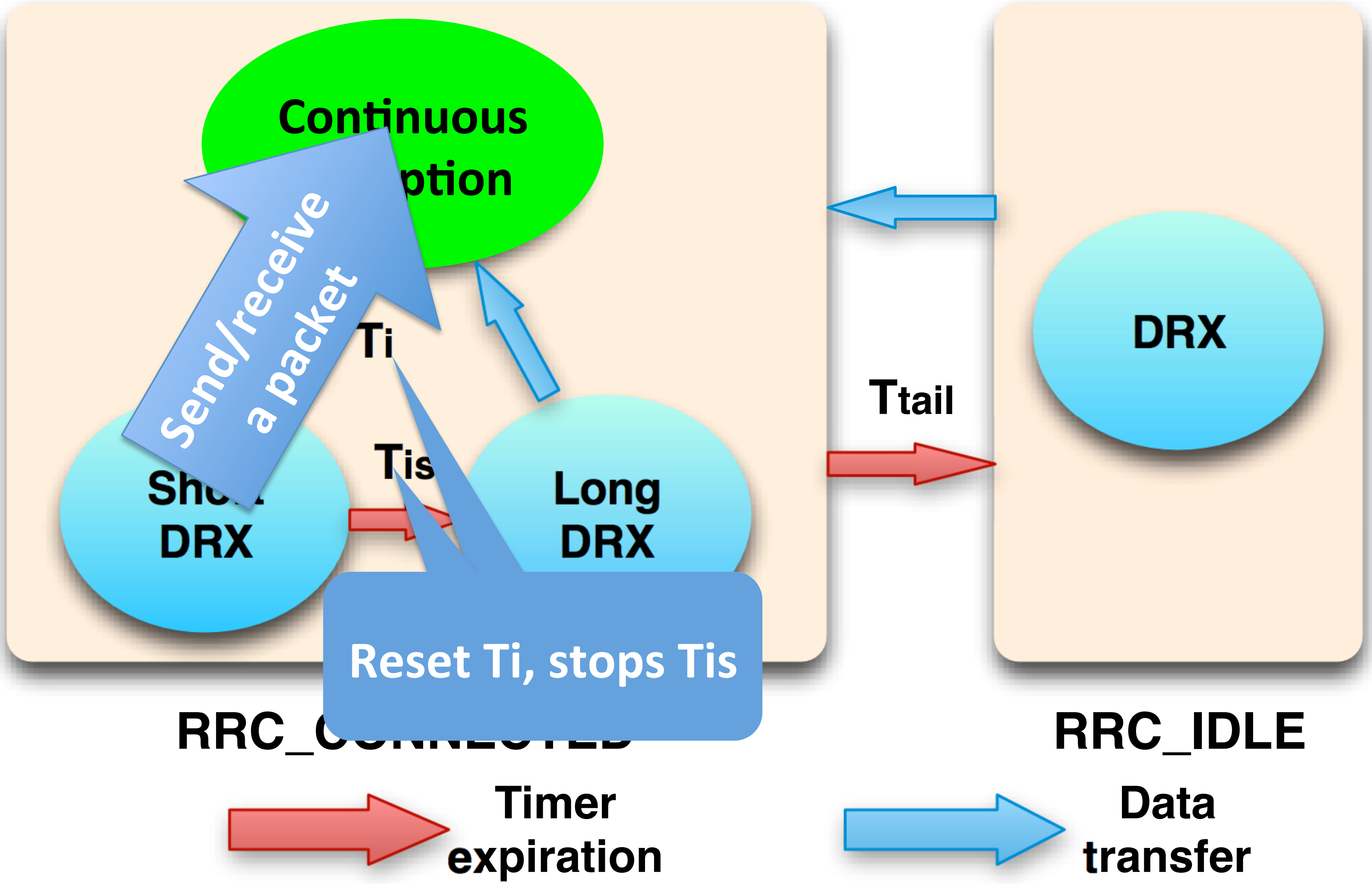

