

Decoupling TCP from IP with Multipath TCP

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Thanks to Sébastien Barré, Christoph Paasch, Grégory Detal, Mark Handley, Costin Raiciu, Alan Ford, Micchio Honda, Fabien Duchene and many others

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Agenda

→ The motivations for Multipath TCP

- The changing Internet
- The Multipath TCP Protocol
- Multipath TCP use cases

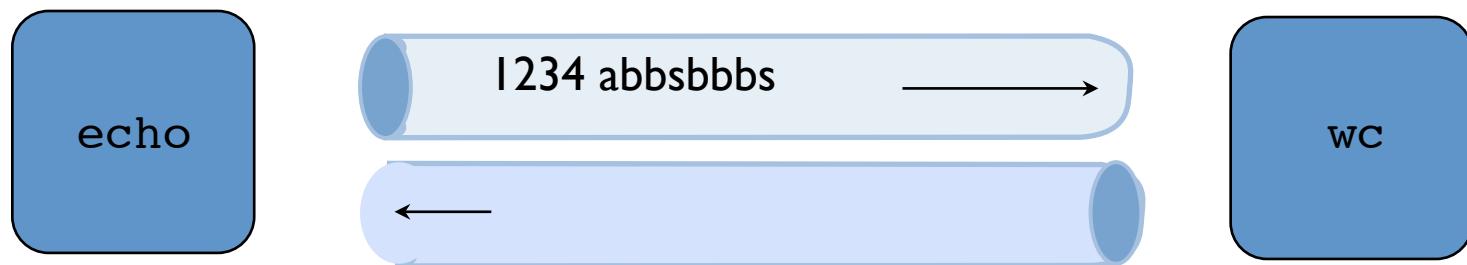
The origins of TCP



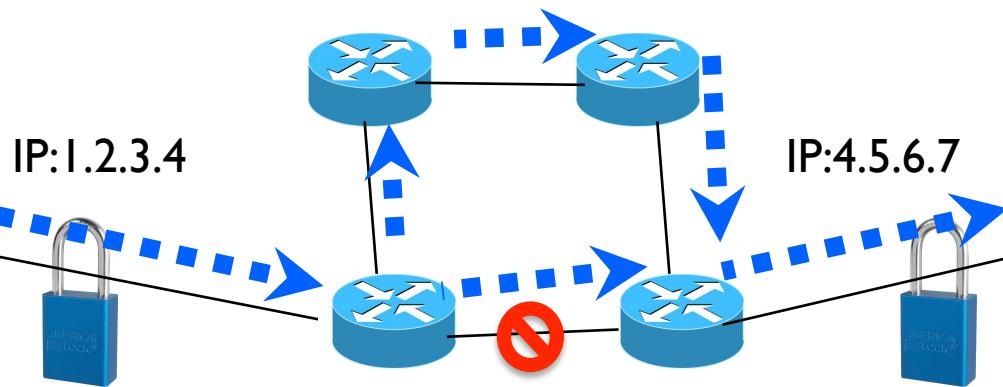
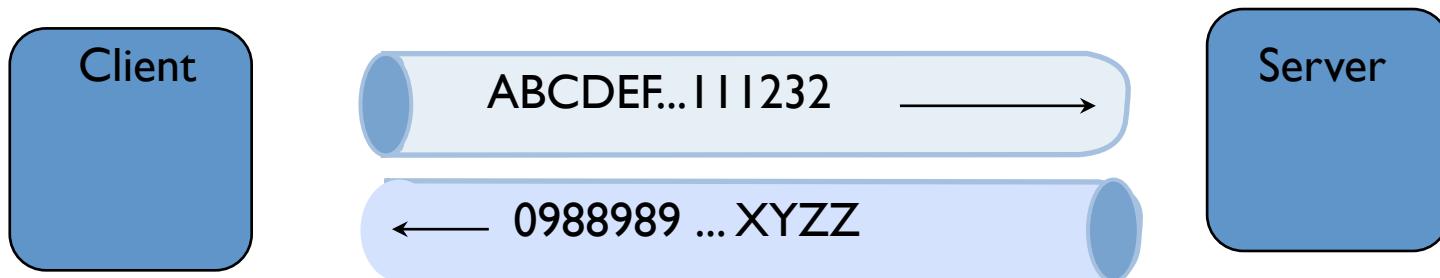
Source : <http://spectrum.ieee.org/computing/software/the-strange-birth-and-long-life-of-unix>

The Unix pipe model

```
Last login: Tue Nov 13 10:07:47 on ttys006
You have new mail.
mbpobo:~ obo$ echo "1234 abbsbbbbs" | wc -c
        14
mbpobo:~ obo$ 
```



The TCP bytestream model



Endhosts have evolved

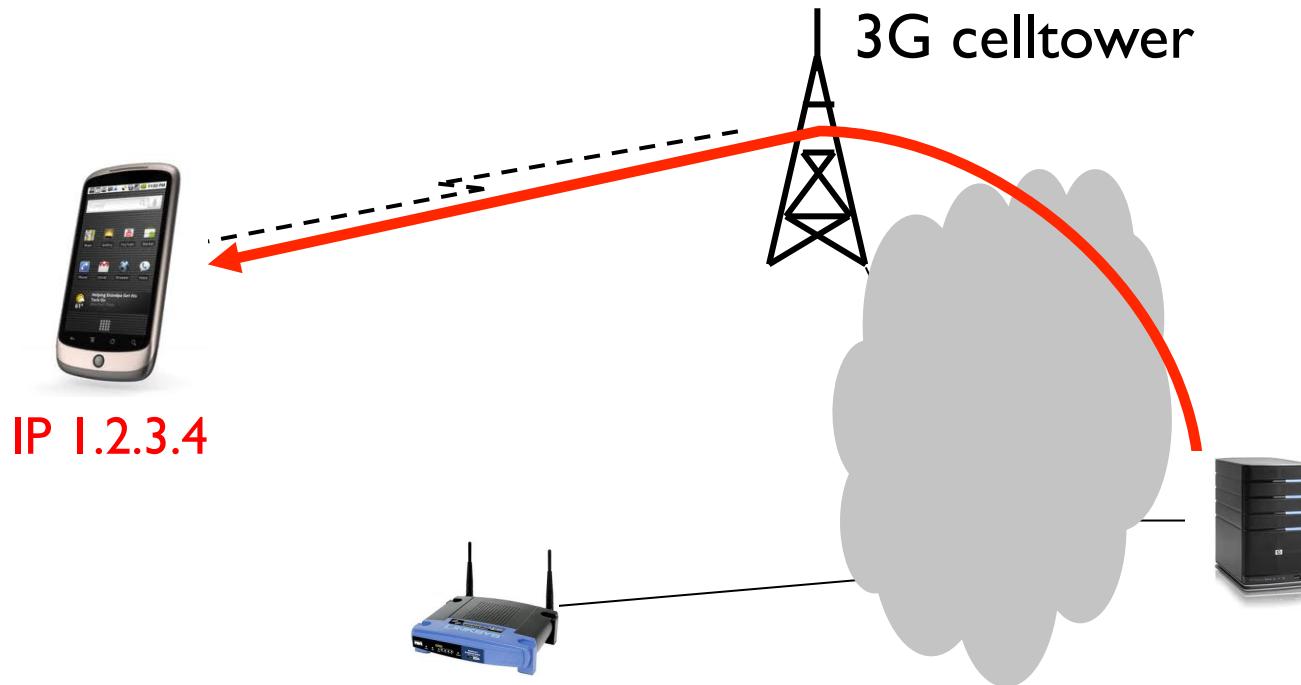


Mobile devices have multiple wireless interfaces

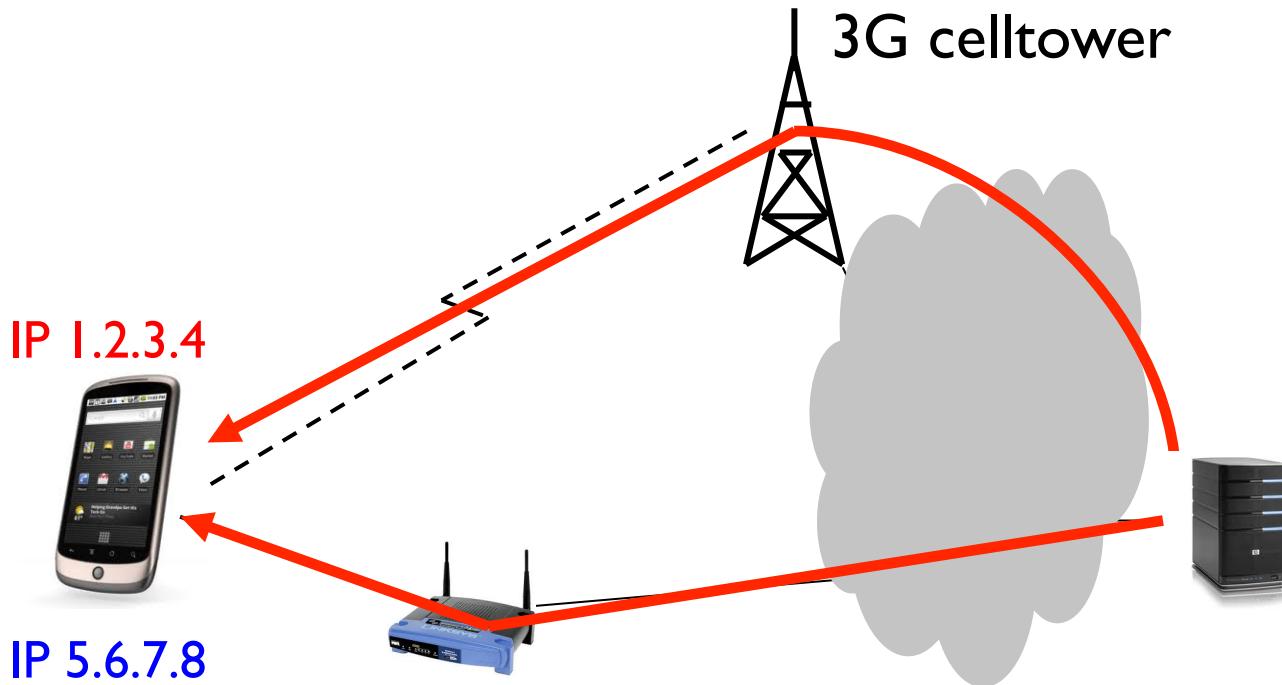
User expectations



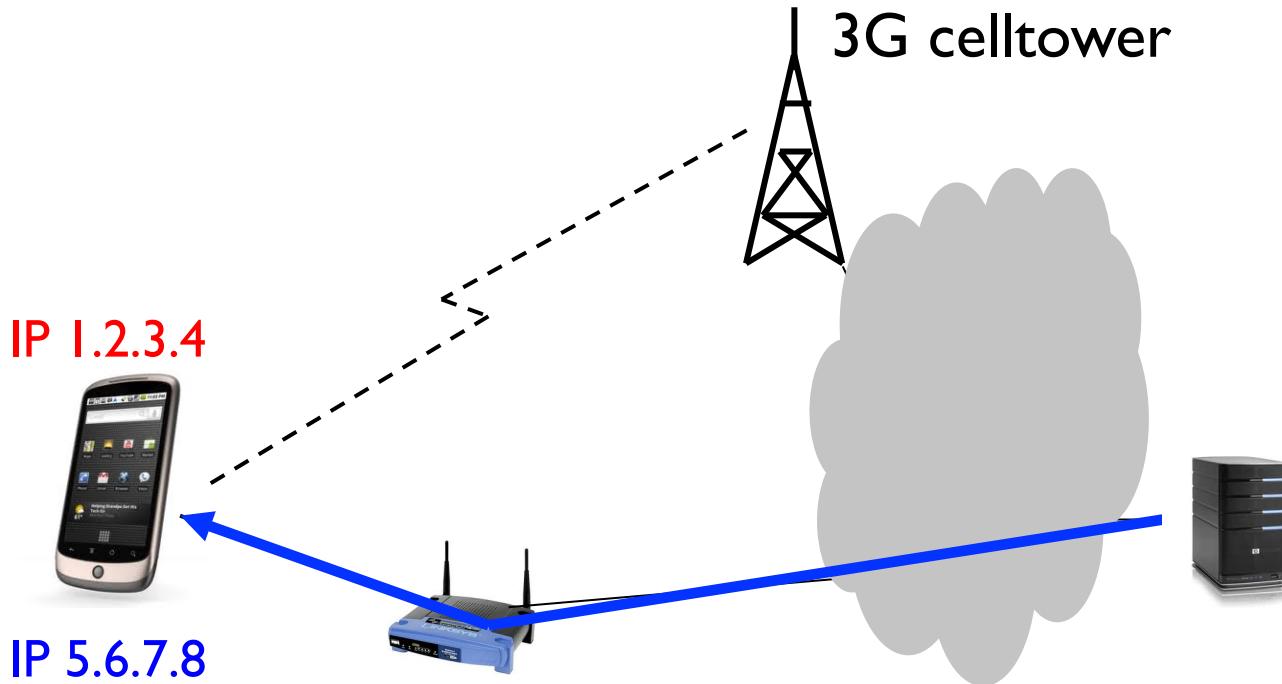
What technology provides



What technology provides



What technology provides



**When IP addresses change TCP connections
have to be re-established !**

Equal Cost Multipath



ECMP implementation

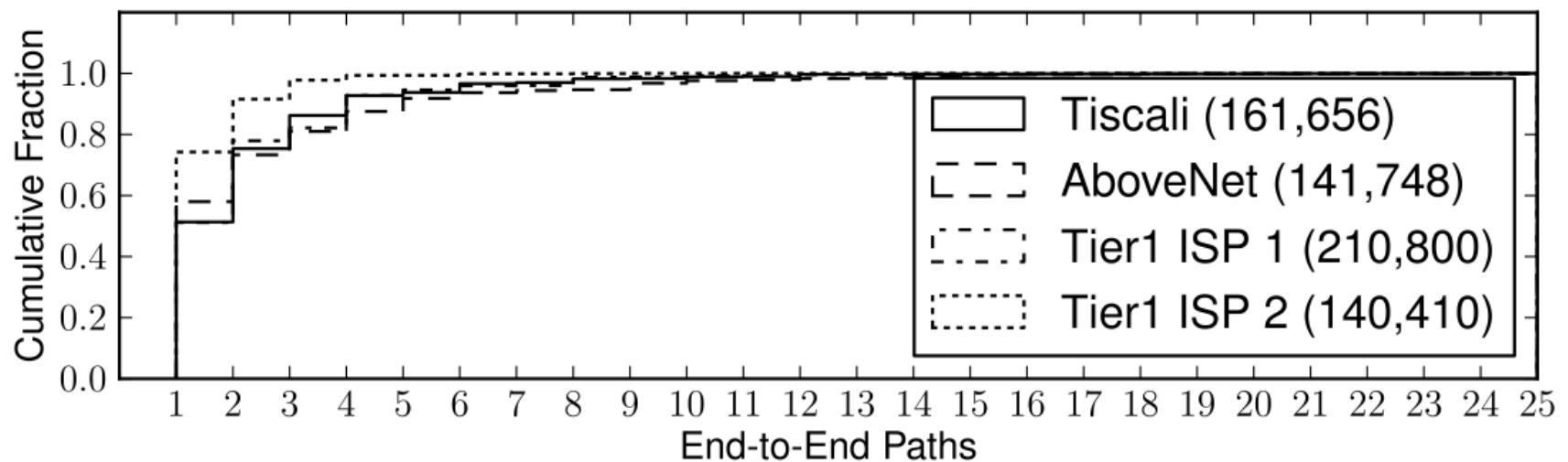
Packet arrival :

$$\text{Hash}(\text{IP}_{\text{src}}, \text{IP}_{\text{dst}}, \text{Prot}, \text{Port}_{\text{src}}, \text{Port}_{\text{dst}}) \bmod \#\text{oif}$$

Packets from one TCP connection follow same path
Different connections follow different paths

How prevalent is ECMP ?

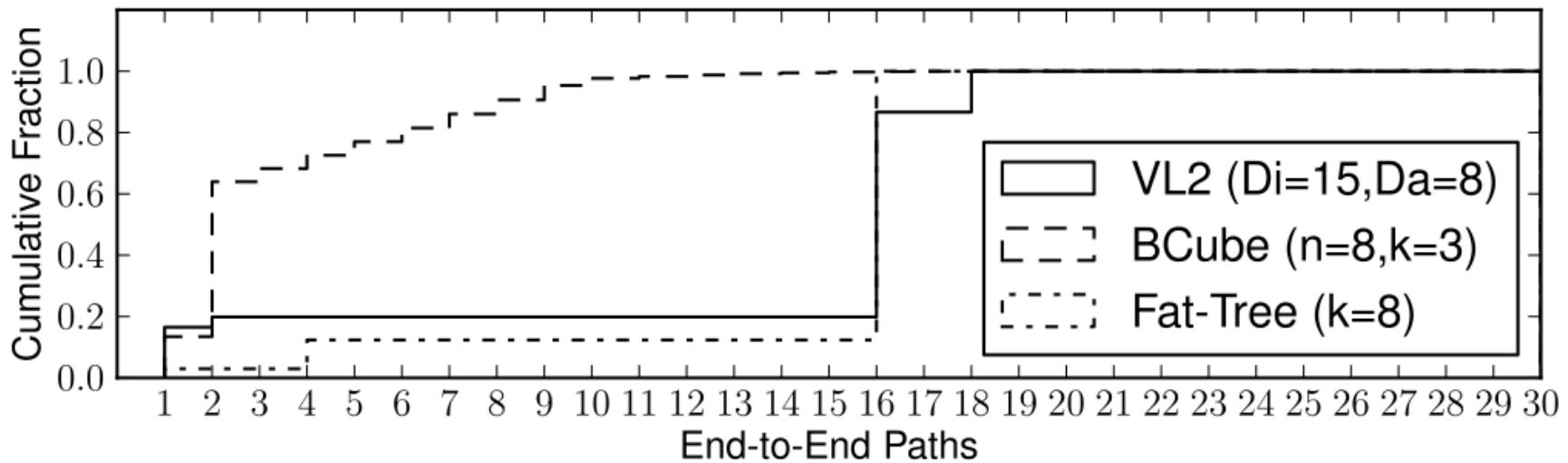
- Analysis of ISP network topologies



Datacenters



ECMP in datacenters



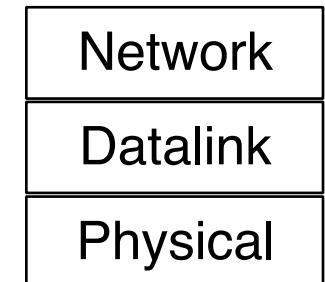
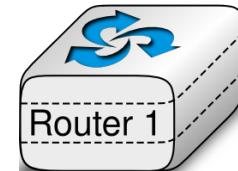
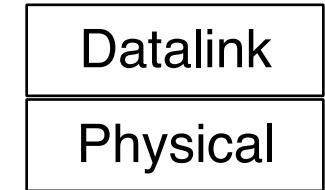
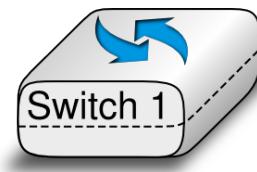
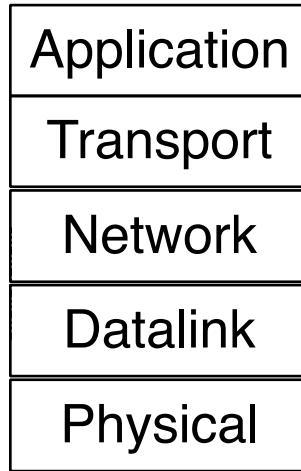
Agenda

- The motivations for Multipath TCP

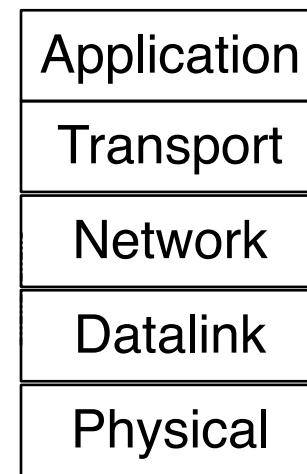
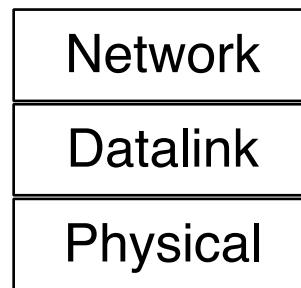
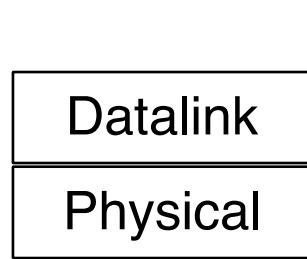
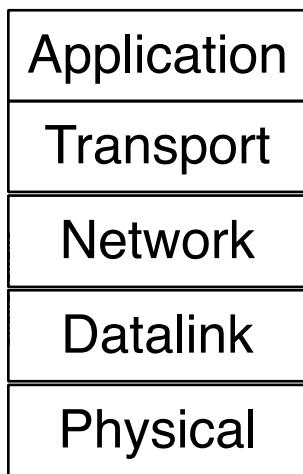
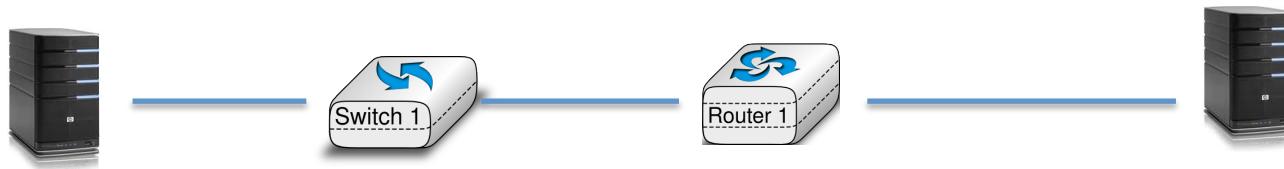
The changing Internet

- The Multipath TCP Protocol
- Multipath TCP use cases

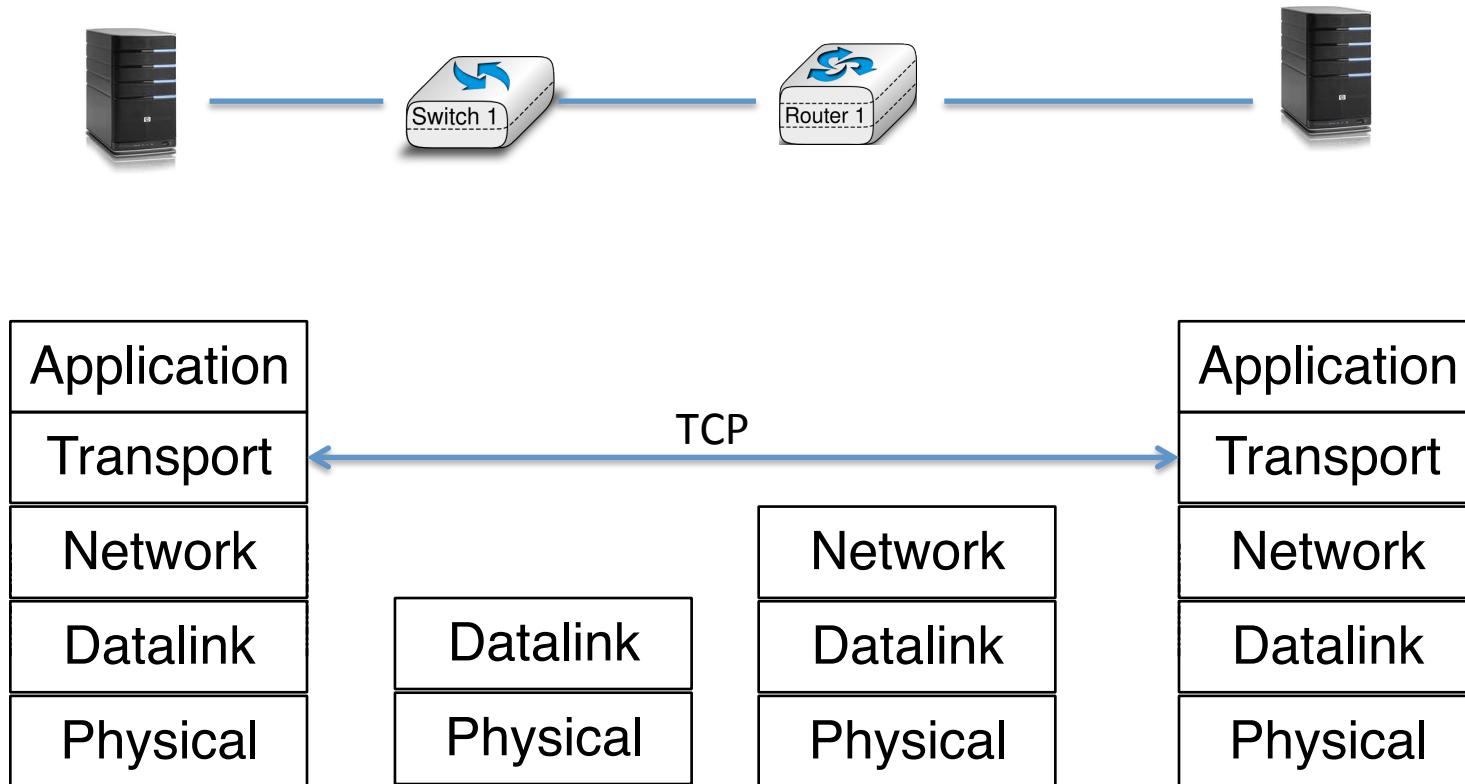
The Internet architecture that we explain to our students



A typical "academic" network



The end-to-end principle



In reality

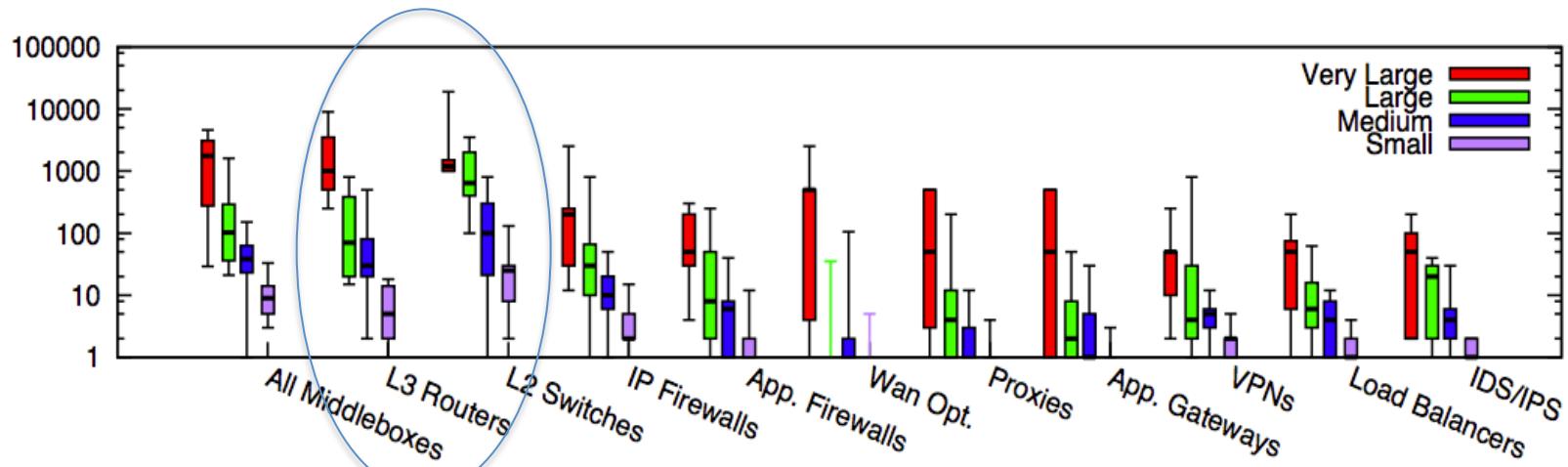


Figure 1: Box plot of middlebox deployments for small (fewer than 1k hosts), medium (1k-10k hosts), large (10k-100k hosts), and very large (more than 100k hosts) enterprise networks. Y-axis is in log scale.

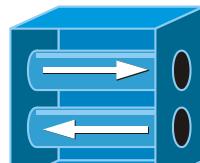
- almost as many middleboxes as routers
- various types of middleboxes are deployed

Sherry, Justine, et al. "Making middleboxes someone else's problem: Network processing as a cloud service." Proceedings of the ACM SIGCOMM 2012 conference. ACM, 2012.

A middlebox zoo



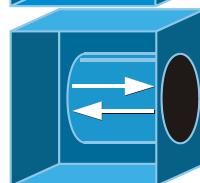
Web Security
Appliance



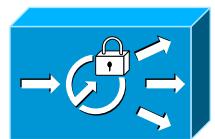
VPN Concentrator



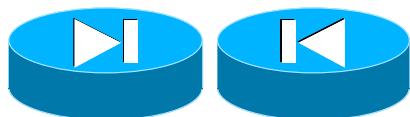
NAC Appliance



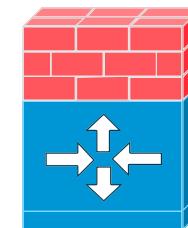
SSL
Terminator



ACE XML
Gateway



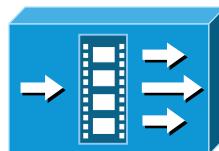
PIX Firewall
Right and Left



Cisco IOS Firewall



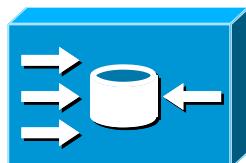
IP Telephony
Router



Streamer



Voice
Gateway



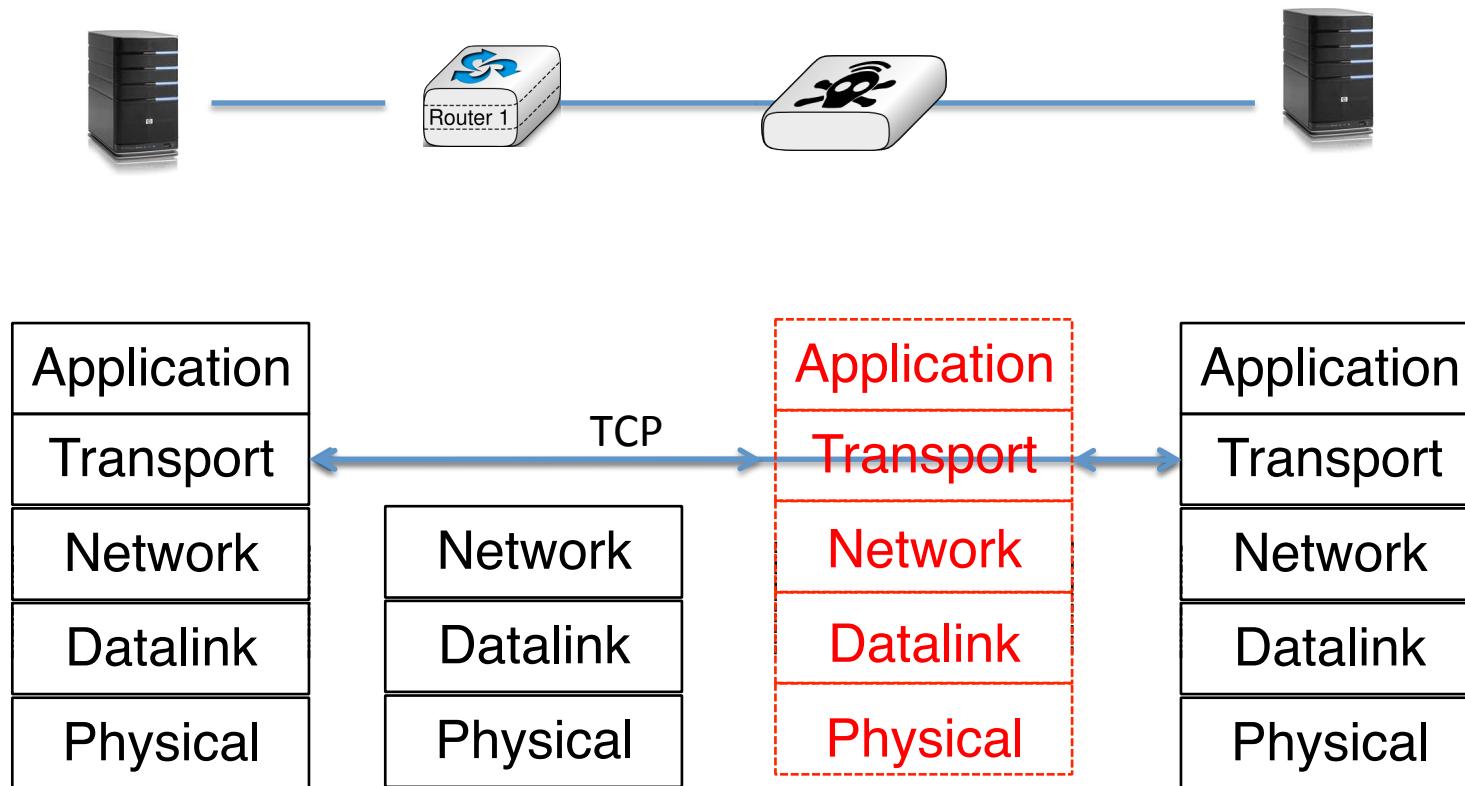
Content
Engine



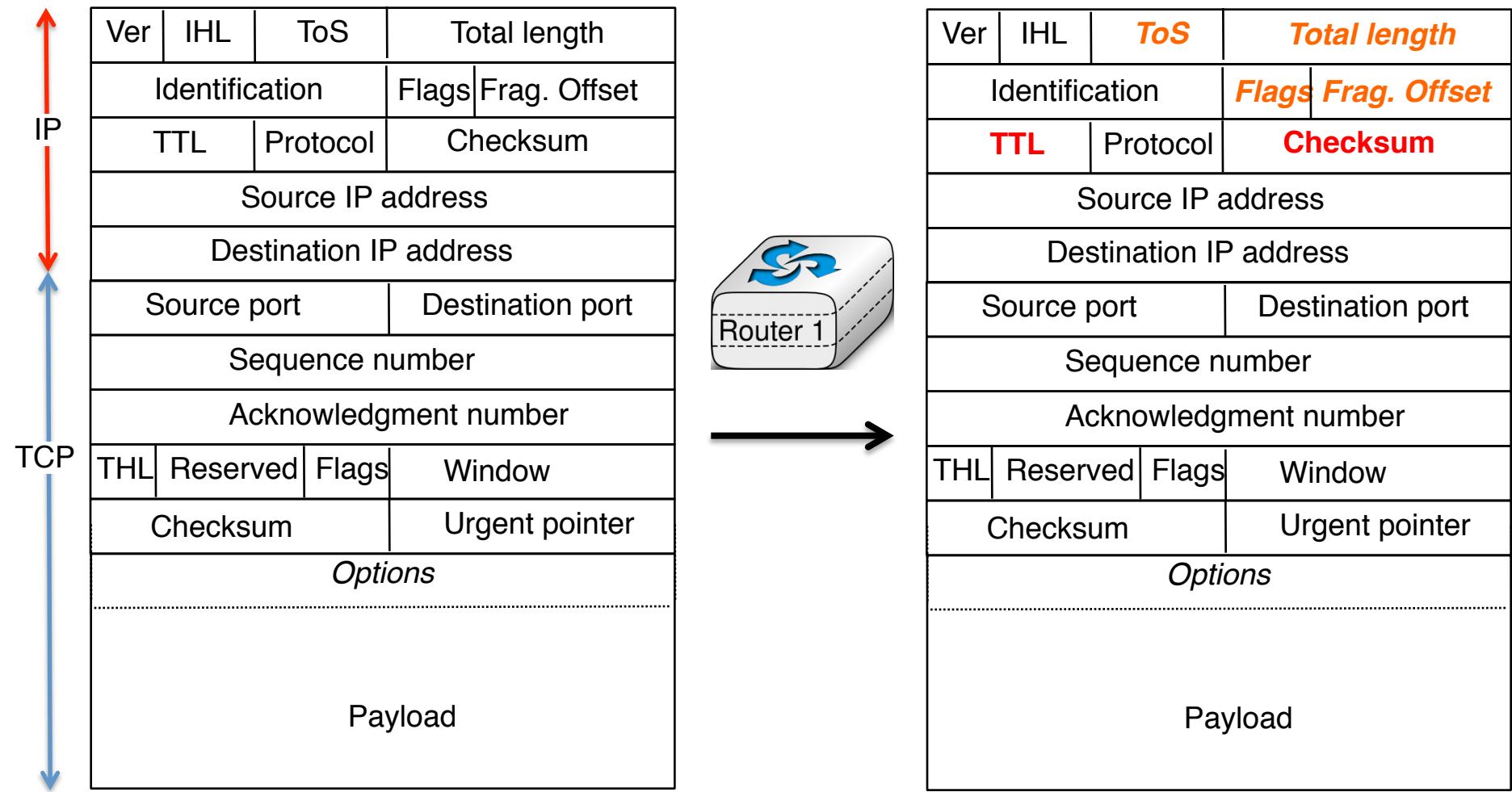
NAT

How to model those middleboxes ?

- In the official architecture, they do not exist
- In reality...

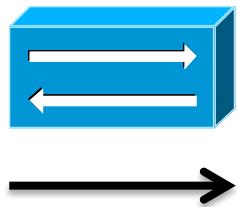


TCP segments processed by a router



TCP segments processed by a NAT

Ver	IHL	ToS	Total length		
Identification	Flags	Frag. Offset			
TTL Protocol Checksum					
Source IP address					
Destination IP address					
Source port		Destination port			
Sequence number					
Acknowledgment number					
THL	Reserved	Flags	Window		
Checksum		Urgent pointer			
<i>Options</i>					
Payload					



Ver	IHL	<i>ToS</i>	<i>Total length</i>		
Identification	Flags	<i>Flags Frag. Offset</i>			
TTL	Protocol	Checksum			
Source IP address					
Destination IP address					
Source port		Destination port			
Sequence number					
Acknowledgment number					
THL	Reserved	Flags	Window		
Checksum		Urgent pointer			
<i>Options</i>					
Payload					

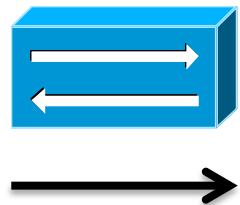
TCP segments processed by a NAT (2)

- active mode ftp behind a NAT

```
220 ProFTPD 1.3.3d Server (BELNET FTPD Server) [193.190.67.15]
ftp_login: user '<null>' pass '<null>' host 'ftp.belnet.be'
Name (ftp.belnet.be:obo): anonymous
---> USER anonymous
331 Anonymous login ok, send your complete email address as your password
Password:
---> PASS XXXX
---> PORT 192,168,0,7,195,120
200 PORT command successful
---> LIST
150 Opening ASCII mode data connection for file list
lrw-r--r-- 1 ftp     ftp        6 Jun 1 2011 pub -> mirror
226 Transfer complete
```

TCP segments processed by an ALG running on a NAT

Ver	IHL	ToS	Total length		
Identification	Flags	Frag. Offset			
TTL	Protocol	Checksum			
Source IP address					
Destination IP address					
Source port		Destination port			
Sequence number					
Acknowledgment number					
THL	Reserved	Flags	Window		
Checksum		Urgent pointer			
<i>Options</i>					
Payload					



Ver	IHL	<i>ToS</i>	<i>Total length</i>		
Identification		<i>Flags Frag. Offset</i>			
TTL	Protocol	<i>Checksum</i>			
Source IP address					
Destination IP address					
<i>Source port</i>		<i>Destination port</i>			
<i>Sequence number</i>					
<i>Acknowledgment number</i>					
THL	Reserved	Flags	Window		
<i>Checksum</i>		Urgent pointer			
<i>Options</i>					
<i>Payload</i>					

How transparent is the Internet ?

- 25th September 2010 to 30th April 2011
- 142 access networks
- 24 countries
- Sent specific TCP segments from client to a server in Japan

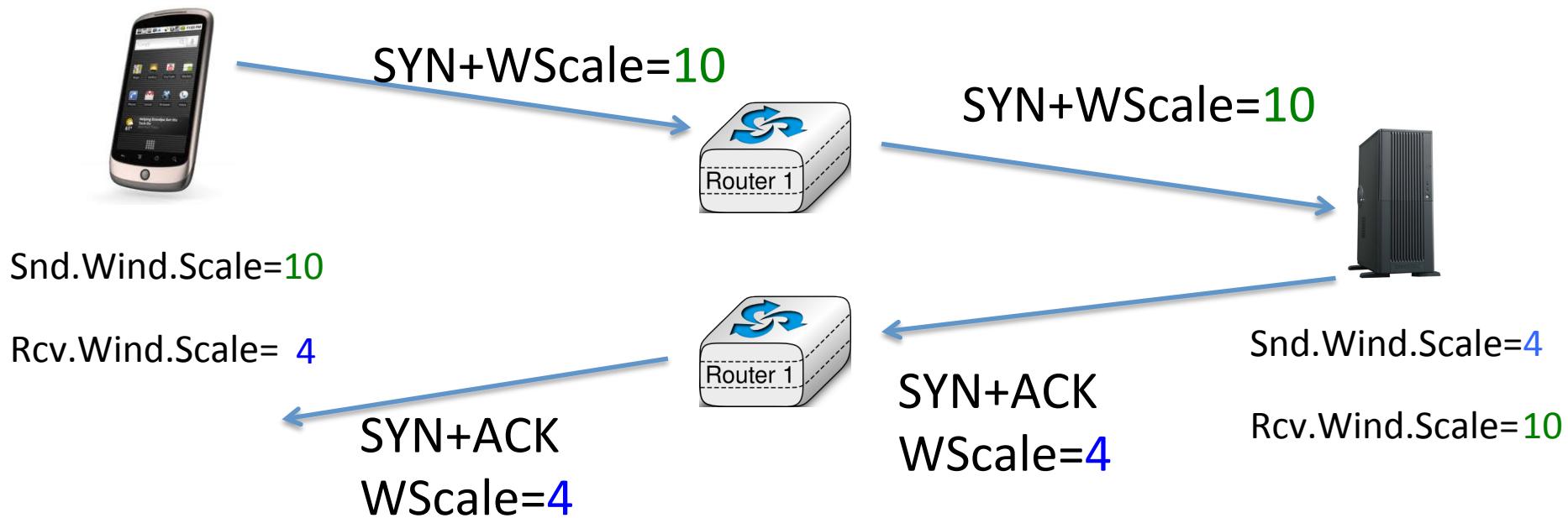
Table 2: Experiment Venues

Country	Home	Hotspot	Cellular	Univ	Ent	Hosting	Total
Australia	0	2	0	0	0	1	3
Austria	0	0	0	0	1	0	1
Belgium	4	0	0	1	0	0	5
Canada	1	0	1	0	1	0	3
Chile	0	0	0	0	1	0	1
China	0	7	0	0	0	0	7
Czech	0	2	0	0	0	0	2
Denmark	0	2	0	0	0	0	2
Finland	1	0	0	3	2	0	6
Germany	3	1	3	4	1	0	12
Greece	2	0	1	0	0	0	3
Indonesia	0	0	0	3	0	0	3
Ireland	0	0	0	0	0	1	1
Italy	1	0	0	0	1	0	2
Japan	19	10	7	3	2	0	41
Romania	1	0	0	0	0	0	1
Russia	0	1	0	0	0	0	1
Spain	0	1	0	1	0	0	2
Sweden	1	0	0	0	0	0	1
Switzerland	2	0	0	0	0	0	2
Thailand	0	0	0	0	2	0	2
U.K.	10	4	4	2	1	1	22
U.S.	3	4	4	0	4	2	17
Vietnam	1	0	0	0	1	0	2
Total	49	34	20	17	17	5	142

How to extend TCP ?

RFC1323

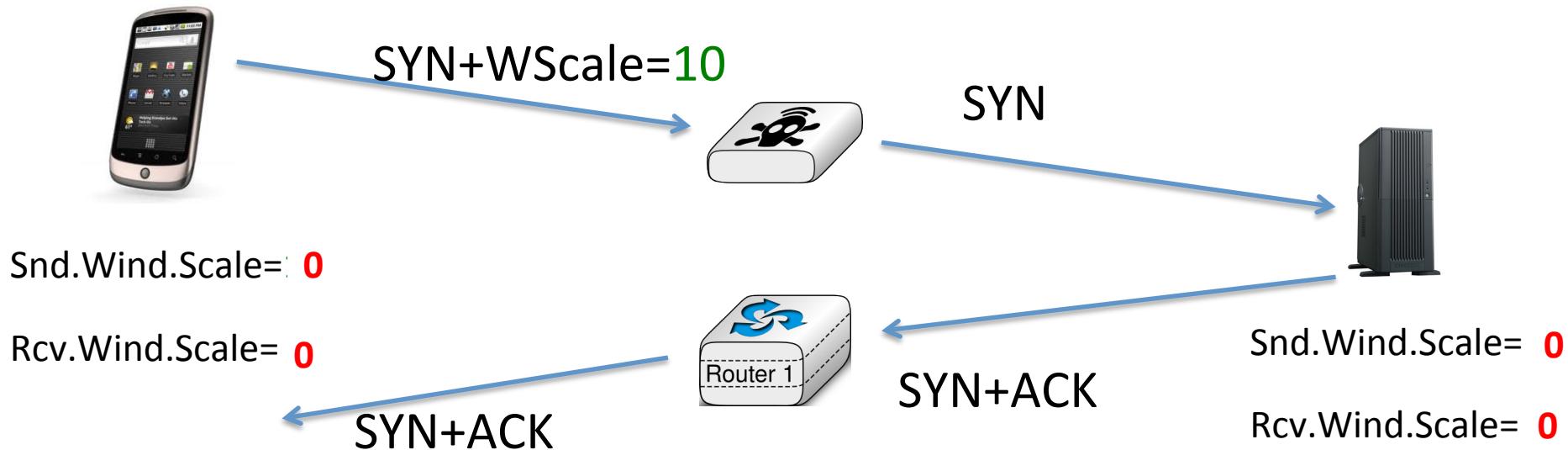
- Large window extension
 - supports >64KBytes windows by shifting window field in TCP segment header



How to extend TCP ?

RFC1323

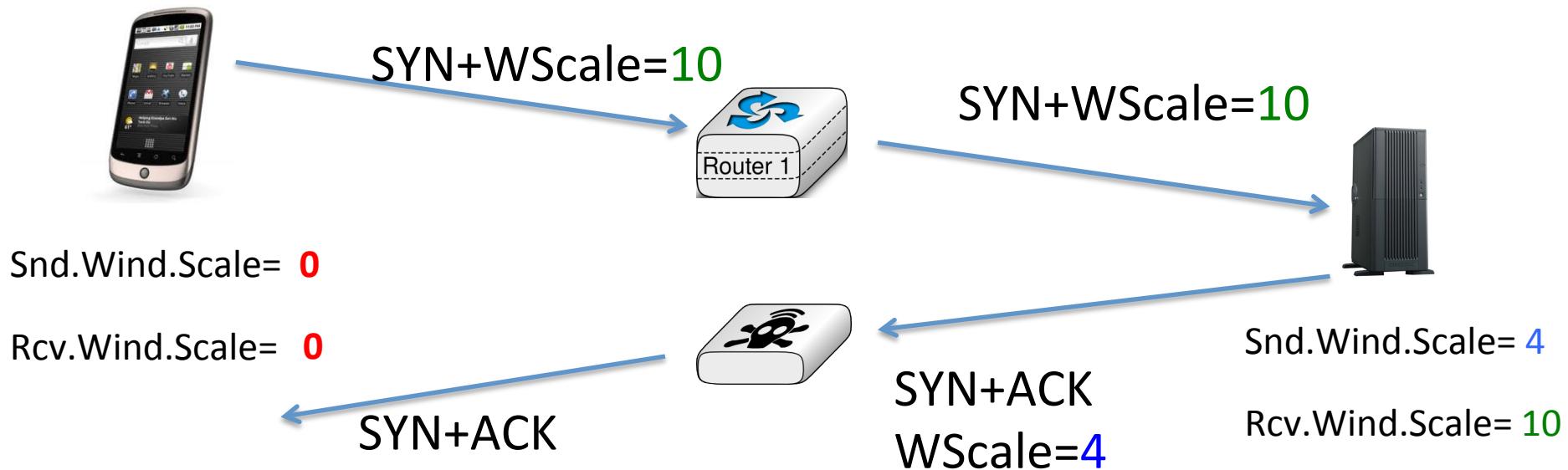
- What happens with middleboxes ?



How to extend TCP ?

RFC1323

- What happens with middleboxes ?



