Challenges in building overlay networks: a case study of Tor

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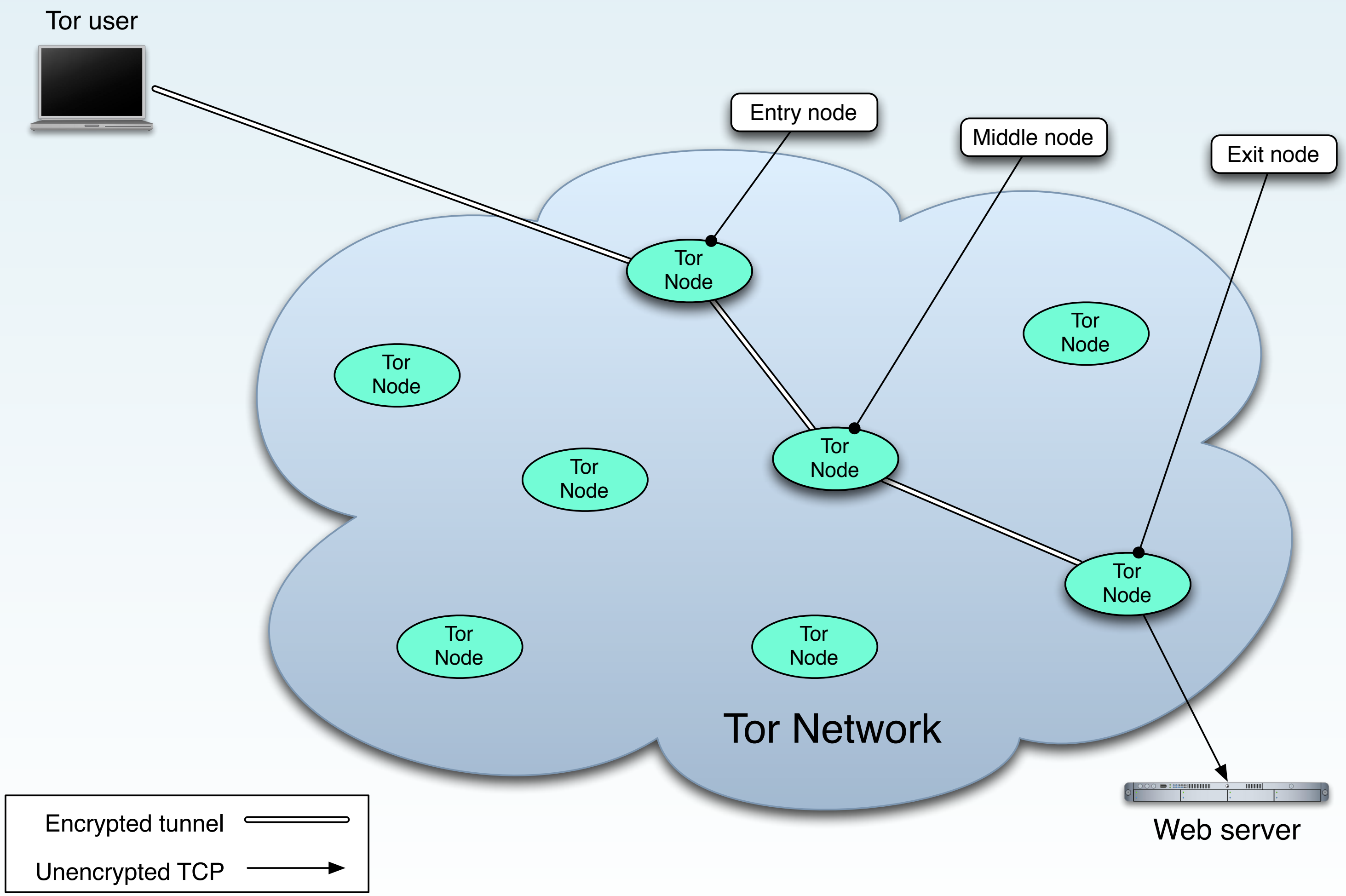
Who uses Tor?