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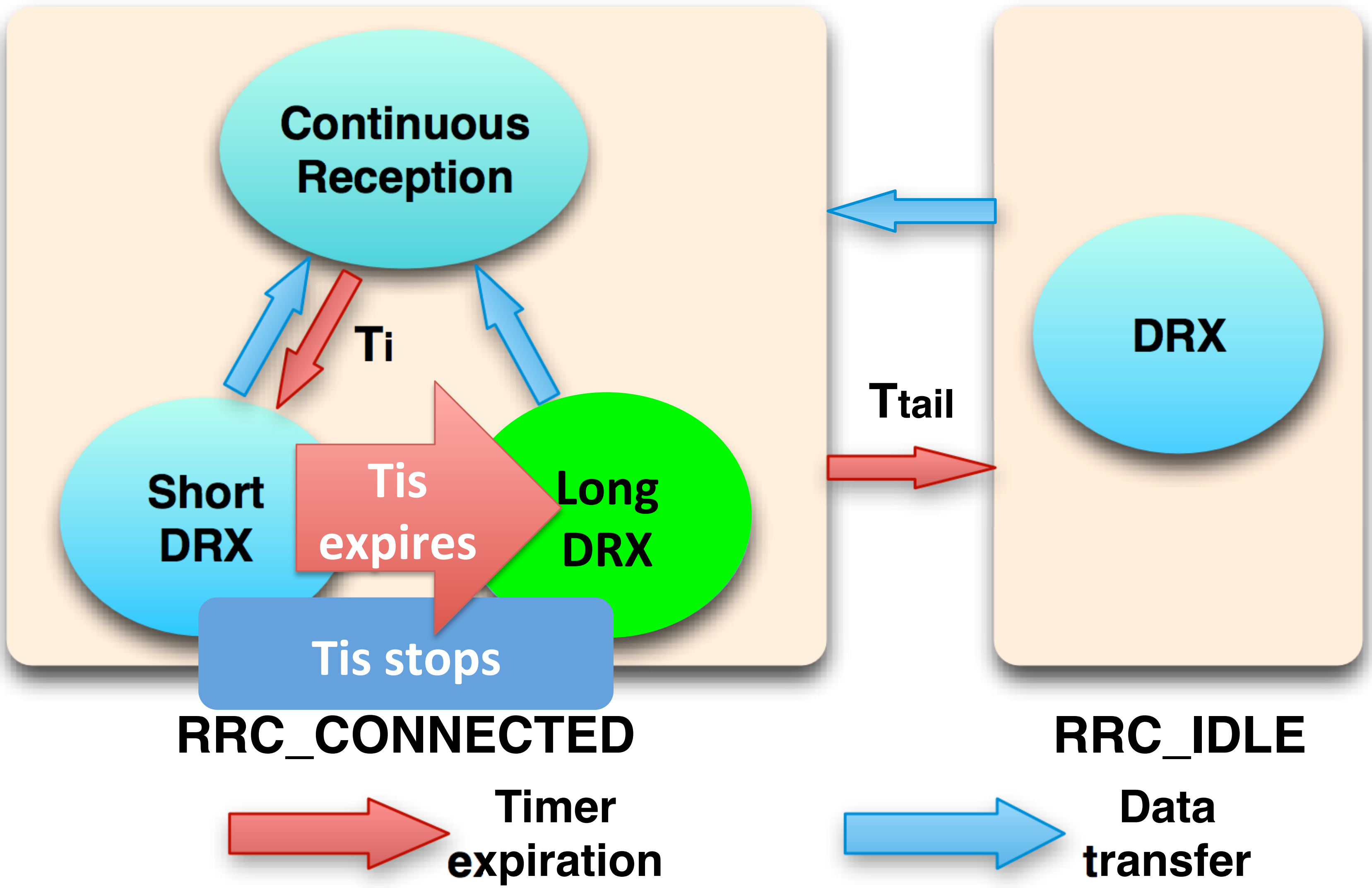