End-to-end transparency today

Ver	IHL	ToS	Total length
Identification	Offset		
TTL	Protocol		
Acknowledgment number			
IHL	Reserved	Flags	Window
Checksum		Urgent pointer	
<i>Options</i>			
Payload			



Middleboxes don't change the Protocol field, but many discard packets with an unknown Protocol field

Ver	IHL	<i>ToS</i>	<i>Total length</i>		
Identification	Flags	<i>Frag.</i>	<i>Offset</i>		
TTL	Protocol				
<i>Source IP address</i>					
<i>Destination IP address</i>					
<i>Source port</i>		<i>Destination port</i>			
<i>Sequence number</i>					
<i>Acknowledgment number</i>					
IHL	Reserved	Flags	Window		
<i>Checksum</i>		<i>Urgent pointer</i>			
<i>Options</i>					
<i>Payload</i>					



Agenda

- The motivations for Multipath TCP
- The changing Internet

The Multipath TCP Protocol

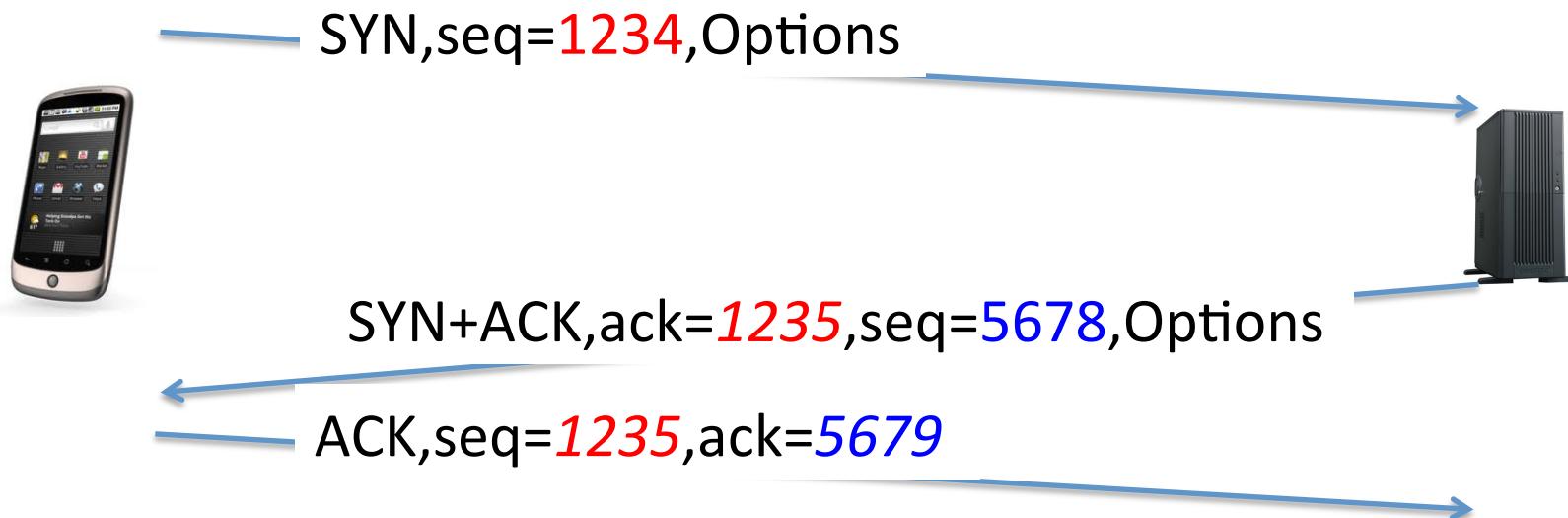
- Multipath TCP use cases

Design objectives

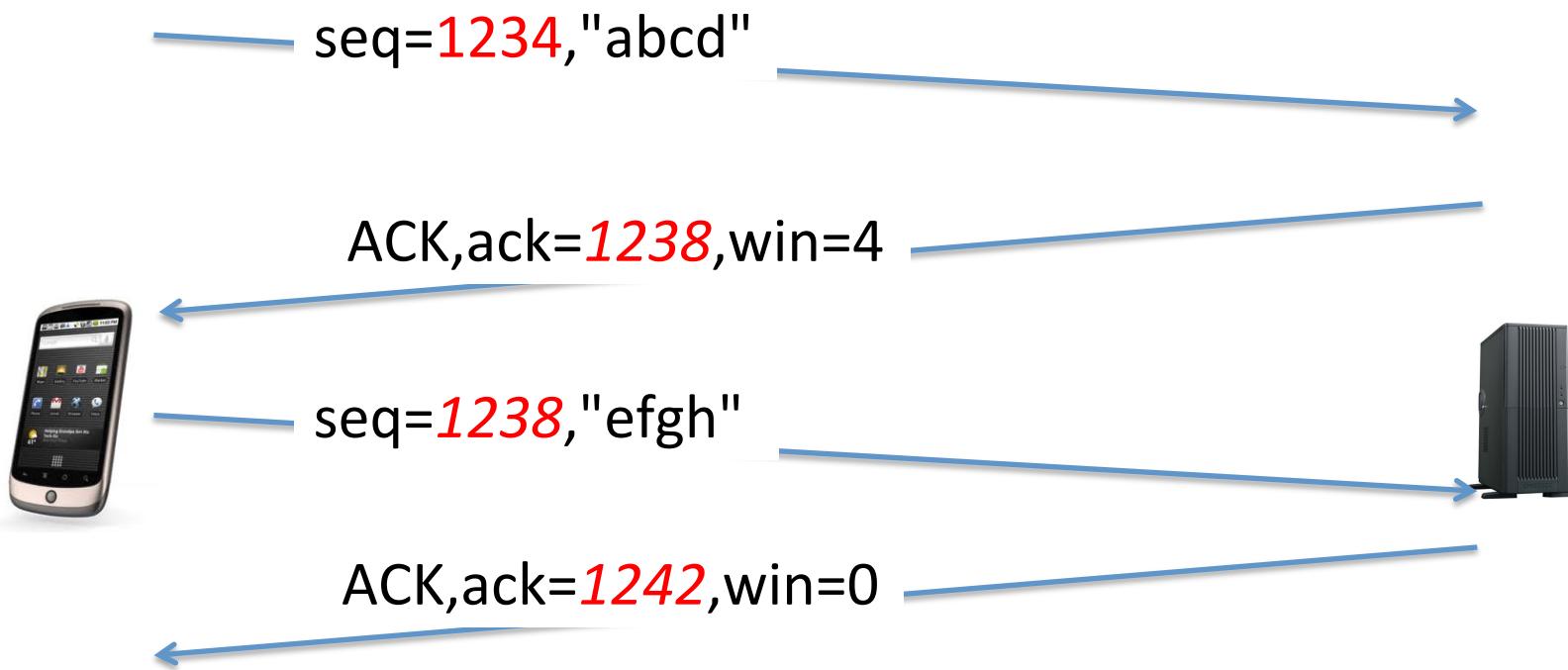
- Multipath TCP is an *evolution* of TCP
- Design objectives
 - Support unmodified applications
 - Work over today's networks
 - Works in all networks where regular TCP works

TCP Connection establishment

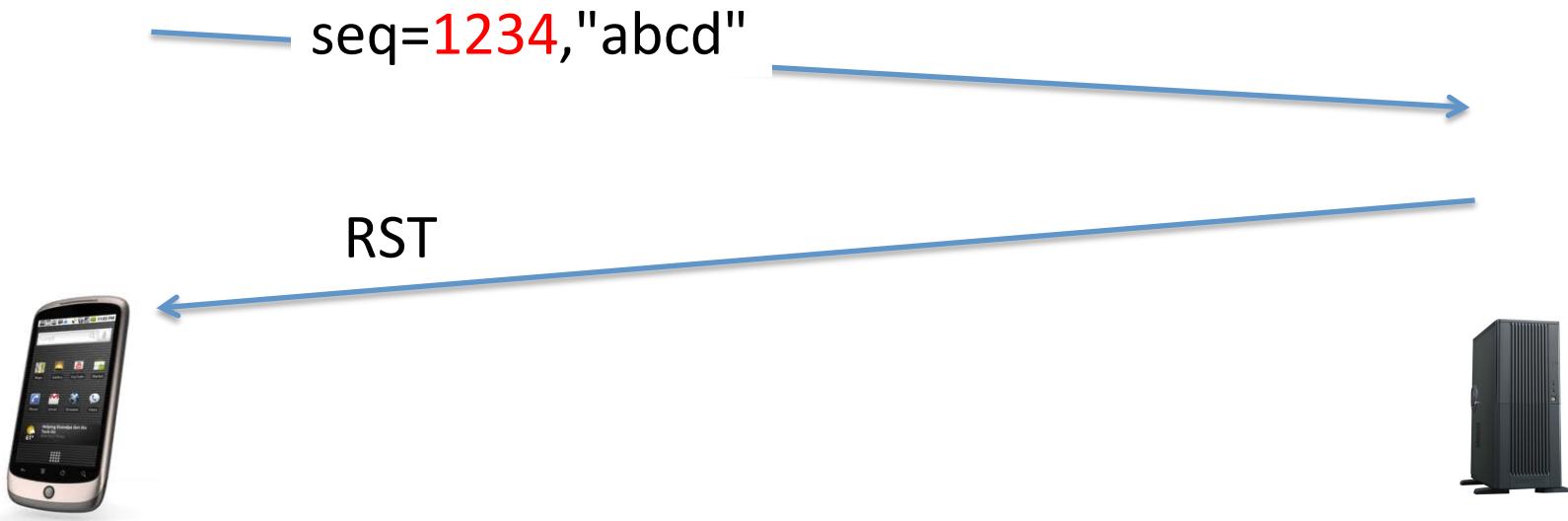
- Three-way handshake



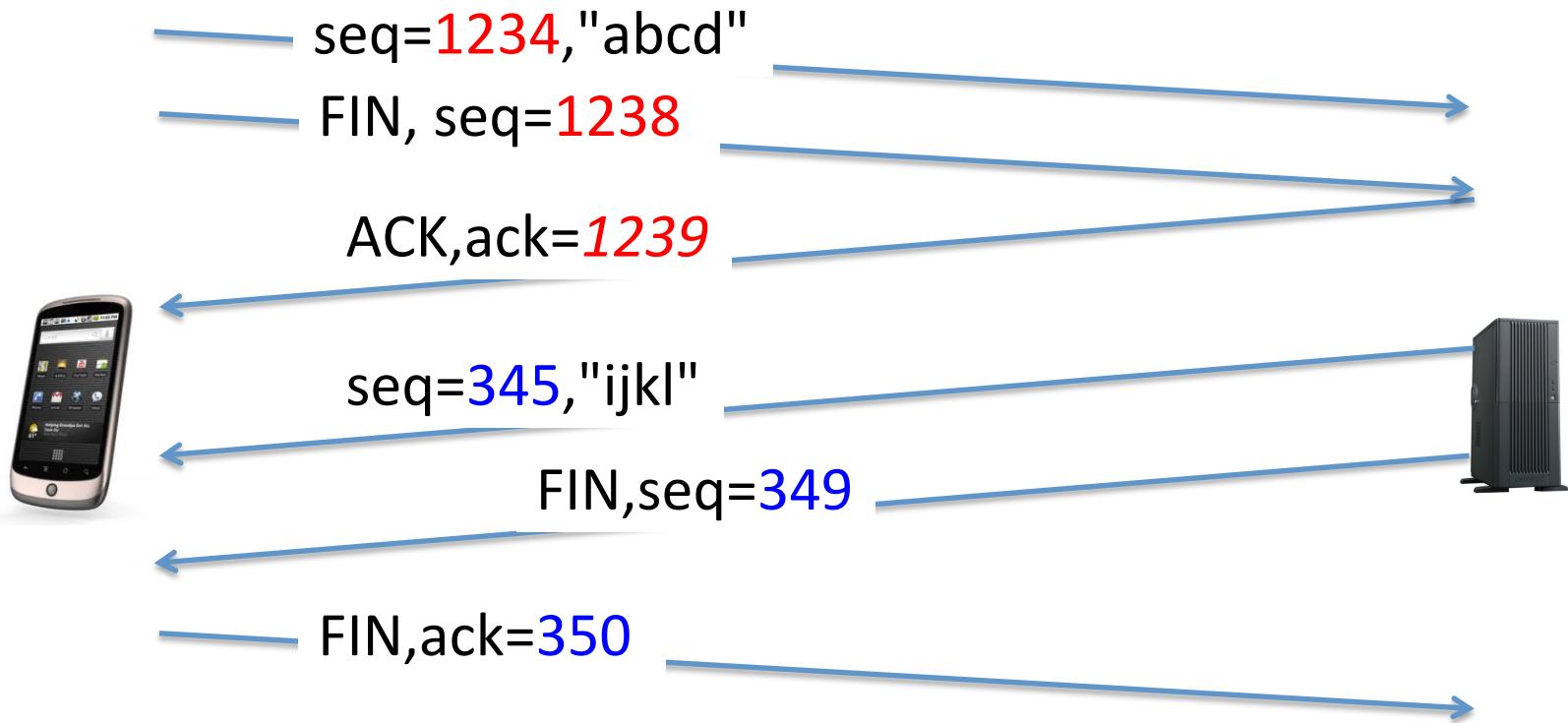
Data transfer



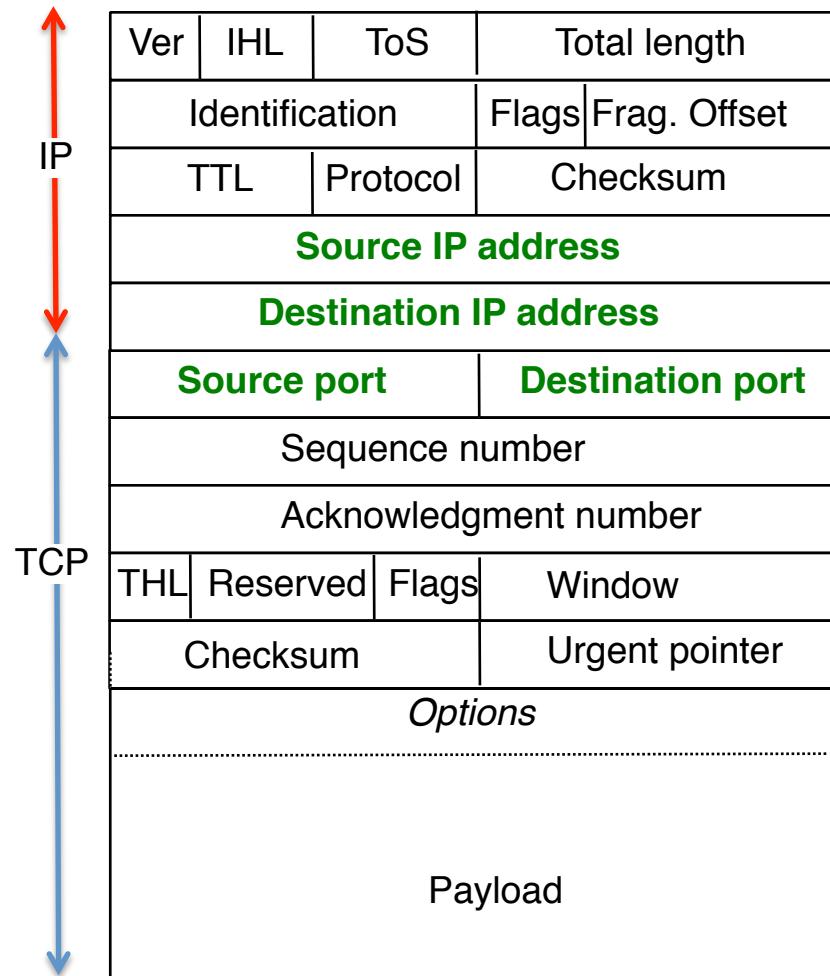
Connection release



Connection release



Identification of a TCP connection

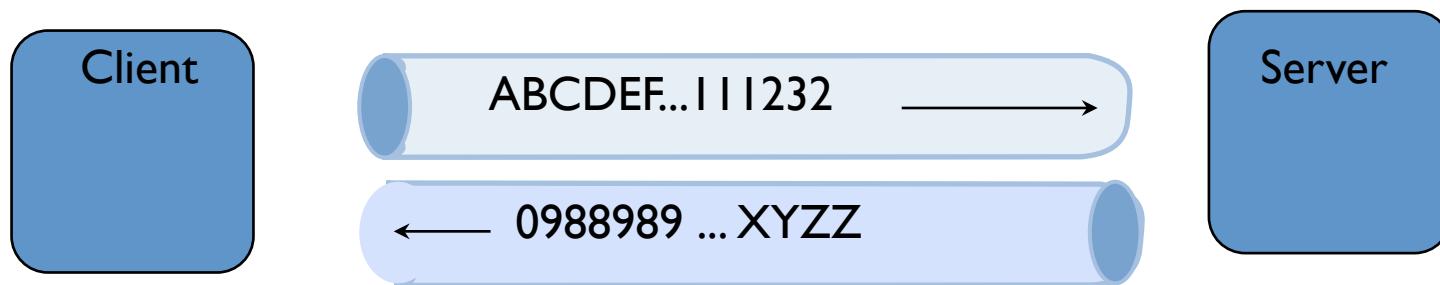


Four tuple

- $\text{IP}_{\text{source}}$
- IP_{dest}
- $\text{Port}_{\text{source}}$
- $\text{Port}_{\text{dest}}$

All TCP segments contain the four tuple

The *new* bytestream model



D C B A



IP:2.3.4.5

IP:1.2.3.4



IP:6.7.8.9

IP:4.5.6.7

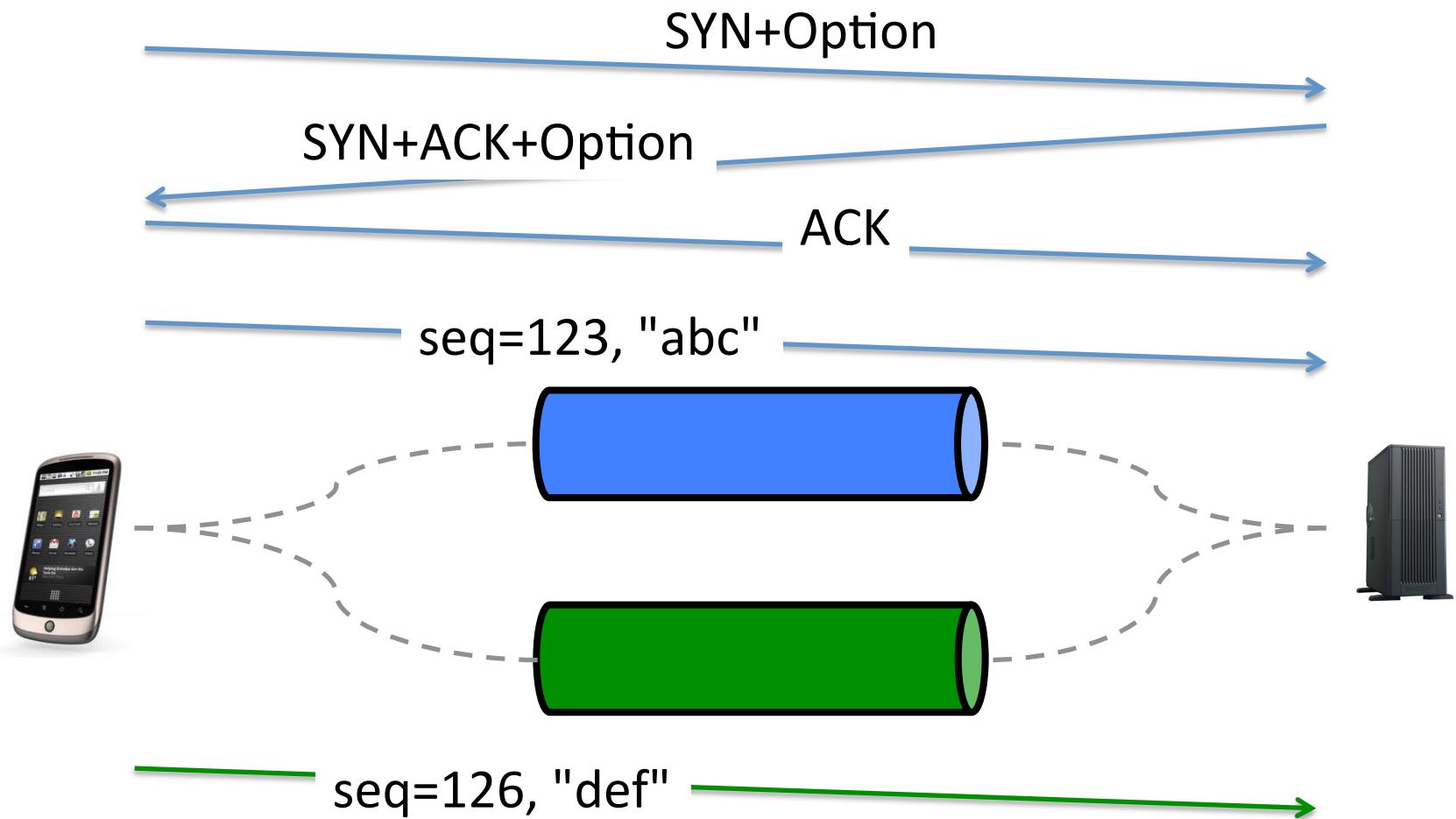


The Multipath TCP protocol

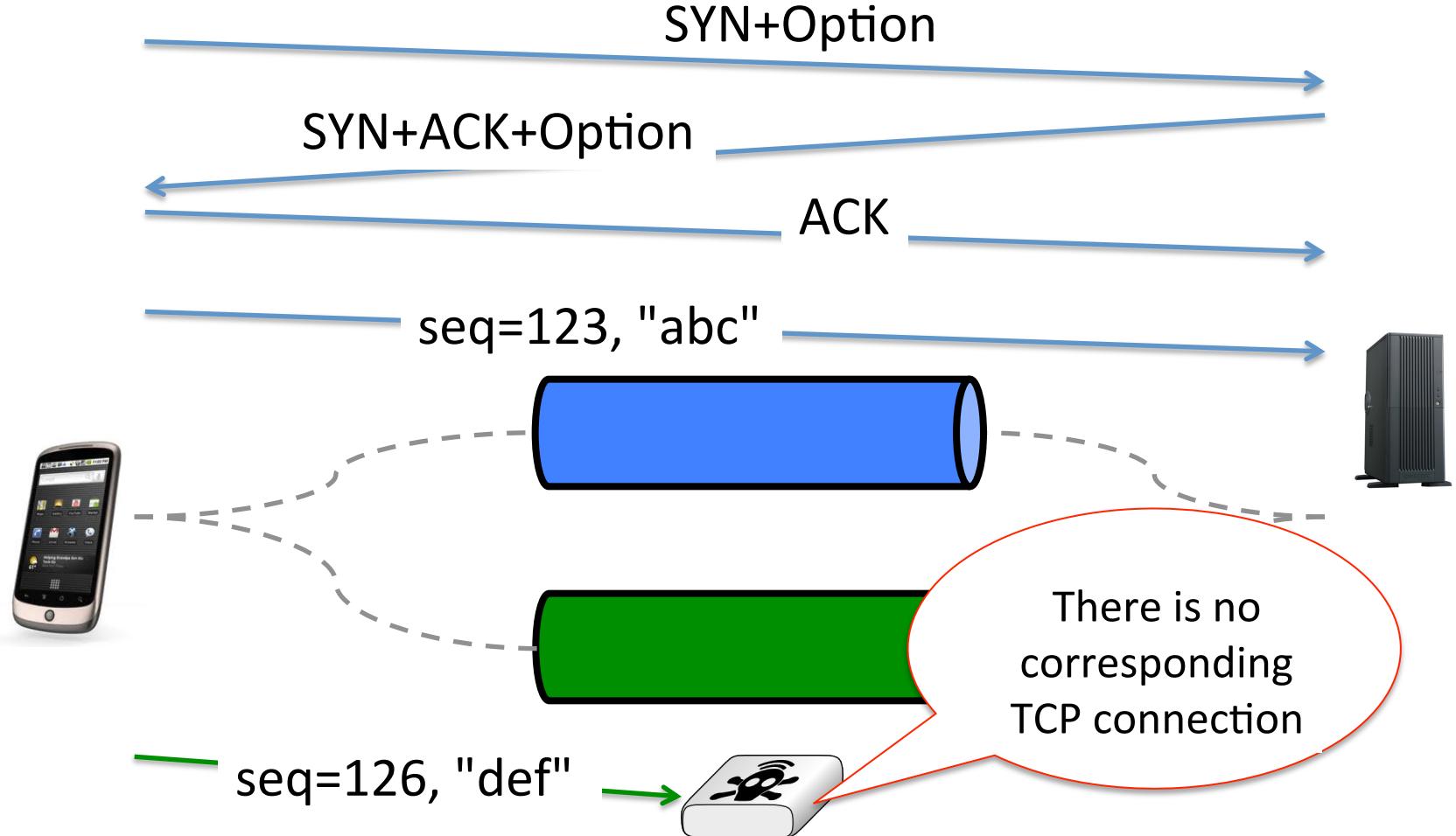
→ Control plane

- How to manage a Multipath TCP connection that uses several paths ?
- Data plane
 - How to transport data ?
- Congestion control
 - How to control congestion over multiple paths ?

A naïve Multipath TCP



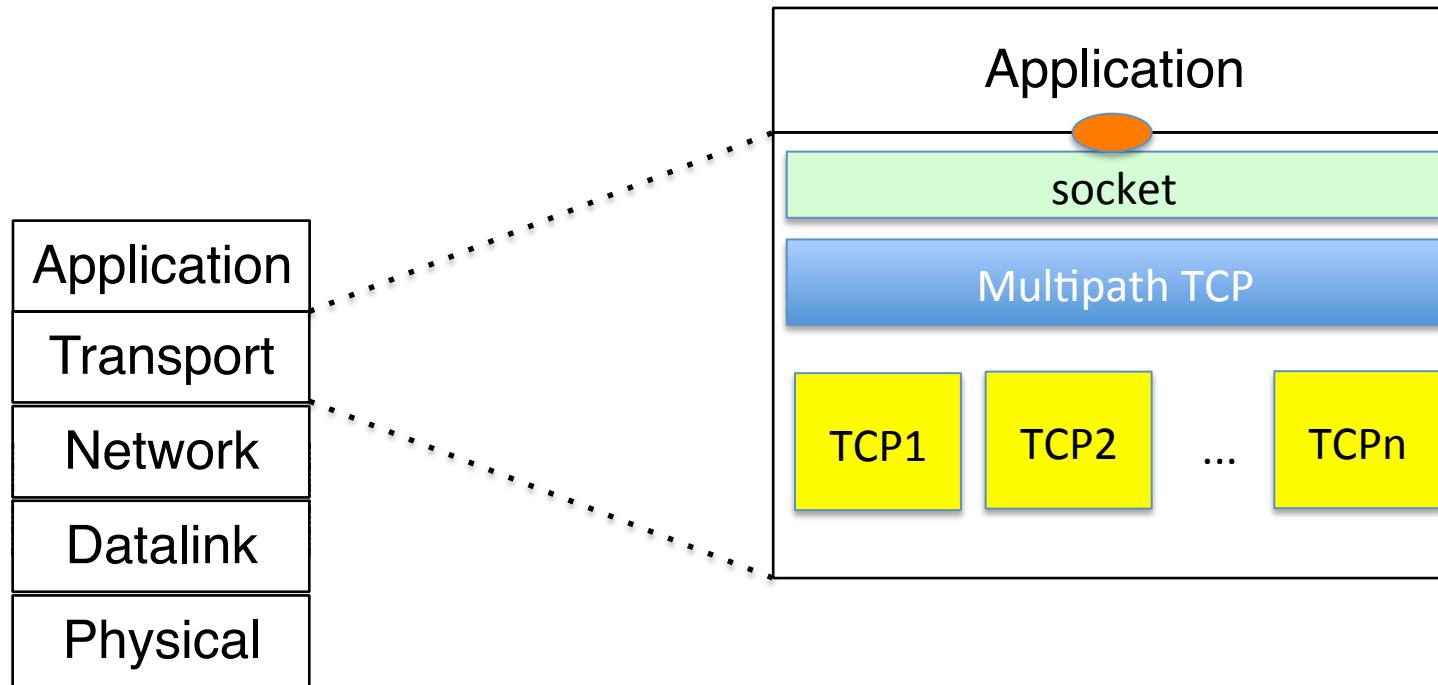
A naïve Multipath TCP In today's Internet ?



Design decision

- *A Multipath TCP connection is composed of one or more regular TCP subflows that are combined*
 - Each host maintains state that glues the TCP subflows that compose a Multipath TCP connection together
 - Each TCP subflow is sent over a single path and appears like a **regular TCP** connection along this path

Multipath TCP and the architecture

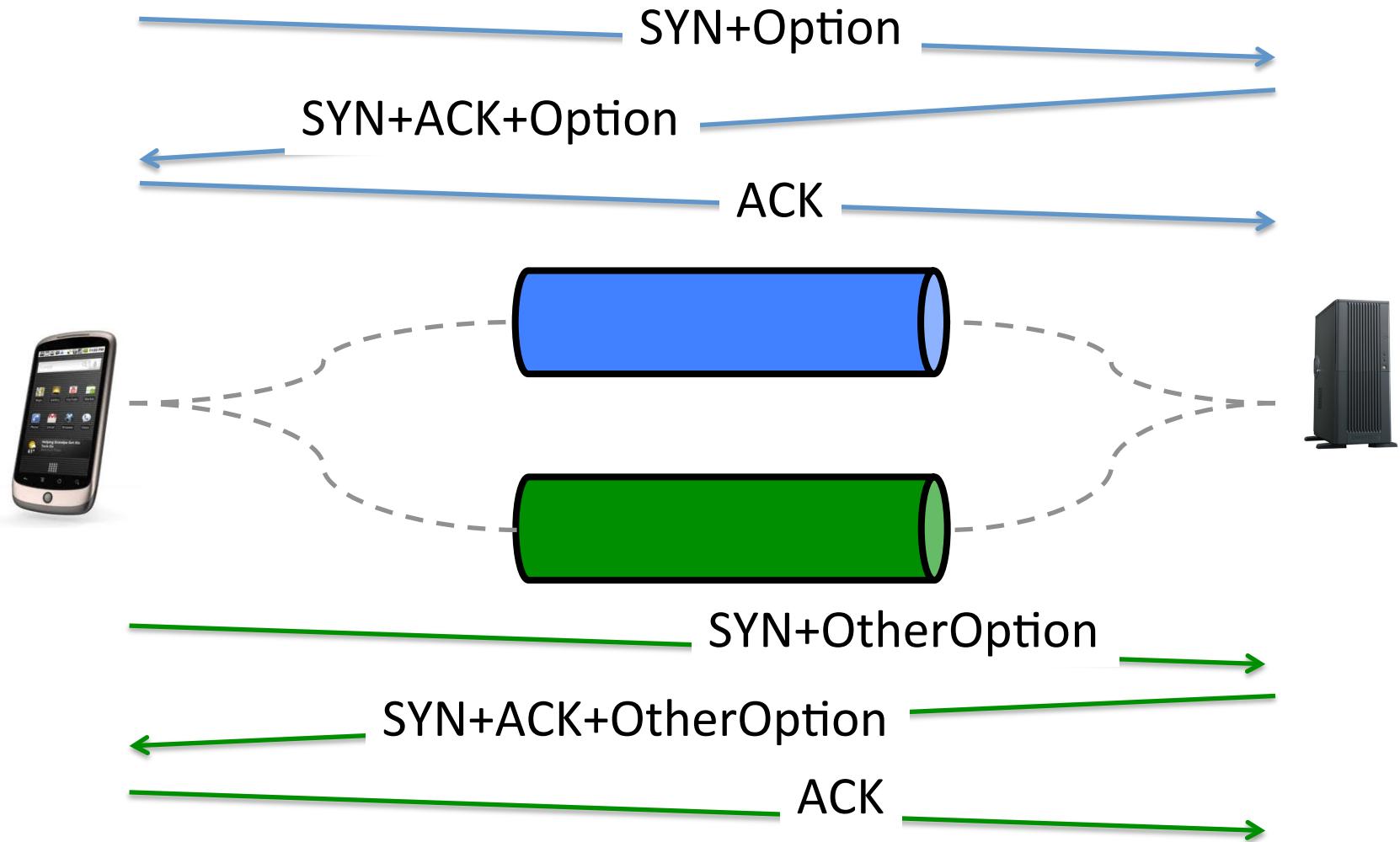


A. Ford, C. Raiciu, M. Handley, S. Barre, and J. Iyengar, "Architectural guidelines for multipath TCP development", RFC6182 2011.

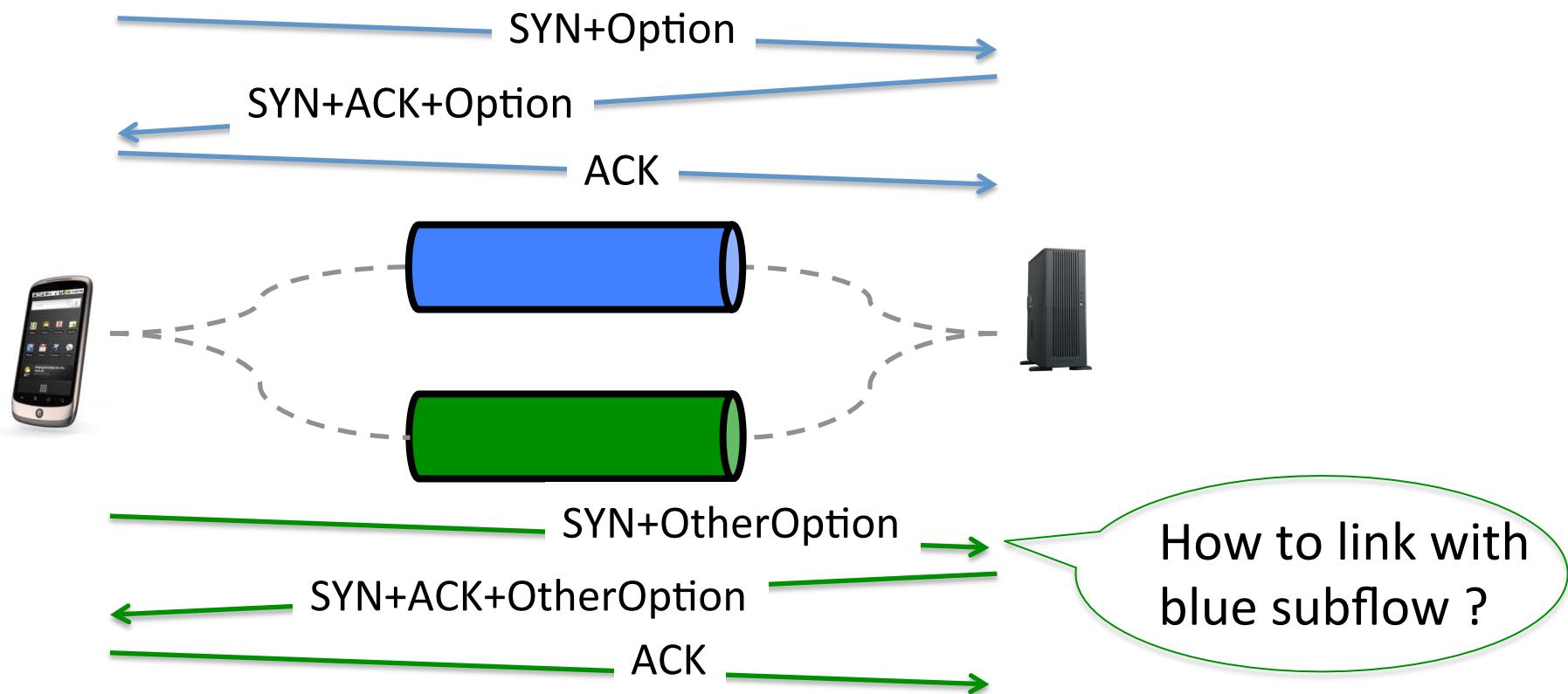
A *regular* TCP connection

- What is a *regular* TCP connection ?
 - It starts with a three-way handshake
 - SYN segments may contain special options
 - All data segments are sent in sequence
 - There is no gap in the sequence numbers
 - It is terminated by using FIN or RST

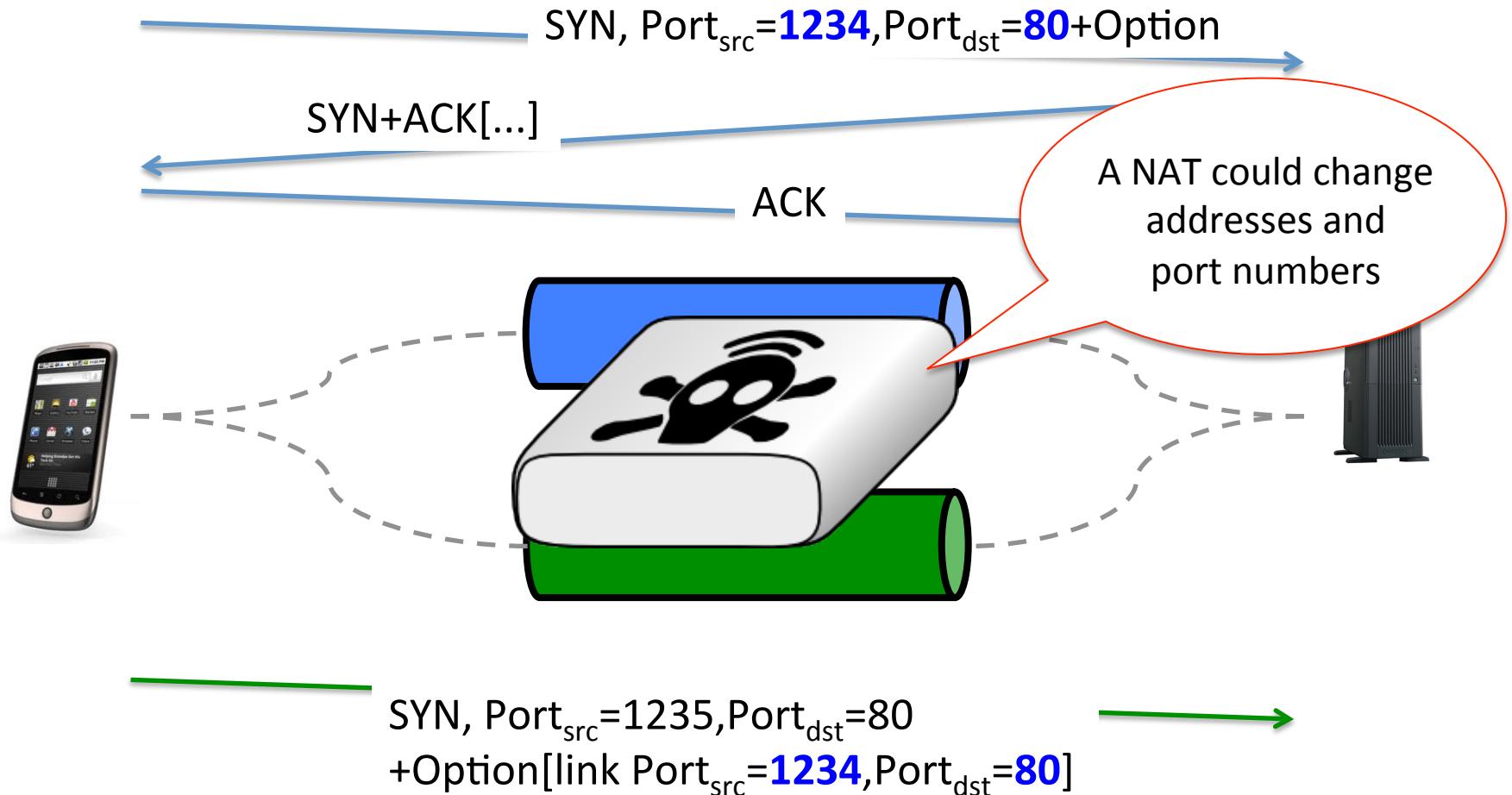
Multipath TCP



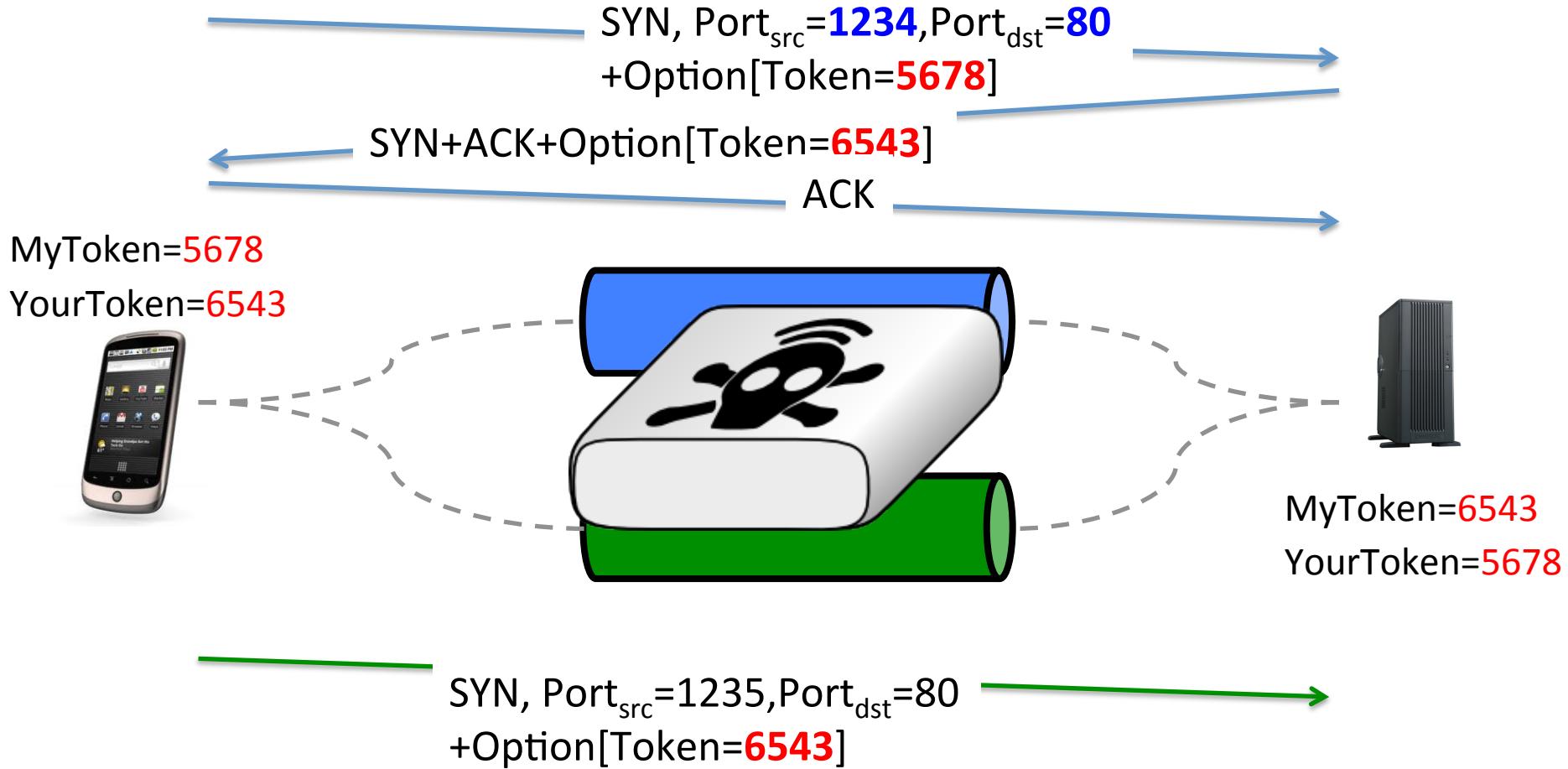
How to combine two TCP subflows ?



How to link TCP subflows ?

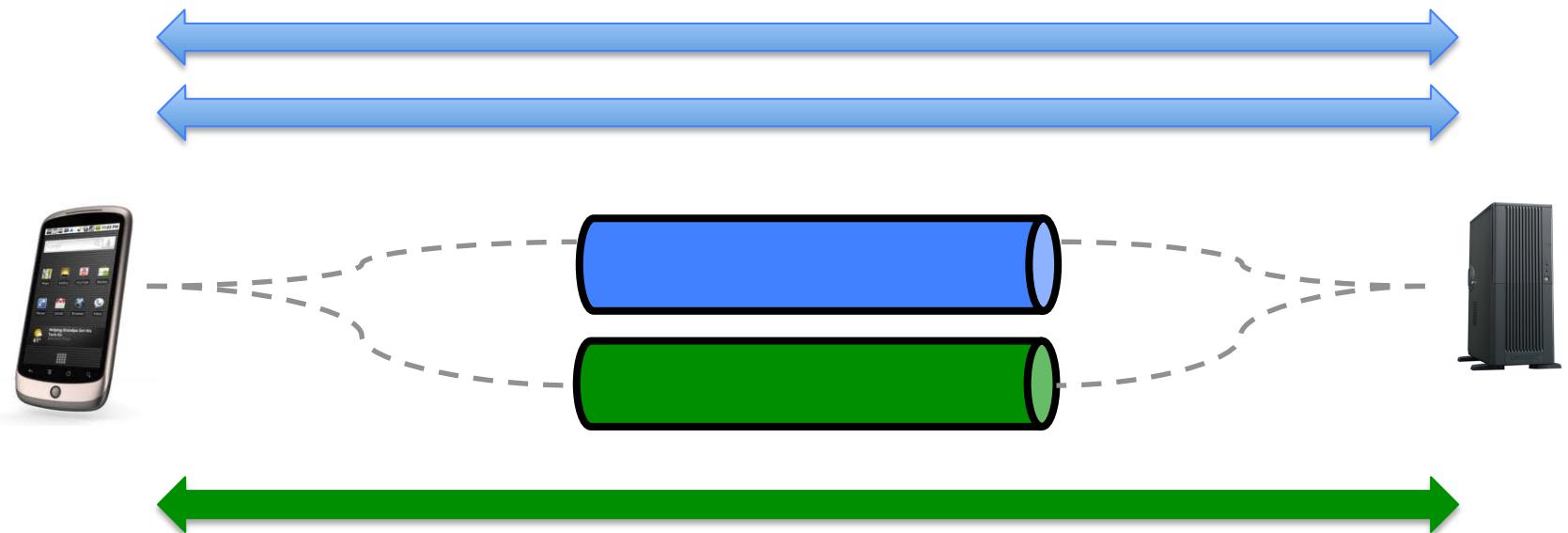


How to link TCP subflows ?



Subflow agility

- Multipath TCP supports
 - addition of subflows
 - removal of subflows



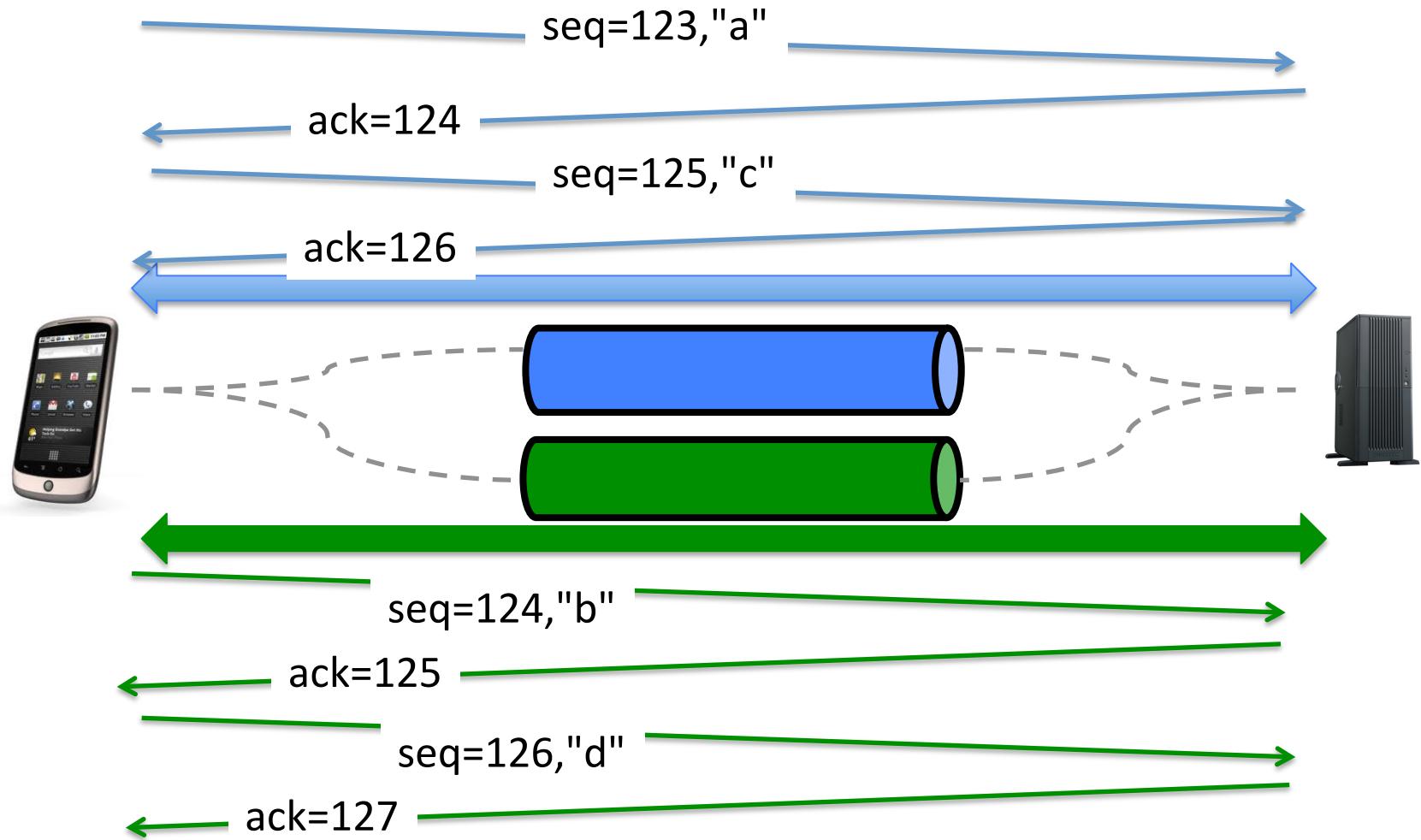
TCP subflows

- Which subflows can be associated to a Multipath TCP connection ?
 - At least one of the elements of the four-tuple needs to differ between two subflows
 - Local IP address
 - Remote IP address
 - Local port
 - Remote port

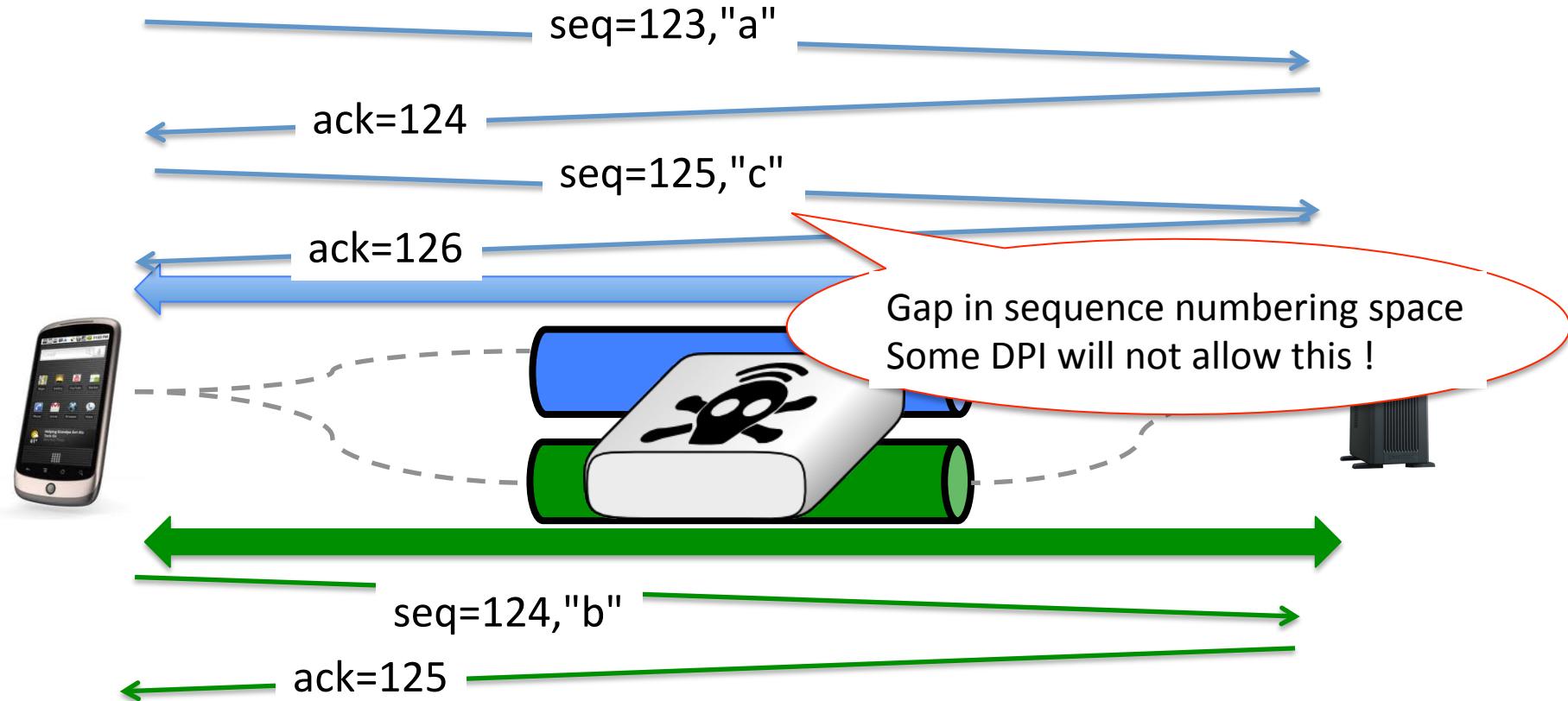
The Multipath TCP protocol

- Control plane
 - How to manage a Multipath TCP connection that uses several paths ?
- **Data plane**
 - How to transport data ?
- Congestion control
 - How to control congestion over multiple paths ?