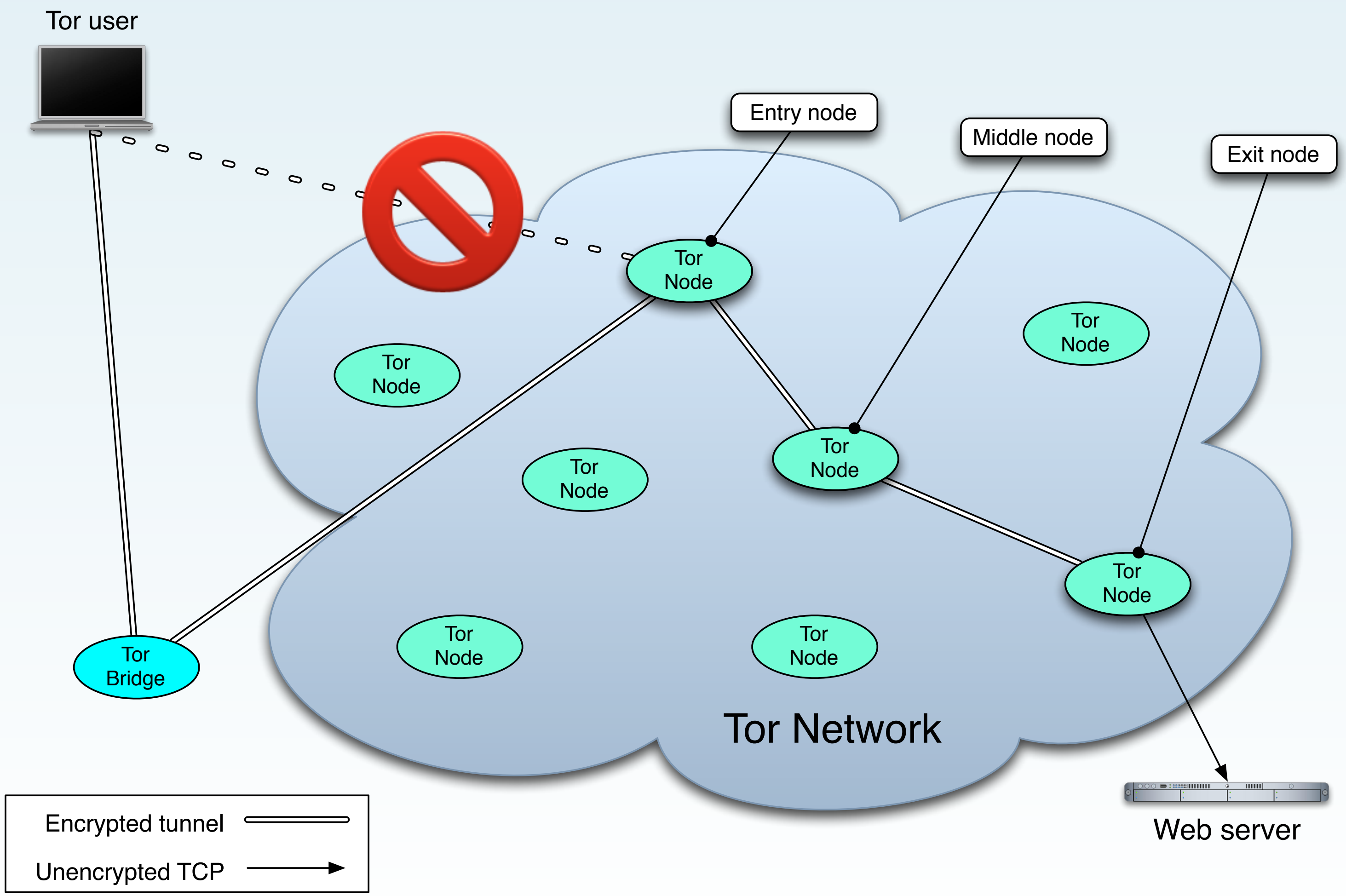
- Ordinary people
  - e.g. to avoid unscrupulous marketers, protect children, research sensitive topics
- Militaries and law enforcement
  - e.g. to protect field agents and sources, intelligence gathering, decentralise services
- Journalists and their audience
  - e.g. preserve safety of journalists working in hostile regimes, resist Internet censorship
- …