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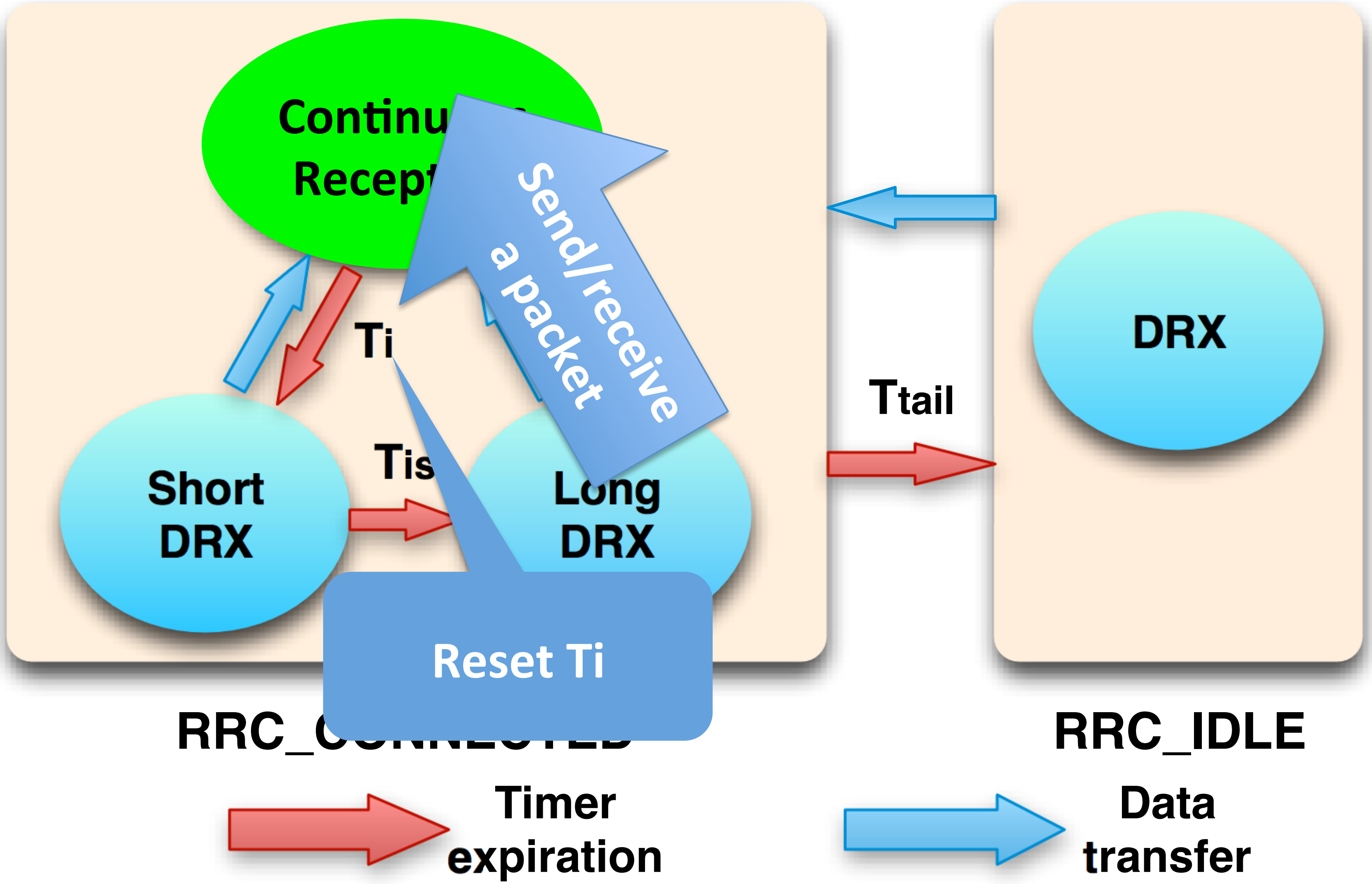
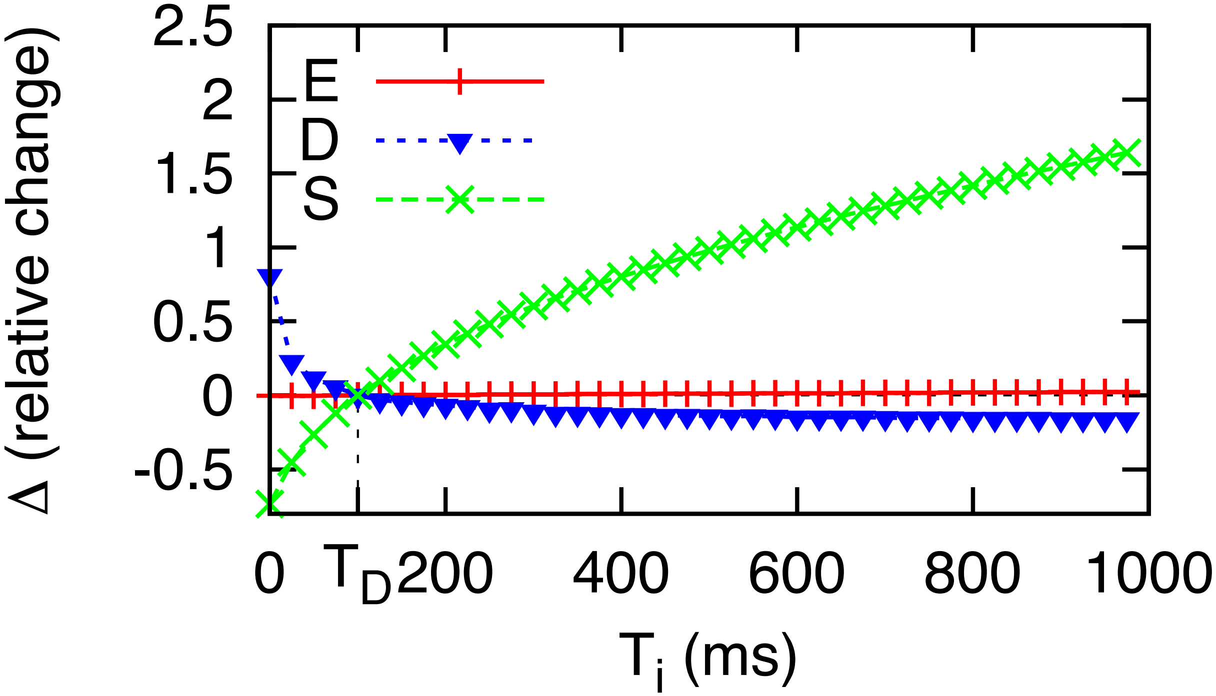