How to transfer data ?

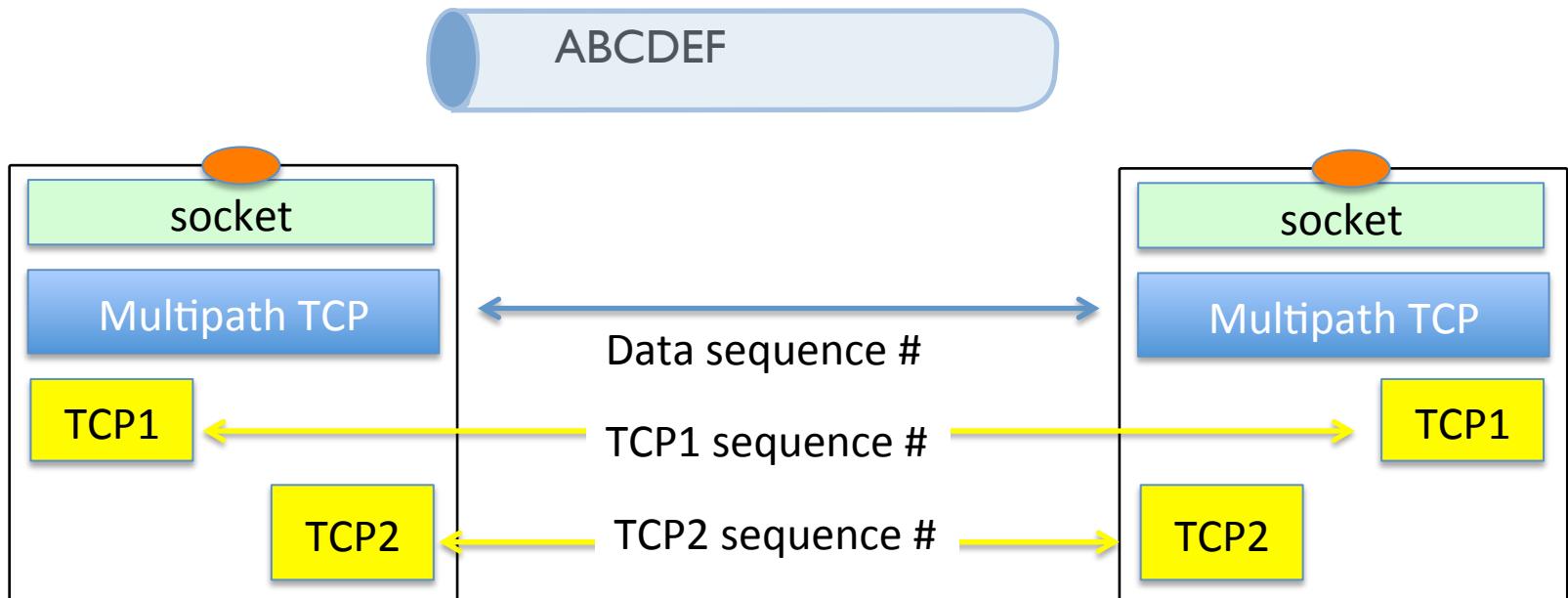


How to transfer data in today's Internet ?

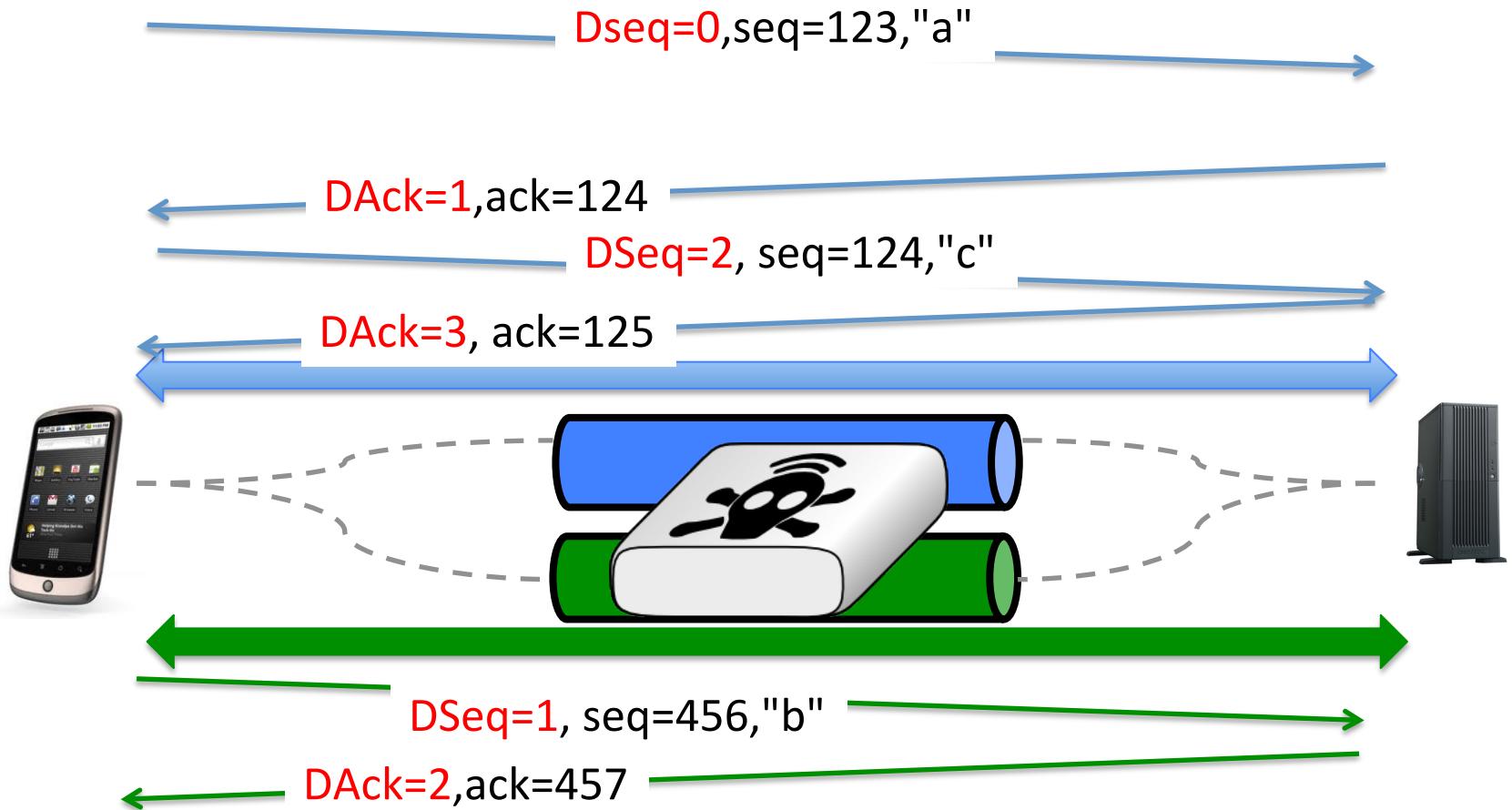


Multipath TCP Data transfer

- Two levels of sequence numbers



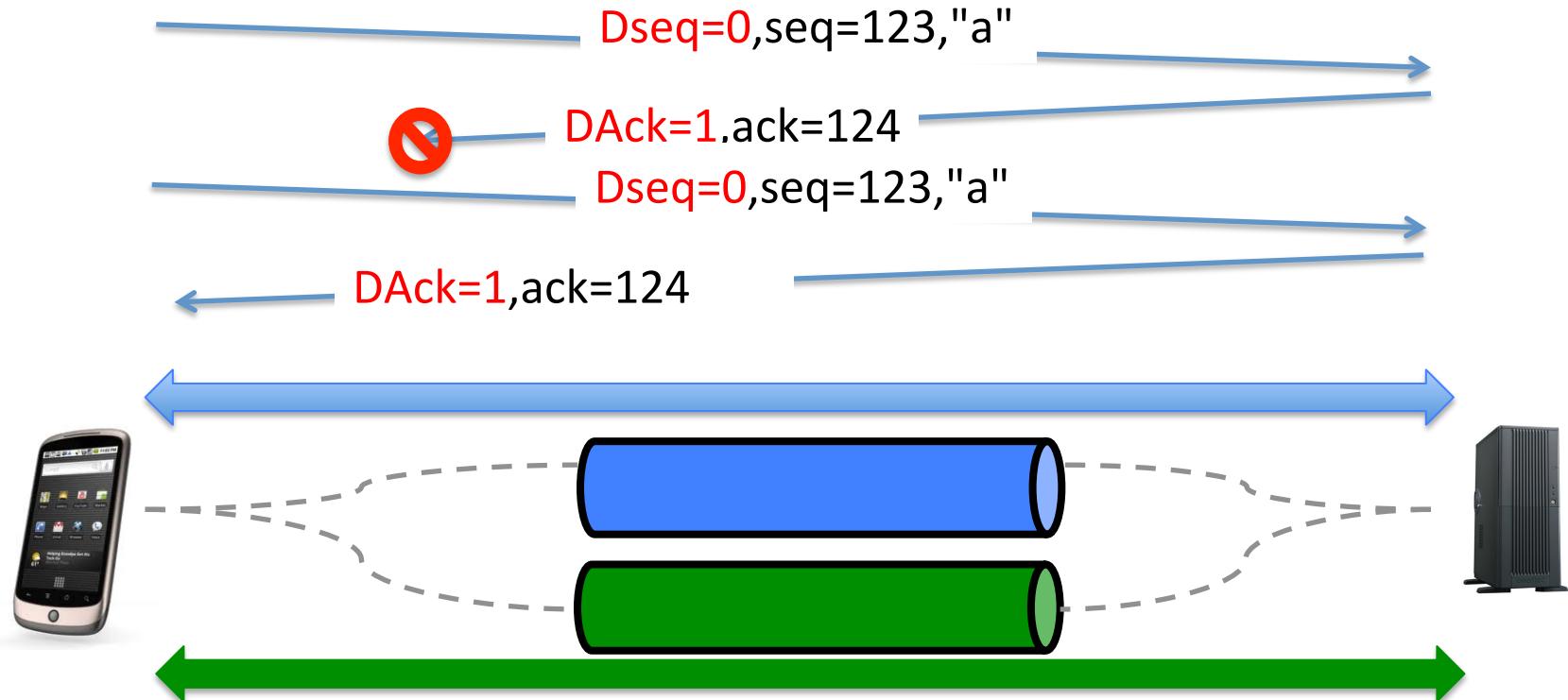
Multipath TCP Data transfer



Multipath TCP

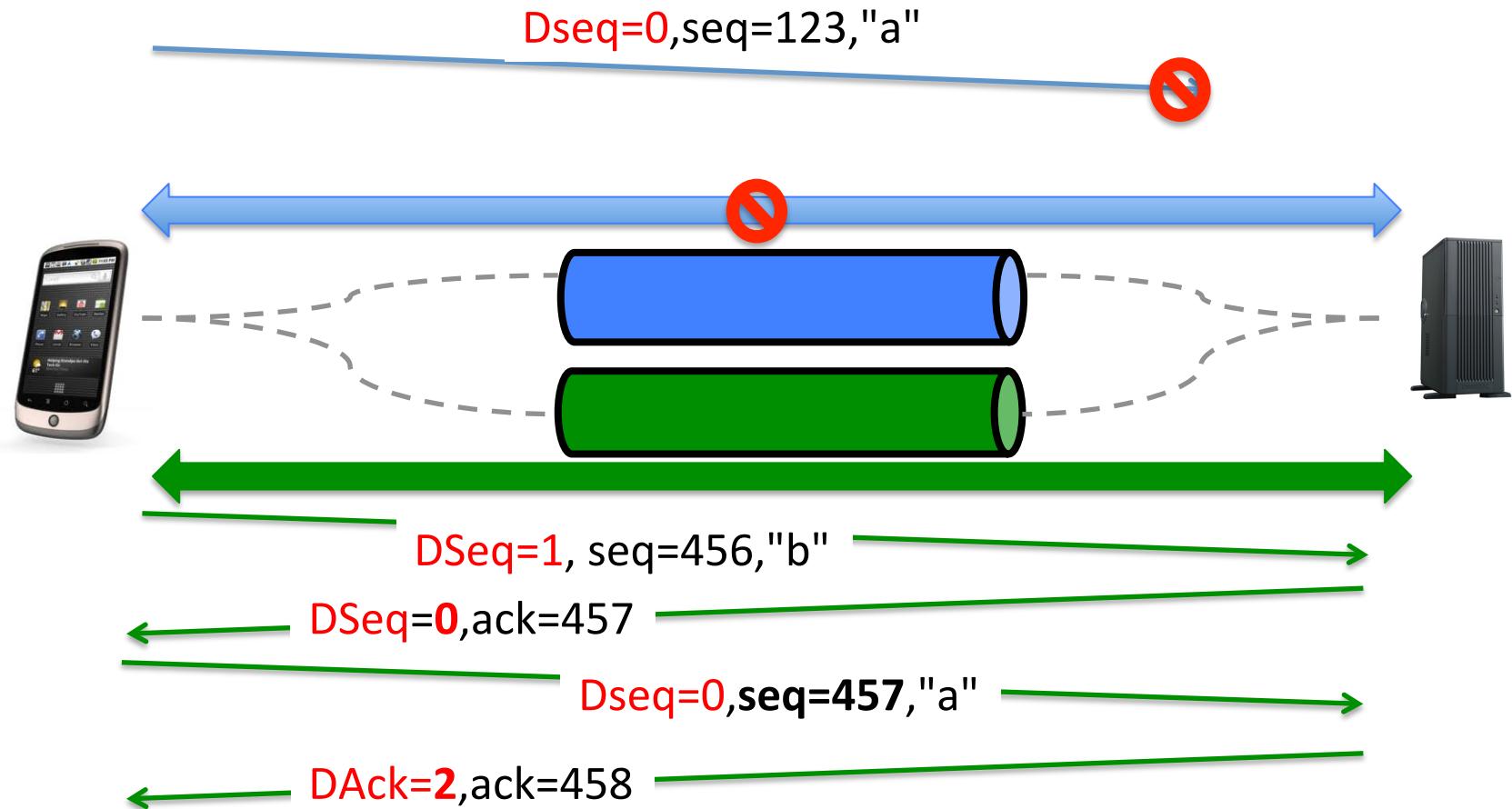
How to deal with losses ?

- Data losses over one TCP subflow
 - Fast retransmit and timeout as in regular TCP



Multipath TCP

- What happens when a TCP subflow fails ?



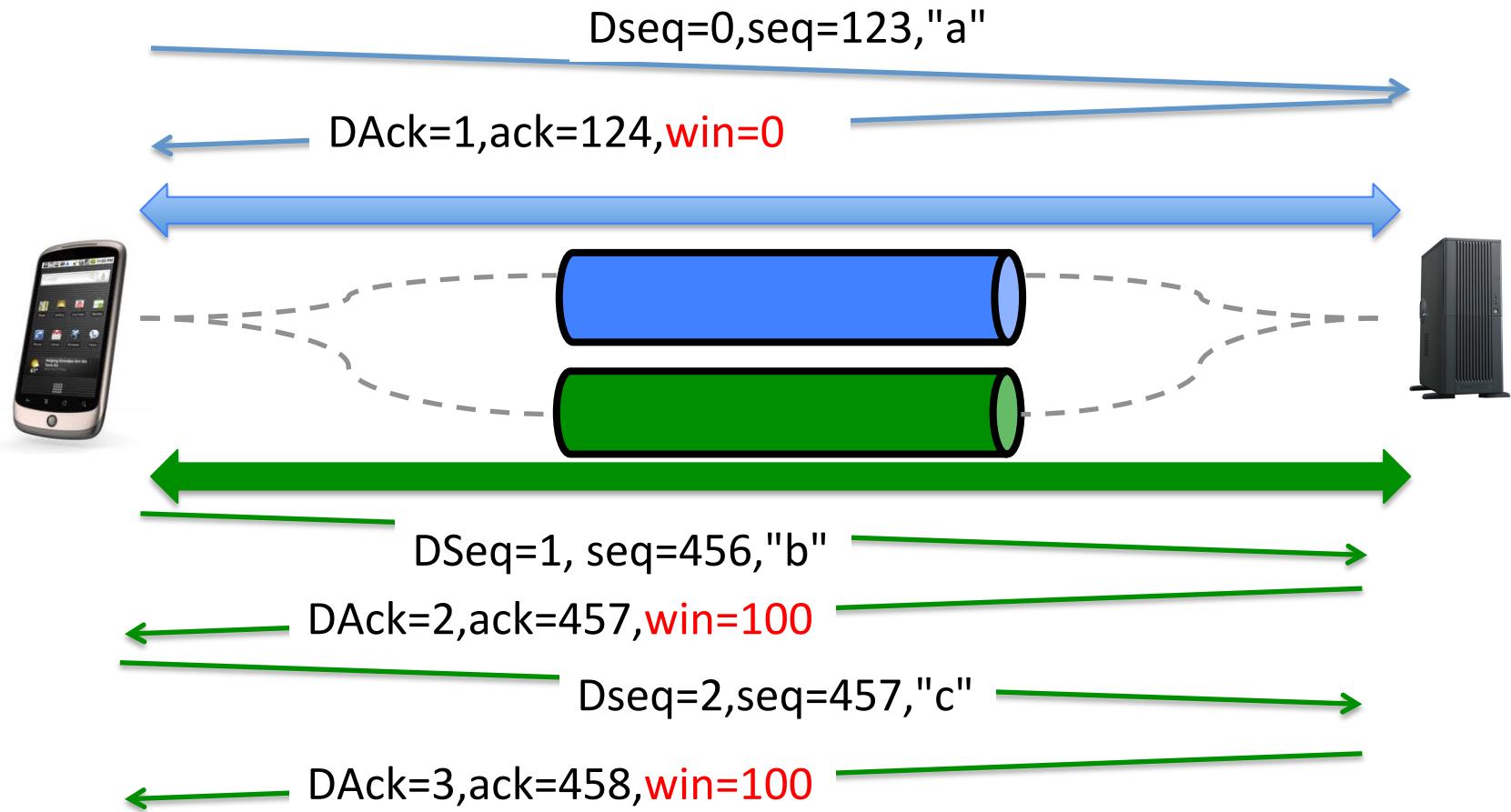
Retransmission heuristics

- Heuristics used by current Linux implementation
 - Fast retransmit is performed on the same subflow as the original transmission
 - Upon timeout expiration, reevaluate whether the segment could be retransmitted over another subflow
 - Upon loss of a subflow, all the unacknowledged data are retransmitted on other subflows

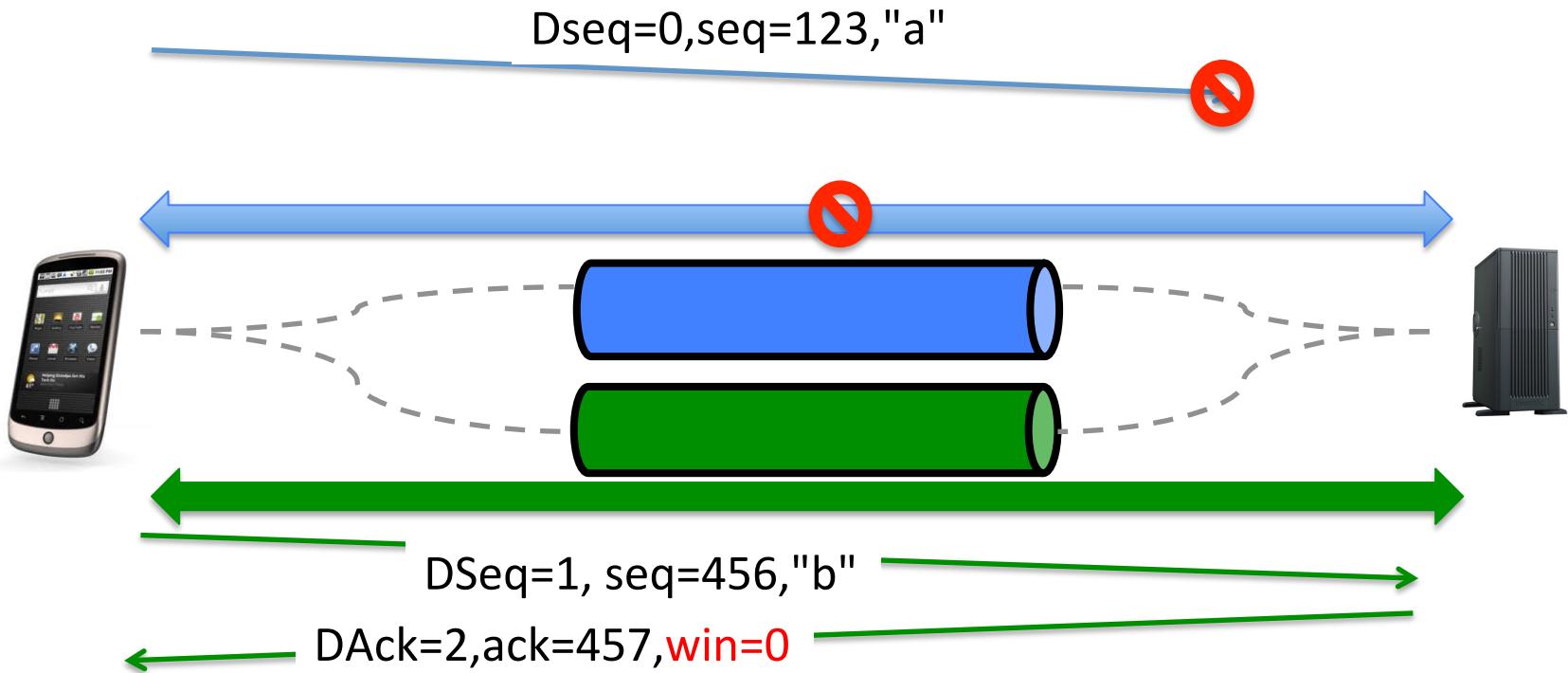
Flow control

- How should the window-based flow control be performed ?
 - Independant windows on each TCP subflow
 - A single window that is shared among all TCP subflows

Independant windows

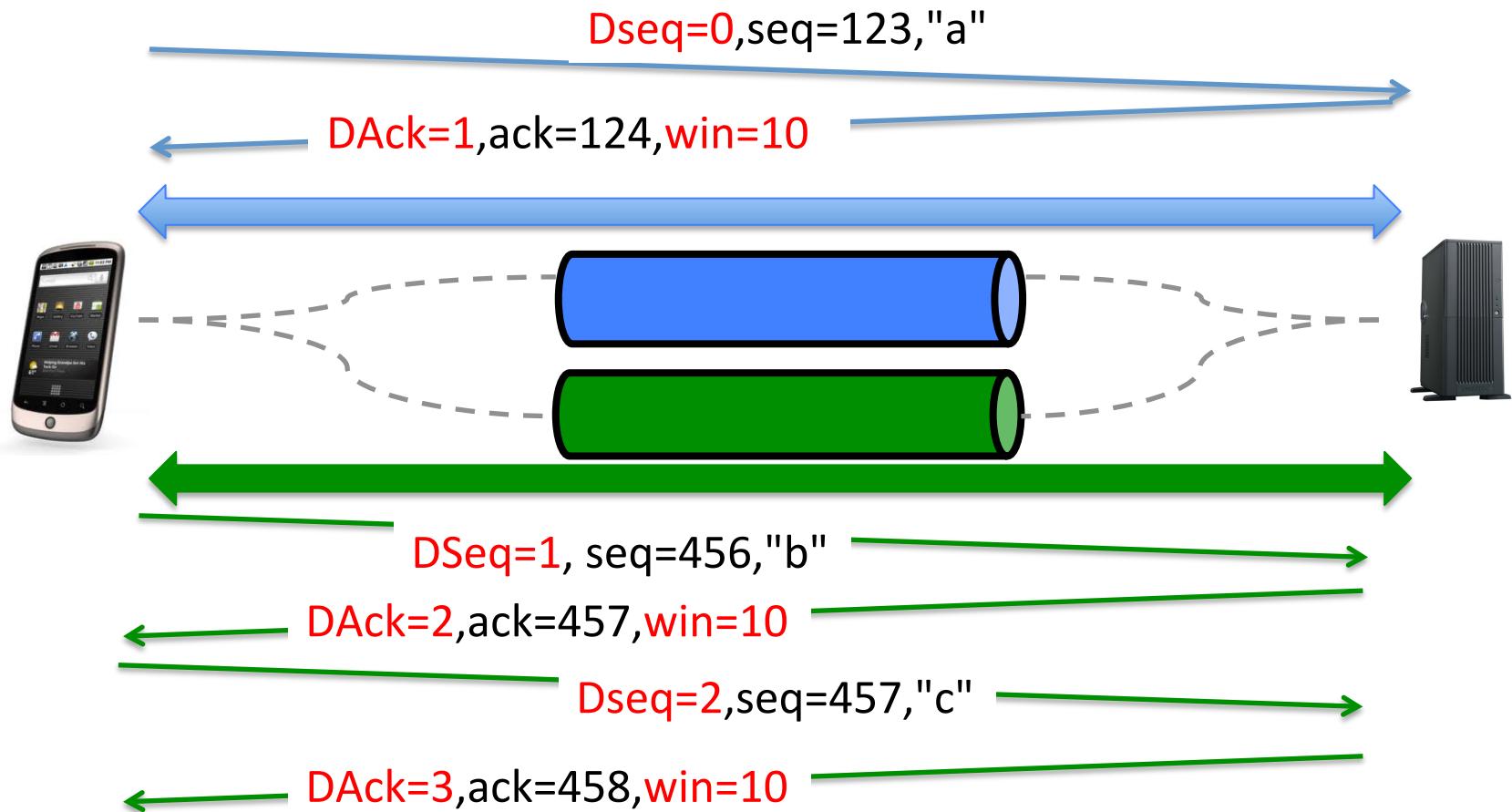


Independant windows possible problem



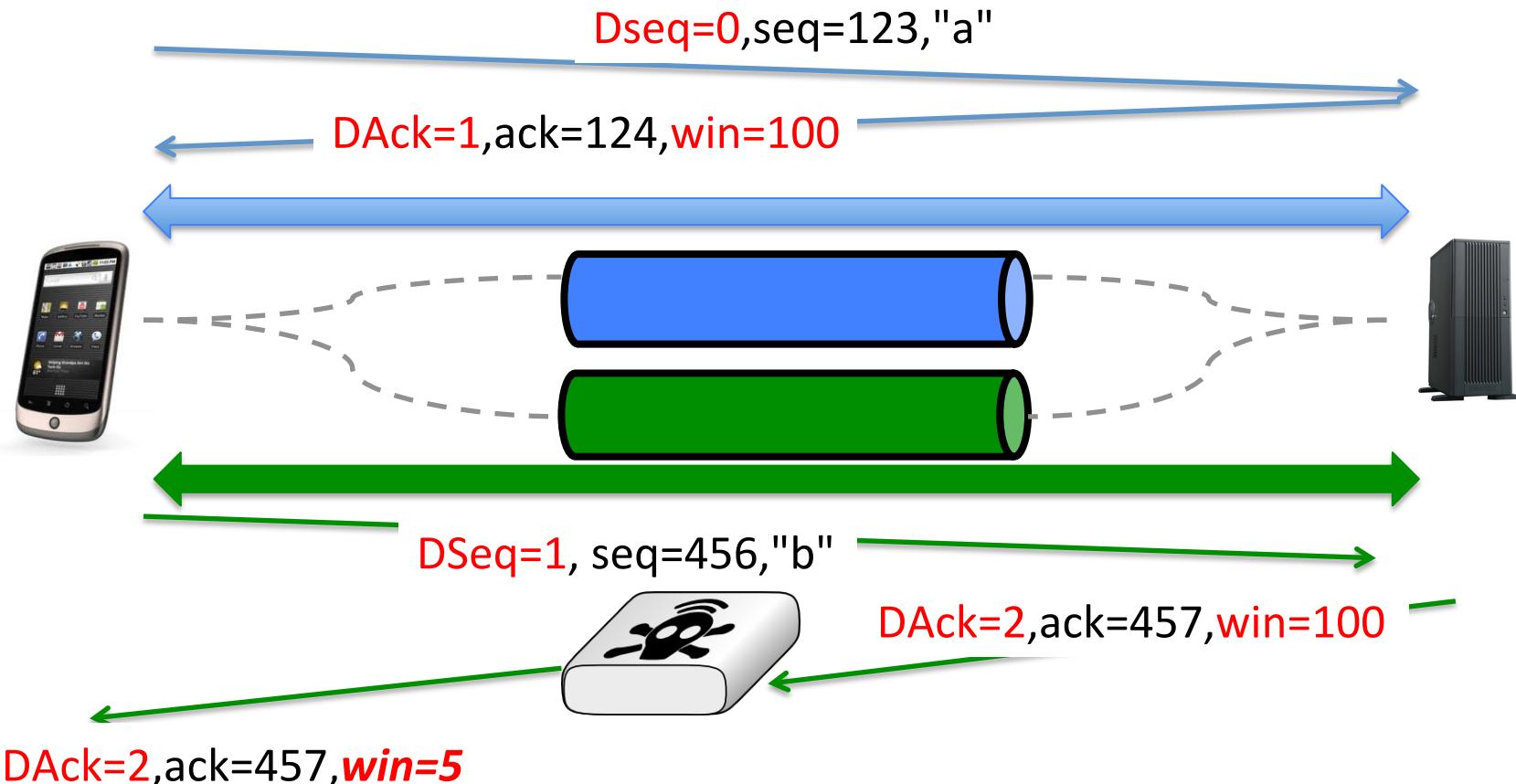
- Impossible to retransmit, window is already full on green subflow

A single window shared by all subflows



A single window shared by all subflows

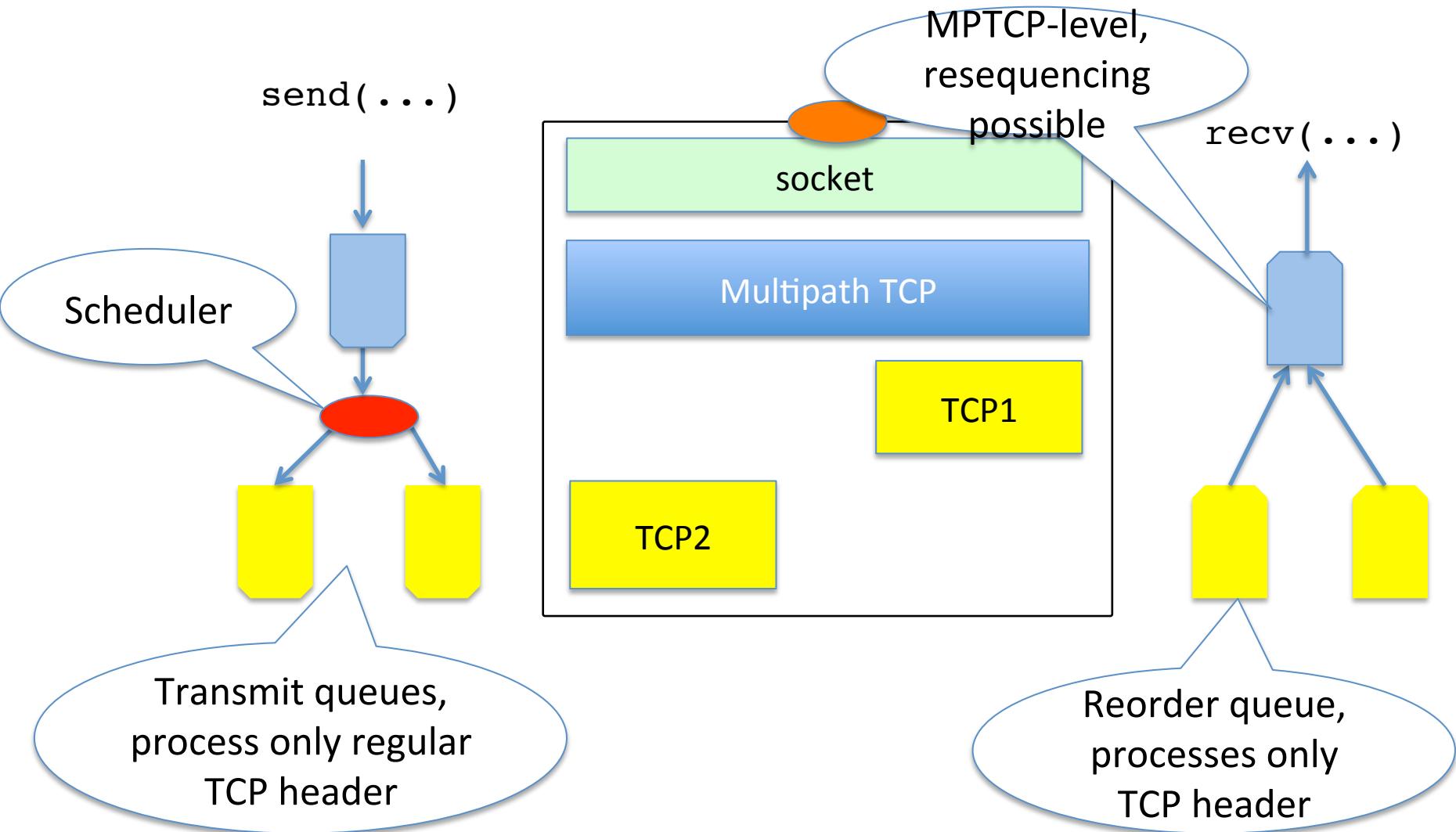
Impact of middleboxes



Multipath TCP Windows

- Multipath TCP maintains one window per Multipath TCP connection
 - Window is relative to the last acked data (**Data Ack**)
 - Window is shared among all subflows
 - It's up to the implementation to decide how the window is shared
 - Window is transmitted inside the `window` field of the regular TCP header
 - If middleboxes change `window` field,
 - use largest `window` received at MPTCP-level
 - use received `window` over each subflow to cope with the flow control imposed by the middlebox

Multipath TCP buffers



Sending Multipath TCP information

- How to exchange the Multipath TCP specific information between two hosts ?
- Option 1
 - Use TLVs to encode data and control information inside payload of subflows
- **Option 2**
 - Use TCP options to encode all Multipath TCP information

Multipath TCP with only options

- Advantages
 - Normal way of extending TCP
 - Should be able to go through middleboxes or fallback
- Drawbacks
 - limited size of the TCP options, notably inside SYN
 - What happens when middleboxes drop TCP options in data segments

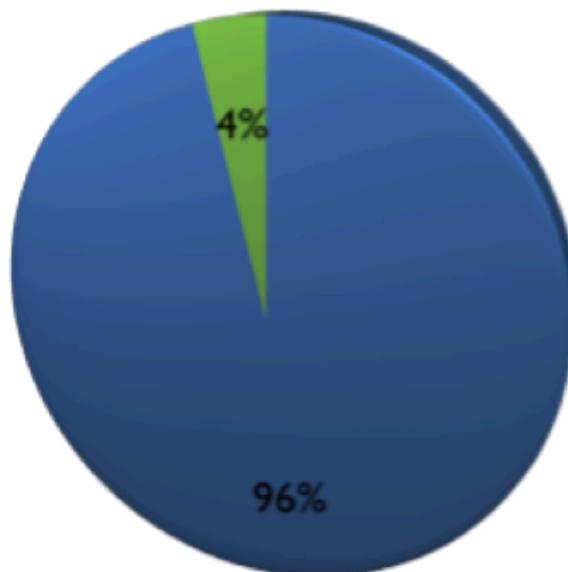
Multipath TCP using TLV

- Advantages
 - Multipath TCP could start as regular TCP and move to Multipath only when needed
 - Could be implemented as a library in userspace
 - TLVs can be easily extended
- Drawbacks
 - TCP segments contain TLVs including the data and not only the data
 - problem for middleboxes, DPI, ..
 - Middleboxes become more difficult

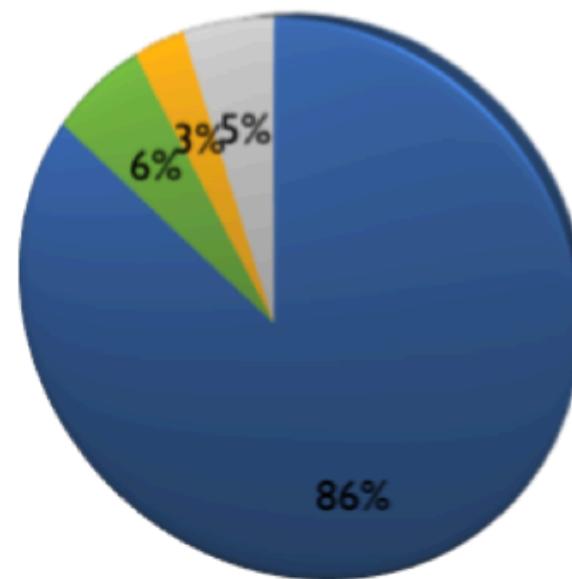
Is it safe to use TCP options ?

- Known option (TS) in Data segments

Data segments, port 34443



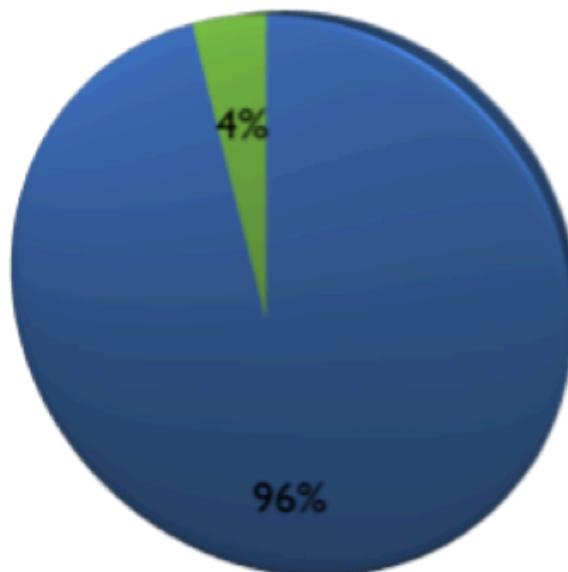
Data segments, port 80



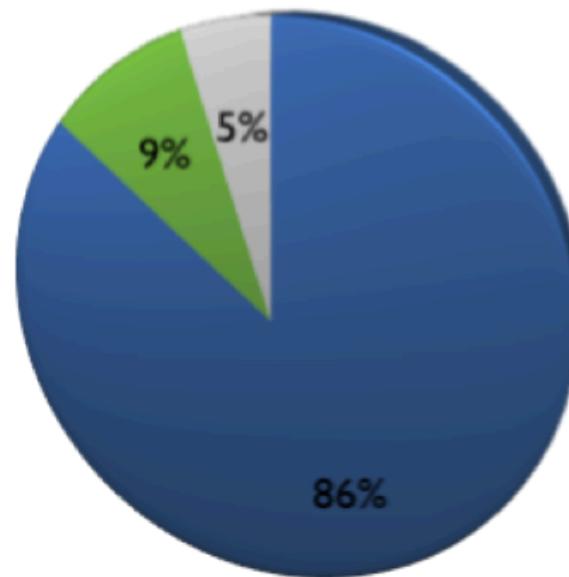
Is it safe to use TCP options ?

- Unknown option in Data segments

Data segments, port 34443

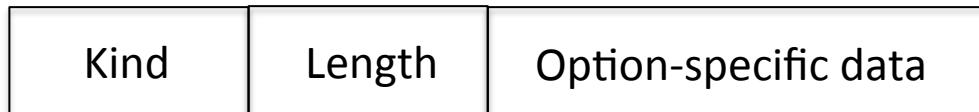


Data segments, port 80



Multipath TCP options

- TCP option format



- Initial design
 - One option kind for each purpose
(e.g. Data Sequence number)
- Final design
 - A single variable-length Multipath TCP option

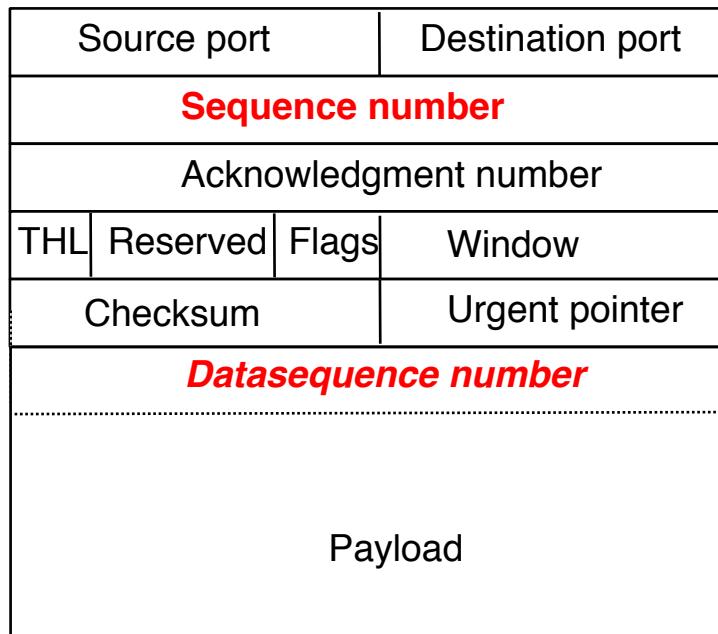
Multipath TCP option

- A single option type
 - to minimise the risk of having one option accepted by middleboxes in SYN segments and rejected in segments carrying data

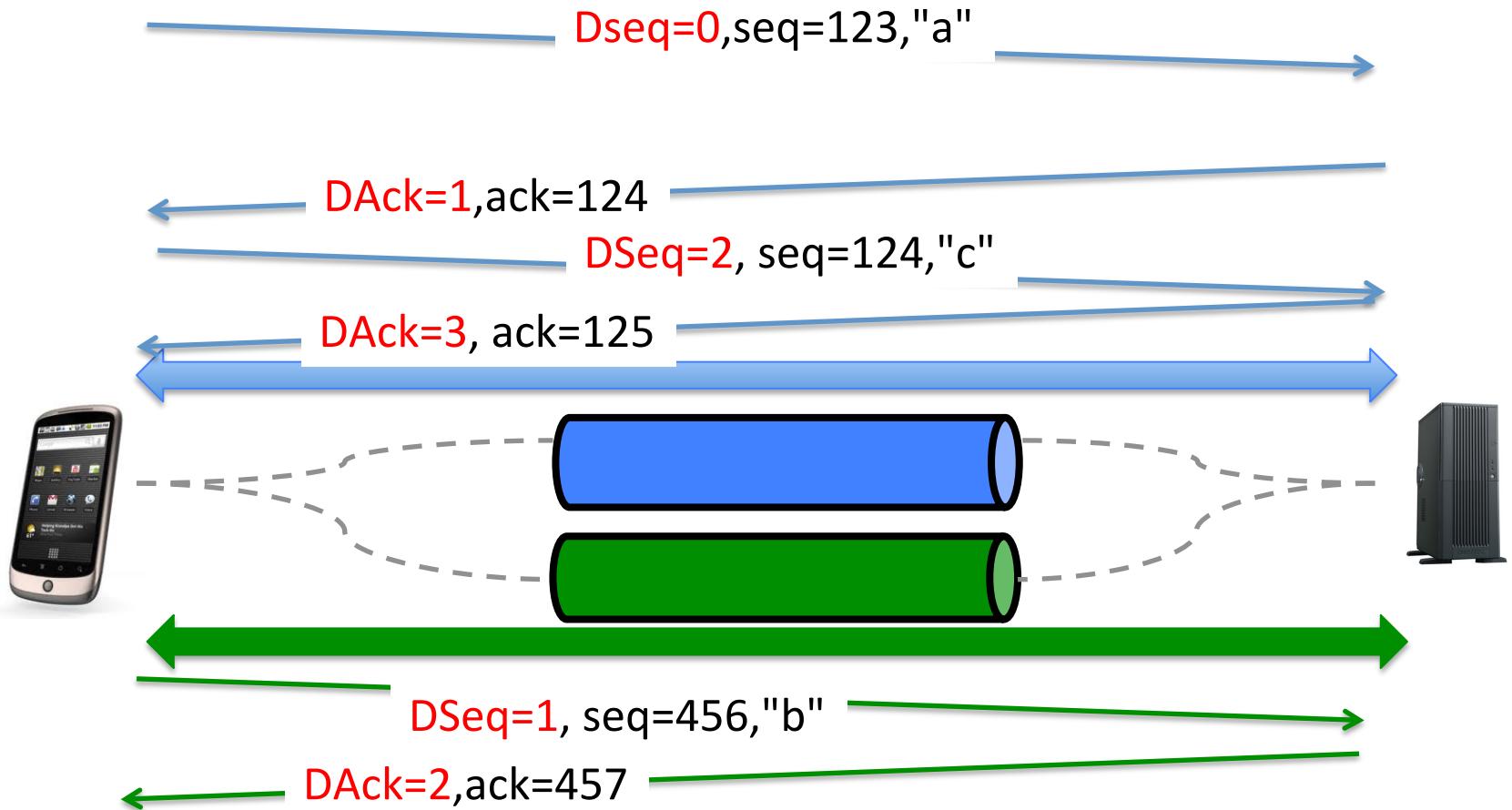
Kind	Length	Subtype
Subtype specific data (variable length)		

Data sequence numbers and TCP segments

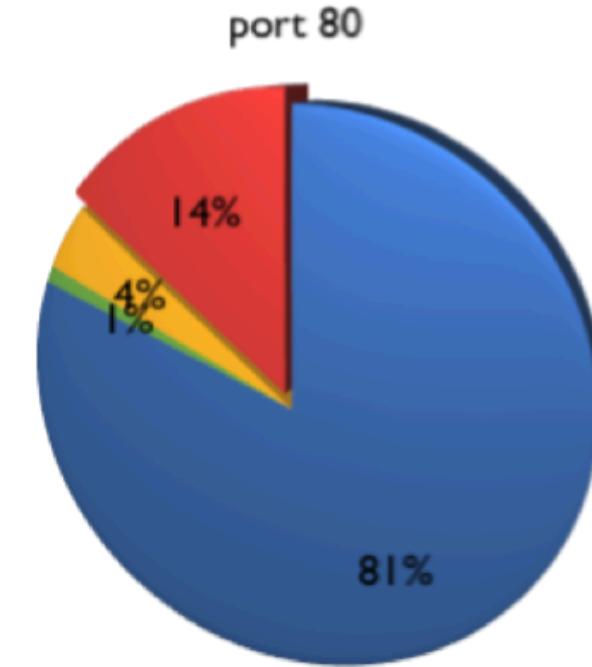
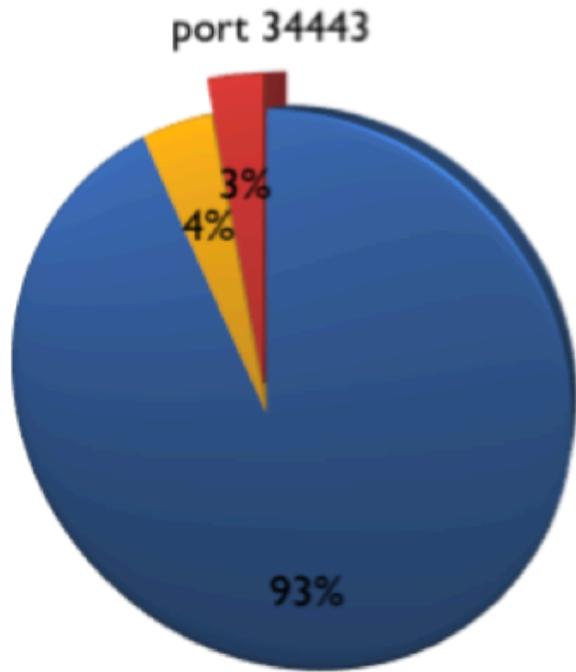
- How to transport Data sequence numbers ?
 - Same solution as for TCP
 - Data sequence number in TCP option is the Data sequence number of the first byte of the segment



Multipath TCP Data transfer



TCP sequence number and middleboxes

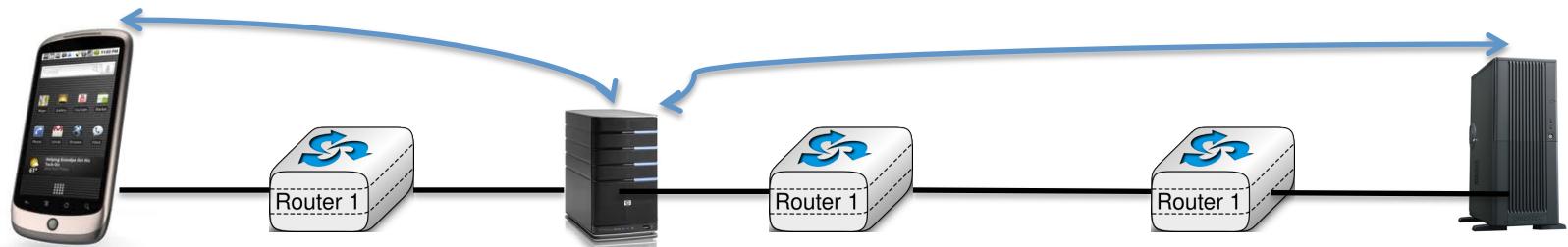


- Transparent
- Change In
- Change Out
- Change Both

- Transparent
- Change In
- Change Out
- Change both

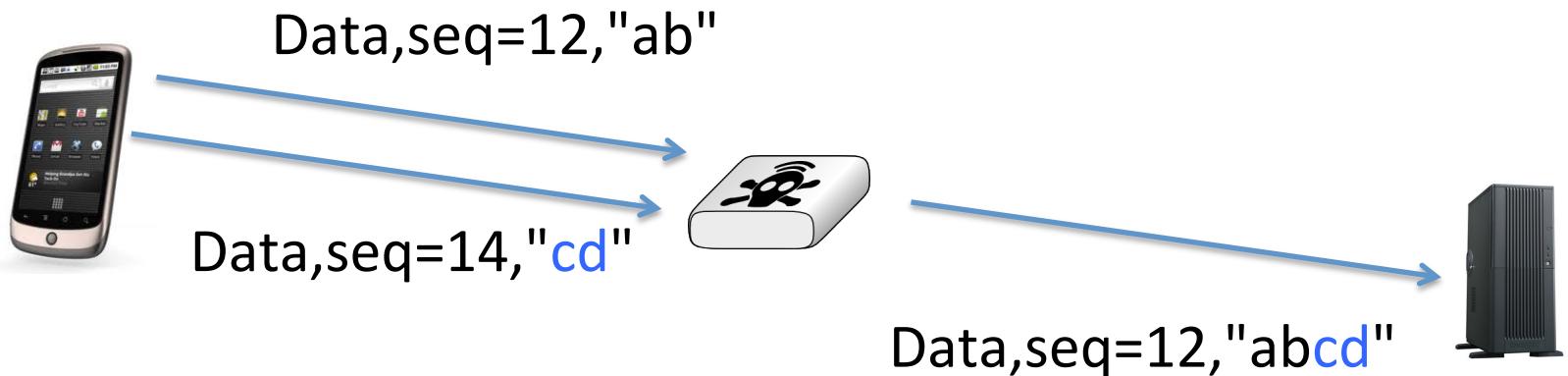
Which middleboxes change TCP sequence numbers ?

- Some firewalls change TCP sequence numbers in SYN segments to ensure randomness
 - fix for old windows95 bug
- Transparent proxies terminate TCP connections



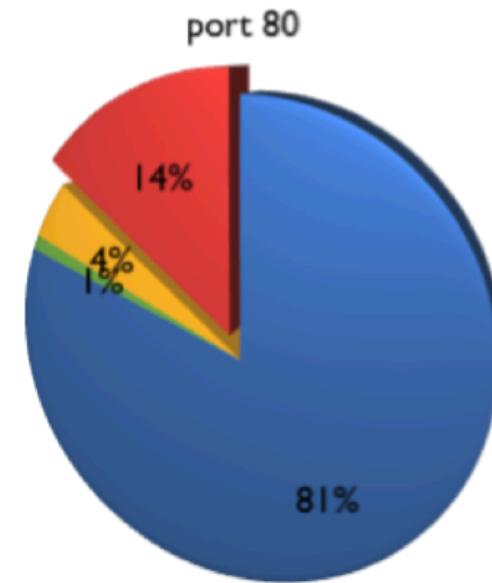
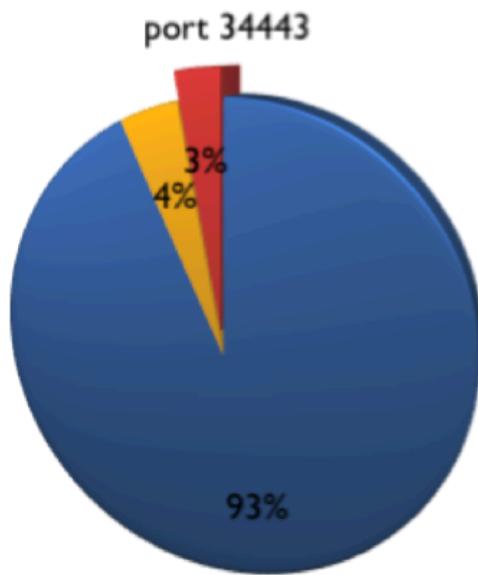
Other types of middlebox interference

- Data segments



Such a middlebox could also be the network adapter of the server that uses LRO to improve performance.

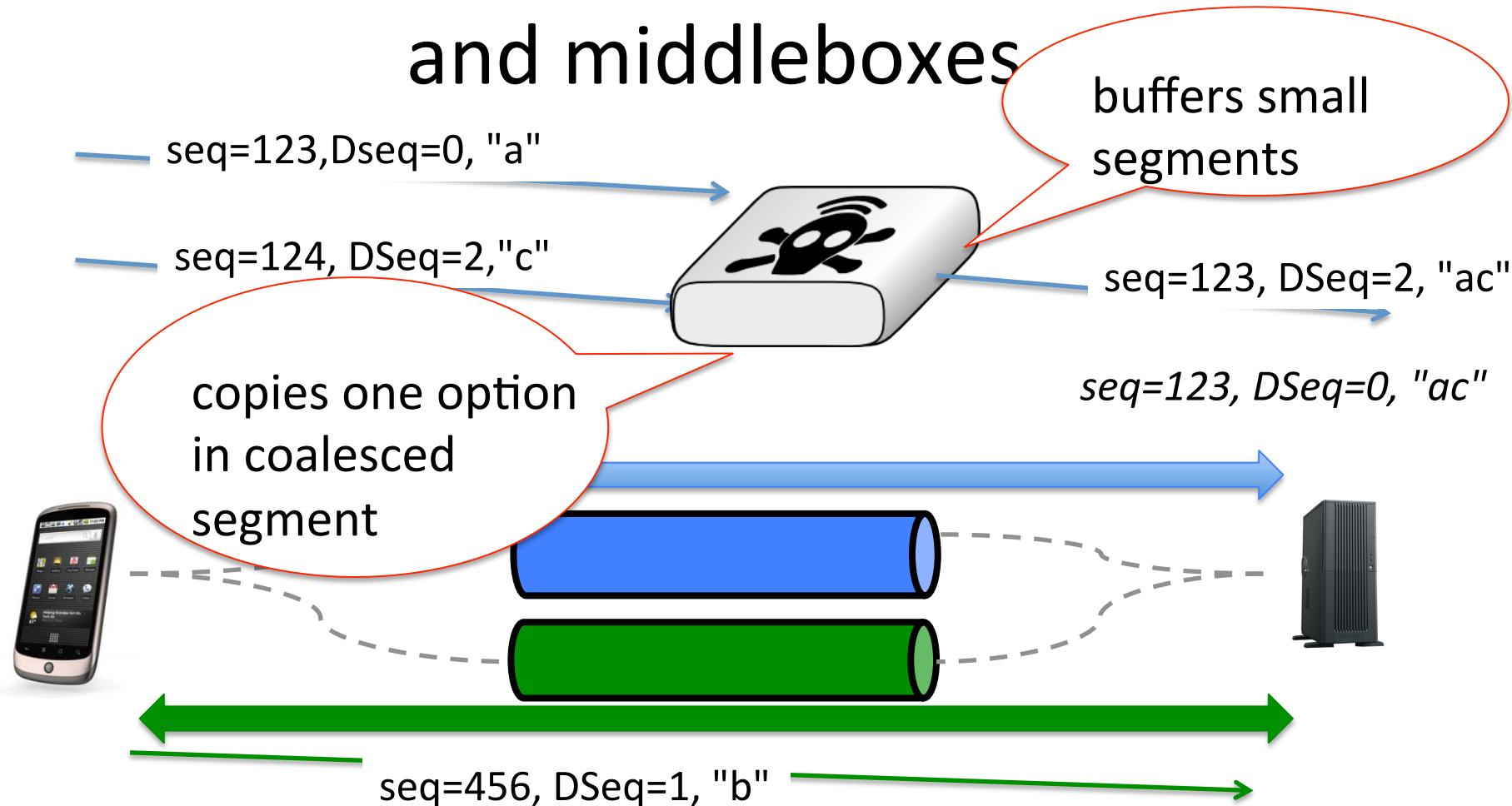
Segment coalescing



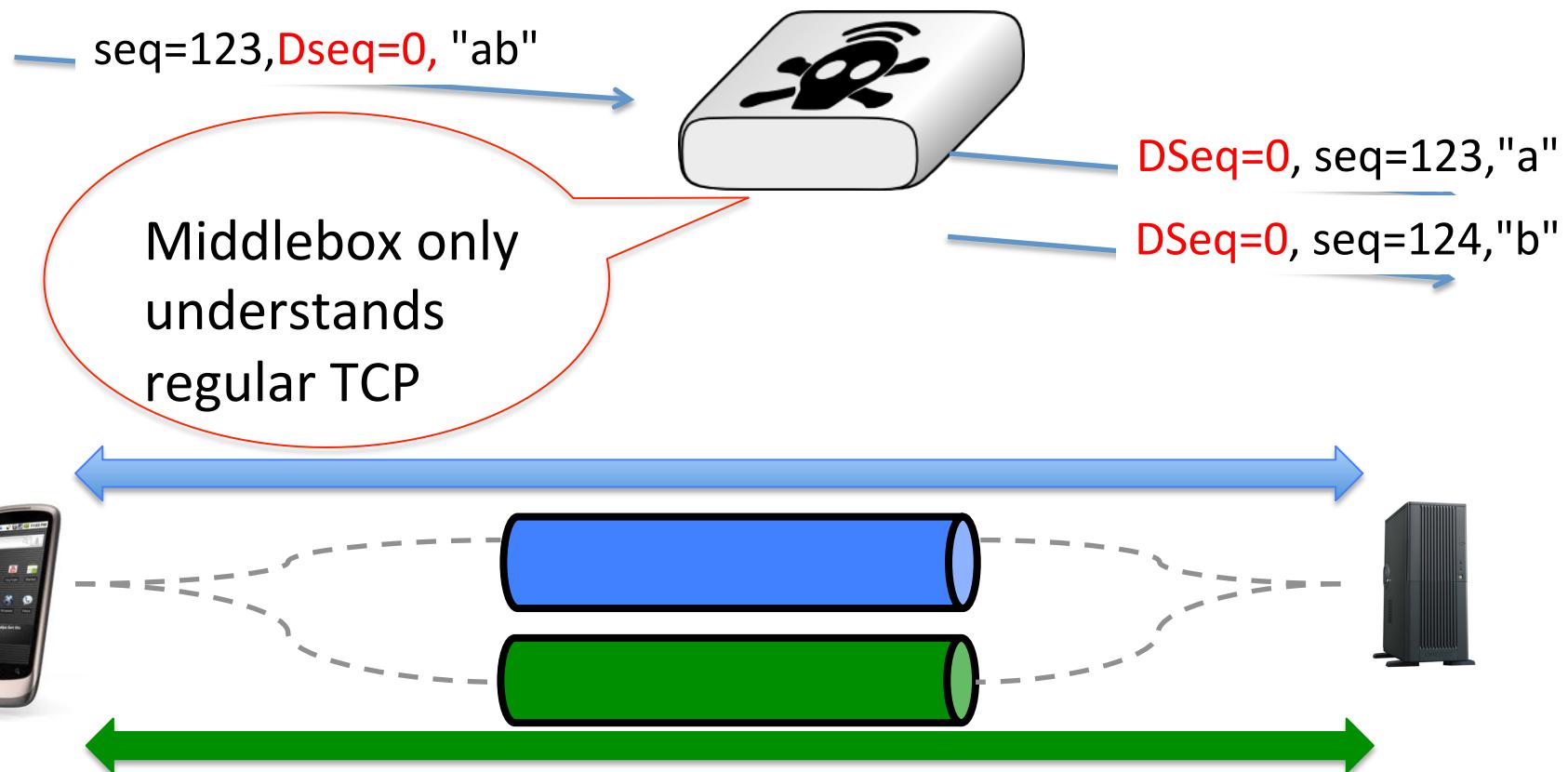
- Transparent
- Change In
- Change Out
- Change Both

- Transparent
- Change In
- Change Out
- Change both

Data sequence numbers and middleboxes



Data sequence numbers and middleboxes



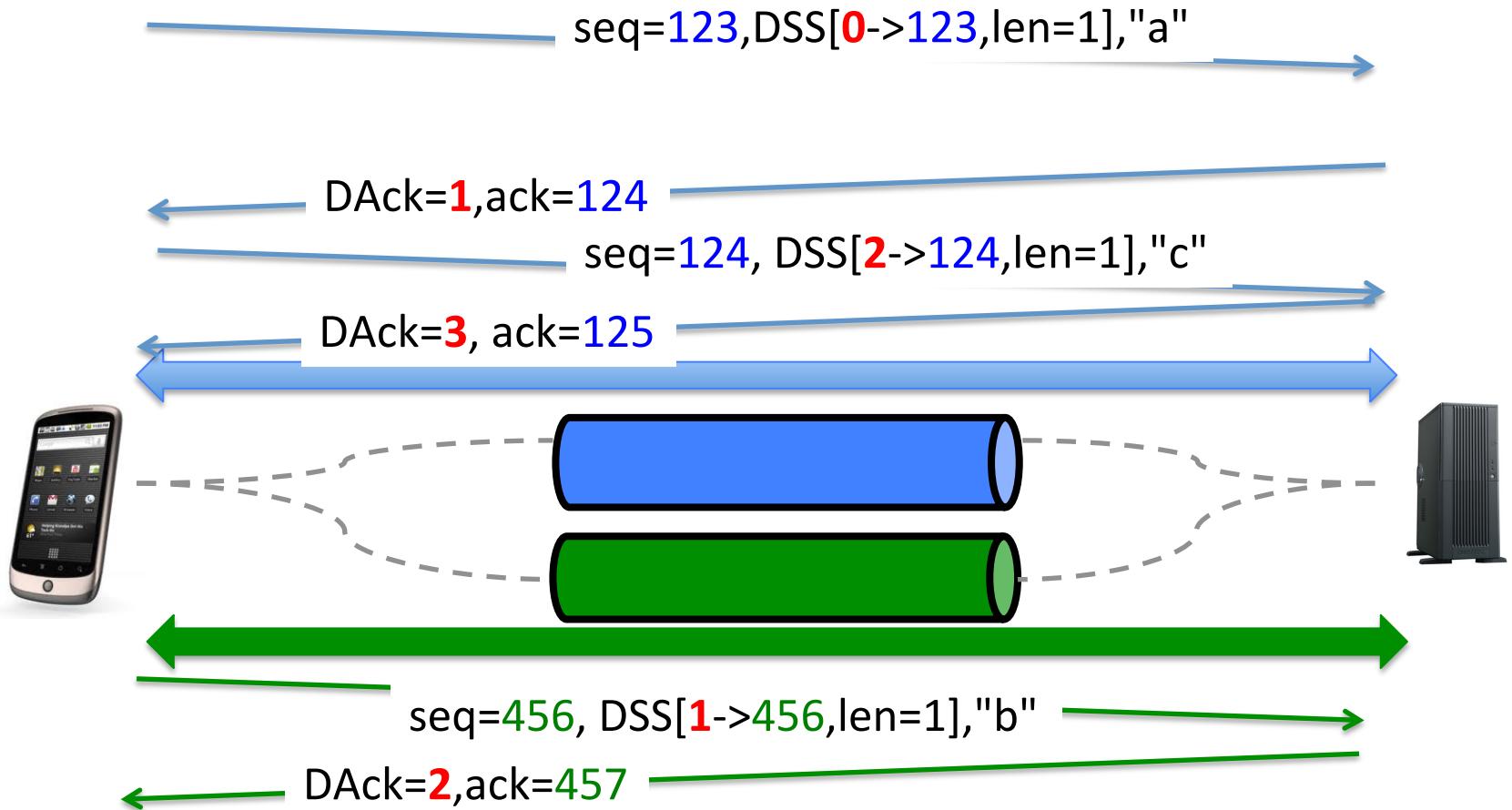
A "middlebox" that both splits and coalesces TCP segments



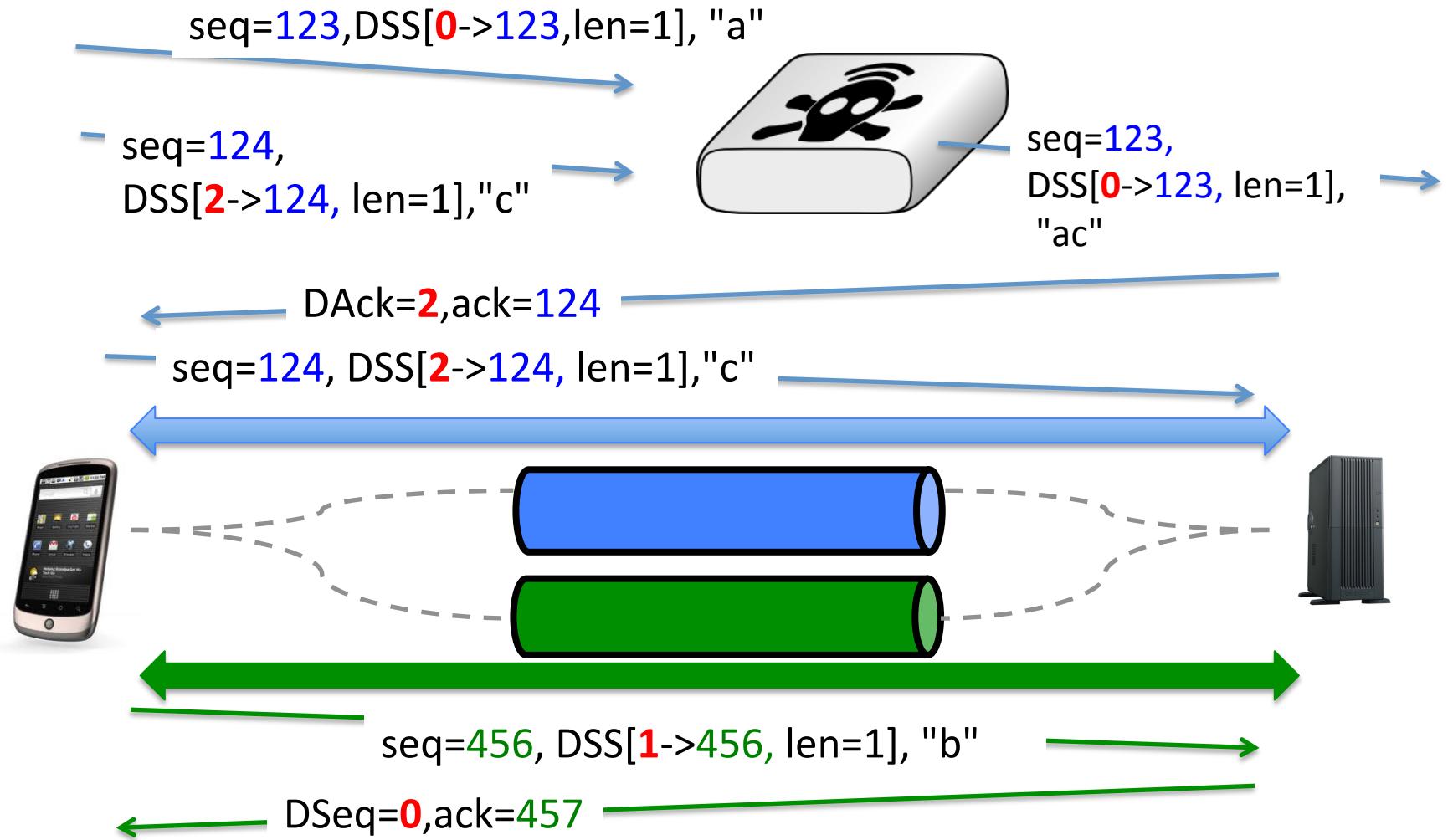
Data sequence numbers and middleboxes

- How to avoid desynchronisation between the bytestream and data sequence numbers ?
- Solution
 - Multipath TCP option carries **mapping** between Data sequence numbers and (*difference between initial and current*) subflow sequence numbers
 - mapping covers a part of the bytestream (length)

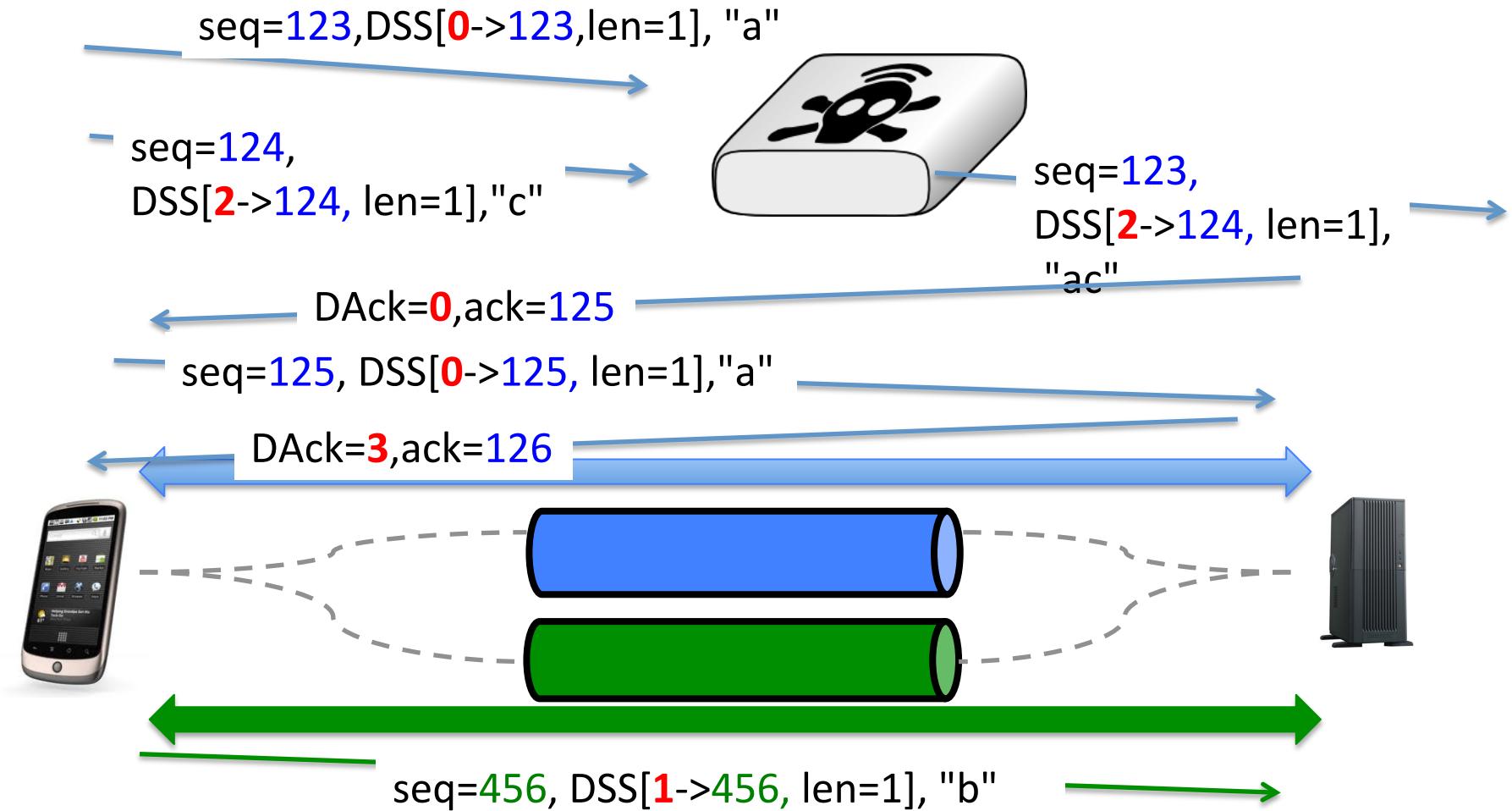
Multipath TCP Data transfer



Data sequence numbers and middleboxes



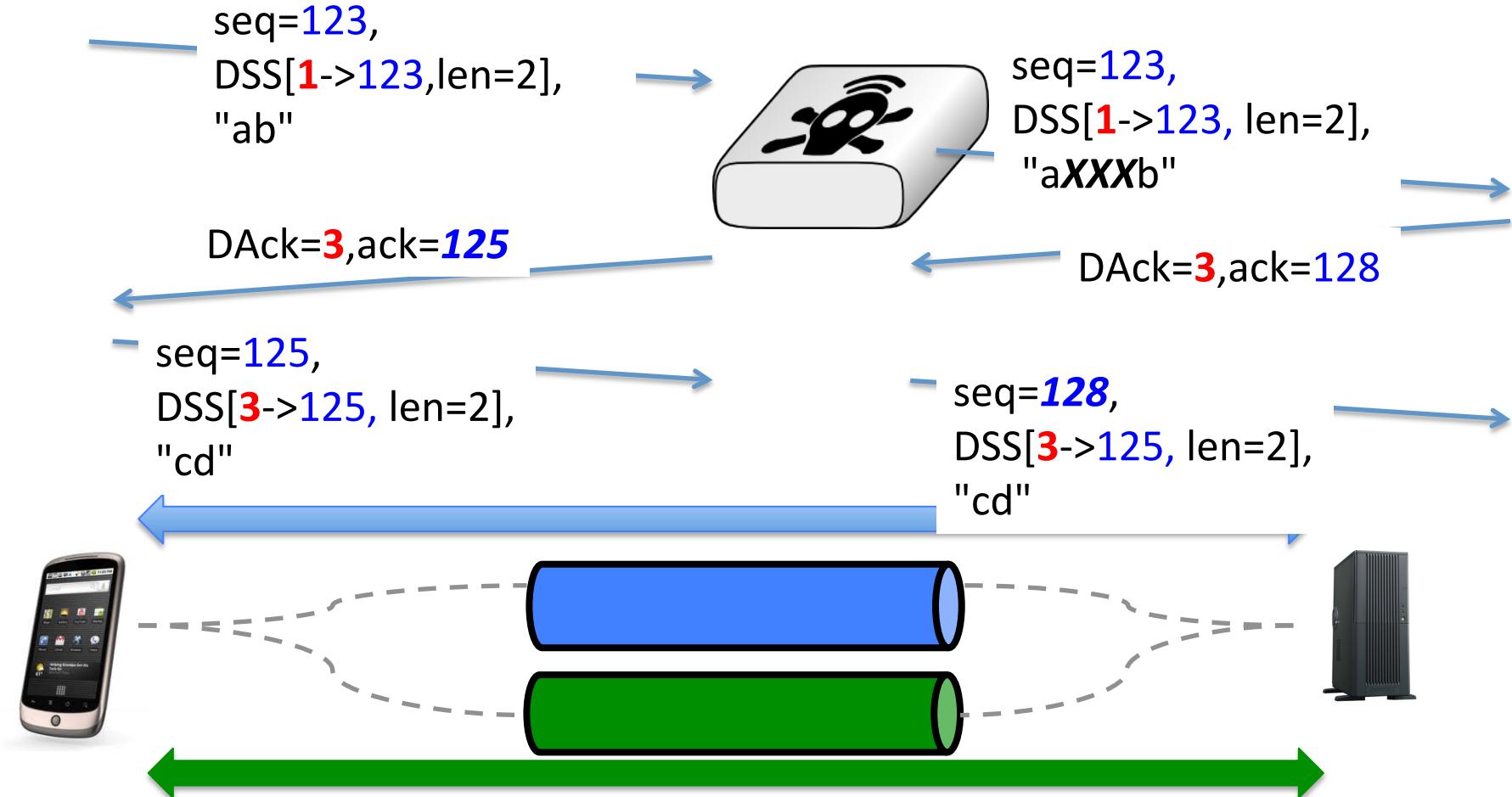
Data sequence numbers and middleboxes



Multipath TCP and middleboxes

- With the DSS mapping, Multipath TCP can cope with middleboxes that
 - combine segments
 - split segments
- Are they the most annoying middleboxes for Multipath TCP ?
 - Unfortunately not

The worst middlebox



The worst middlebox

- Is unfortunately very old...
 - Any ALG for a NAT

220 ProFTPD 1.3.3d Server (BELNET FTPD Server) [193.190.67.15]

ftp_login: user '<null>' pass '<null>' host 'ftp.belnet.be'

Name (ftp.belnet.be:obo): anonymous

---> USER anonymous

331 Anonymous login ok, send your complete email address as your password

Password:

---> PASS XXXX

---> **PORT 192,168,0,7,195,120**

200 PORT command successful

---> LIST

150 Opening ASCII mode data connection for file list

lrw-r--r-- 1 ftp ftp 6 Jun 1 2011 pub -> mirror

226 Transfer complete

Coping with the worst middlebox

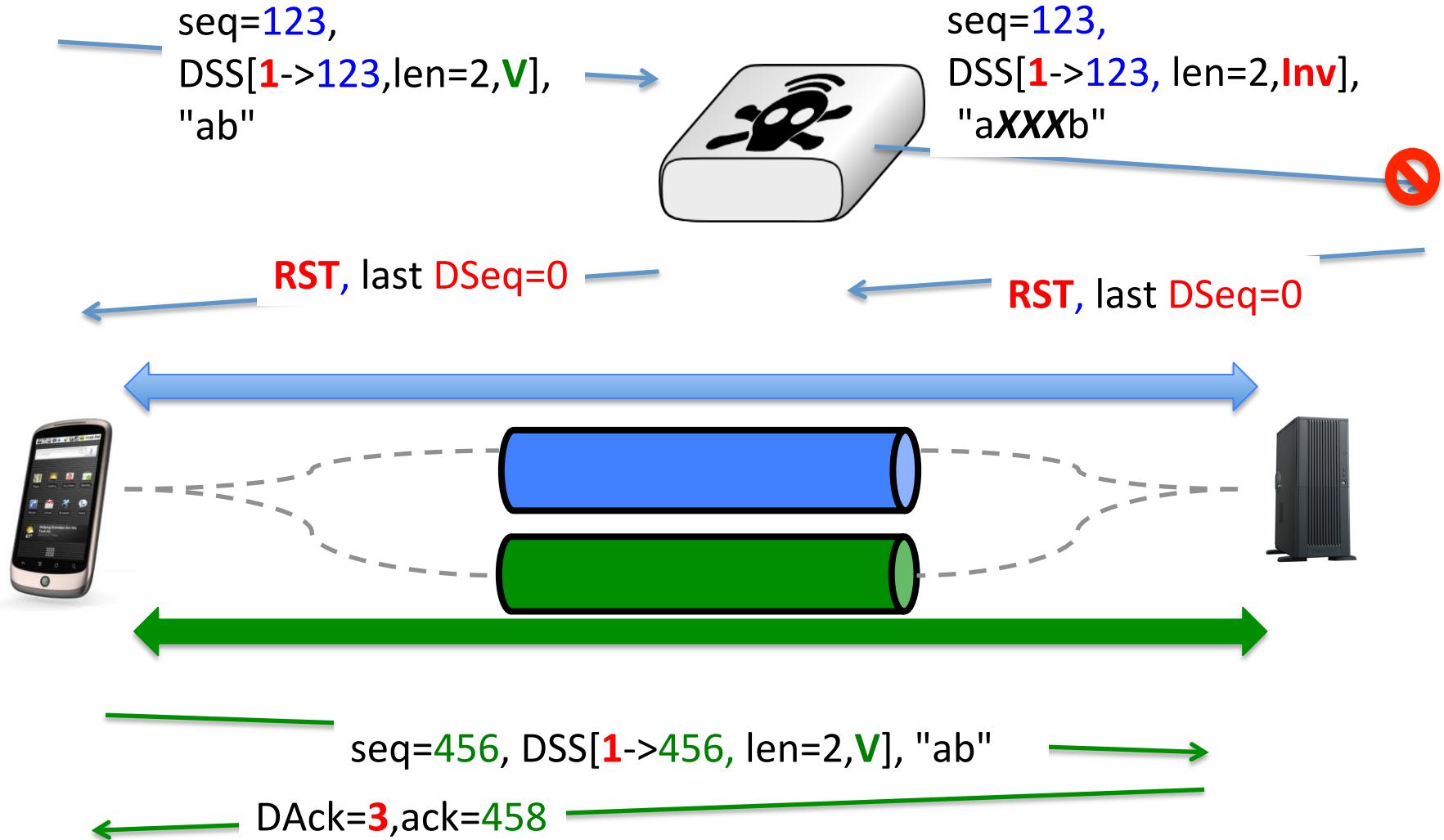
- What should Multipath TCP do in the presence of such a worst middlebox ?
 - Do nothing and ignore the middlebox
 - but then the bytestream and the application would be broken and this problem will be difficult to debug by network administrators
 - Detect the presence of the middlebox
 - and fallback to regular TCP (i.e. use a single path and nothing fancy)

Multipath TCP **MUST** work in all networks where regular TCP works.

Detecting the worst middlebox ?

- How can Multipath TCP detect a middlebox that modifies the bytestream and inserts/ removes bytes ?
 - Various solutions were explored
 - In the end, Multipath TCP chose to include its own checksum to detect insertion/deletion of bytes

The worst middlebox



Multipath TCP

Data sequence numbers

- What should be the length of the data sequence numbers ?
 - 32 bits
 - compact and compatible with TCP
 - wrap around problem at highspeed requires PAWS
 - 64 bits
 - wrap around is not an issue for most transfers today
 - takes more space inside each segment

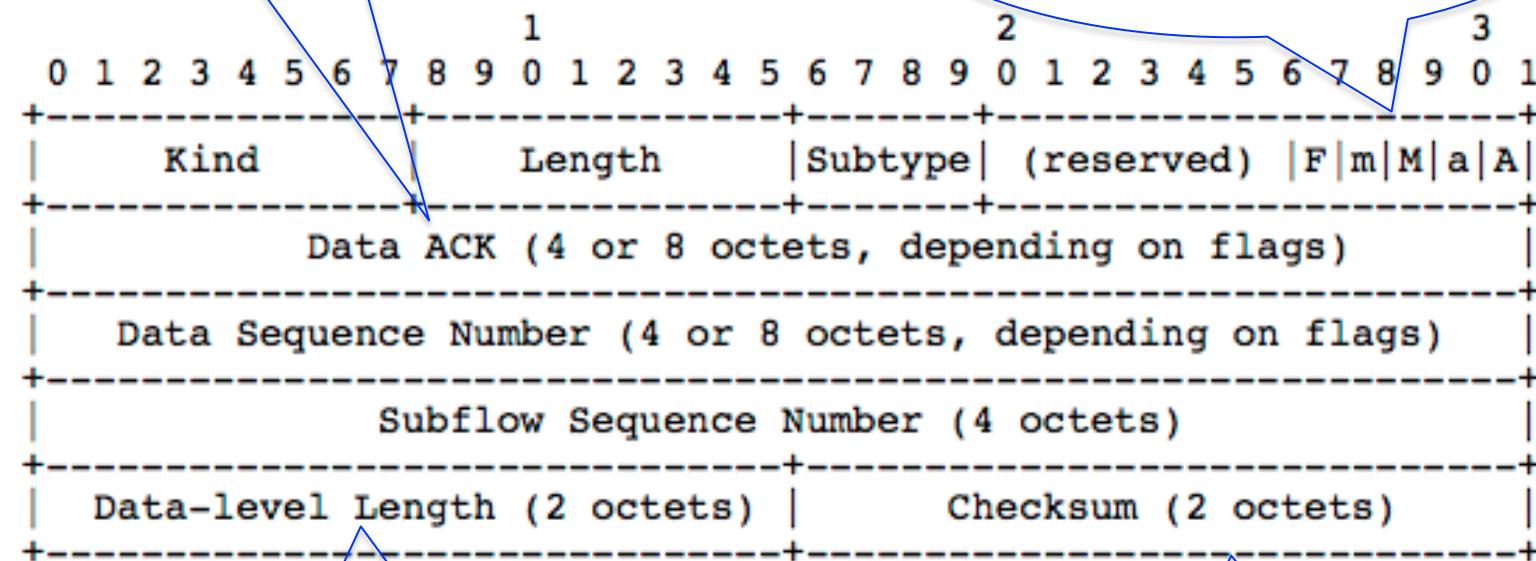
Multipath TCP

Data sequence numbers

- Data sequence numbers and Data acknowledgements
 - Maintained inside implementation as 64 bits field
 - Implementations can, as an optimisation, only transmit the lower 32 bits of the data sequence and acknowledgements

Data Sequence Signal option

Cumulative Data ack



A = Data ACK present

a = Data ACK is 8 octets

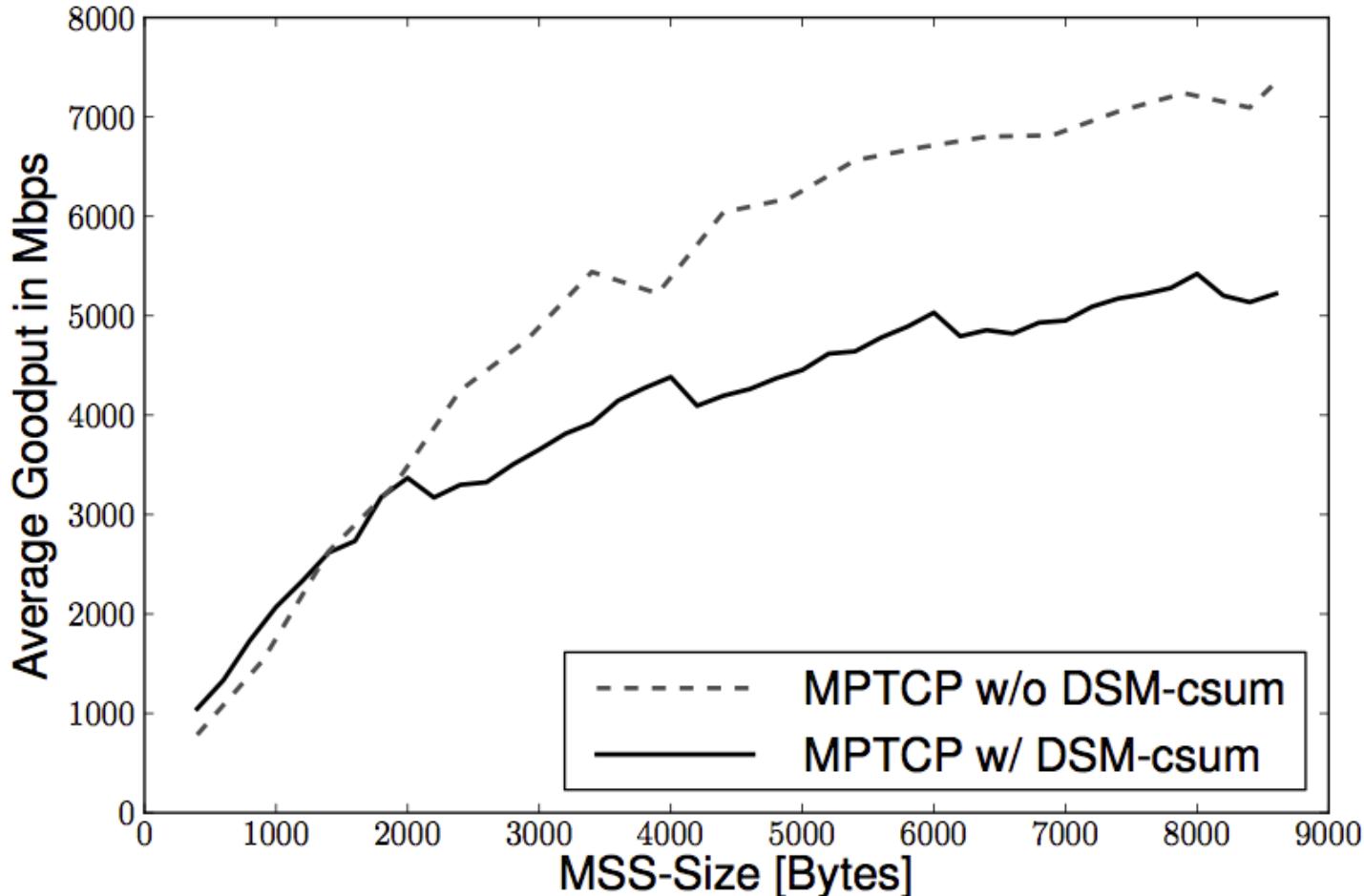
M = mapping present

m = DSN is 8

Length of mapping, can extend beyond this segment

Computed over data covered by entire mapping + pseudo header

Cost of the DSN checksum



C. Raiciu, et al. "How hard can it be? designing and implementing a deployable multipath TCP," NSDI'12: Proceedings of the 9th USENIX conference on Networked Systems Design and Implementation, 2012.

The Multipath TCP protocol

- Control plane
 - How to manage a Multipath TCP connection that uses several paths ?
- Data plane
 - How to transport data ?

→ **Congestion control**

- How to control congestion over multiple paths ?

TCP congestion control

- A linear rate adaption algorithm
 - $rate(t + 1) = \alpha_C + \beta_C rate(t)$ when the network is congested
 - $rate(t + 1) = \alpha_N + \beta_N rate(t)$ when the network is *not* congested

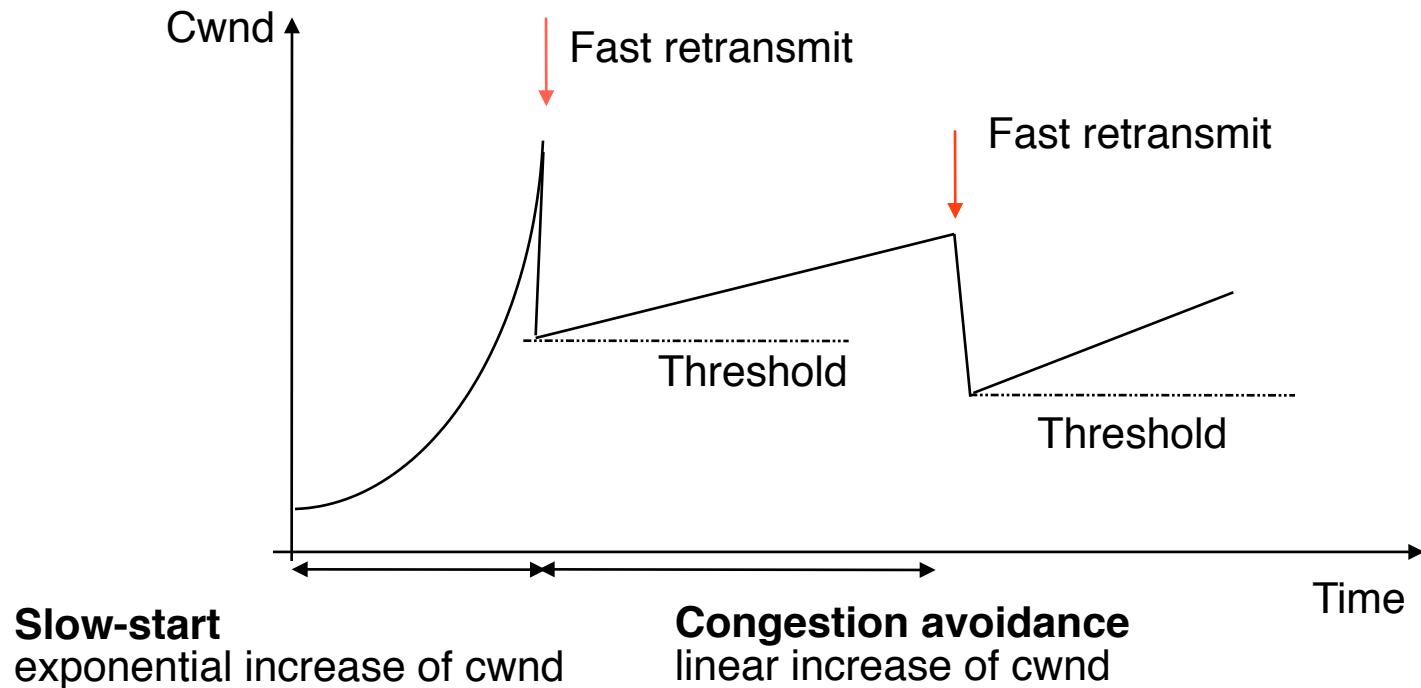
To be fair and efficient, a linear algorithm must use additive increase and multiplicative decrease (AIMD)

```
# Additive Increase Multiplicative Decrease
if congestion :
    rate=rate*betaC      # multiplicative decrease, betaC<1
else
    rate=rate+alphaN     # additive increase, v0>0
```

AIMD in TCP

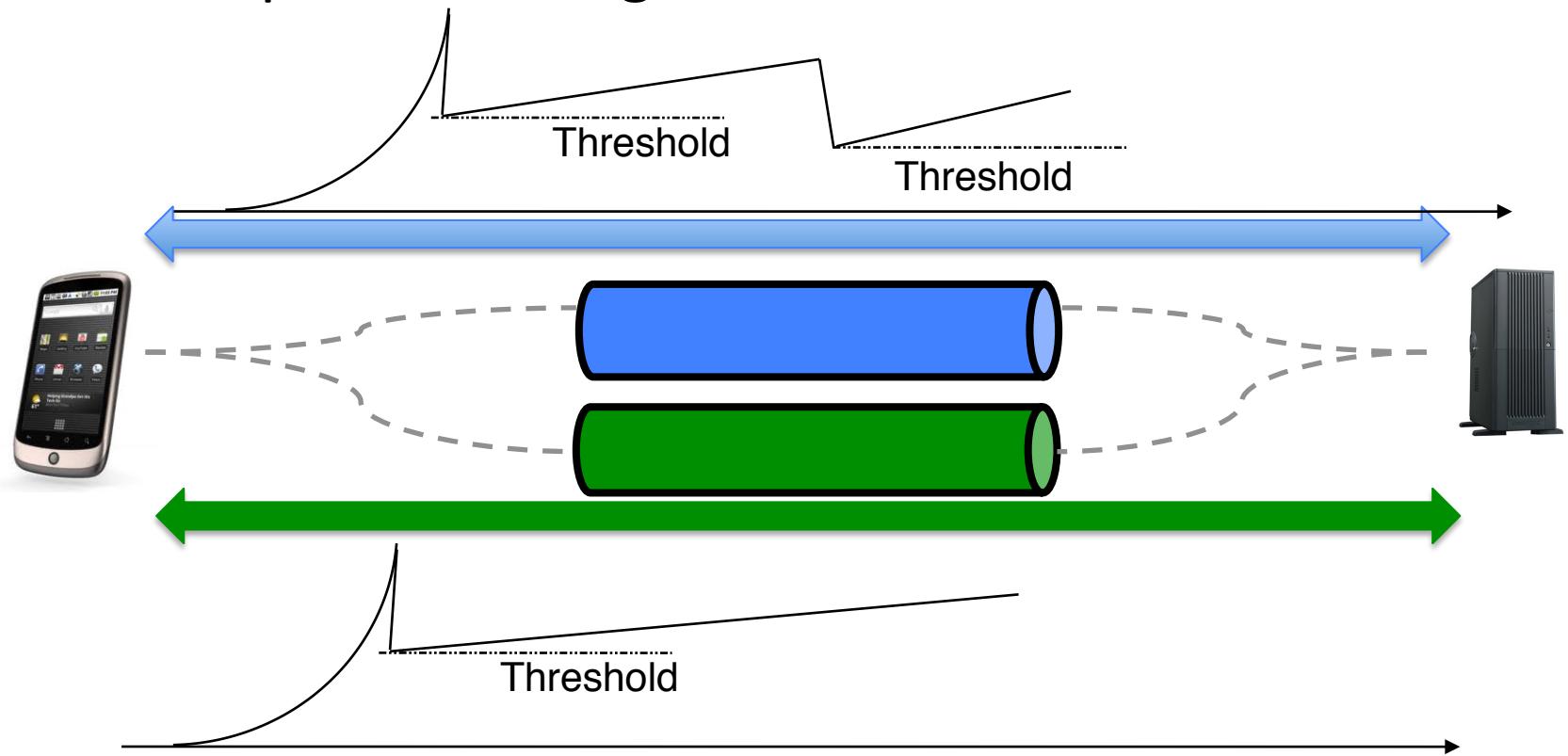
- Congestion control mechanism
 - Each host maintains a *congestion window (cwnd)*
 - No congestion
 - Congestion avoidance (**additive increase**)
 - increase $cwnd$ by one segment every round-trip-time
 - Congestion
 - TCP detects congestion by detecting losses
 - Mild congestion (fast retransmit – **multiplicative decrease**)
 - $cwnd=cwnd/2$ and restart congestion avoidance
 - Severe congestion (timeout)
 - $cwnd=1$, set slow-start-threshold and restart slow-start

Evolution of the congestion window



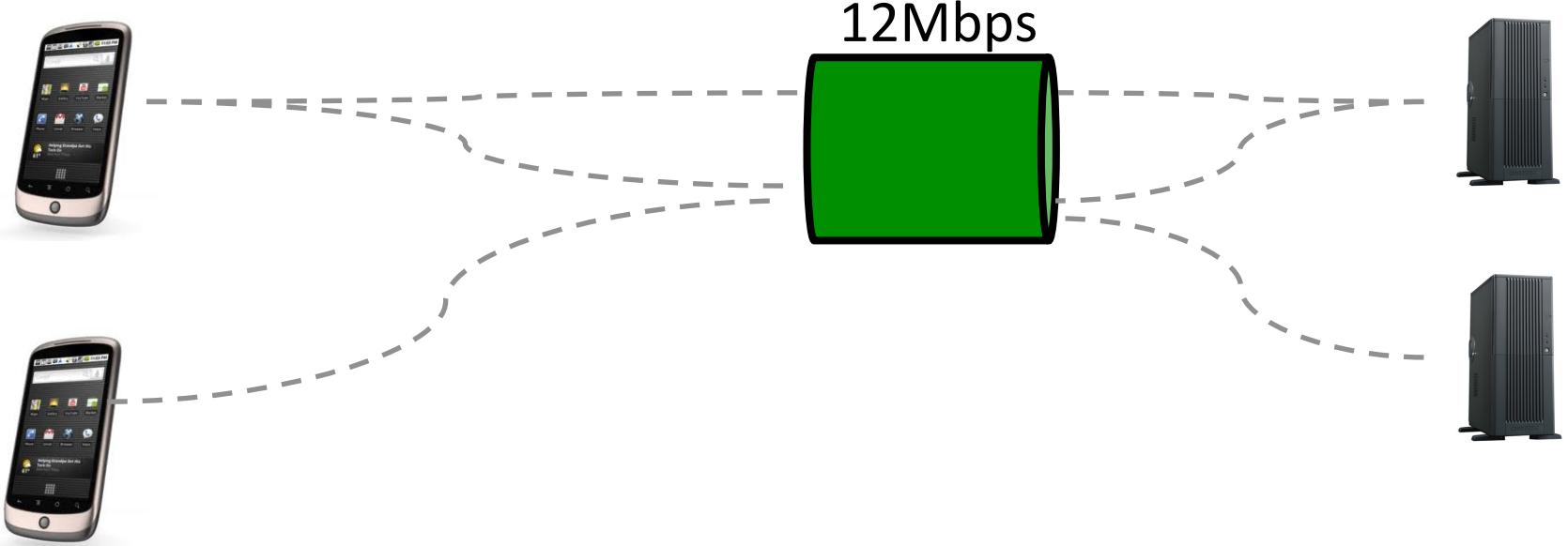
Congestion control for Multipath TCP

- Simple approach
 - independant congestion windows



Independant congestion windows

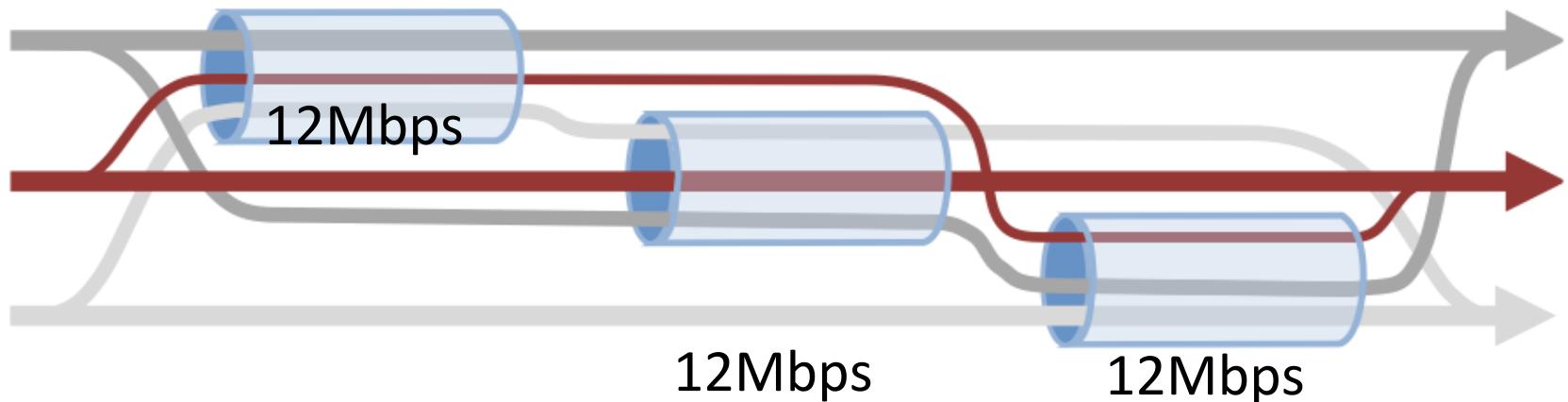
- Problem



Coupling the congestion windows

- Principle
 - The TCP subflows are not independant and their congestion windows must be coupled
- EWTCP
 - For each ACK on path r , $cwin_r = cwin_r + a/cwin_r$ (in segments)
 - For each loss on path r , $cwin_r = cwin_r/2$
 - Each subflow gets window size proportional to a^2
 - Same throughput as TCP if
$$a = \frac{1}{\sqrt{n}}$$

Can we split traffic equally among all subflows ?