Impact of DRX inactivity timer (T_i): Continuous reception to short DRX

- Differently, S is defined as the sum of the continuous reception time and DRX on durations in **RRC_CONNECTED**
- T_i has negligible impact on E, however, S is significantly affected

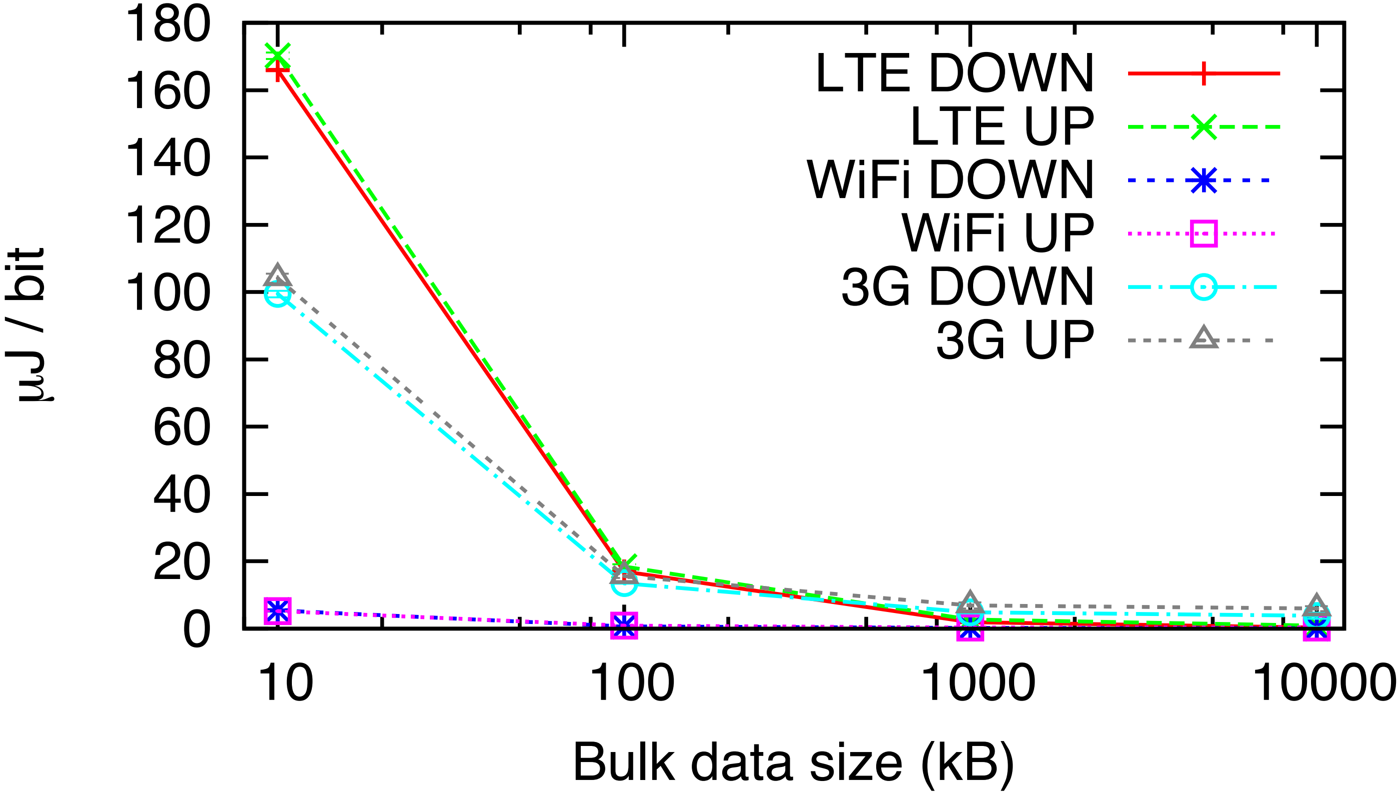


Interesting questions about LTE

- To users: what is the end performance?
  - Network performance, such as RTT and throughput, how it compares with WiFi, 3G and WiMAX, etc.