In this scenario, EWTCP would get 3.5 Mbps on the two hops path and 5 Mbps on the one hop path, less than the optimum of 12 Mbps for each Multipath TCP connection

Linked increases congestion control

- Algorithm
 - For each loss on path r , $cwin_r = cwin_r / 2$
 - Additive increase

$$cwin_r = cwin_r + \min\left(\frac{\max\left(\frac{cwnd_i}{(rtt_i)^2}\right)}{\left(\sum_i \frac{cwnd_i}{rtt_i}\right)^2}, \frac{1}{cwnd_r}\right)$$

Other Multipath-aware congestion control schemes

R. Khalili, N. Gast, M. Popovic, U. Upadhyay, J.-Y. Le Boudec , MPTCP is not Pareto-optimal: Performance issues and a possible solution, Proc. ACM Conext 2012

Y. Cao, X. Mingwei, and X. Fu, “Delay-based Congestion Control for Multipath TCP,” ICNP2012, 2012.

T. A. Le, C. S. Hong, and E.-N. Huh, “Coordinated TCP Westwood congestion control for multiple paths over wireless networks,” ICOIN '12: Proceedings of the The International Conference on Information Network 2012, 2012, pp. 92–96.

T. A. Le, H. Rim, and C. S. Hong, “A Multipath Cubic TCP Congestion Control with Multipath Fast Recovery over High Bandwidth-Delay Product Networks,” *IEICE Transactions*, 2012.

T. Dreibholz, M. Becke, J. Pulinthanath, and E. P. Rathgeb, “Applying TCP-Friendly Congestion Control to Concurrent Multipath Transfer,” Advanced Information Networking and Applications (AINA), 2010 24th IEEE International Conference on, 2010, pp. 312–319.

The Multipath TCP protocol

→ Control plane

- How to manage a Multipath TCP connection that uses several paths ?
- Data plane
 - How to transport data ?
- Congestion control
 - How to control congestion over multiple paths ?

The Multipath TCP control plane

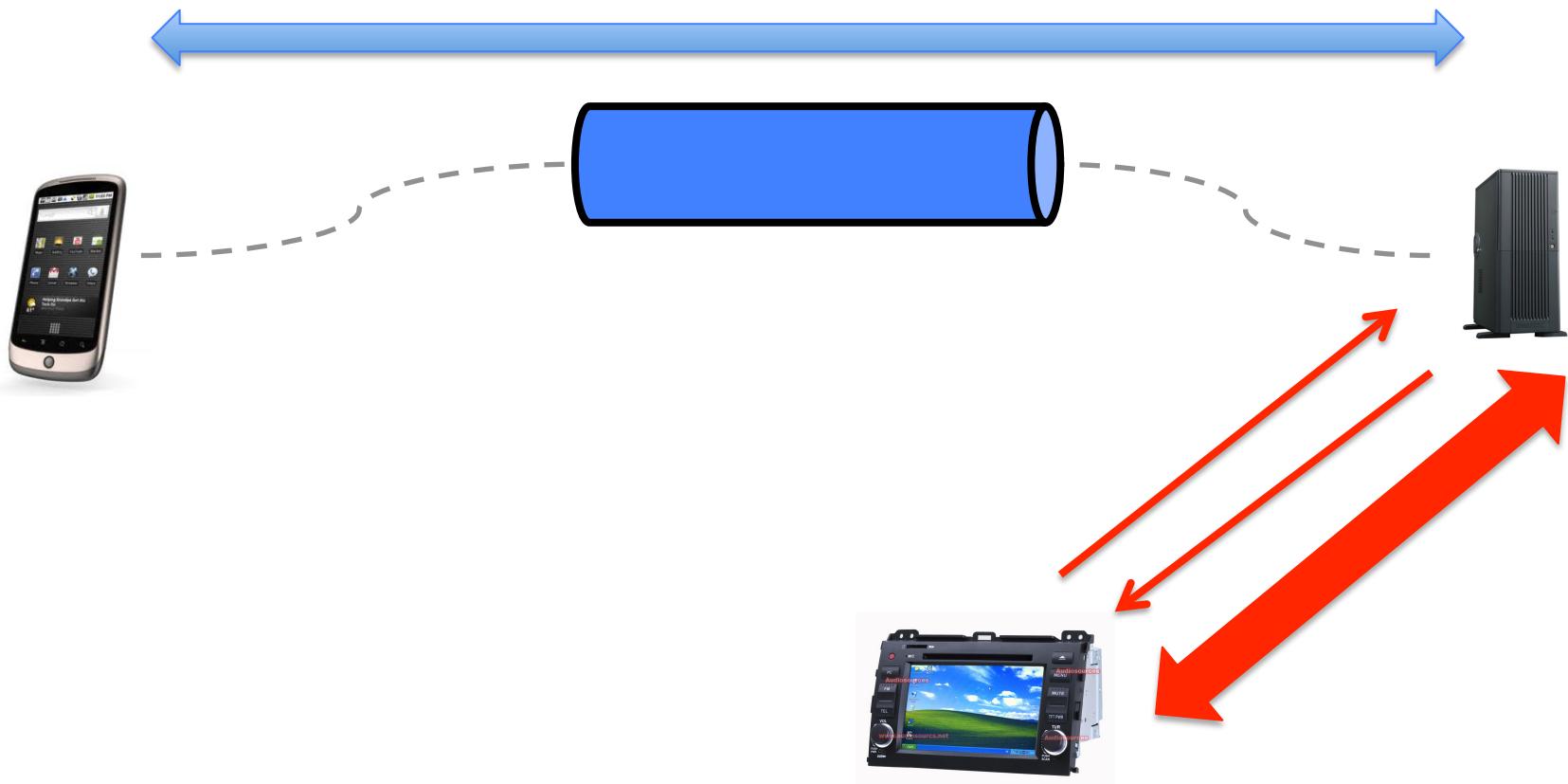
- Connection establishment in details
- Closing a Multipath TCP connection
- Address dynamics

Security threats

- Three main security threats were considered
 - flooding attack
 - man-in-the middle attack
 - hijacking attach

Security goal :
Multipath TCP should not be
worse than regular TCP

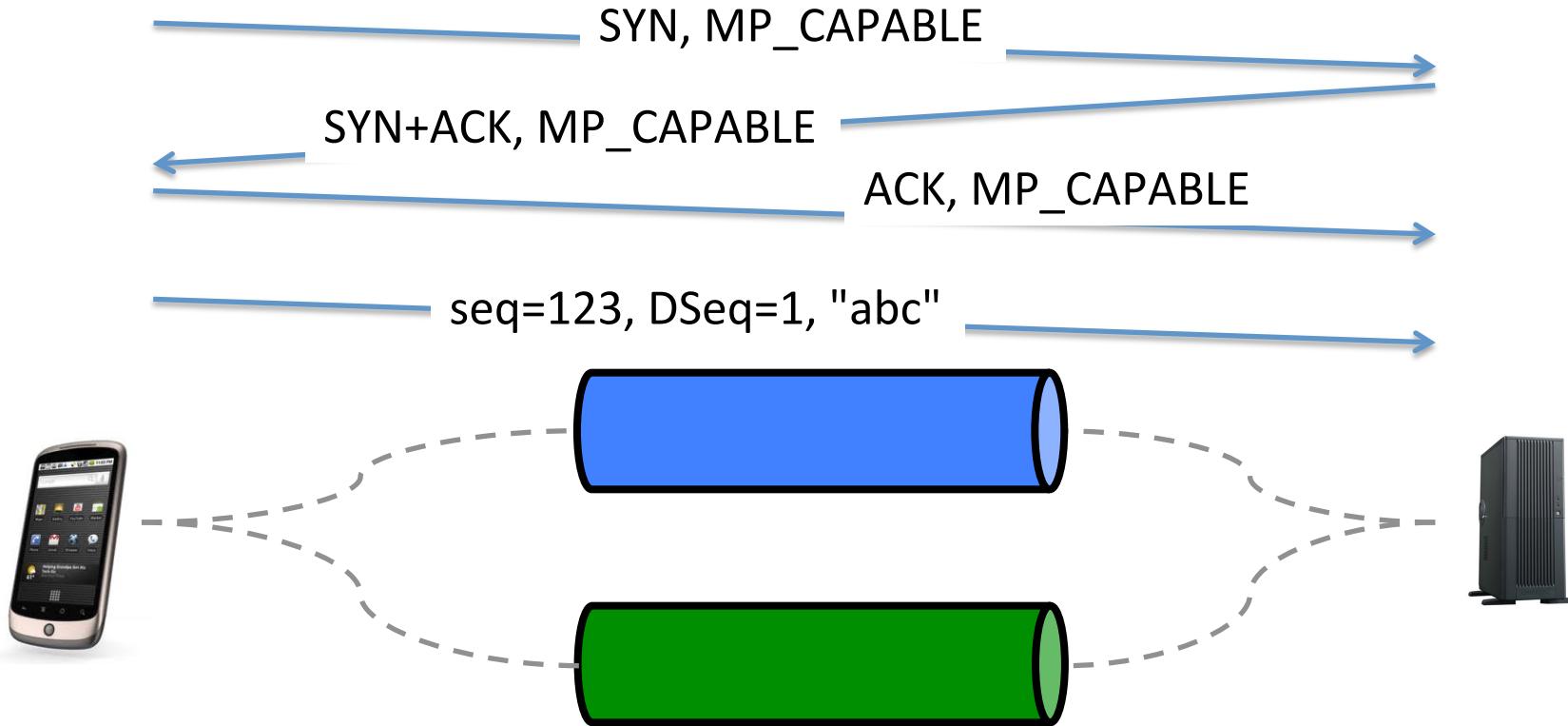
Hijacking attack



Multipath TCP

Connection establishment

- Principle



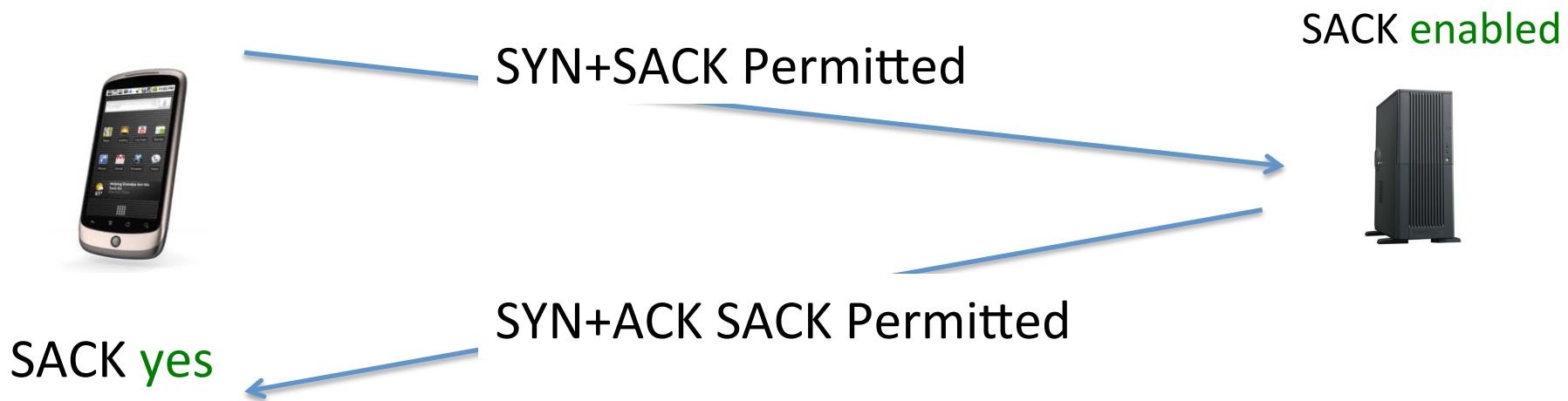
Roles of the initial TCP handshake

- Check willingness to open TCP connection
 - Propose initial sequence number
 - Negotiate Maximum Segment Size
- TCP options
 - negotiate Timestamps, SACK, Window scale
- Multipath TCP
 - check that server supports Multipath TCP
 - propose Token in each direction
 - propose initial Data sequence number in each direction
 - Exchange keys to authenticate subflows

How to extend TCP ?

Theory

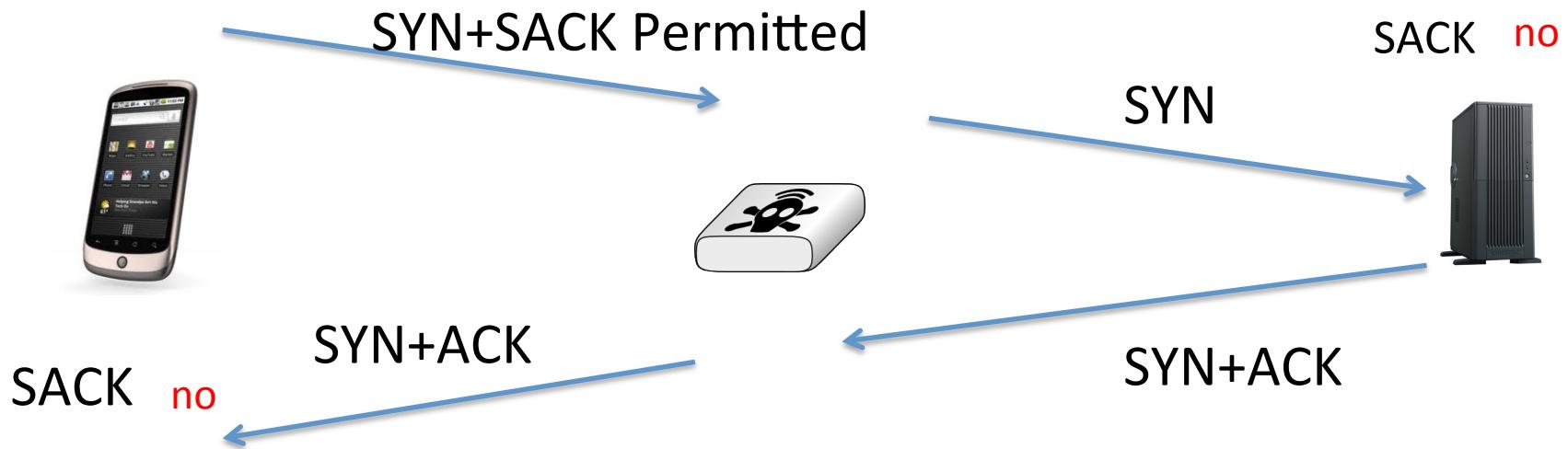
- TCP options were invented for this purpose
 - Exemple SACK



How to extend TCP ?

practice

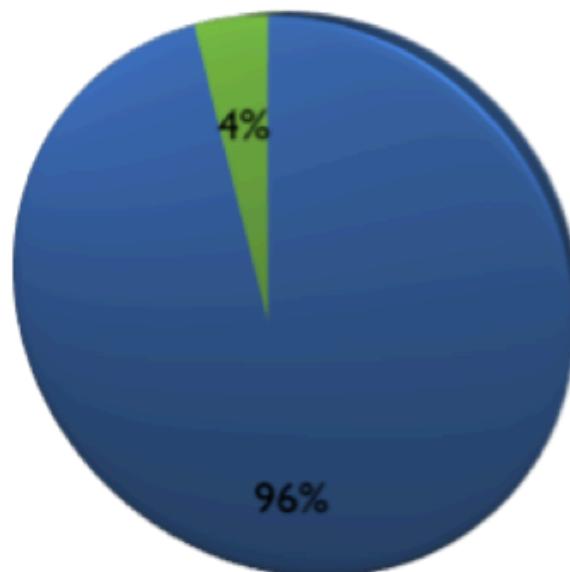
- What happens when there are middleboxes on the path ?



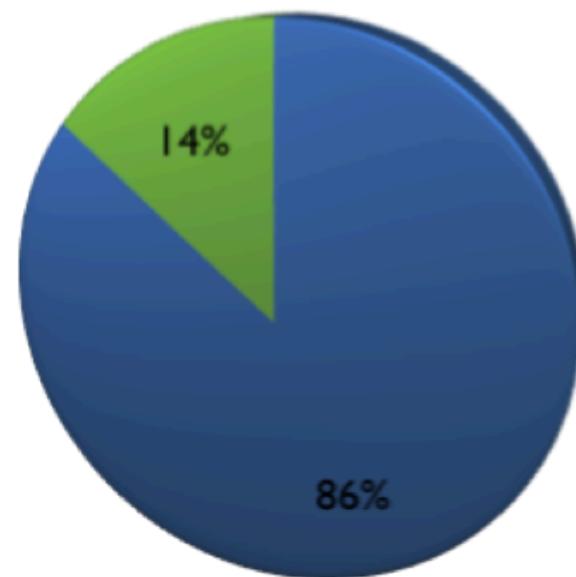
TCP options

- In SYN segments

SYN segments, port 34443



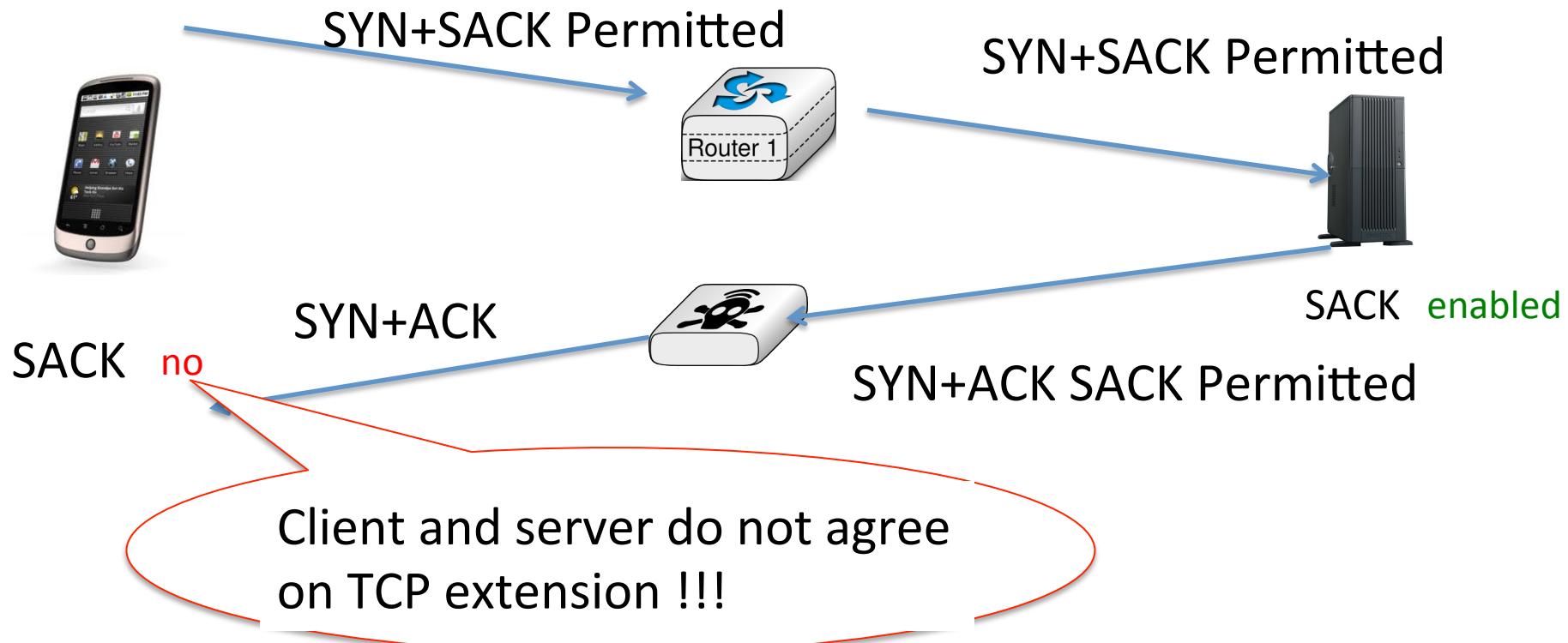
SYN segments, port 80



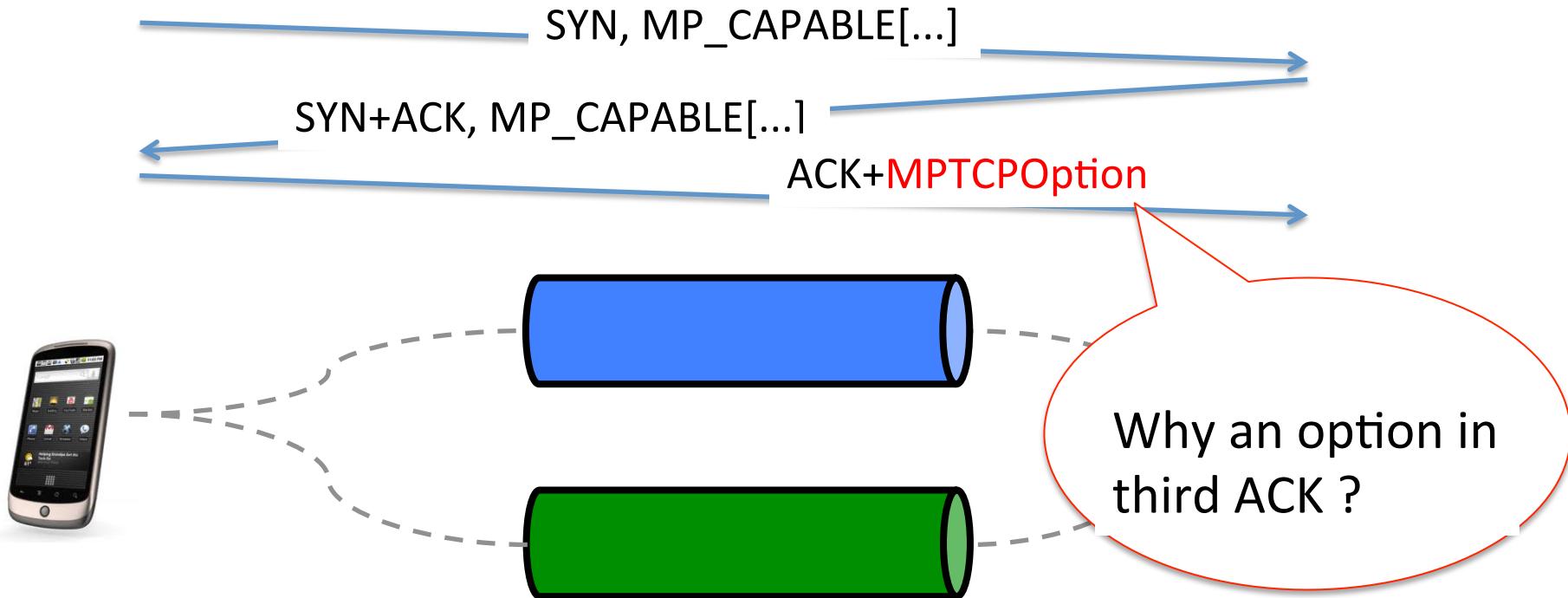
How to extend TCP ?

The worst case

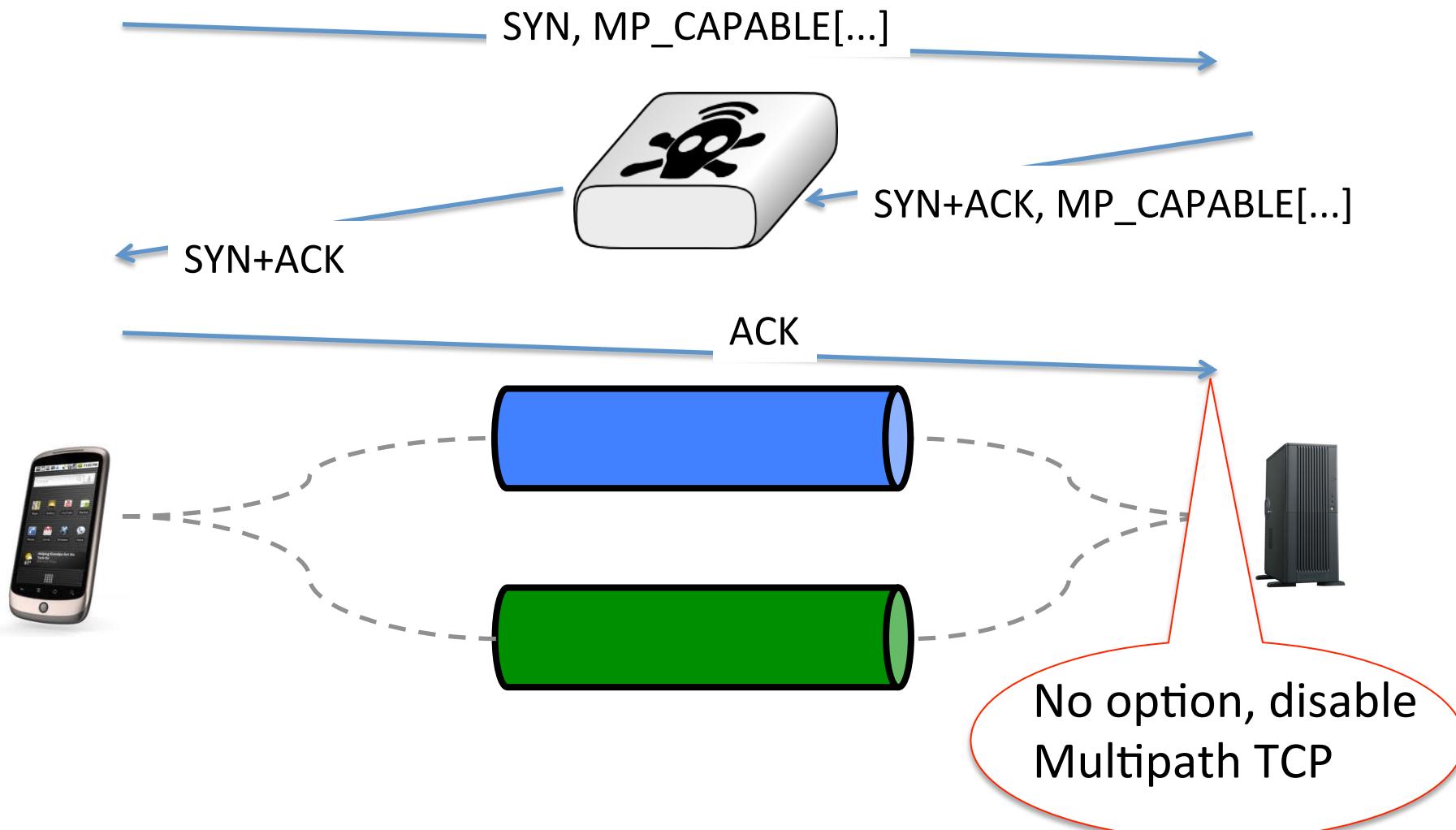
- What happens when there are middleboxes on the path ?



Multipath TCP handshake

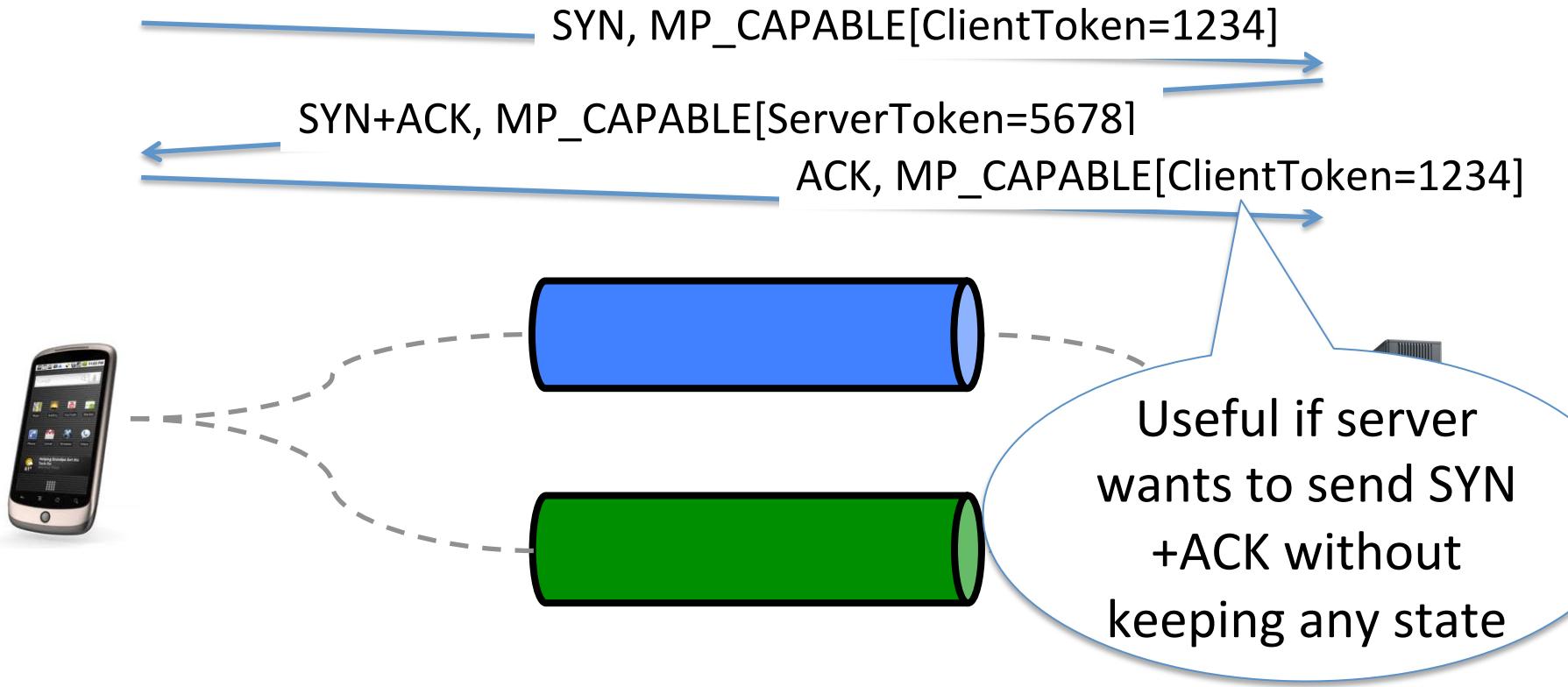


Multipath TCP option in third ACK



Multipath TCP handshake

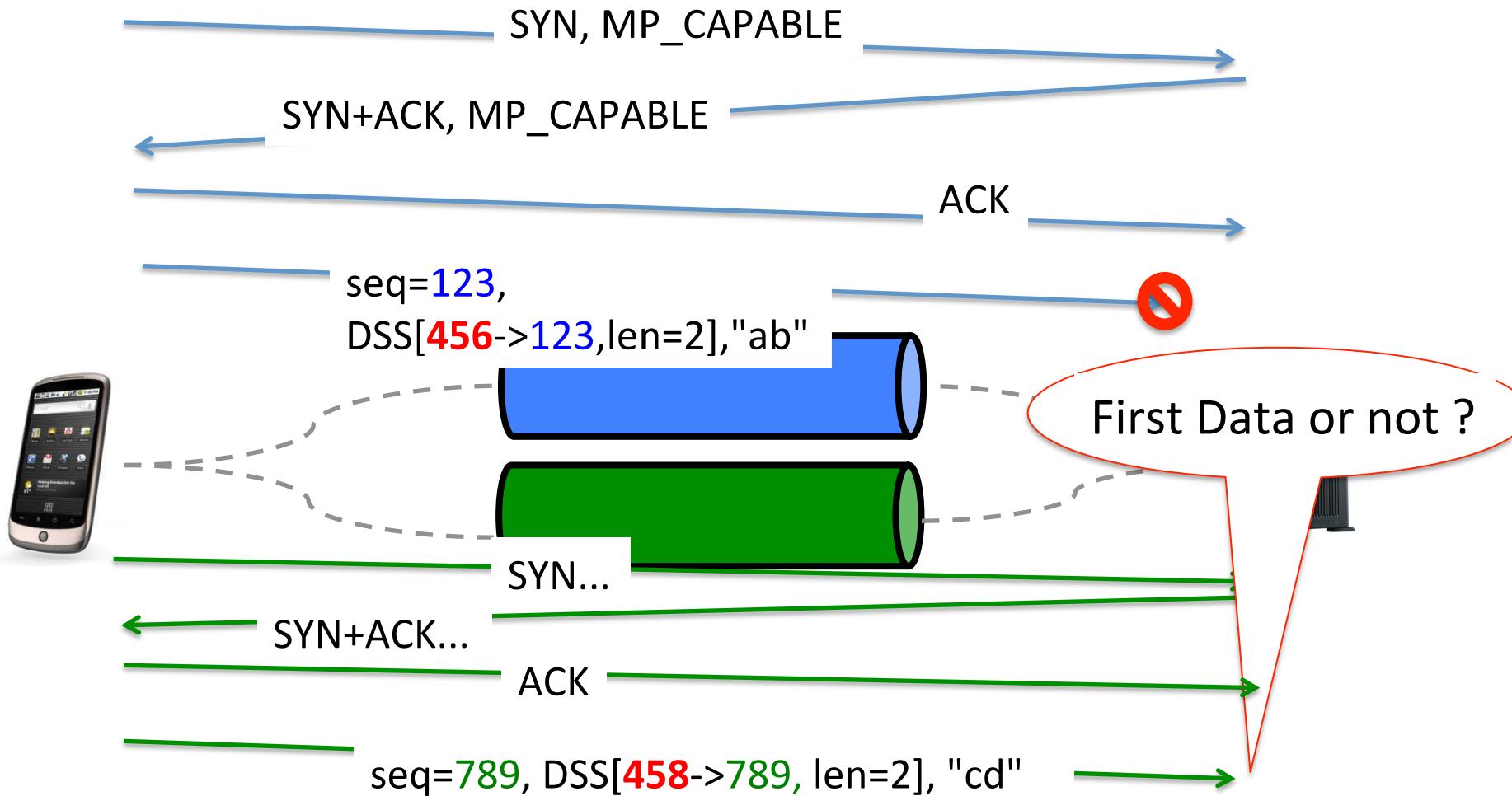
Token exchange



Initial Data Sequence number

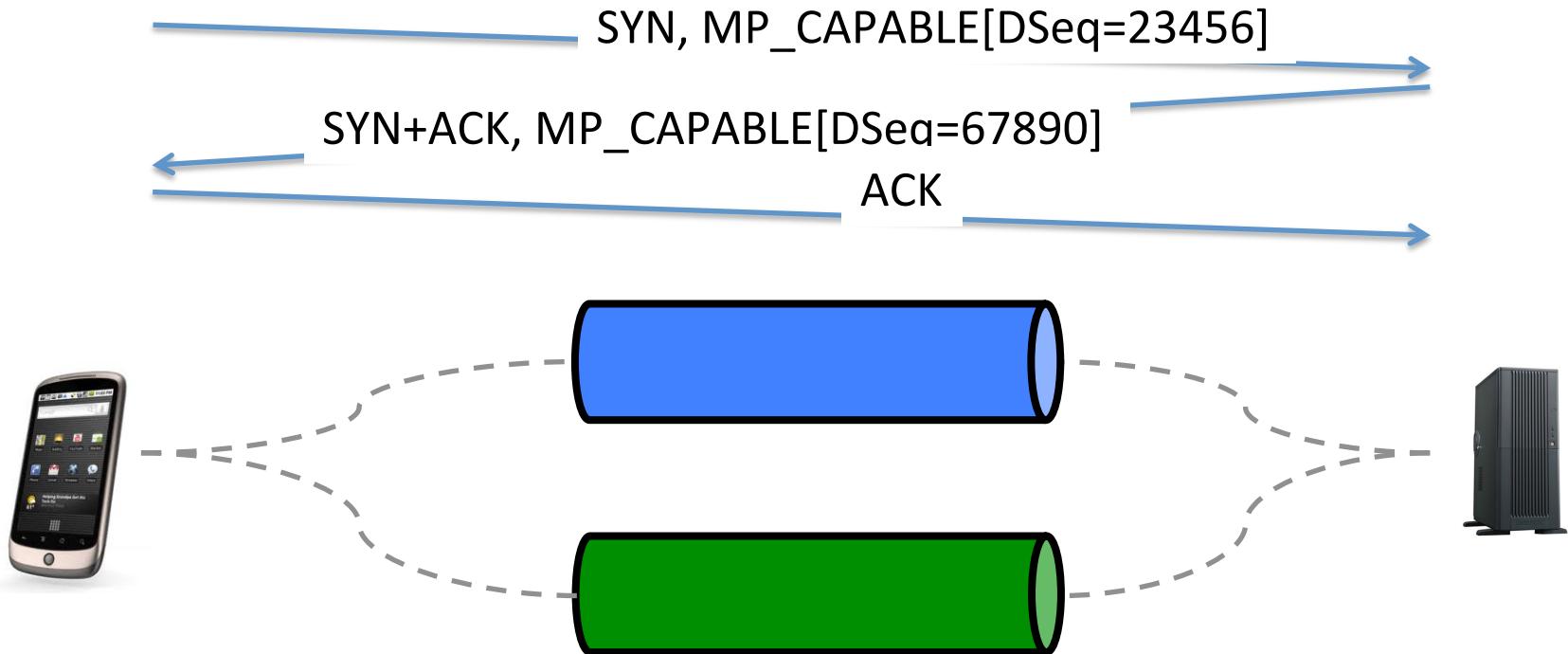
- Why do we need an initial Data Sequence number ?
 - Setting IDSN to a random value improves security
 - Hosts must know IDSN to avoid losing data in some special cases

Initial Data Sequence number



Initial Data Sequence number

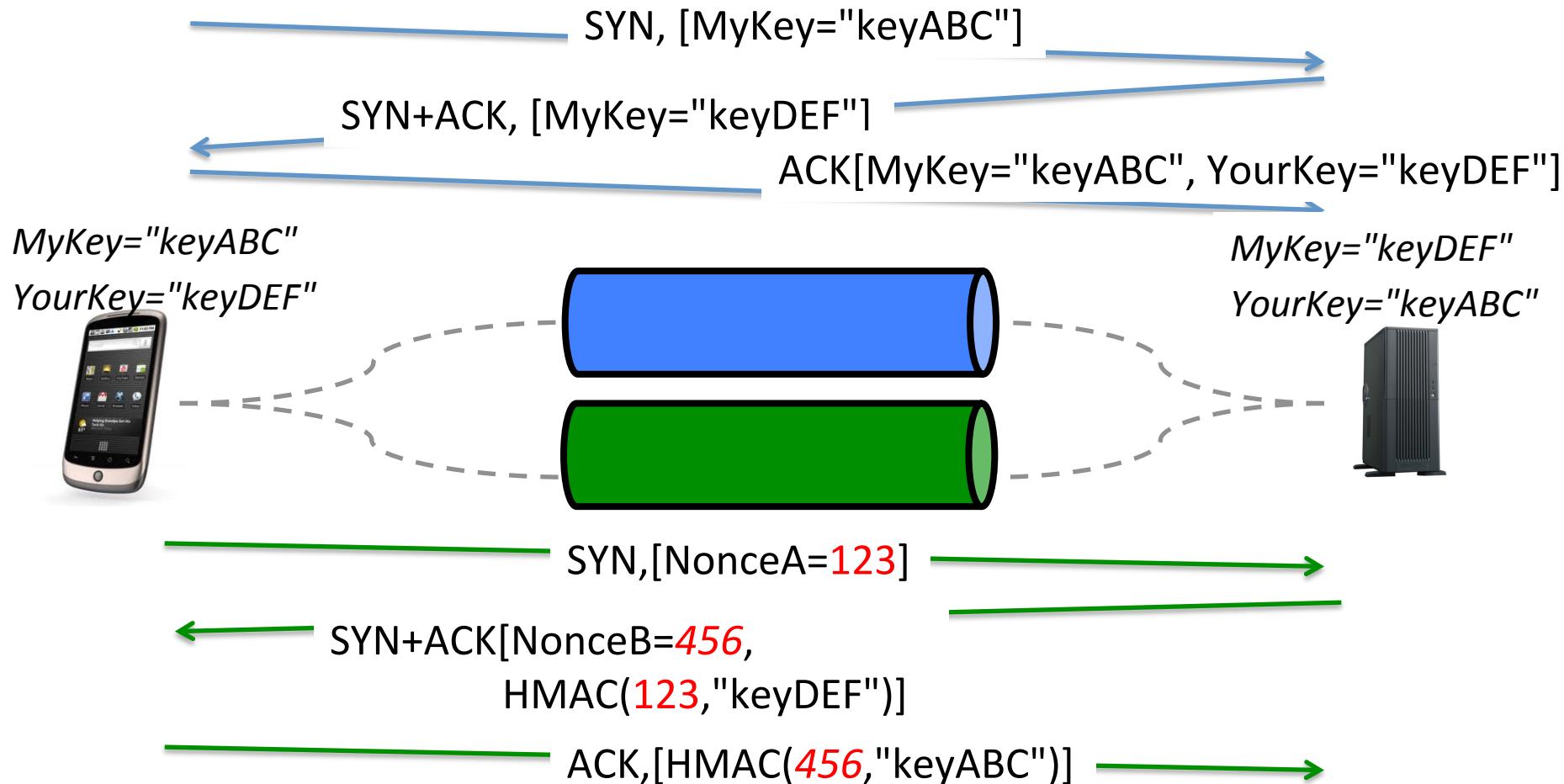
- How to negotiate the IDSN ?



How to secure Multipath TCP

- Main goal
 - Authenticate the establishment of subflows
- Principles
 - Each host announces a key during initial handshake
 - keys are exchanged in clear
 - When establishing a subflow, use HMAC + key to authenticate subflow

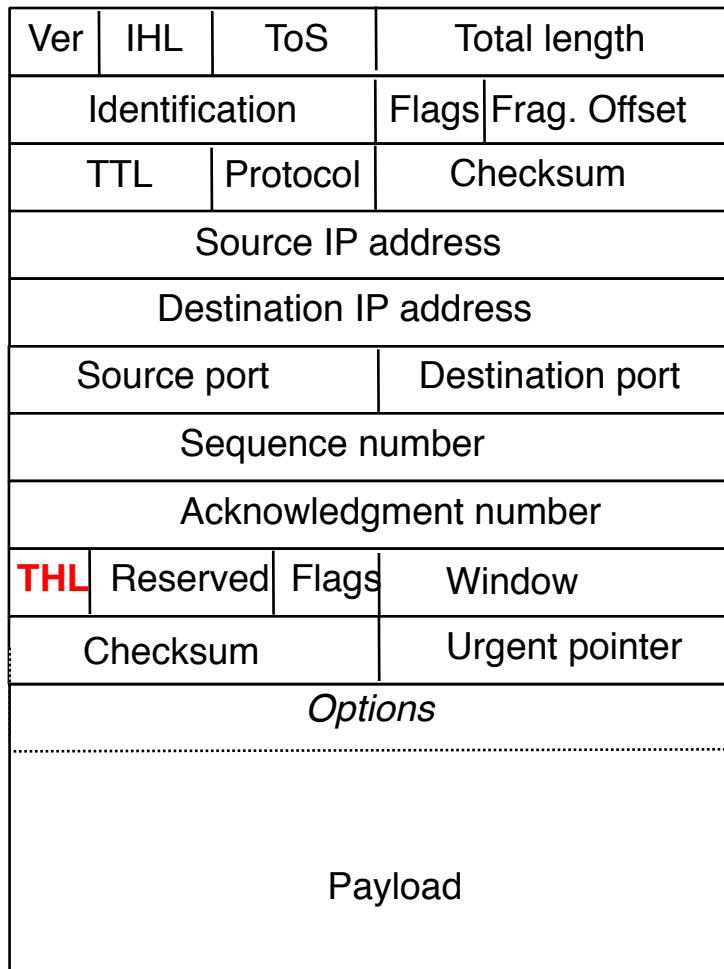
Key exchange



Putting everything inside the SYN

- How can we place inside SYN segment ?
 - Initial Data Sequence Number (64 bits)
 - Token (32 bits)
 - Authentication Key (the longer the better)

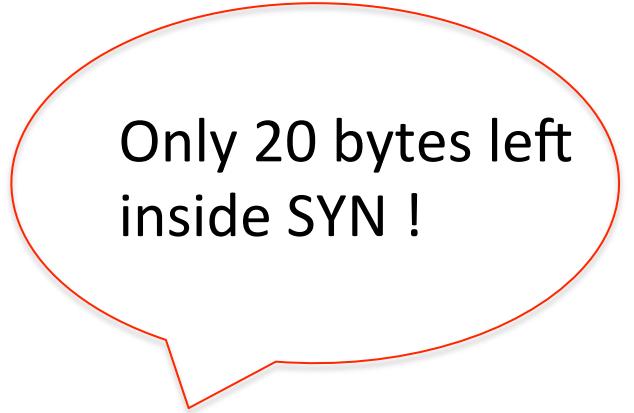
Constraint on TCP options



- Total length of TCP header : max 64 bytes
 - max 44 bytes for TCP options
 - *Options* length must be multiple of 4 bytes

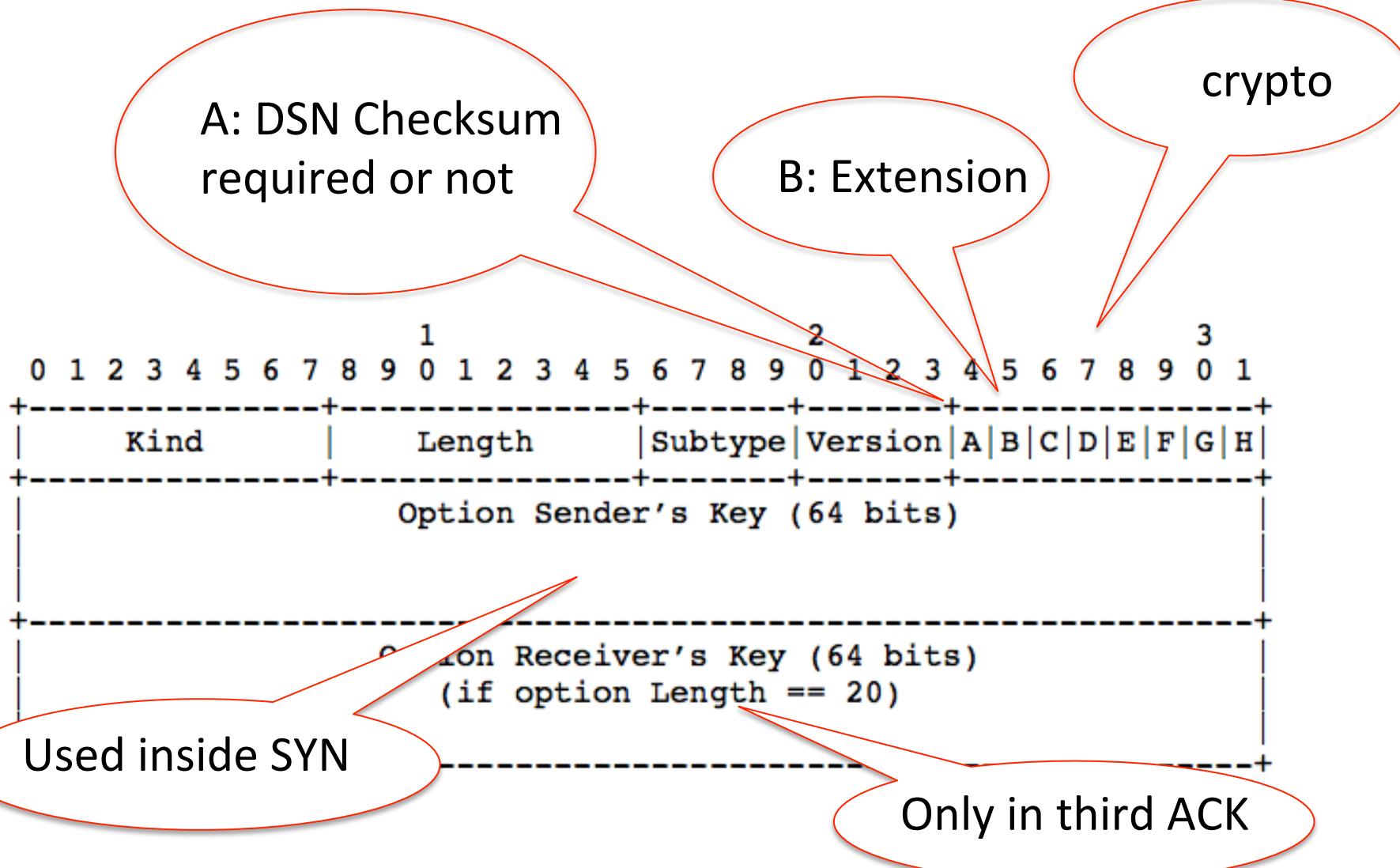
TCP options in the wild

- MSS option [4 bytes]
 - Used only inside SYN segments
- Timestamp option [10 bytes]
 - Used in potentially all segments
- Window scale option [3 bytes]
 - Used only inside SYN segments
- SACK permitted option [2 bytes]
 - Used only inside SYN segments
- Selective Acknowledgements [N bytes]
 - Used in data segments



Only 20 bytes left
inside SYN !

The MP_CAPABLE option



Initial Data Sequence Numbers and Tokens

- Computation of initial Data Sequence Number

$$\text{IDSN}_A = \text{Lower}_{64}(\text{SHA-1}(\text{Key}_A))$$

$$\text{IDSN}_B = \text{Lower}_{64}(\text{SHA-1}(\text{Key}_B))$$

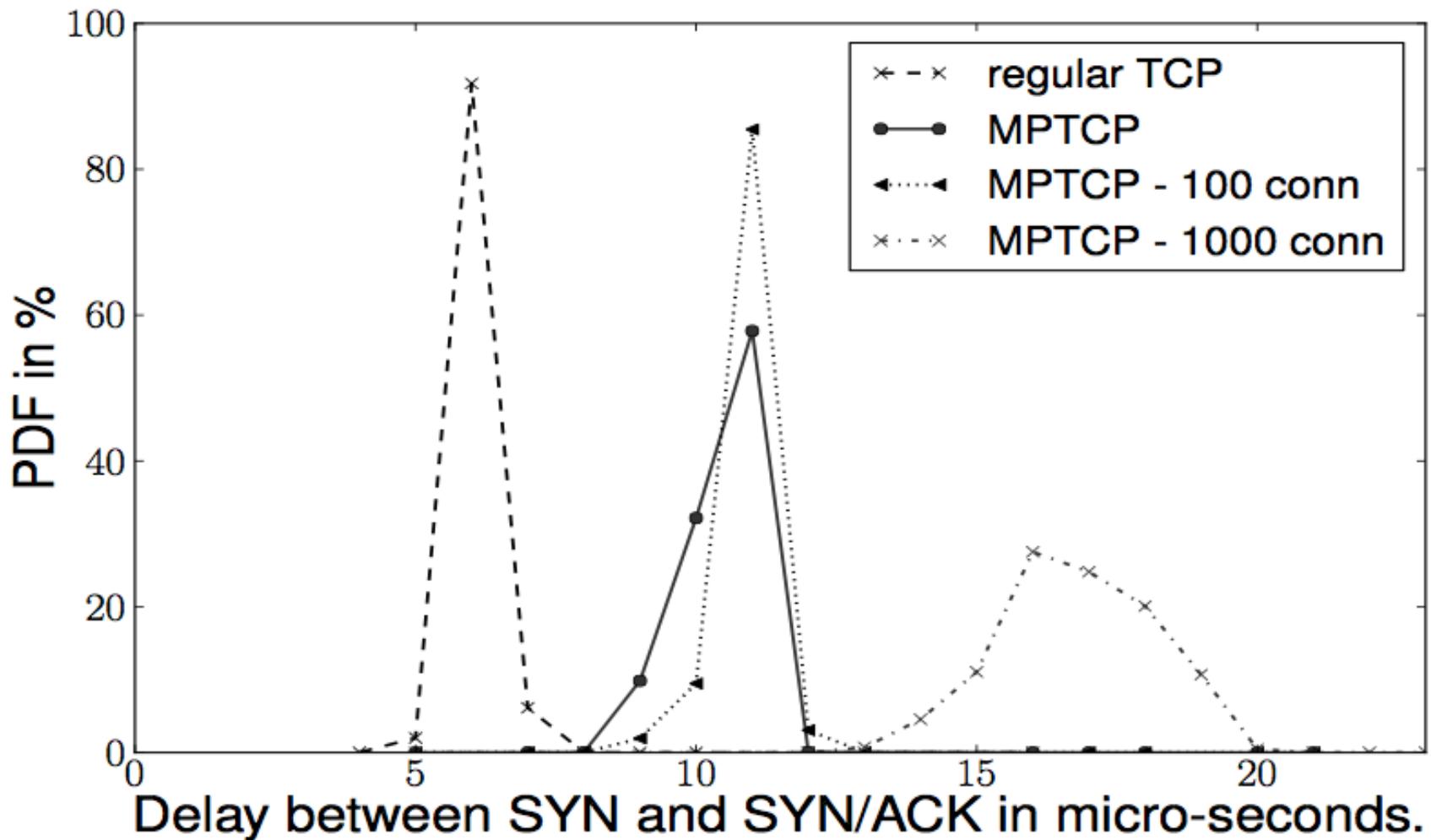
- Computation of token

$$\text{Token}_A = \text{Upper}_{32}(\text{SHA-1}(\text{Key}_A))$$

$$\text{Token}_B = \text{Upper}_{32}(\text{SHA-1}(\text{Key}_B))$$

There is a small risk of collision,
different keys same token

Cost of the Multipath TCP handshake

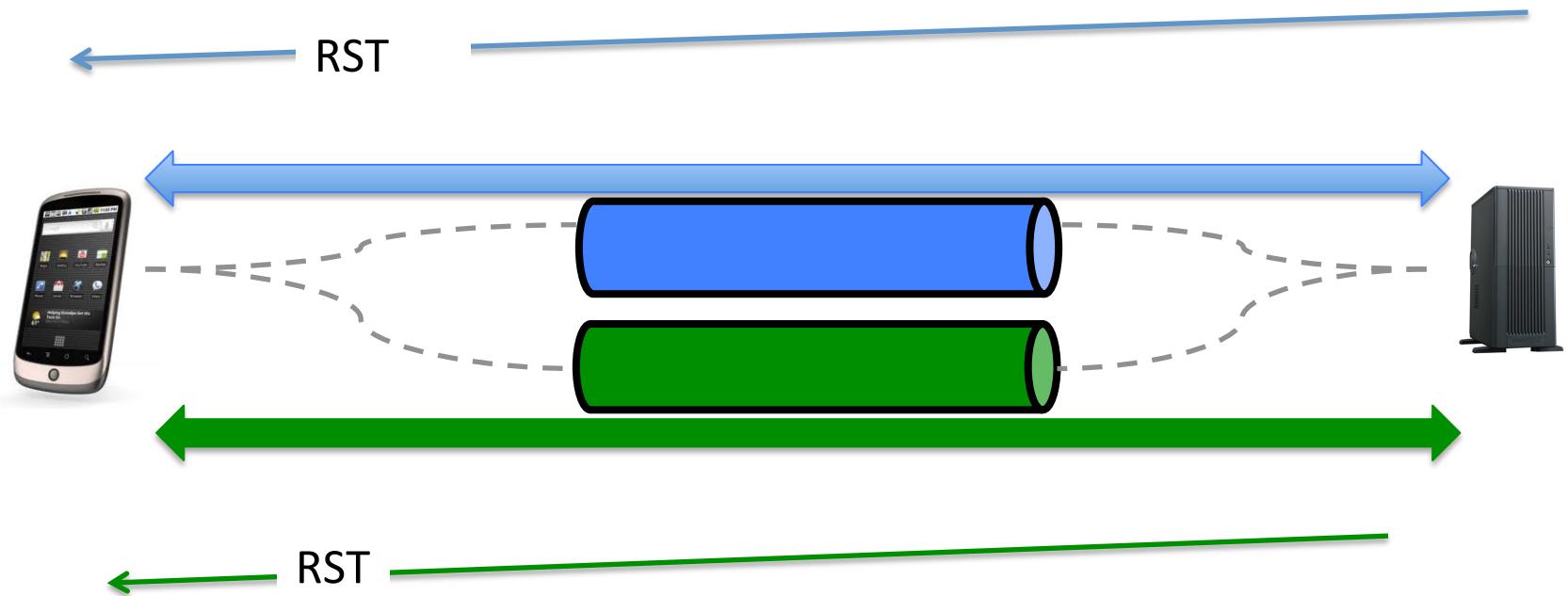


The Multipath TCP control plane

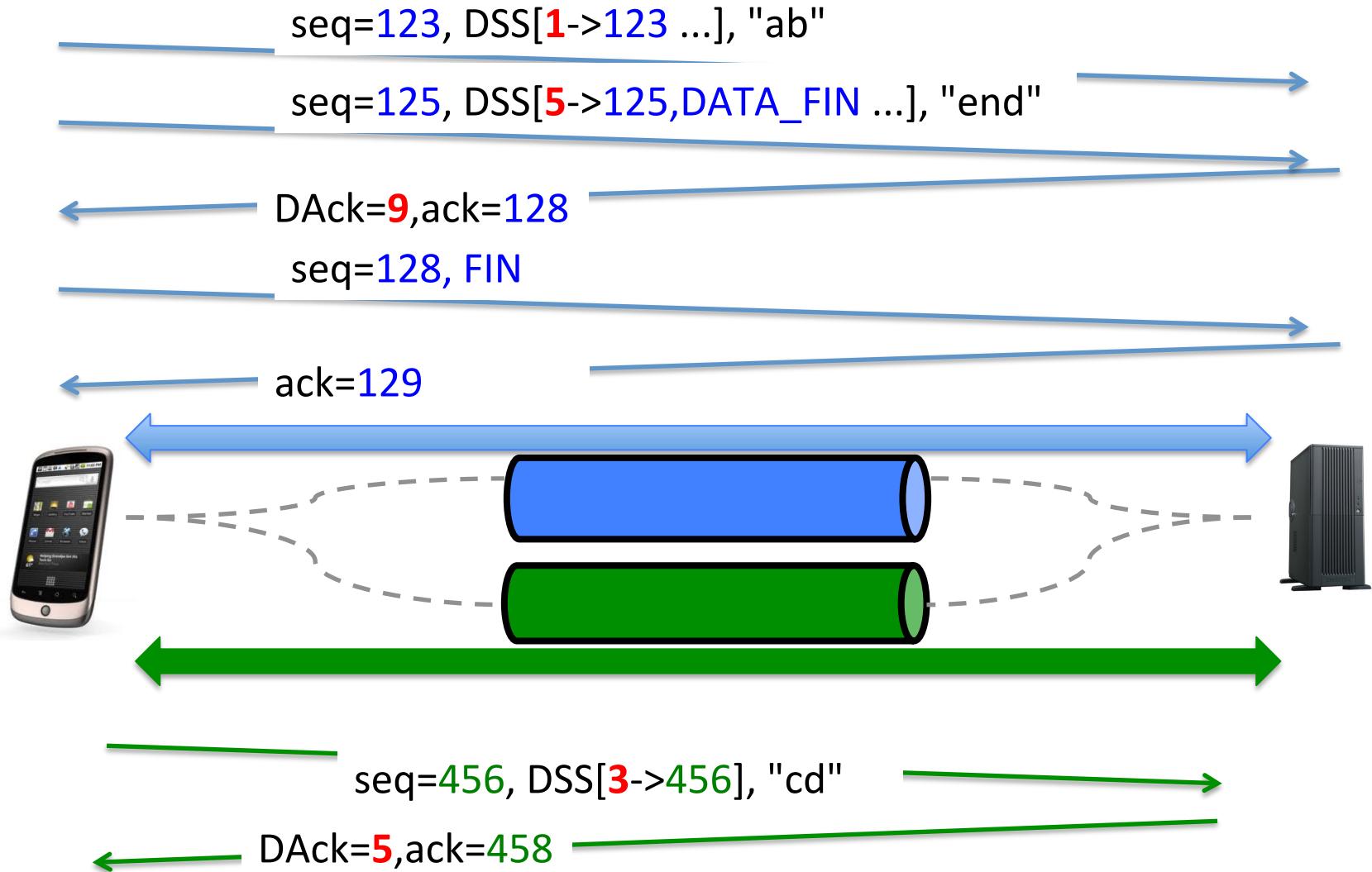
- Connection establishment in details
- Closing a Multipath TCP connection
- Address dynamics

Closing a Multipath TCP connection

- How to close a Multipath TCP connection ?
 - By closing all subflows ?

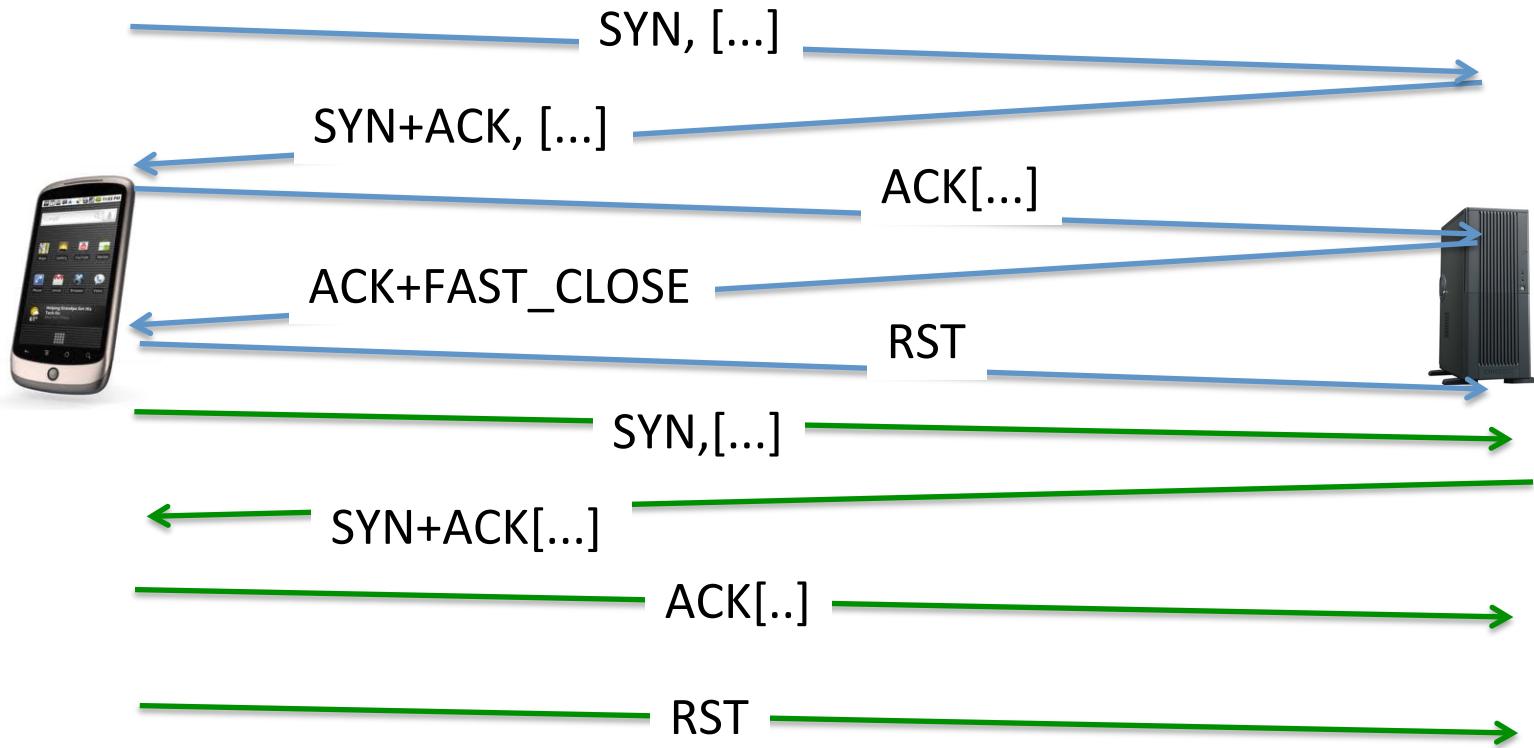


Closing a Multipath TCP connection



Closing a Multipath TCP connection

- FAST Close

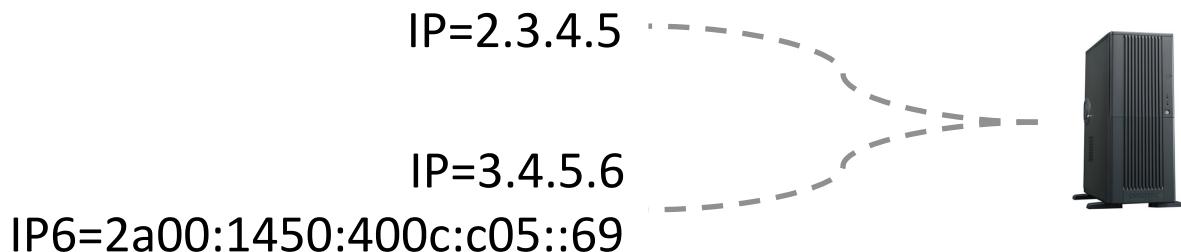


The Multipath TCP control plane

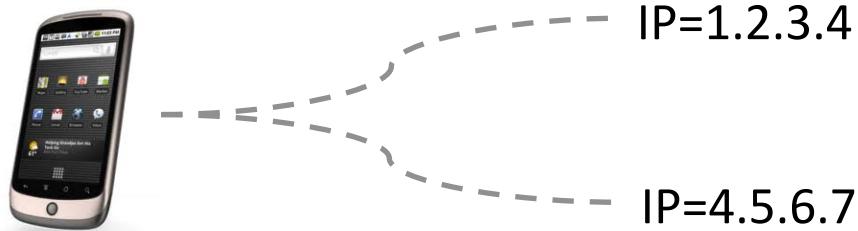
- Connection establishment in details
- Closing a Multipath TCP connection
- Address dynamics

Multipath TCP Address dynamics

- How to learn the addresses of a host ?

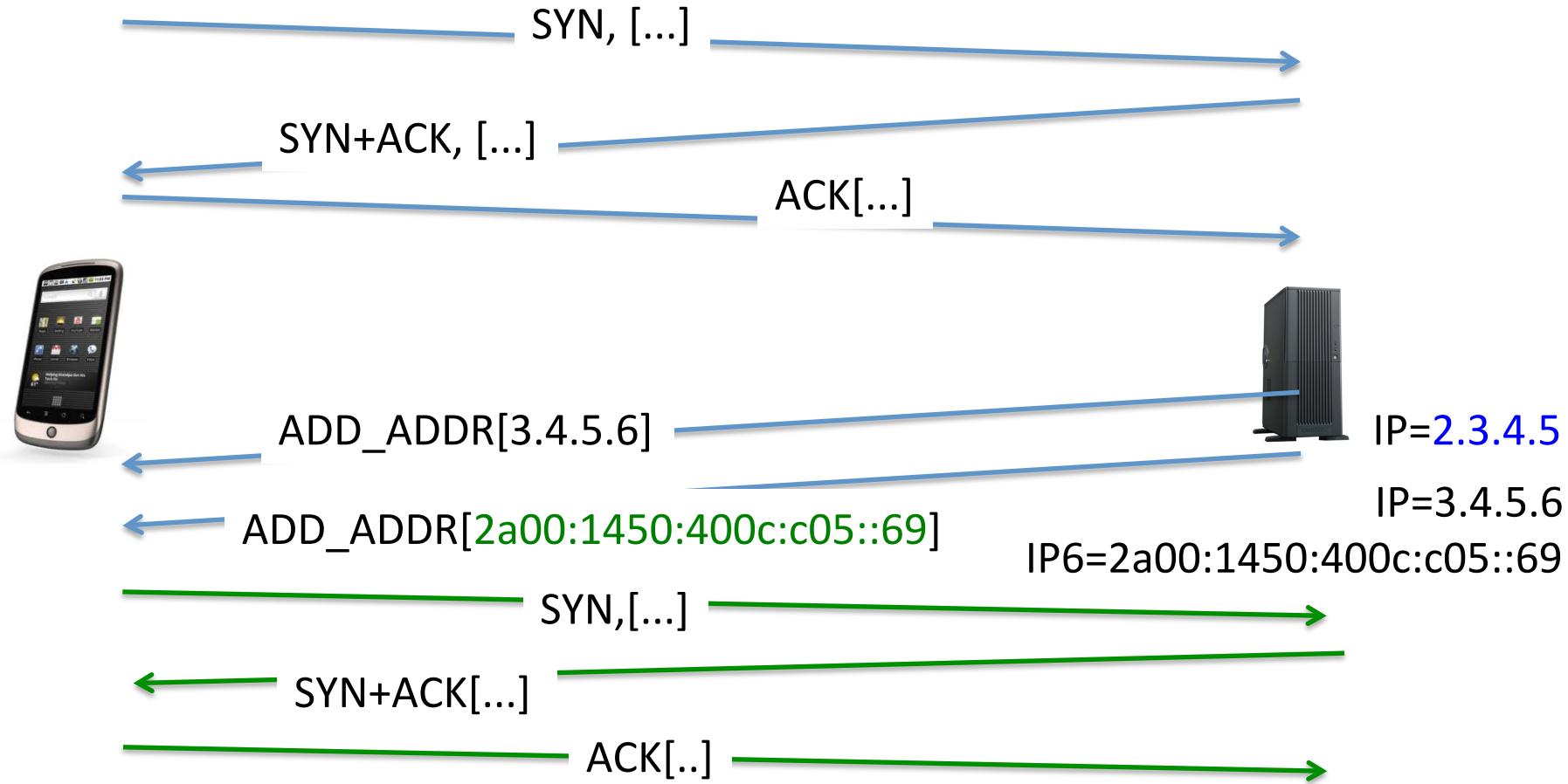


- How to deal with address changes ?



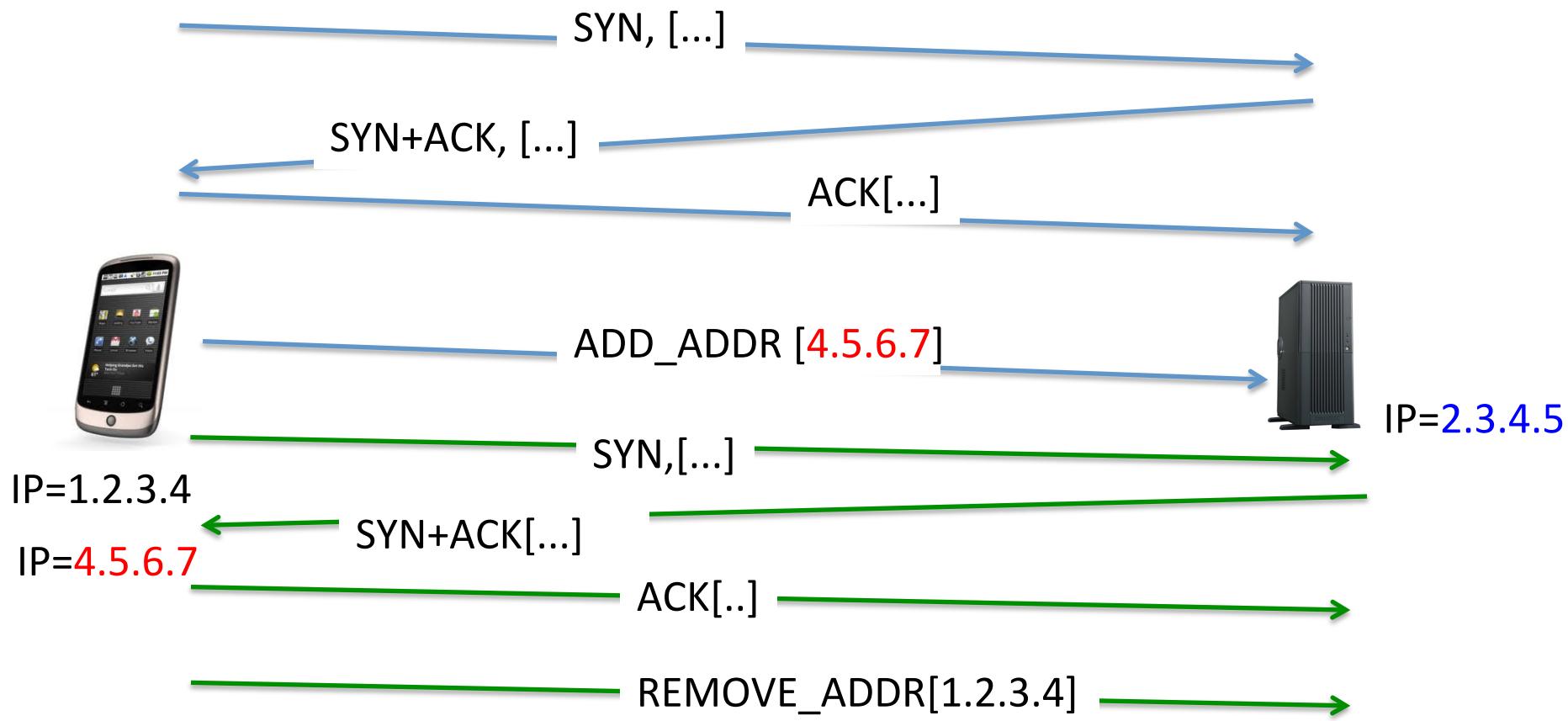
Address dynamics

- Basic solution : multihomed server

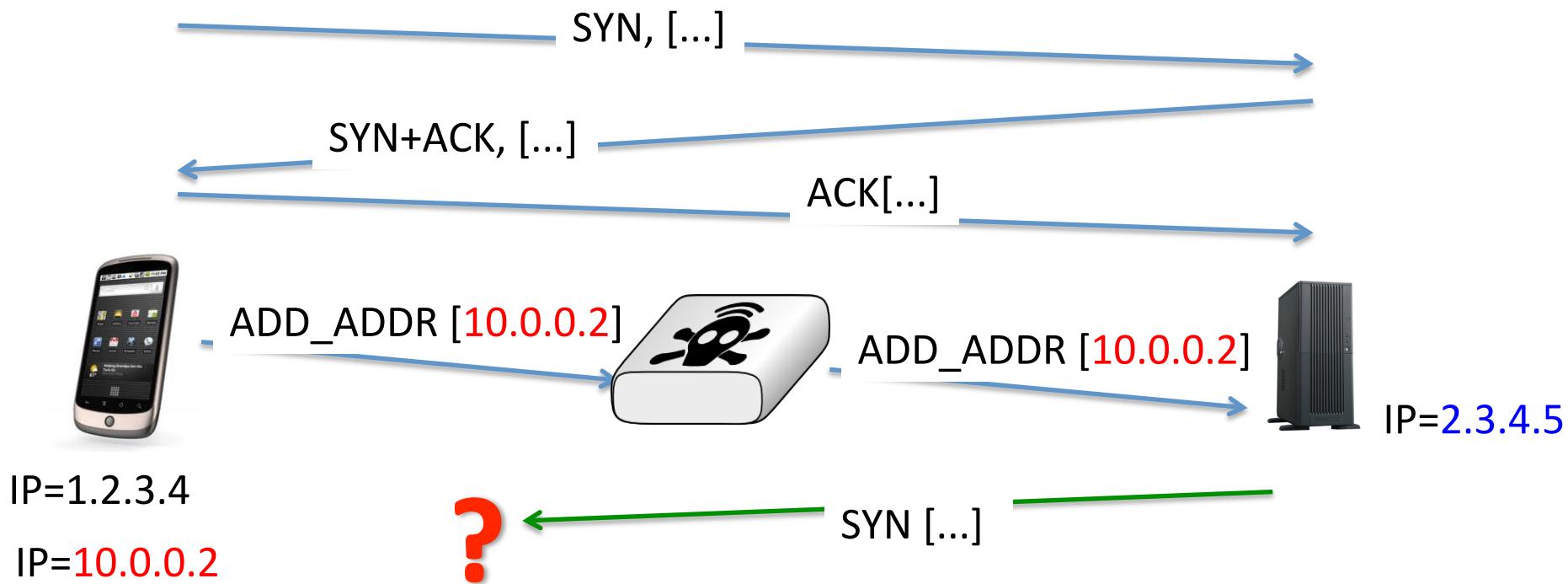


Address dynamics

- Basic solution : mobile client



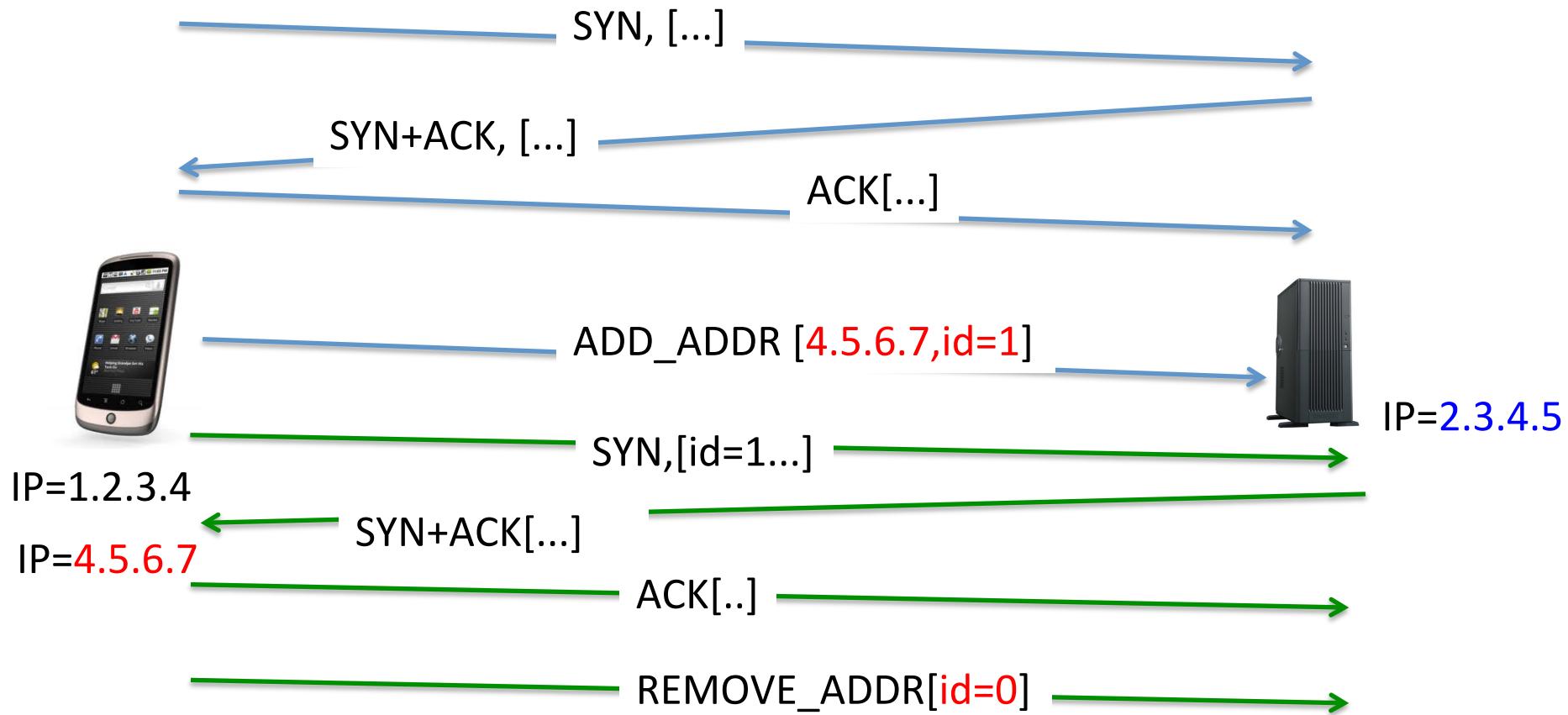
Address dynamics in today's Internet



Address dynamics with NATs

- Solution
 - Each address has one identifier
 - Subflow is established between id=0 addresses
 - Each host maintains a list of <address,id> pairs of the addresses associated to an MPTCP endpoint
 - MPTCP options refer to the address identifier
 - ADD_ADDR contains <address,id>
 - REMOVE_ADDR contains <id>

Address dynamics



Agenda

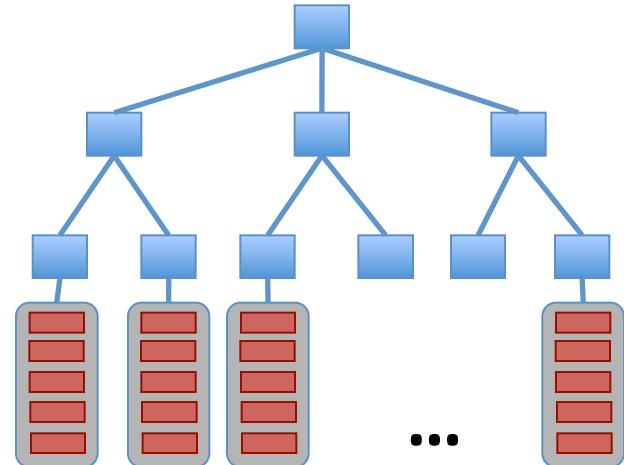
- The motivations for Multipath TCP
- The changing Internet
- The Multipath TCP Protocol

→ Multipath TCP use cases

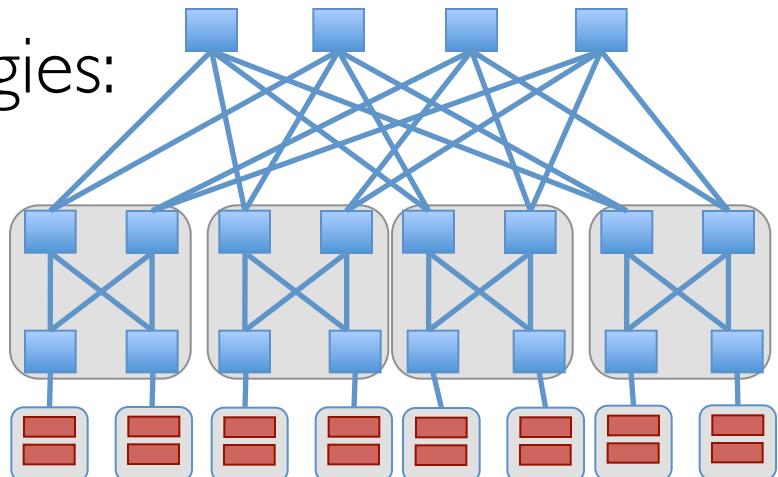
- Datacenters
- Smartphones

Datacenters evolve

- Traditional Topologies are tree-based
 - Poor performance
 - Not fault tolerant



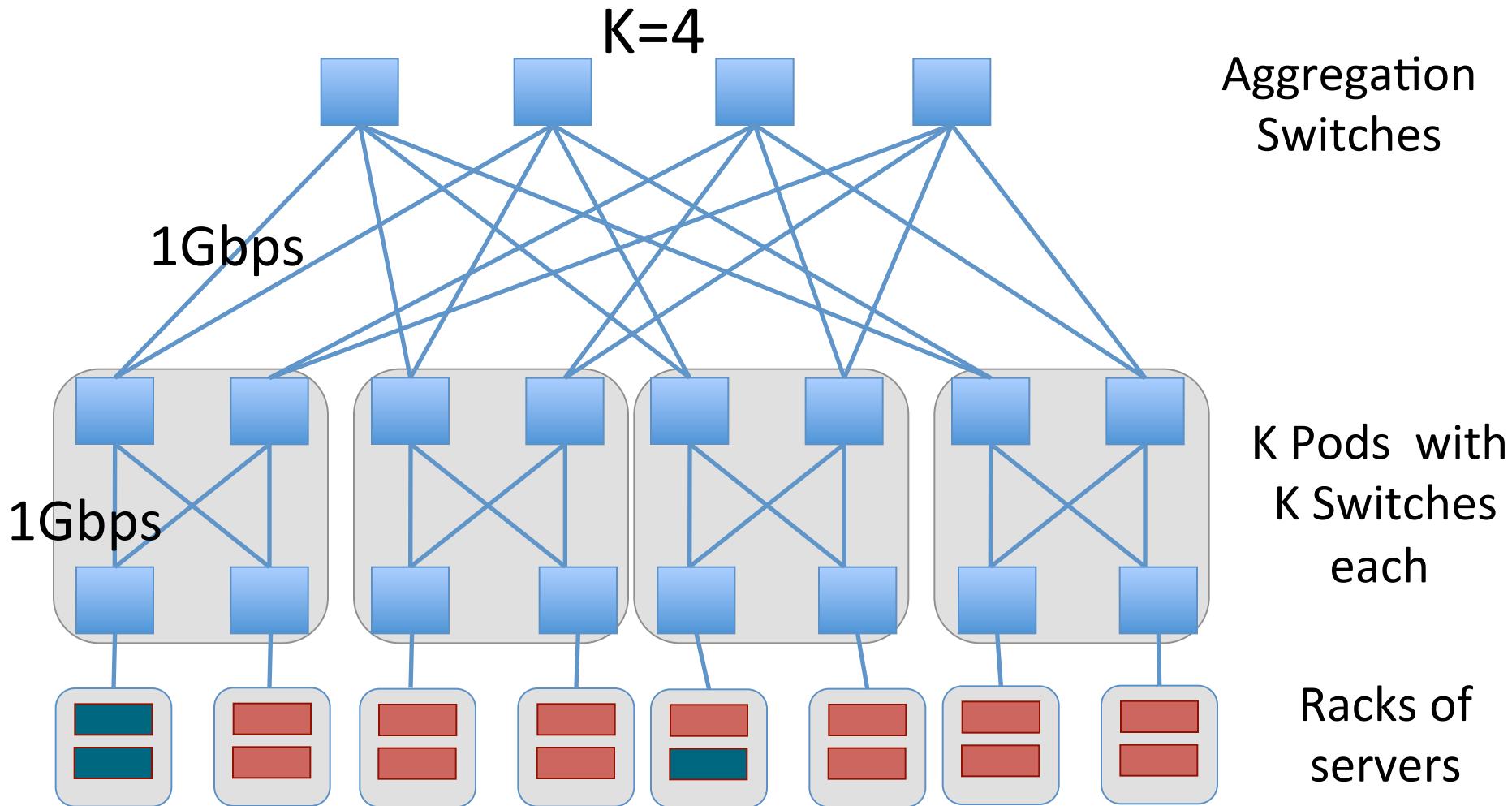
- Shift towards multipath topologies:
FatTree, BCube, VL2,
Cisco, EC2



C. Raiciu, et al. "Improving datacenter performance and robustness with multipath TCP," ACM SIGCOMM 2011.

Fat Tree Topology

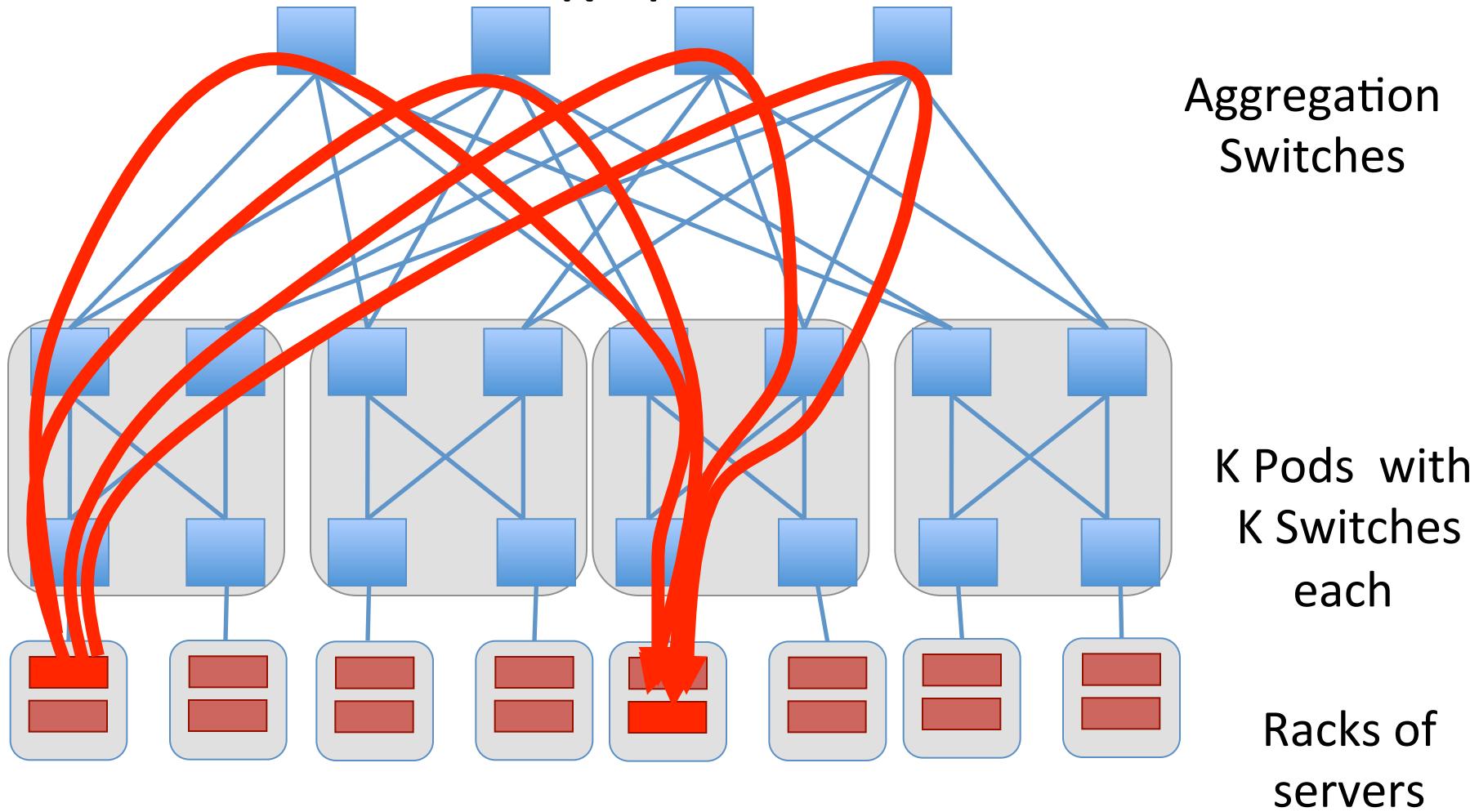
[Fares et al., 2008; Clos, 1953]



Fat Tree Topology

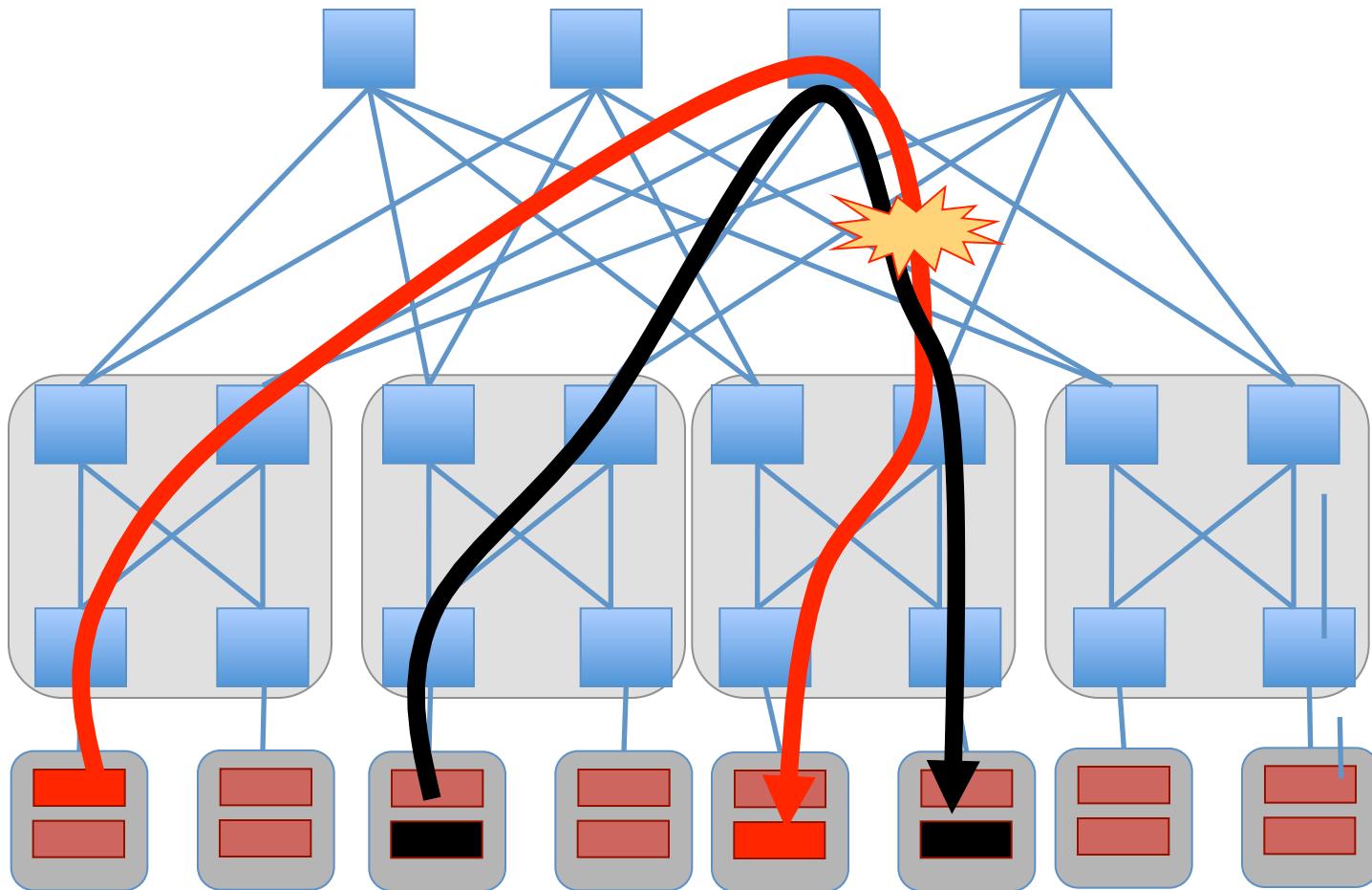
[Fares et al., 2008; Clos, 1953]