  - Energy efficiency affecting battery life, is LTE more power efficient than 3G or WiFi?
- To ISPs: what is the impact of configuring LTE-related parameters on UE power saving, and delay/signaling overhead?
- To OS/application developers: what is the performance bottleneck of applications in LTE network, CPU or network speed?

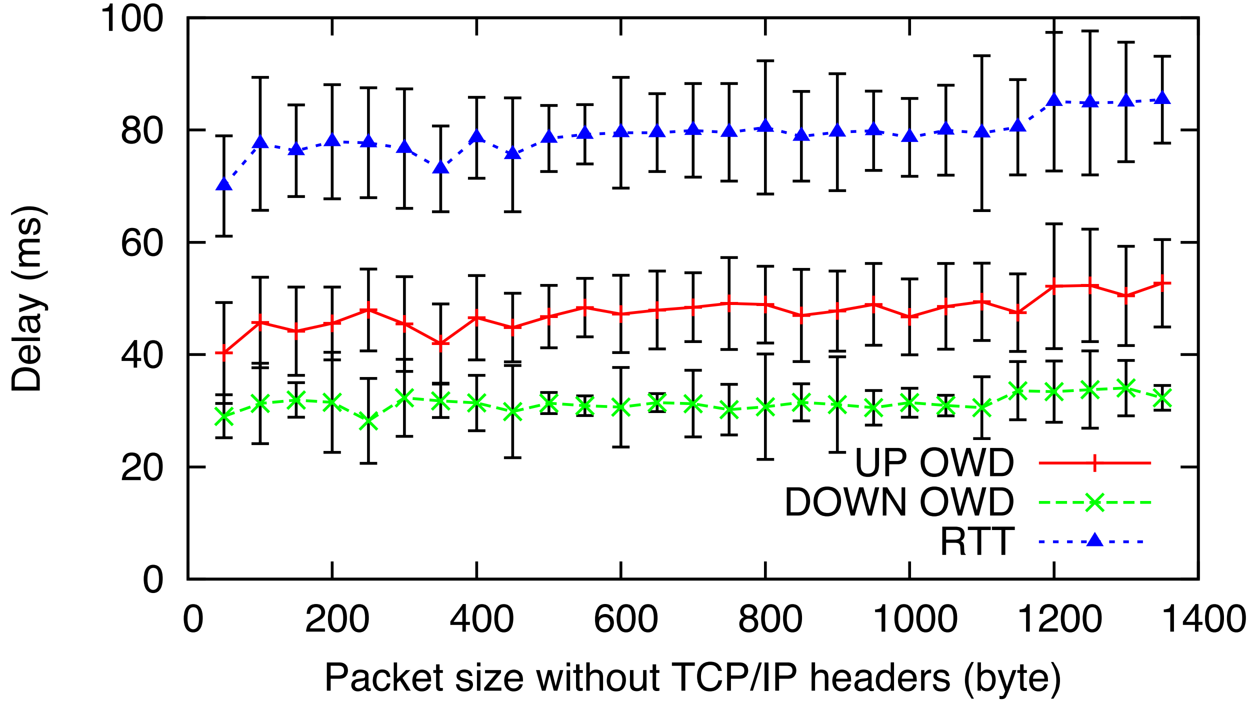
Energy per bit comparison

- For large data transfer with maximum rate, LTE's energy efficiency is comparable with WiFi, due to LTE's high downlink throughput