K=4

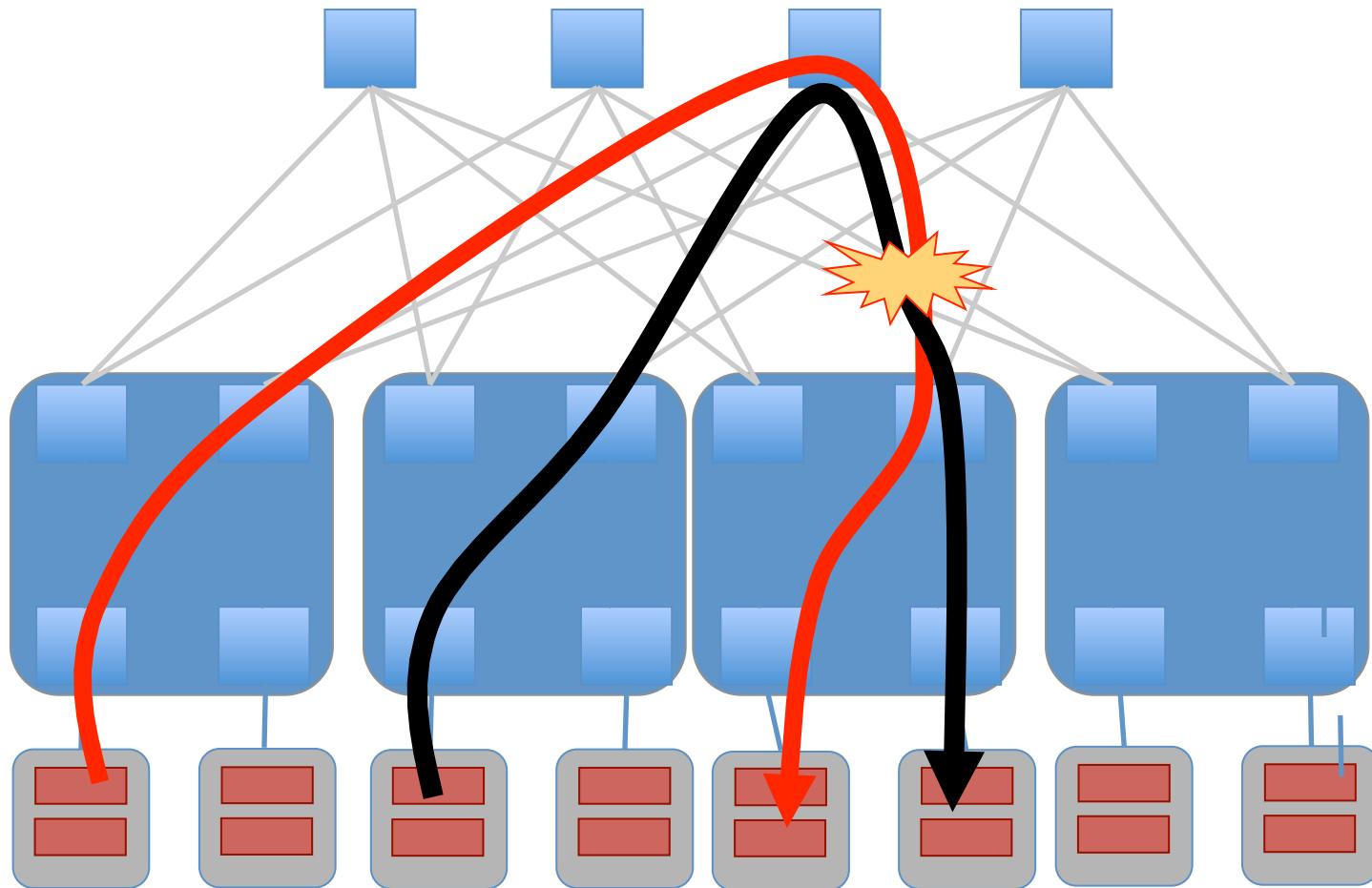


C. Raiciu, et al. "Improving datacenter performance and robustness with multipath TCP," ACM SIGCOMM 2011.

Collisions

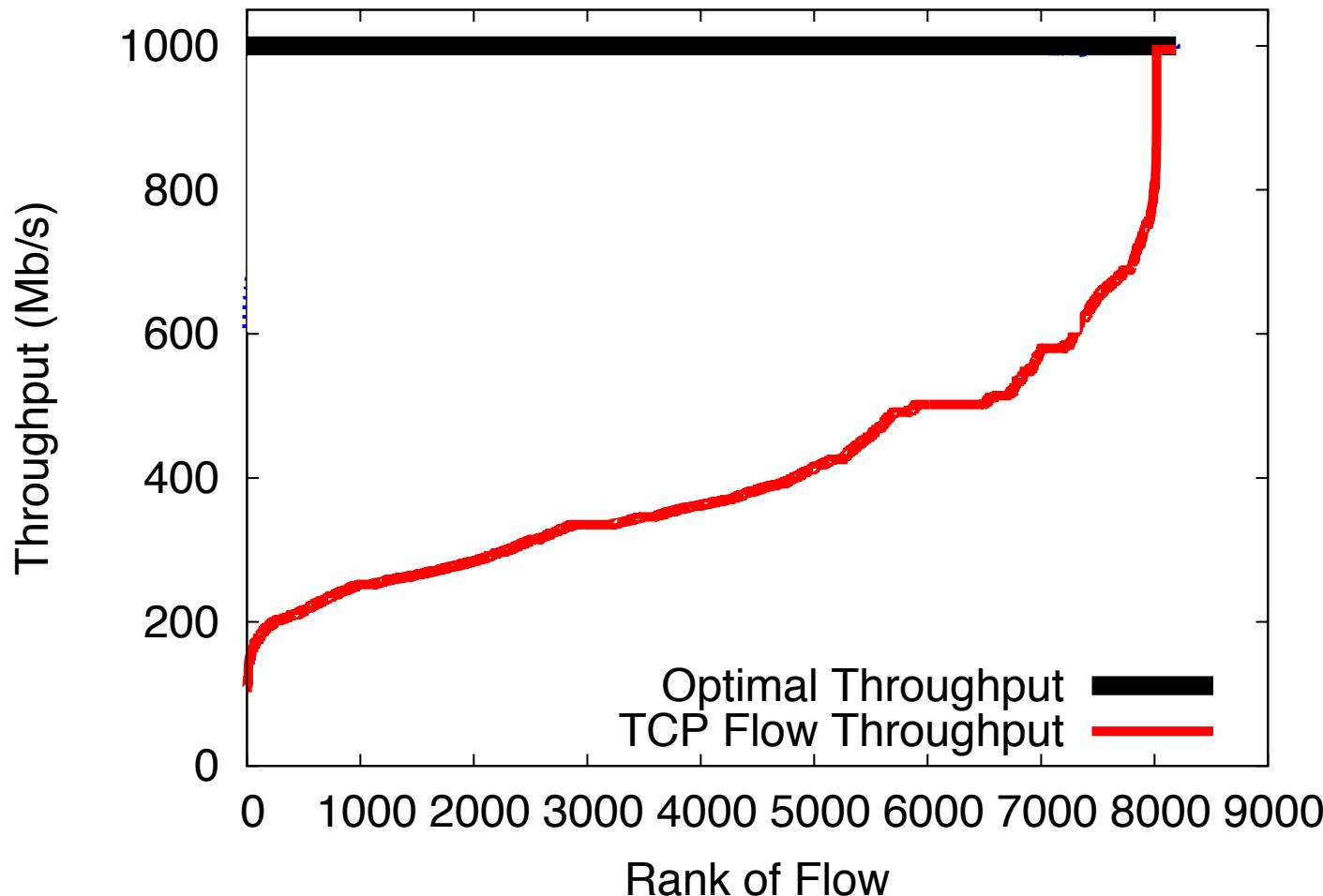


TCP in data centers



TCP in FAT tree networks

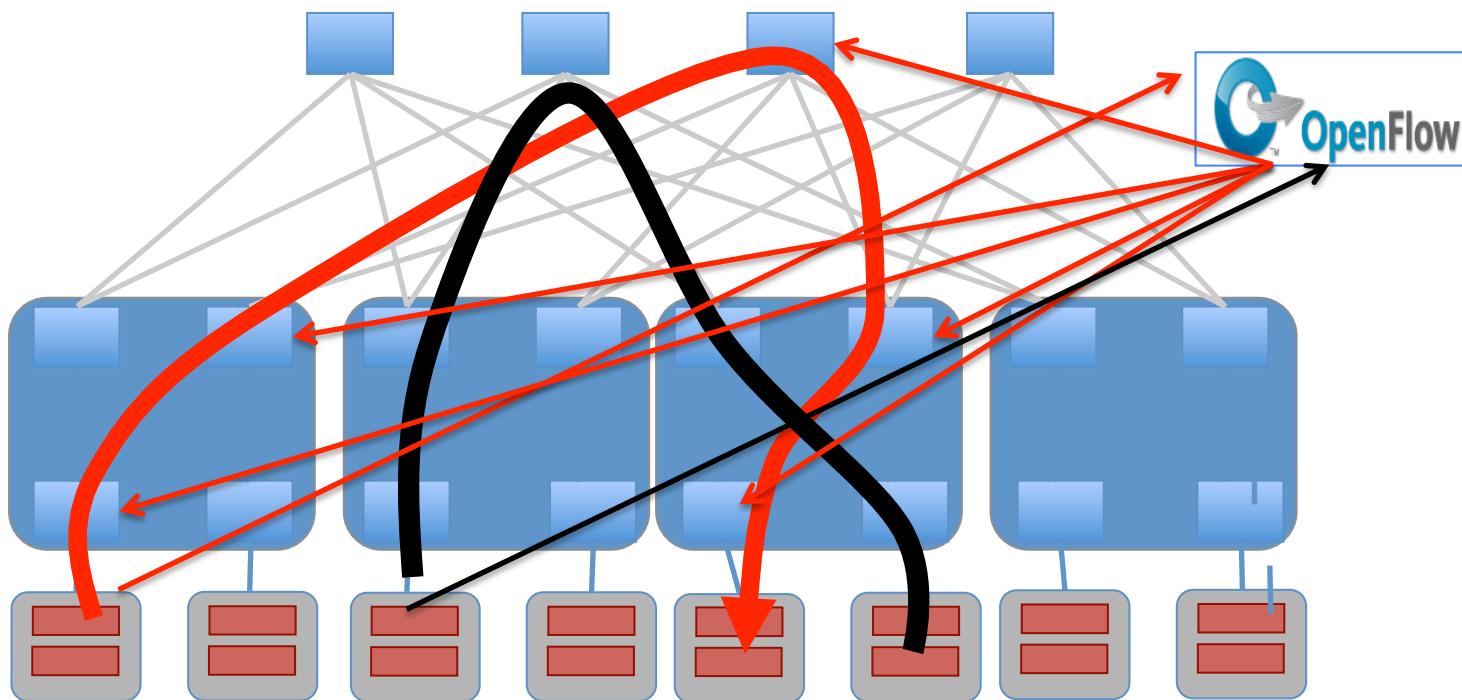
Cost of collisions



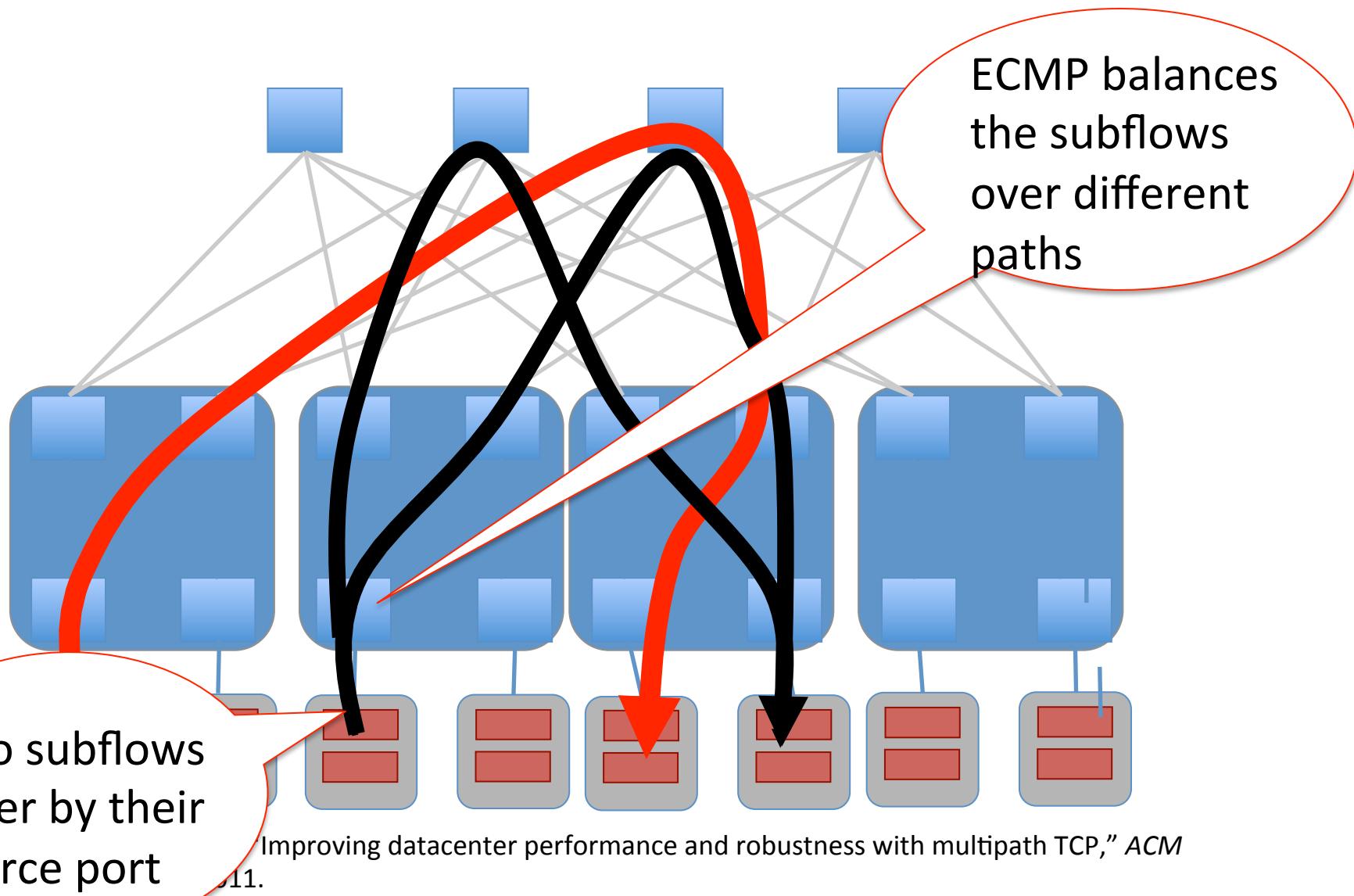
C. Raiciu, et al. "Improving datacenter performance and robustness with multipath TCP," ACM SIGCOMM 2011.

How to get rid of these collisions ?

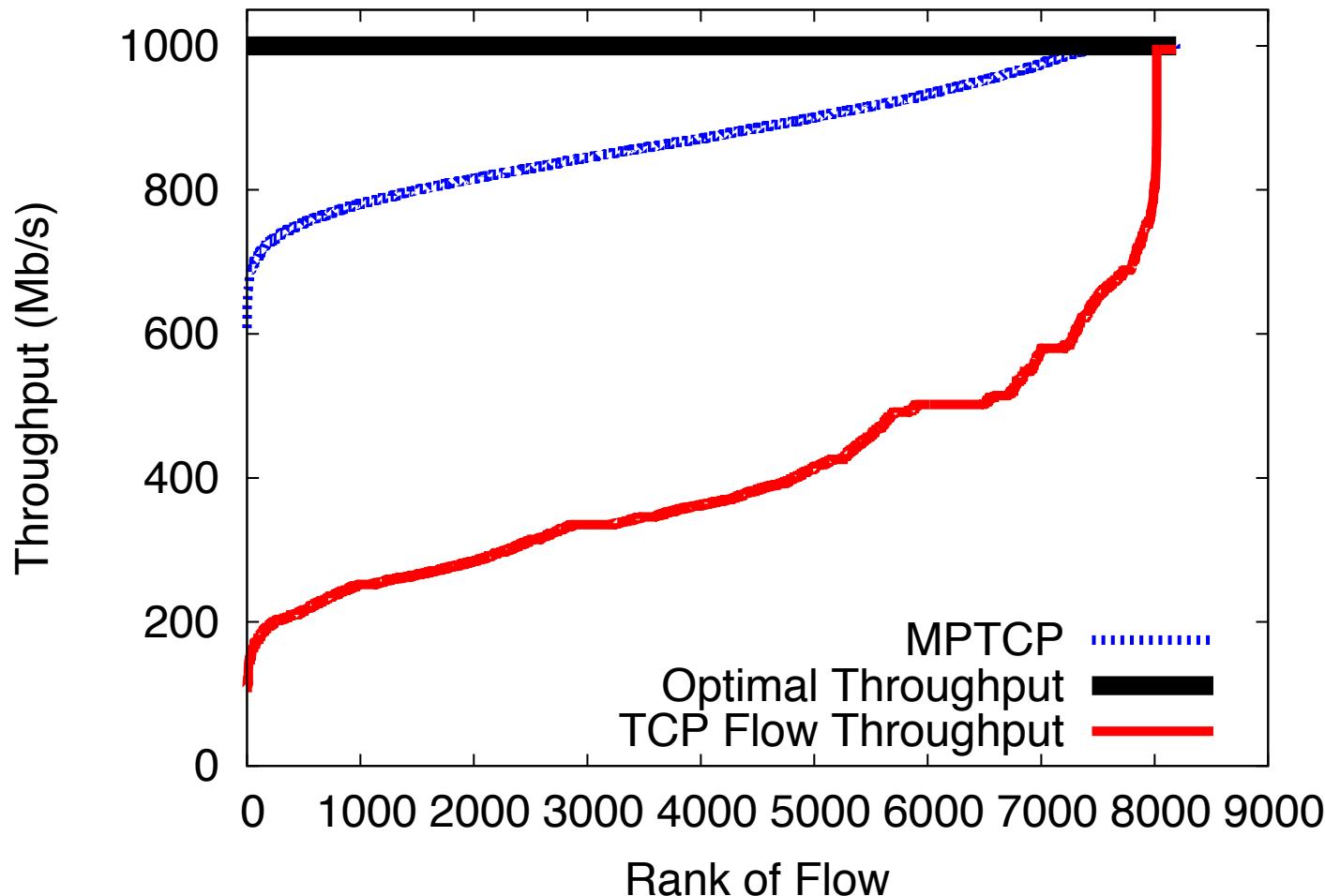
- Consider TCP performance as an optimisation problem



The Multipath TCP way

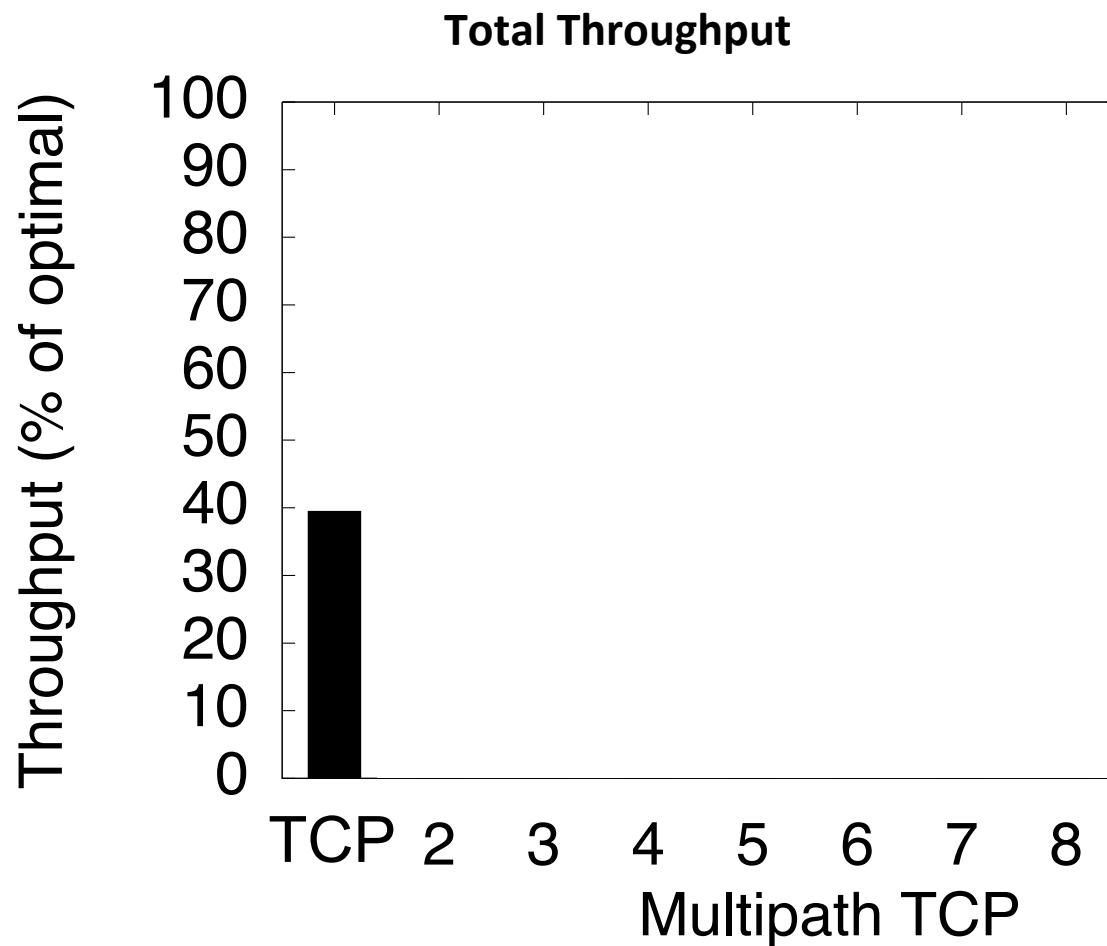


MPTCP better utilizes the FatTree network



C. Raiciu, et al. "Improving datacenter performance and robustness with multipath TCP," ACM SIGCOMM 2011.

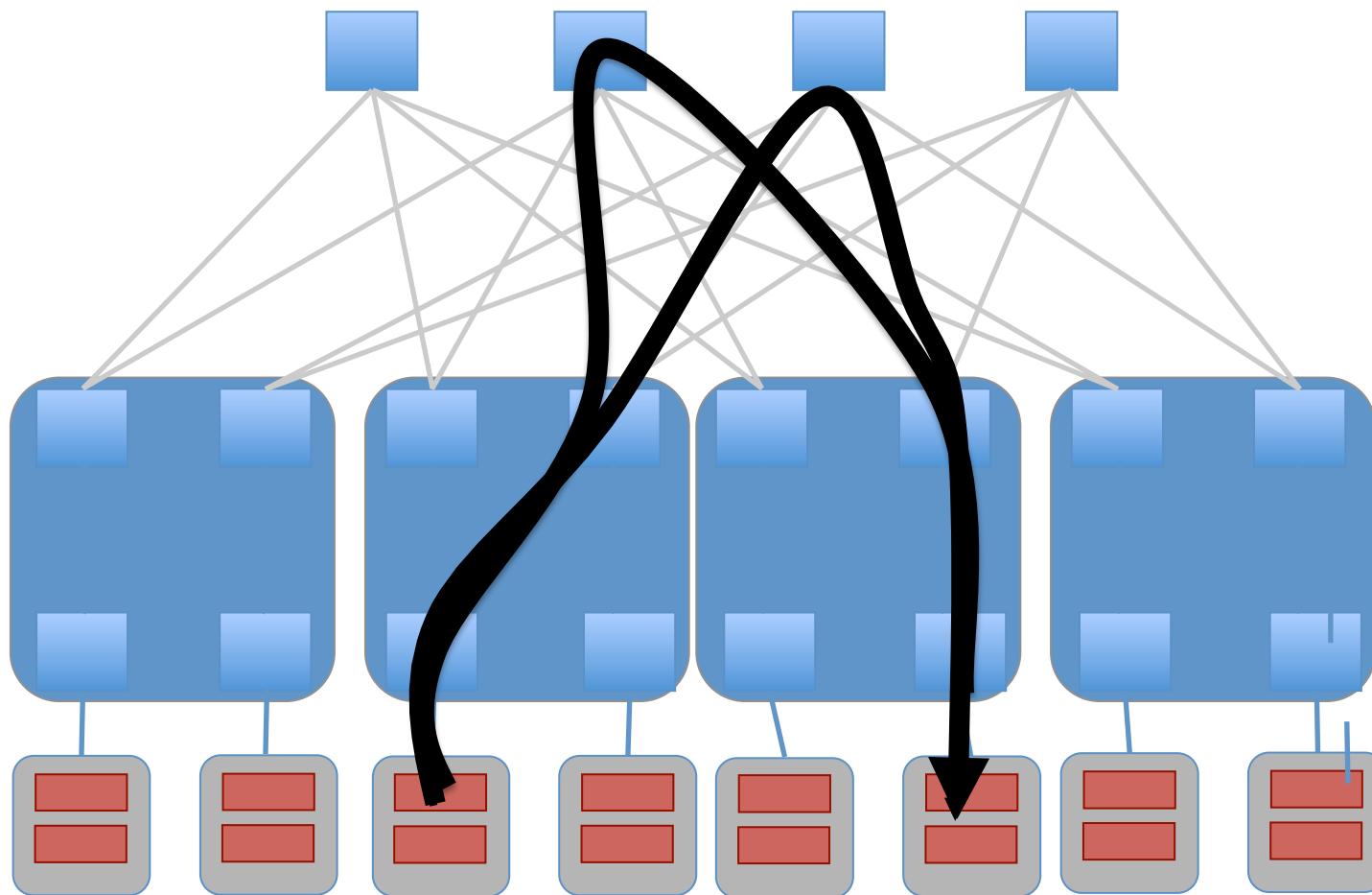
How many subflows does Multipath TCP need ?



C. Raiciu, et al. "Improving datacenter performance and robustness with multipath TCP," ACM SIGCOMM 2011.

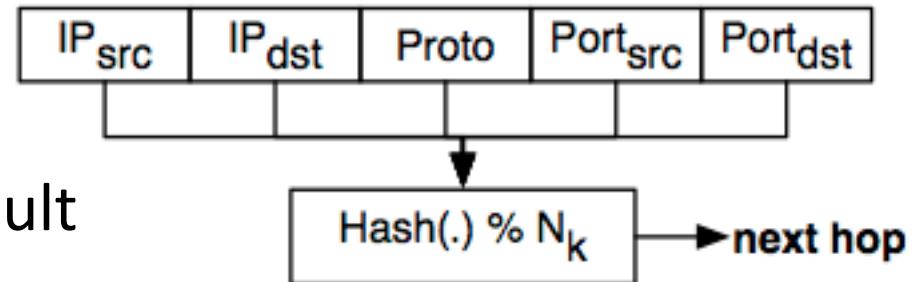
Can we improve Multipath TCP ?

- Two subflows may follow similar paths

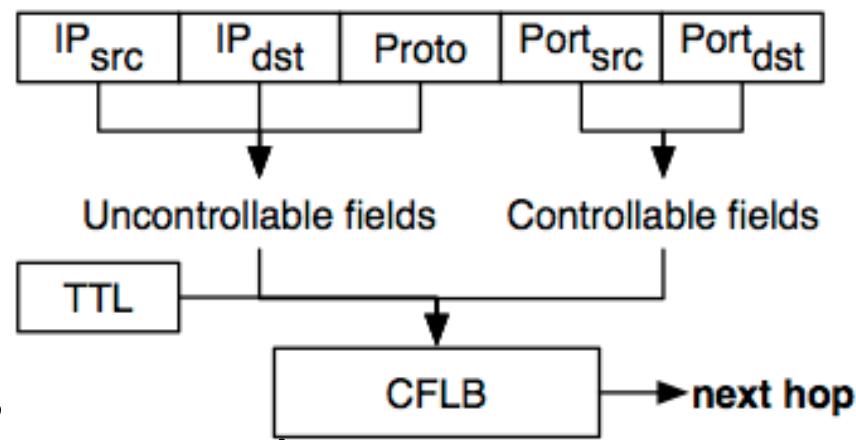


Improving ECMP

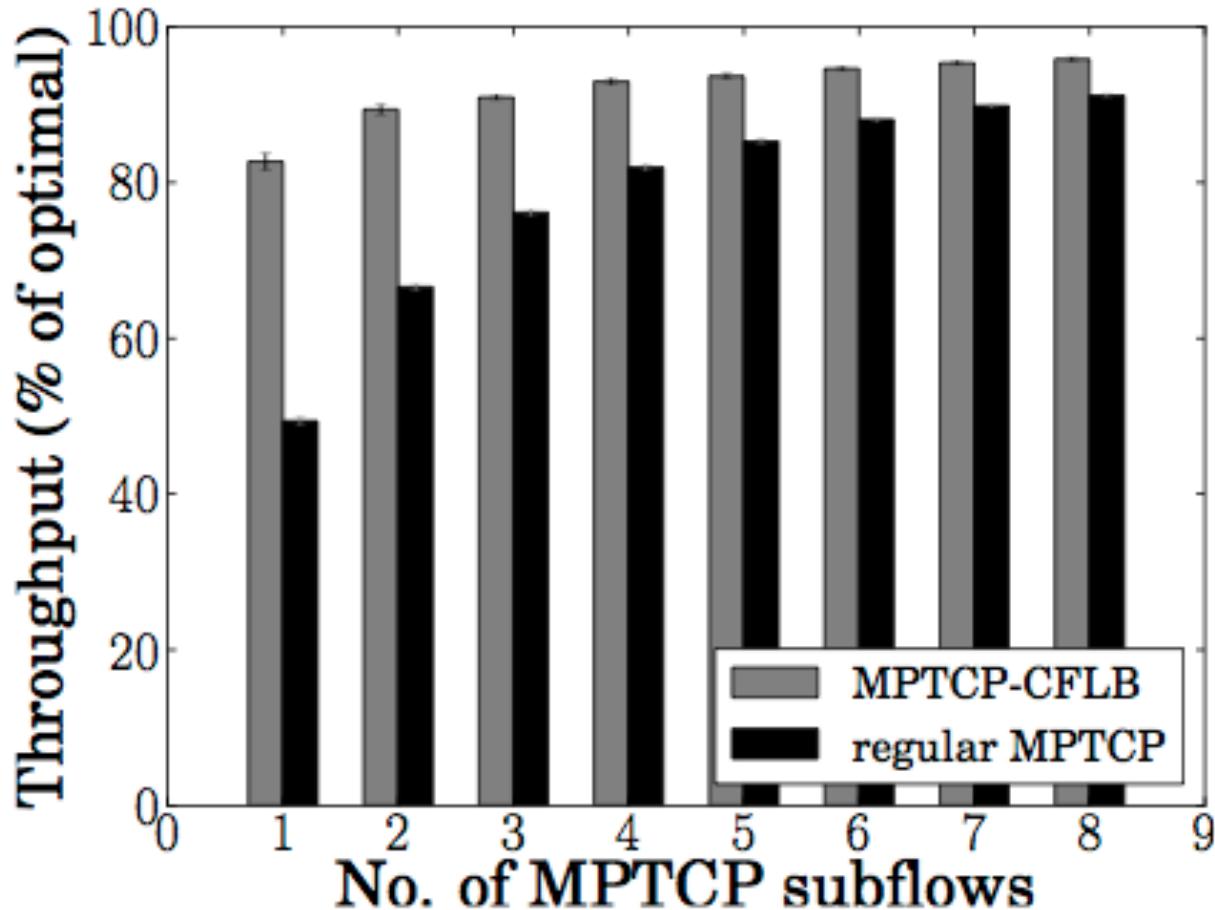
- ECMP's hash
 - good load balancing
 - impossible to predict result



- CFLB
 - replaces hash with block cipher
 - hosts can select paths for Multipath TCP subflows provided they know datacenter topology



Multipath TCP with CFLB in Fat-Tree



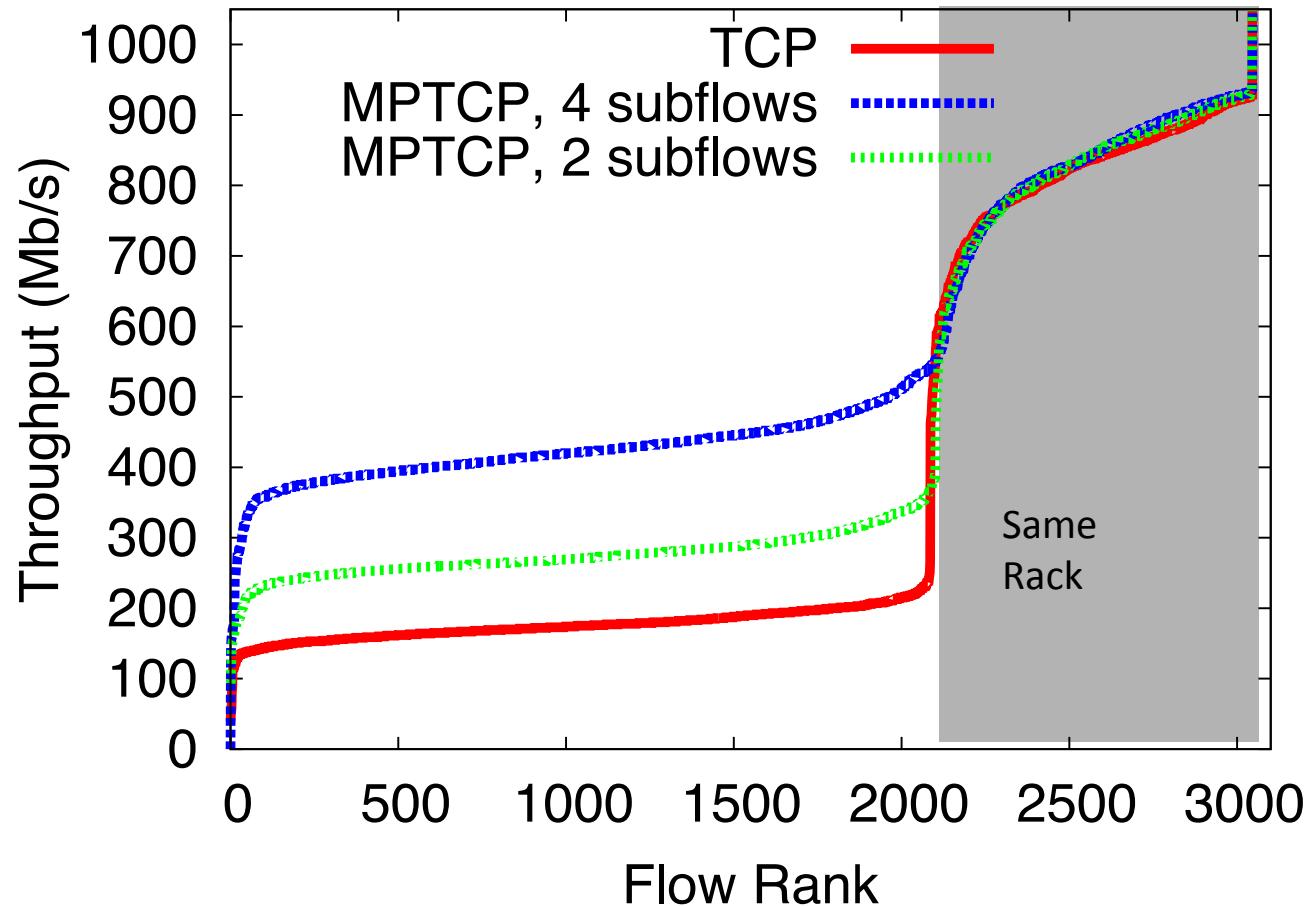
Multipath TCP on EC2

- Amazon EC2: infrastructure as a service
 - We can borrow virtual machines by the hour
 - These run in Amazon data centers worldwide
 - We can boot our own kernel
- A few availability zones have multipath topologies
 - 2-8 paths available between hosts not on the same machine or in the same rack
 - Available via ECMP

Amazon EC2 Experiment

- 40 medium CPU instances running MPTCP
- During 12 hours, we sequentially ran all-to-all iperf cycling through:
 - TCP
 - MPTCP (2 and 4 subflows)

MPTCP improves performance on EC2



C. Raiciu, et al. "Improving datacenter performance and robustness with multipath TCP," ACM SIGCOMM 2011.

Agenda

- The motivations for Multipath TCP
- The changing Internet
- The Multipath TCP Protocol
- Multipath TCP use cases
 - Datacenters
 - Smartphones

Motivation

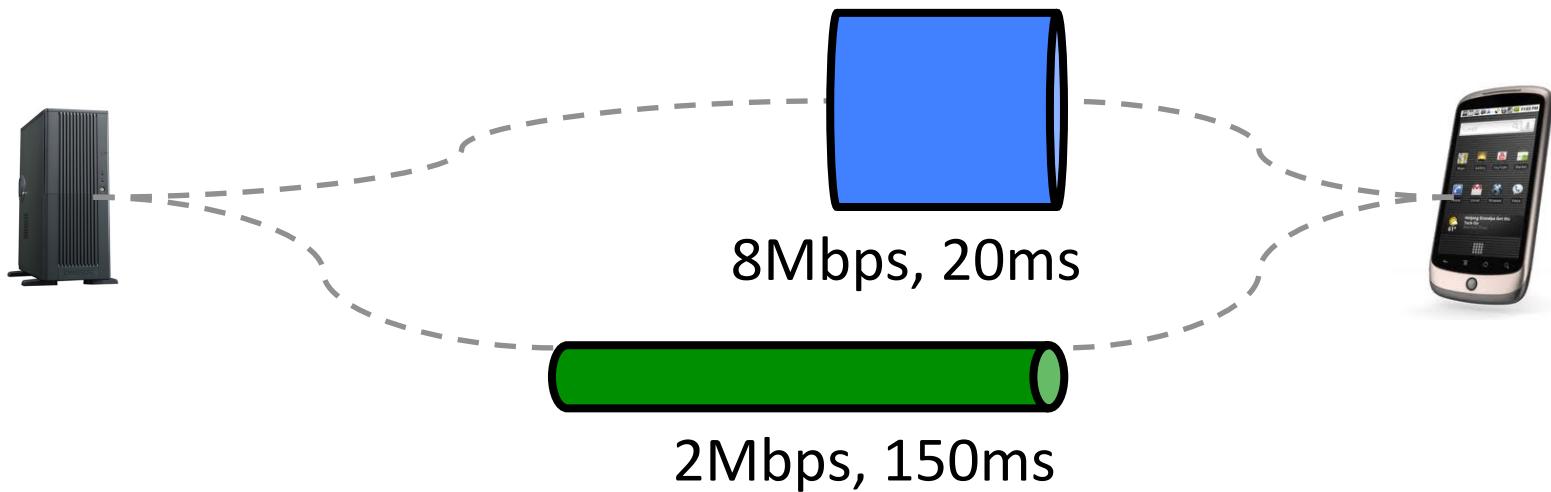
- One device, many IP-enabled interfaces



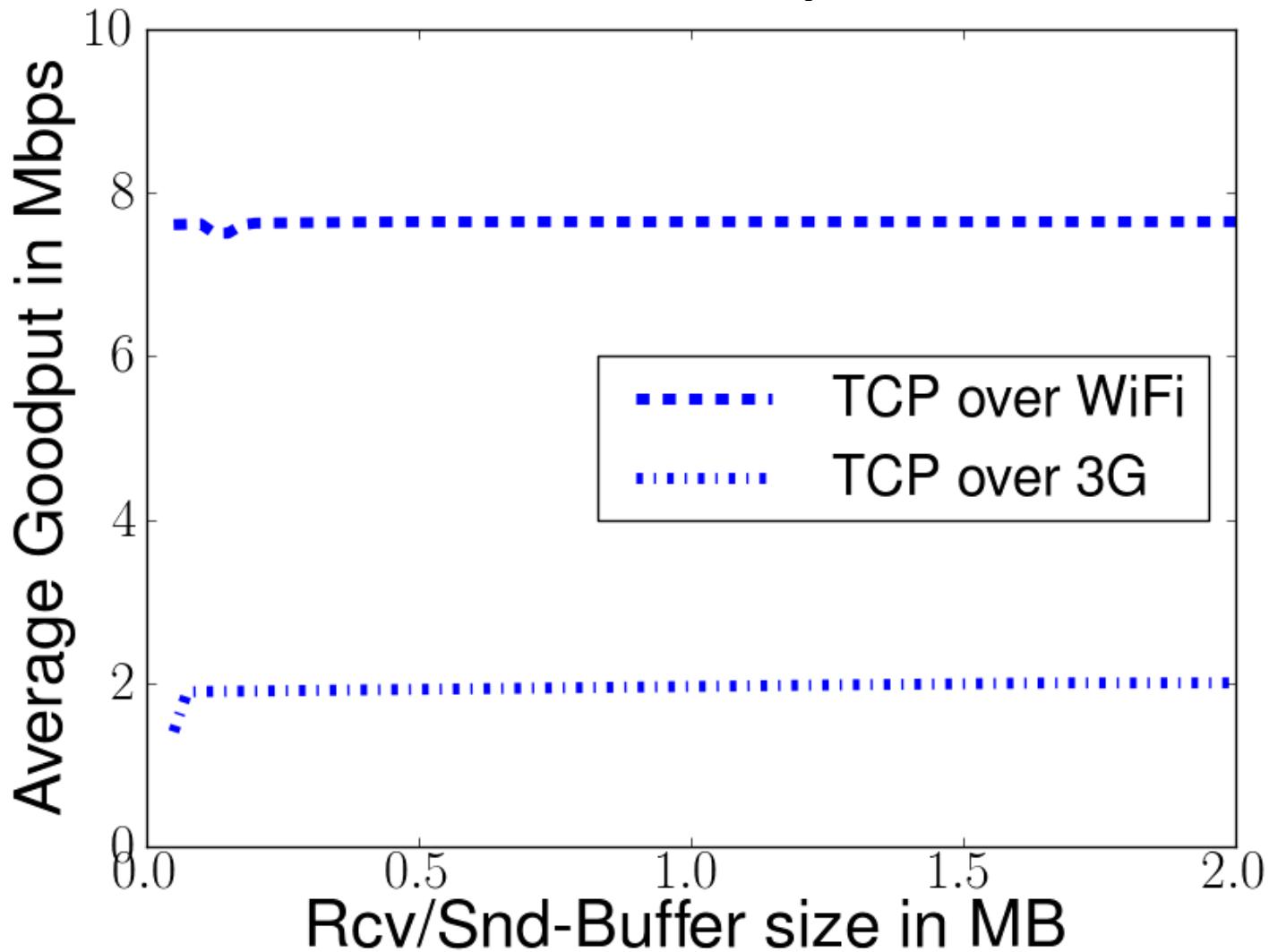
Bluetooth®



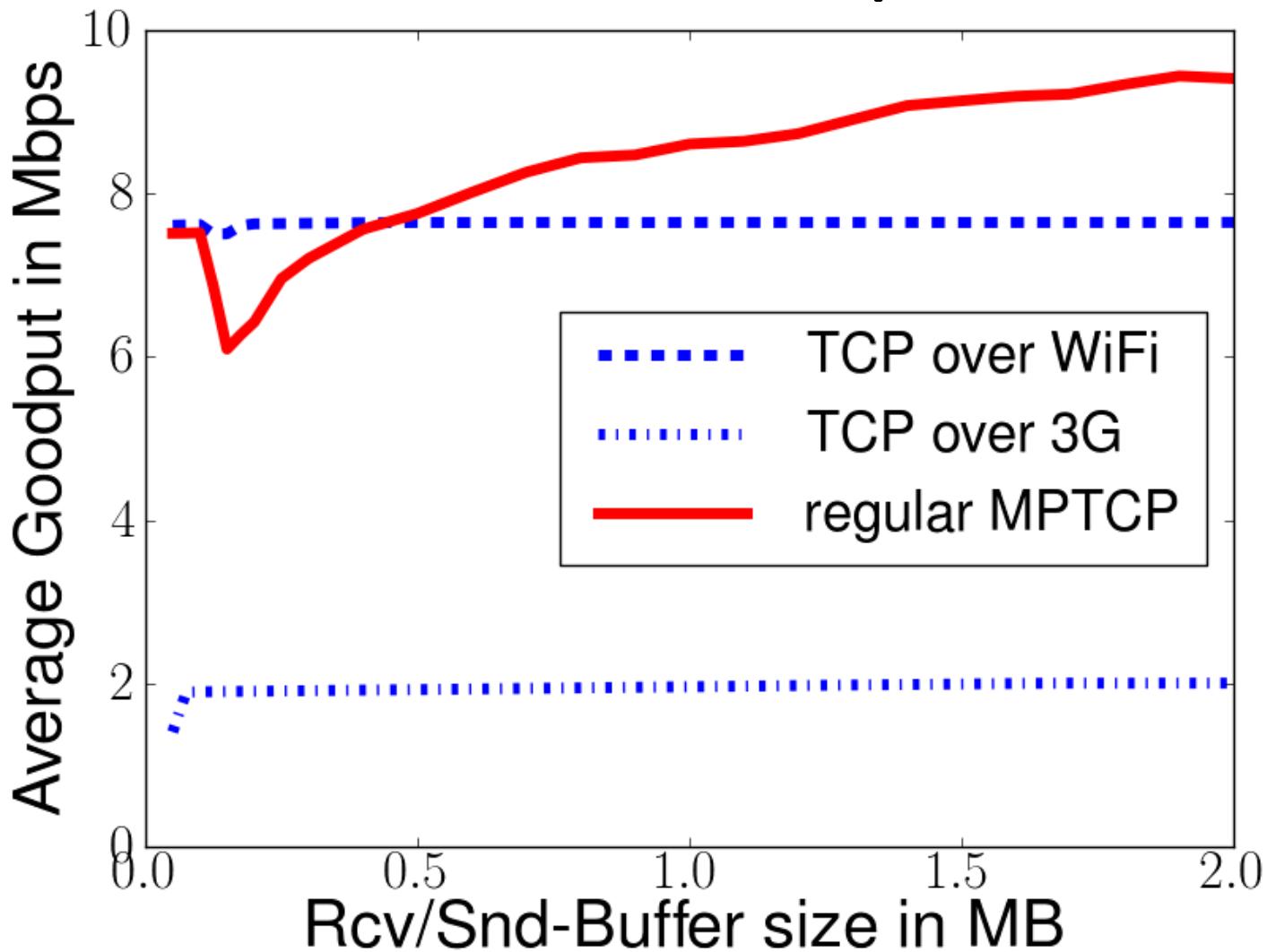
MPTCP over WiFi/3G



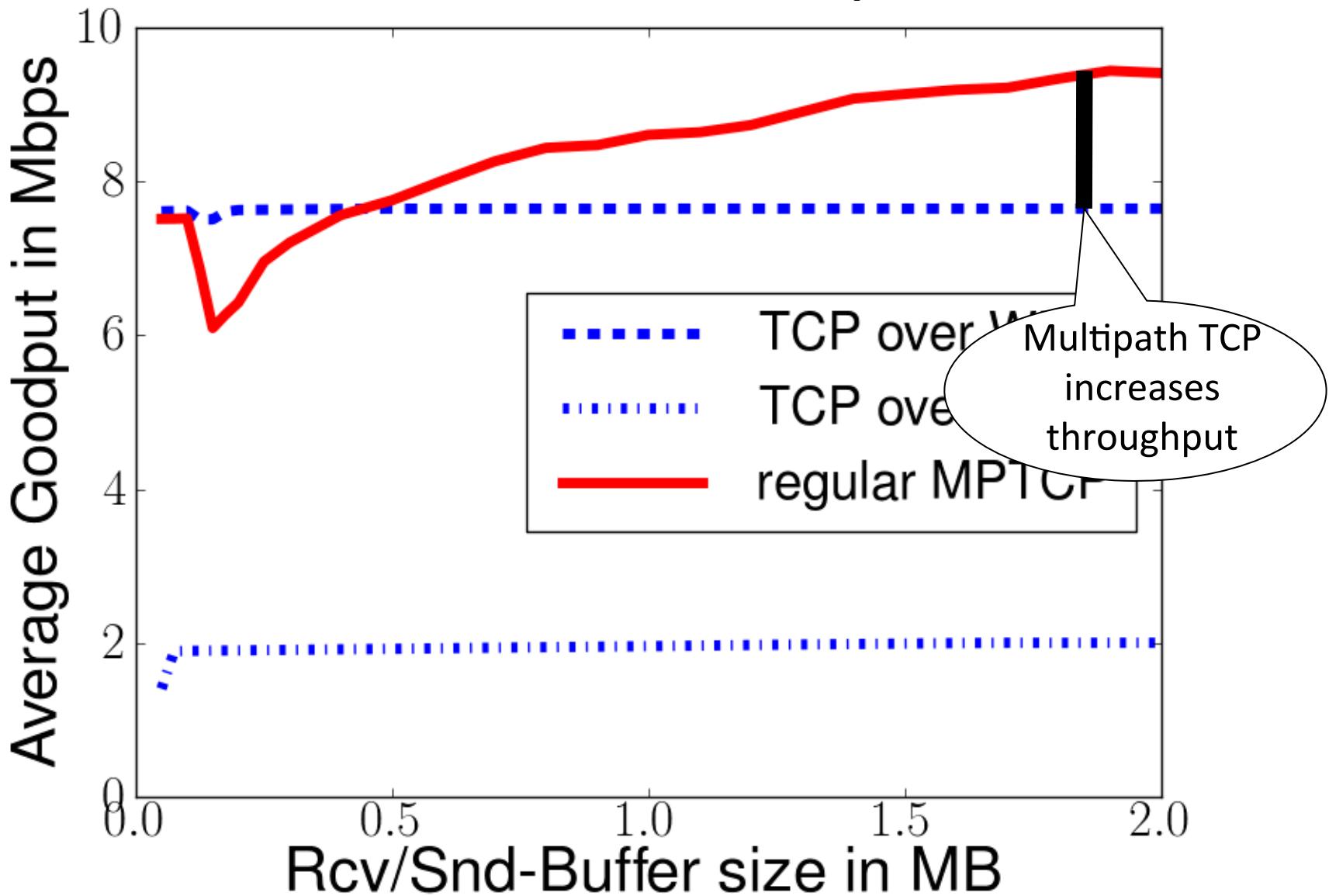
TCP over WiFi/3G



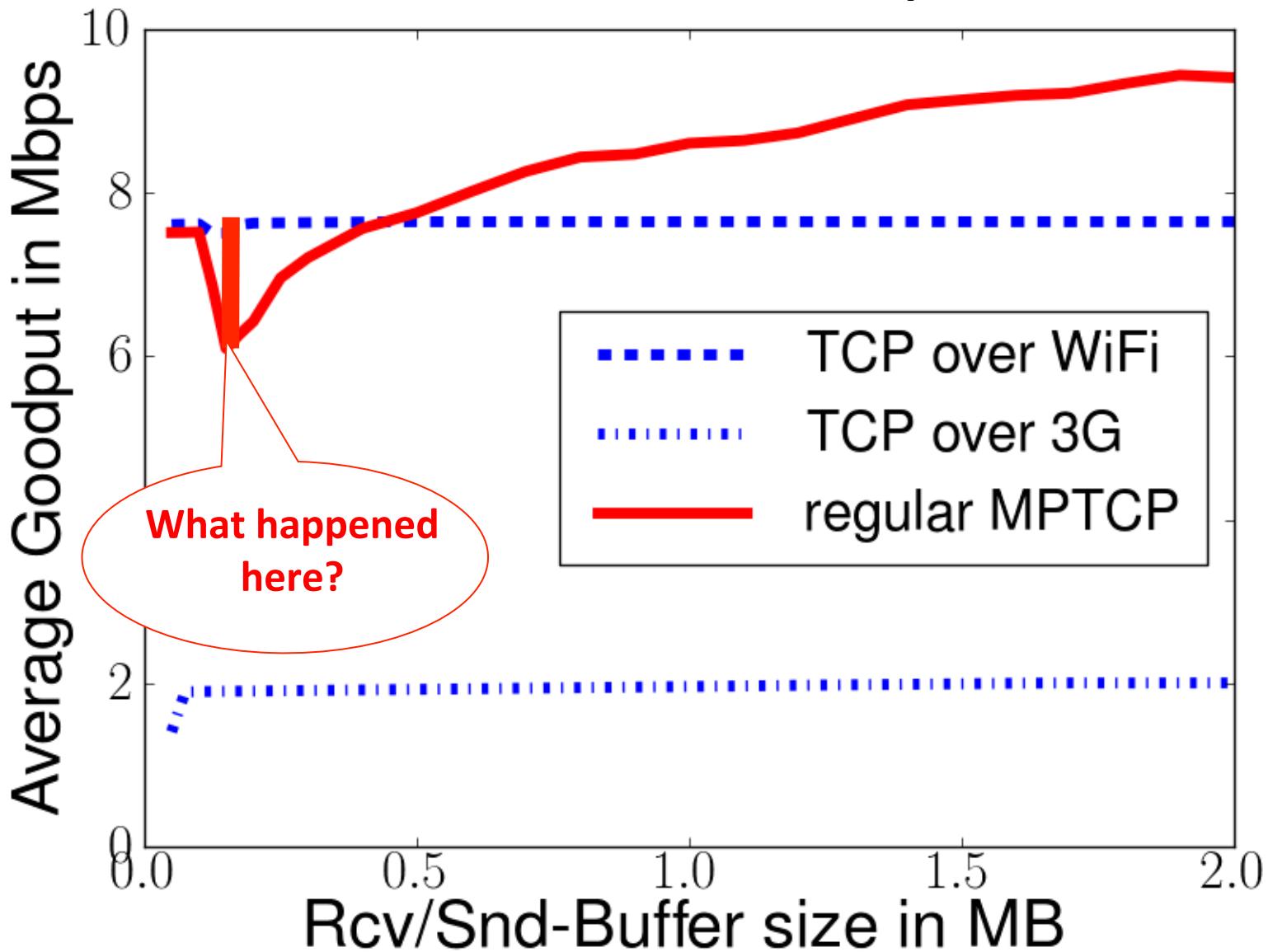
MPTCP over WiFi/3G



MPTCP over WiFi/3G



MPTCP over WiFi/3G

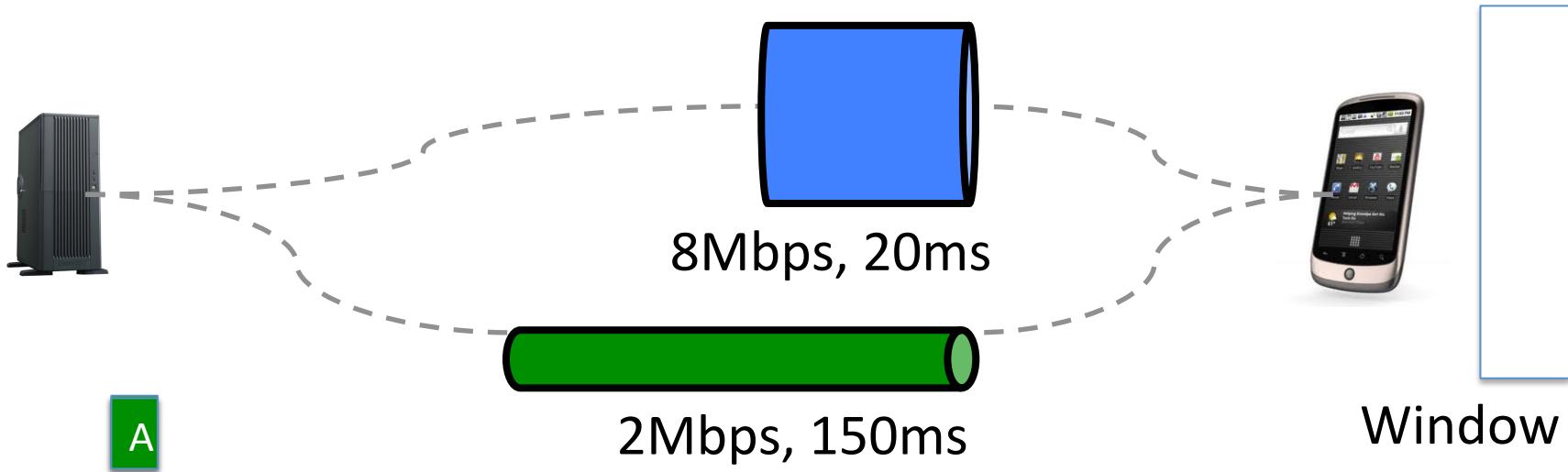


Understanding the performance issue

D C B

Window full !