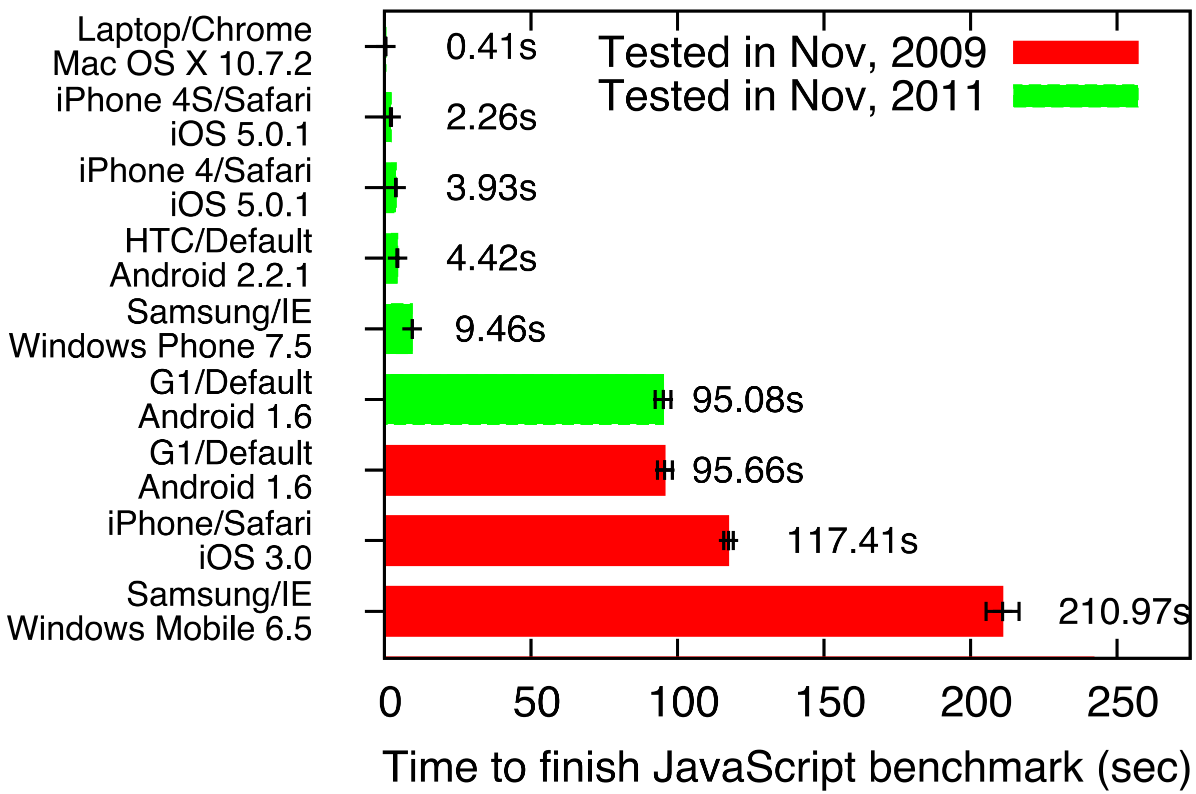
One way delay and impact of packet size (not quite related)

- LTE uplink one way delay (OWD) is larger than that of downlink
- RTT in LTE is more sensitive to packet size than WiFi, mainly due to uplink OWD



JavaScript execution speed: a representative view of smartphone processing capability

- From 2009 to 2011, smartphones have significantly improved JavaScript execution speed



Power model for data transfer

- A linear model is used to quantify instant power level:
  - Uplink/downlink throughput t_u/t_d (Mbps)

$$P = \alpha_u t_u + \alpha_d t_d + \beta$$

	α_u (mW/Mbps)	α_d (mW/Mbps)	β (mW)	α_u/α_d
LTE	438.39	51.97	1288.04	8.44
3G	868.98	122.12	817.88	7.12
WiFi	283.17	137.01	132.86	2.07

Data transfer power model

< 6% error rate for predicting energy usage of 5 real applications