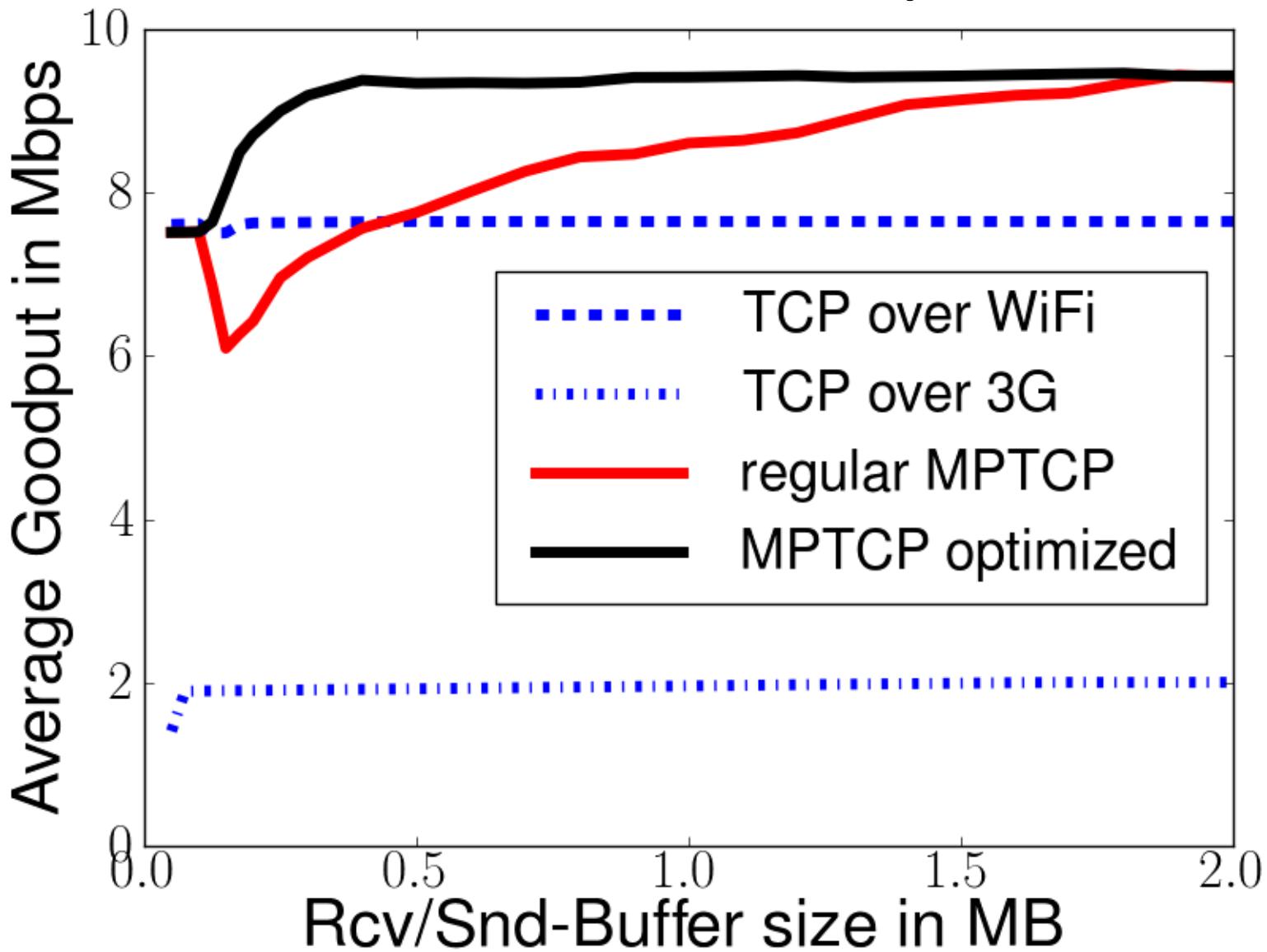
No new data can be sent on WiFi path



Reinject segment on fast path

Halve congestion window on slow subflow

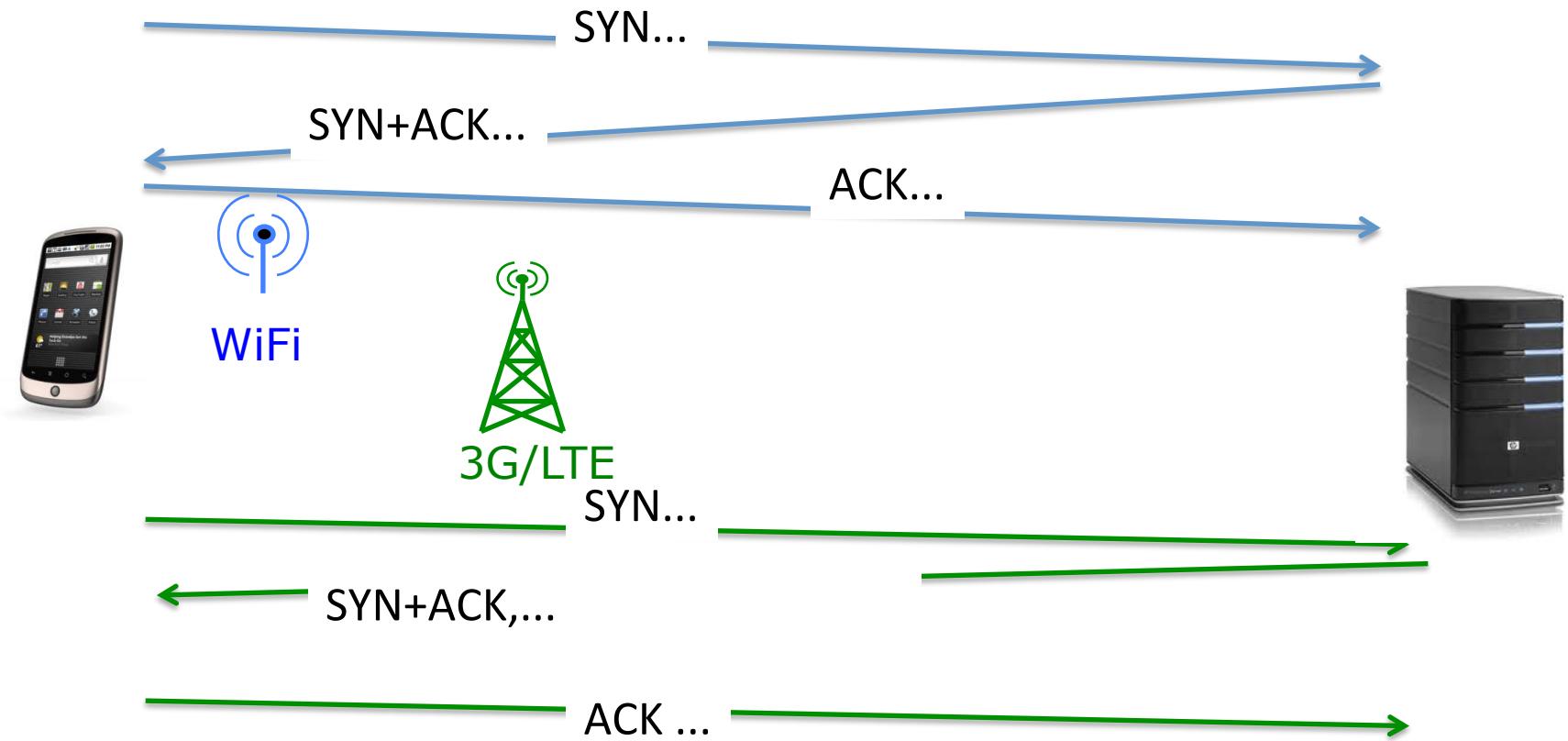
MPTCP over WiFi/3G



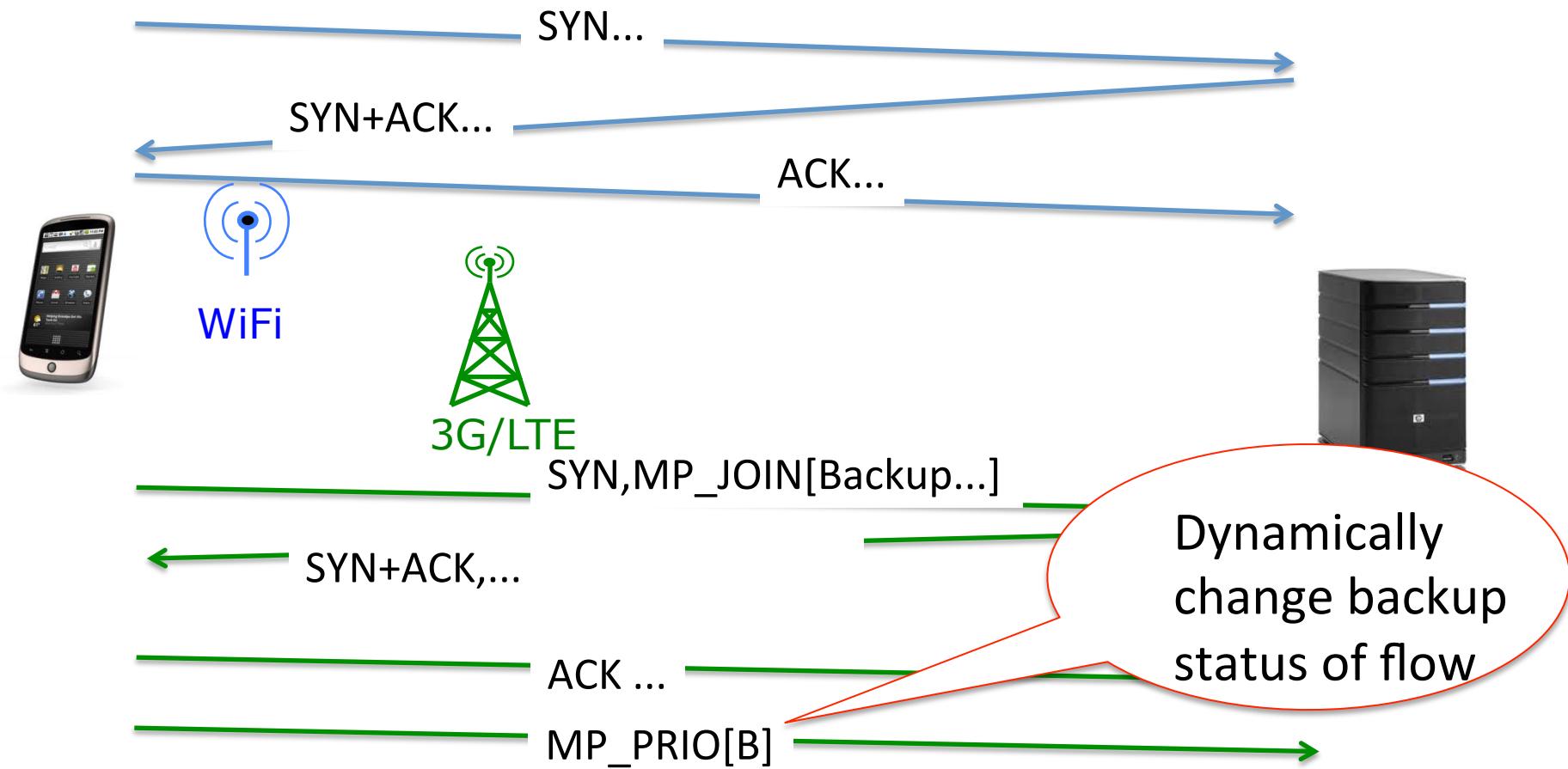
Usage of 3G and WiFi

- How should Multipath TCP use 3G and WiFi ?
 - Full mode
 - Both wireless networks are used at the same time
 - Backup mode
 - Prefer WiFi when available, open subflows on 3G and use them as backup
 - Single path mode
 - Only one path is used at a time, WiFi preferred over 3G

Multipath TCP : Full mode

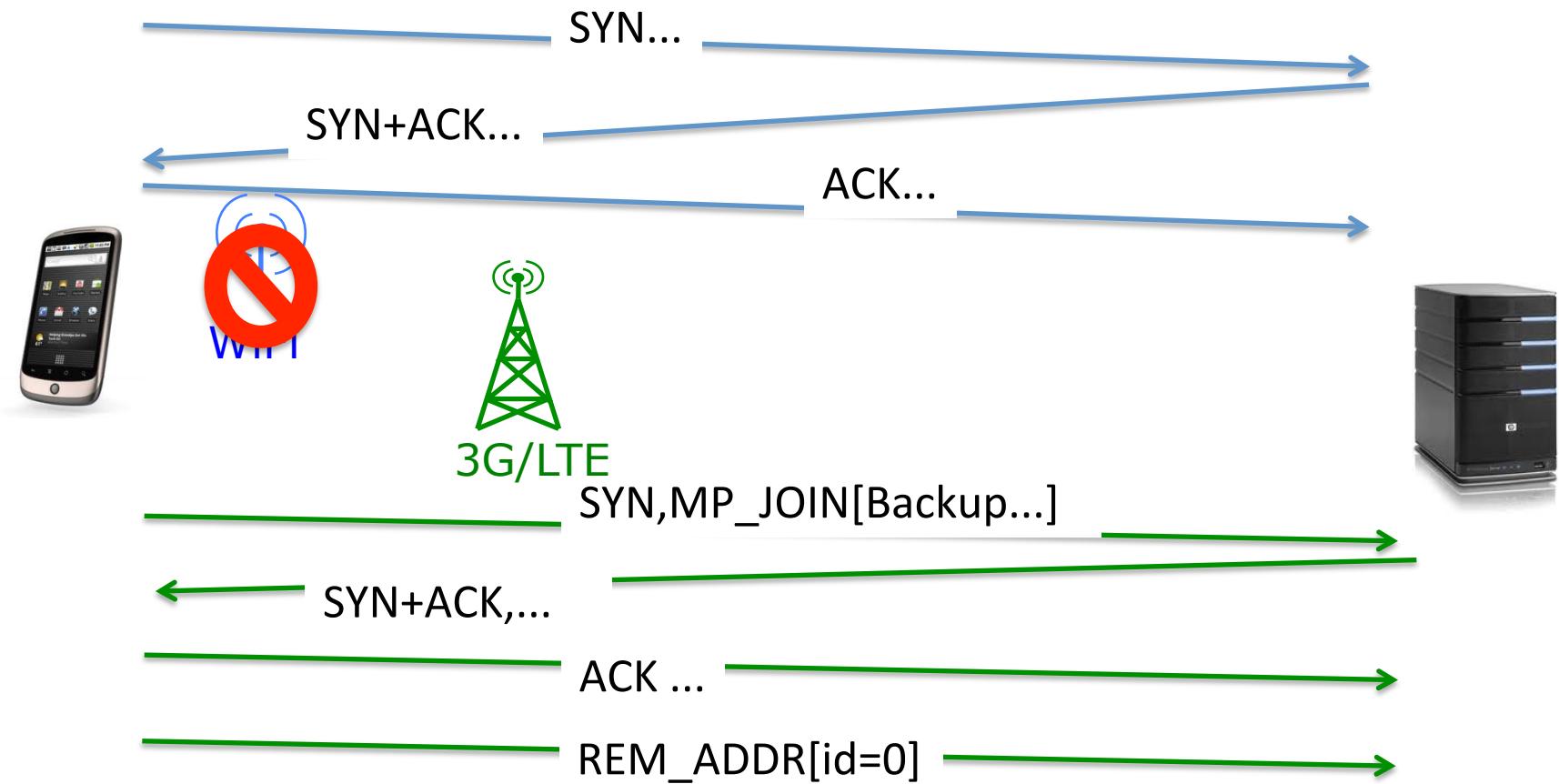


Multipath TCP : Backup mode



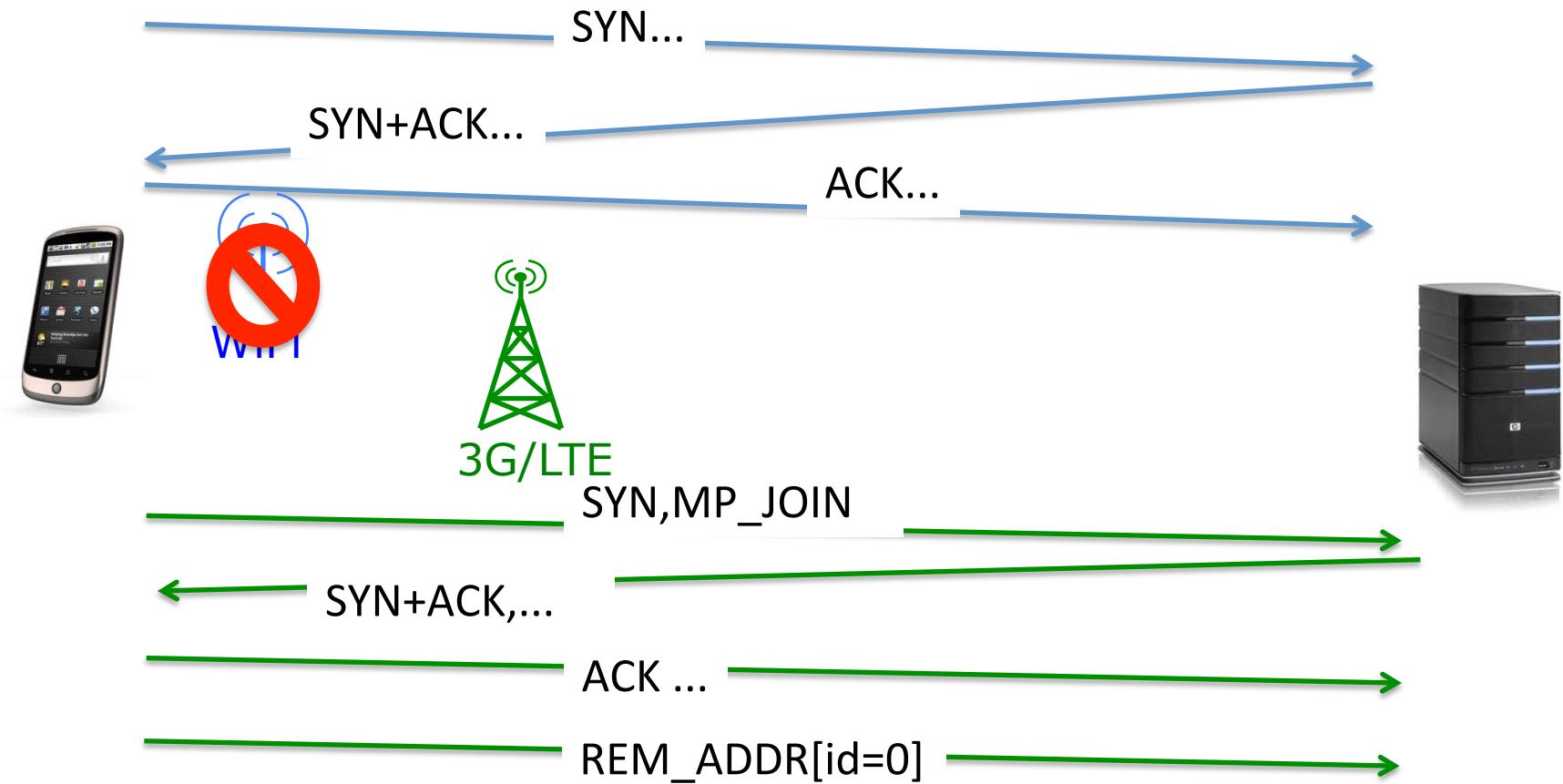
Multipath TCP : Backup mode

- What happens when link fails ?

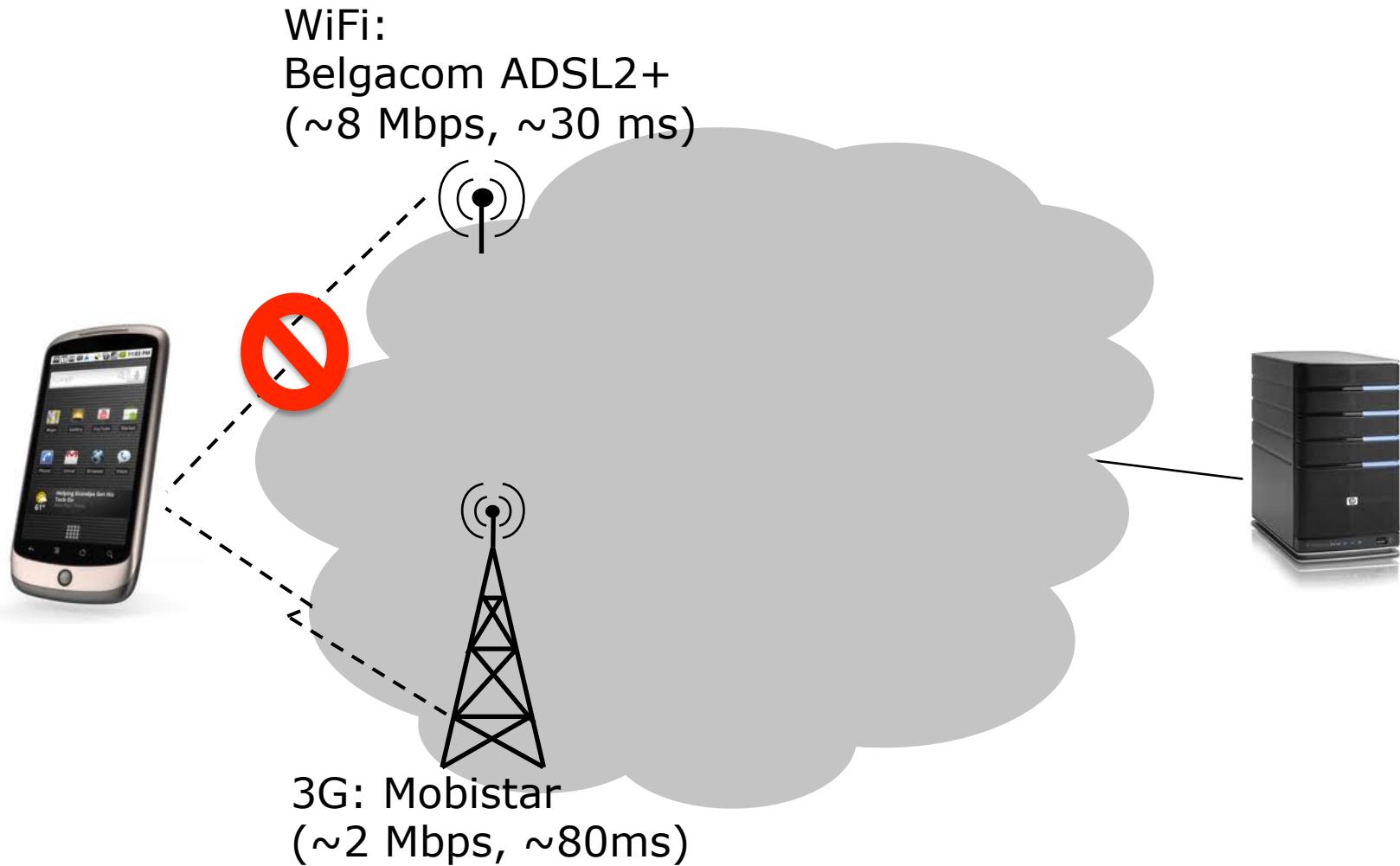


Multipath TCP : single-path mode

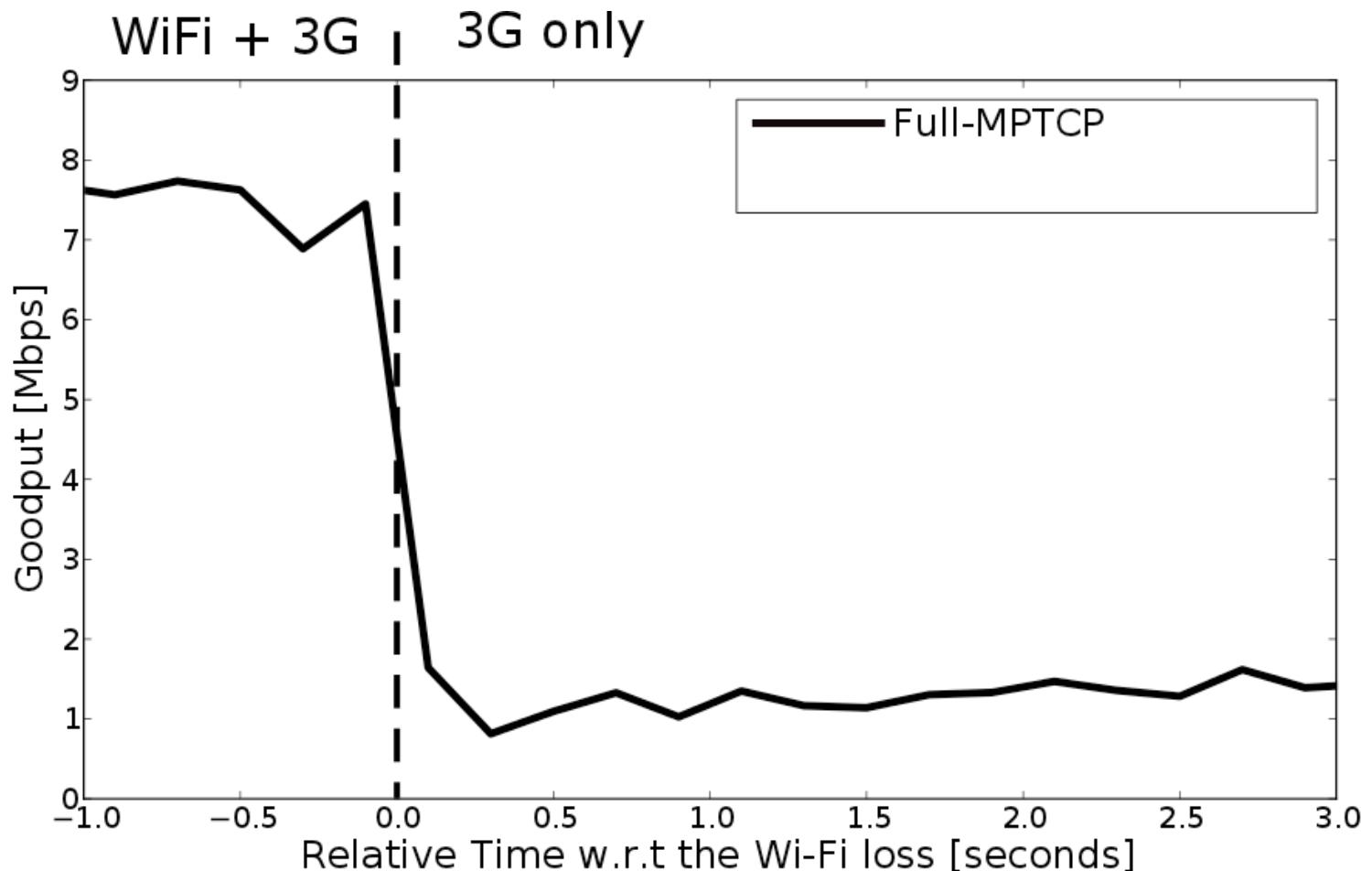
- Multipath TCP supports break before make



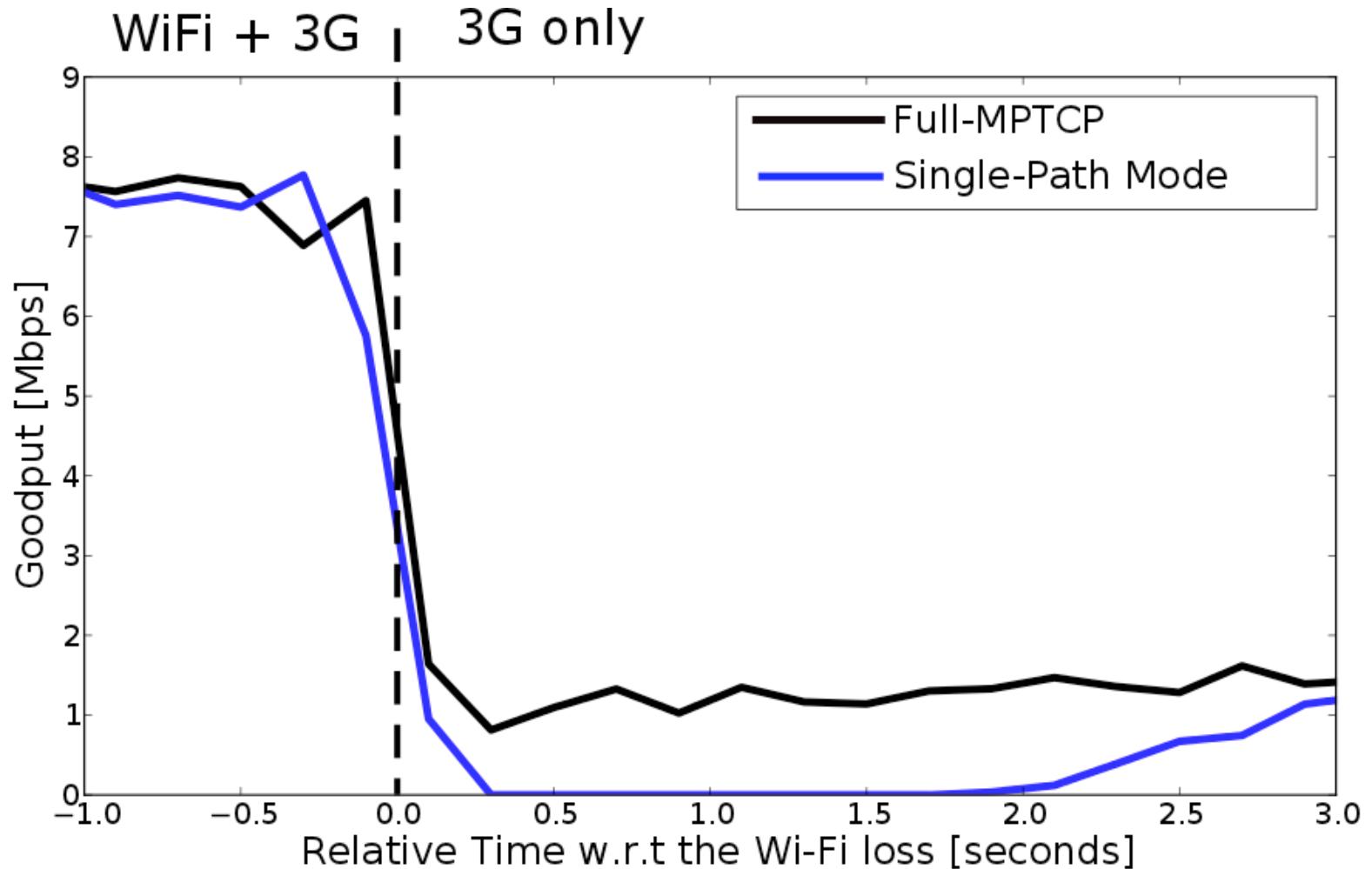
Evaluation scenario



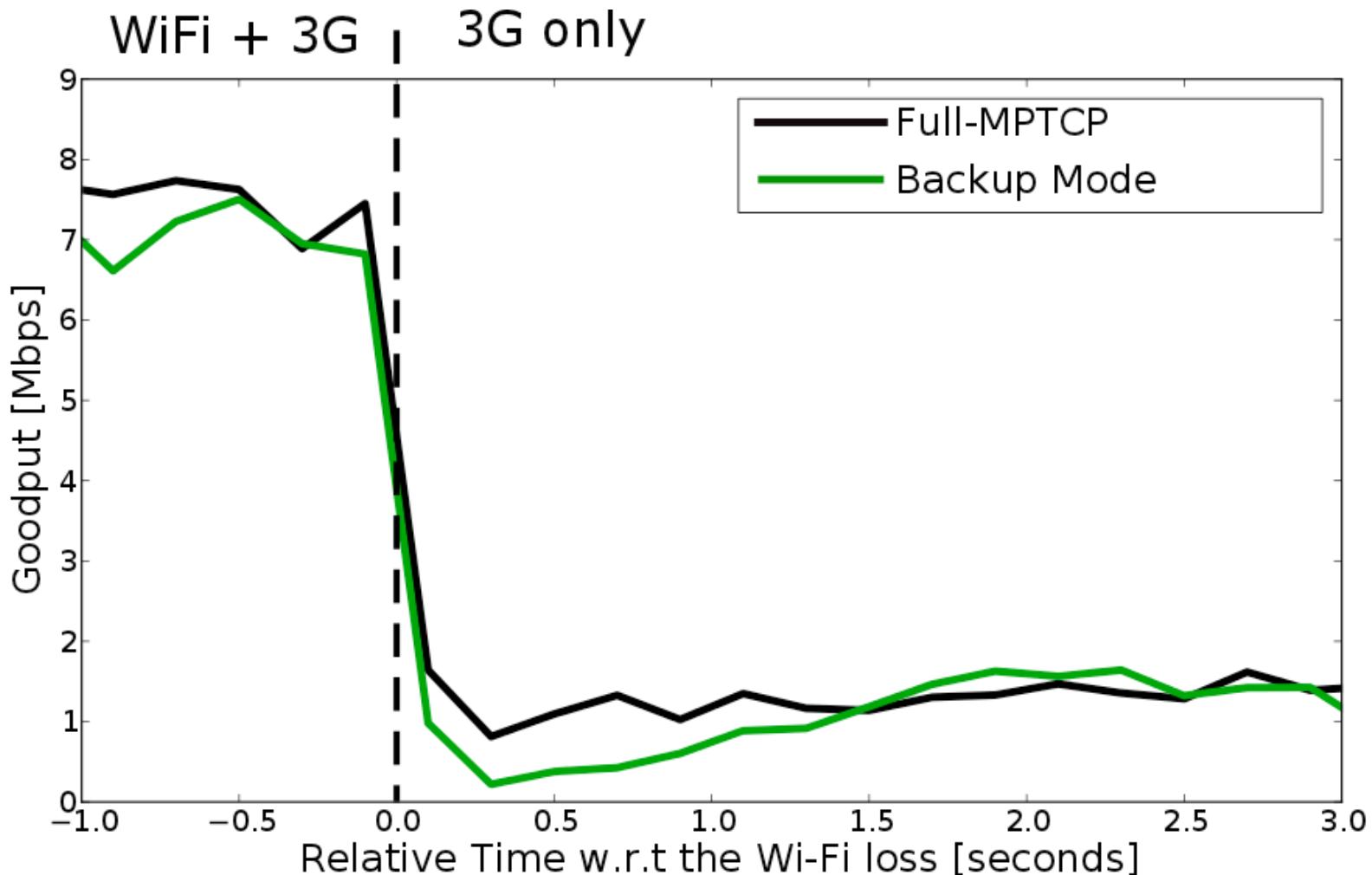
Recovery after failure



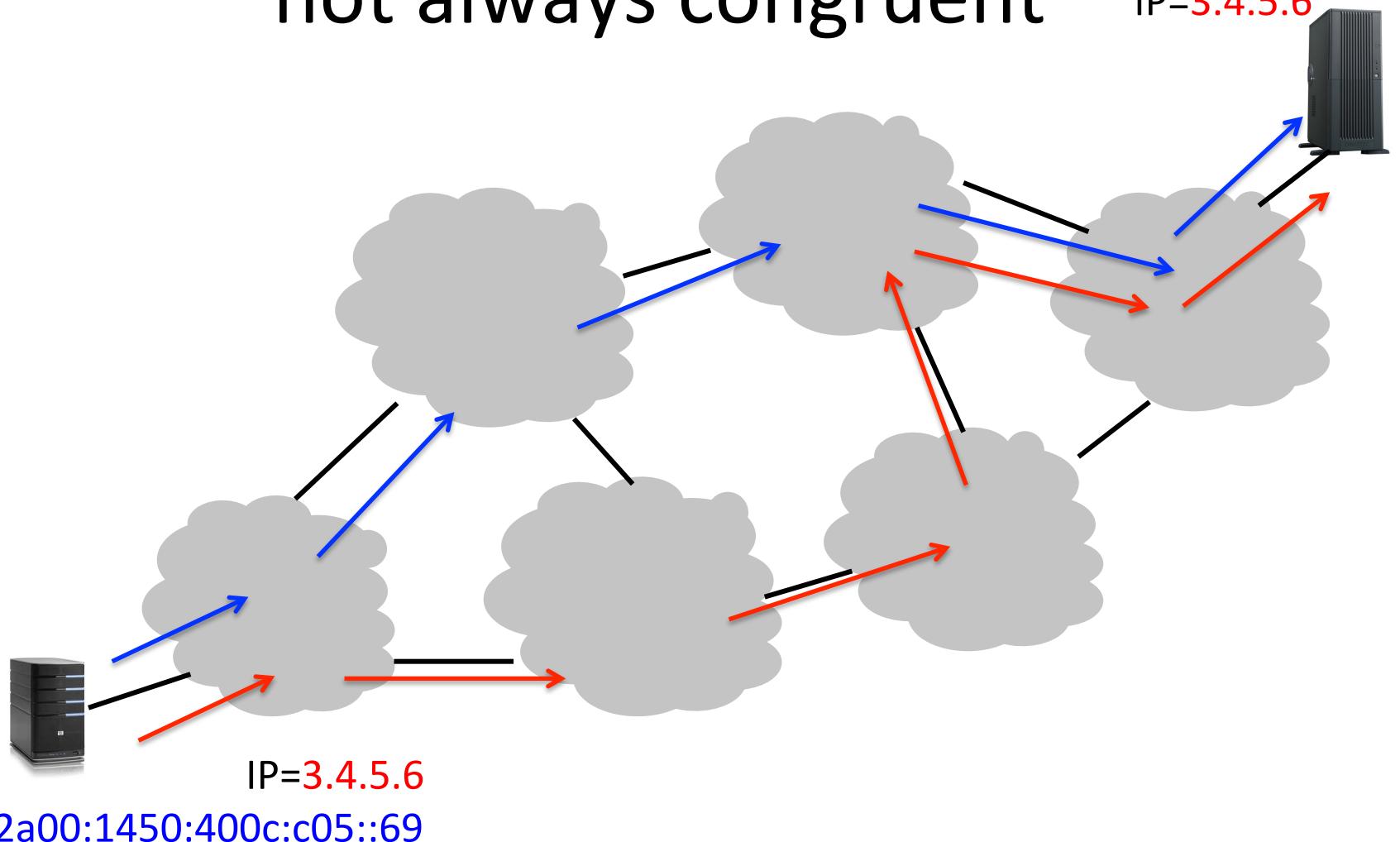
Recovery after failure



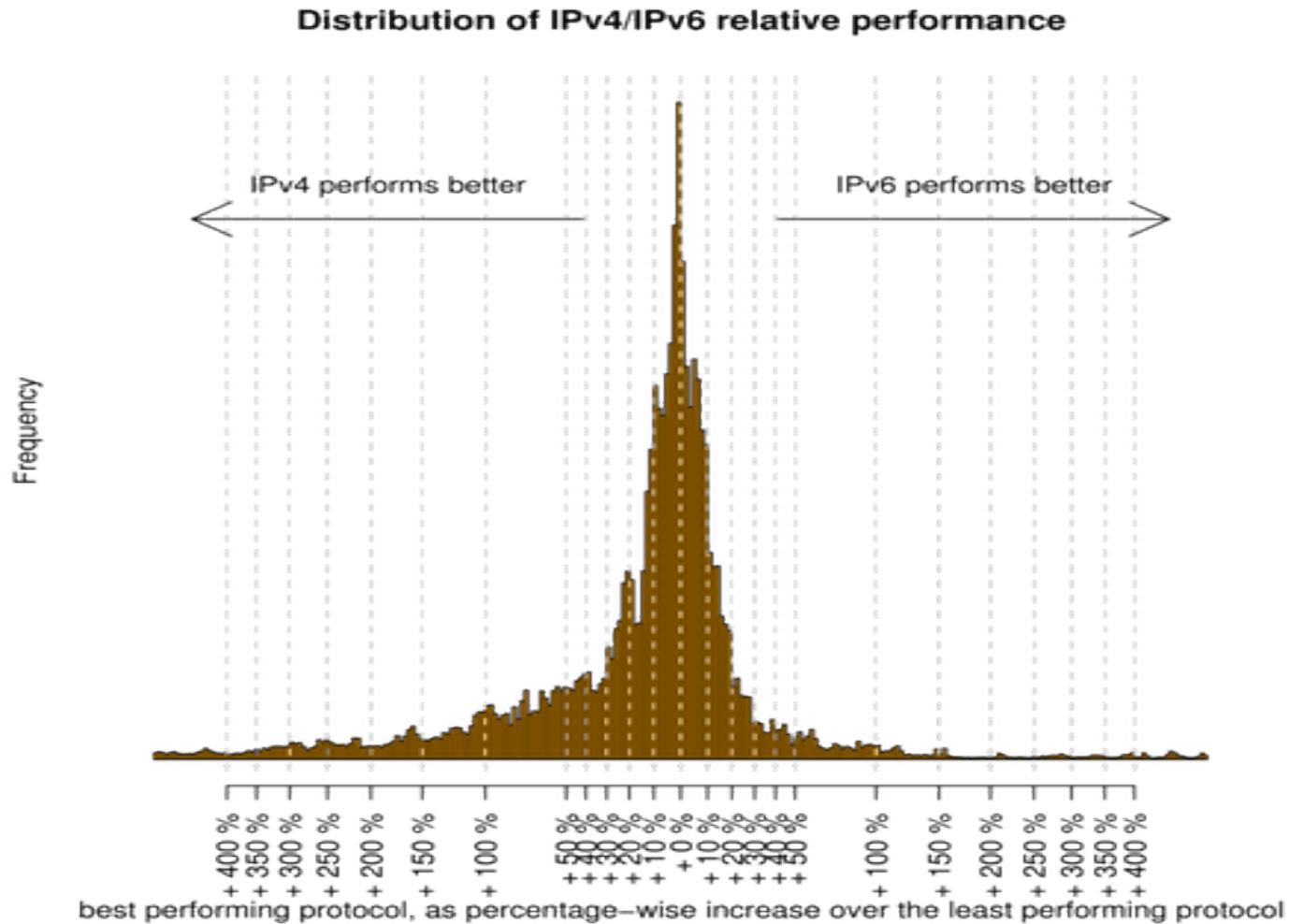
Recovery after failure



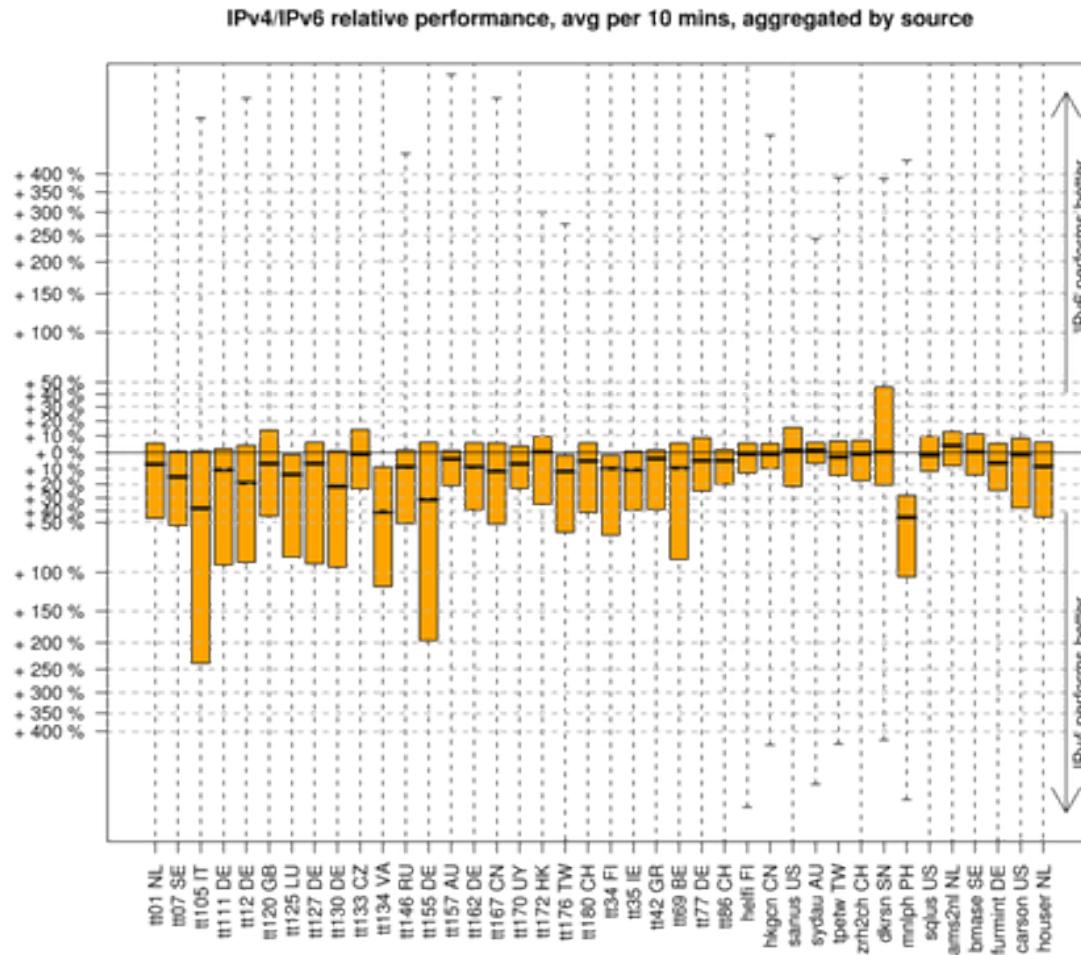
IPv4 and IPv6 paths are not always congruent



IPv4 and IPv6 performance may differ



IPv4 versus IPv6 performance



Conclusion

- Multipath TCP is becoming a reality
 - Due to the middleboxes, the protocol is more complex than initially expected
 - RFC has been published
 - there is running code !
 - Multipath TCP works over today's Internet !
- What's next ?
 - More use cases
 - IPv4/IPv6, anycast, load balancing, deployment
 - Measurements and improvements to the protocol
 - Time to revisit 20+ years of heuristics added to TCP



References

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 - <http://tools.ietf.org/wg/mptcp/>

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Implementations

- Linux
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 - S. Barre, C. Paasch, and O. Bonaventure, “Multipath tcp: From theory to practice,” *NETWORKING 2011*, 2011.
 - Sébastien Barré. Implementation and assessment of Modern Host-based Multipath Solutions. PhD thesis. UCL, 2011
- FreeBSD
 - <http://caia.swin.edu.au/urp/newtcp/mptcp/>
- Simulators
 - <http://nrg.cs.ucl.ac.uk/mptcp/implementation.html>
 - <http://code.google.com/p/mptcp-ns3/>

Middleboxes

M. Honda, Y. Nishida, C. Raiciu, A. Greenhalgh, M. Handley, and H. Tokuda, “Is it still possible to extend TCP?,” IMC ’11: Proceedings of the 2011 ACM SIGCOMM conference on Internet measurement conference, 2011.

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Multipath congestion control

– Background

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P. Key, L. Massoulie, and P. D. Towsley, “Path Selection and Multipath Congestion Control,” *INFOCOM 2007*. 2007, pp. 143–151.

– Coupled congestion control

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D. Wischik, C. Raiciu, A. Greenhalgh, and M. Handley, “Design, implementation and evaluation of congestion control for multipath TCP,” *NSDI'11: Proceedings of the 8th USENIX conference on Networked systems design and implementation*, 2011.

Multipath congestion control

– More

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Y. Cao, X. Mingwei, and X. Fu, “Delay-based Congestion Control for Multipath TCP,” ICNP2012, 2012.

T. A. Le, C. S. Hong, and E.-N. Huh, “Coordinated TCP Westwood congestion control for multiple paths over wireless networks,” ICOIN '12: Proceedings of the The International Conference on Information Network 2012, 2012, pp. 92–96.

T. A. Le, H. Rim, and C. S. Hong, “A Multipath Cubic TCP Congestion Control with Multipath Fast Recovery over High Bandwidth-Delay Product Networks,” *IEICE Transactions*, 2012.

T. Dreibholz, M. Becke, J. Pulinthanath, and E. P. Rathgeb, “Applying TCP-Friendly Congestion Control to Concurrent Multipath Transfer,” Advanced Information Networking and Applications (AINA), 2010 24th IEEE International Conference on, 2010, pp. 312–319.

Use cases

– Datacenter

C. Raiciu, S. Barre, C. Pluntke, A. Greenhalgh, D. Wischik, and M. J. Handley, “Improving datacenter performance and robustness with multipath TCP,” *ACM SIGCOMM* 2011.

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– Mobile

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