BBC Horizon

Network Topology

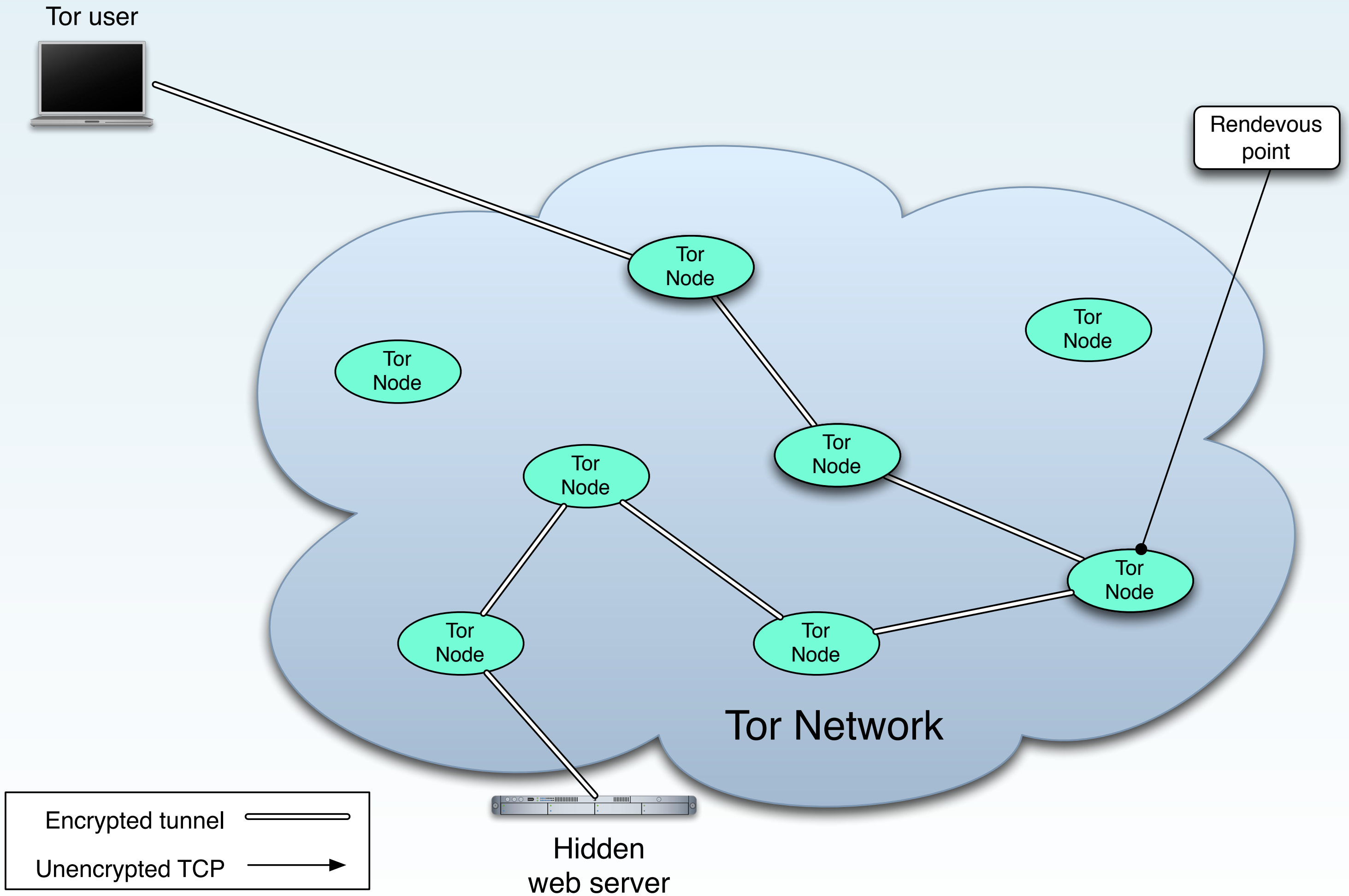


Network Topology (censored network)

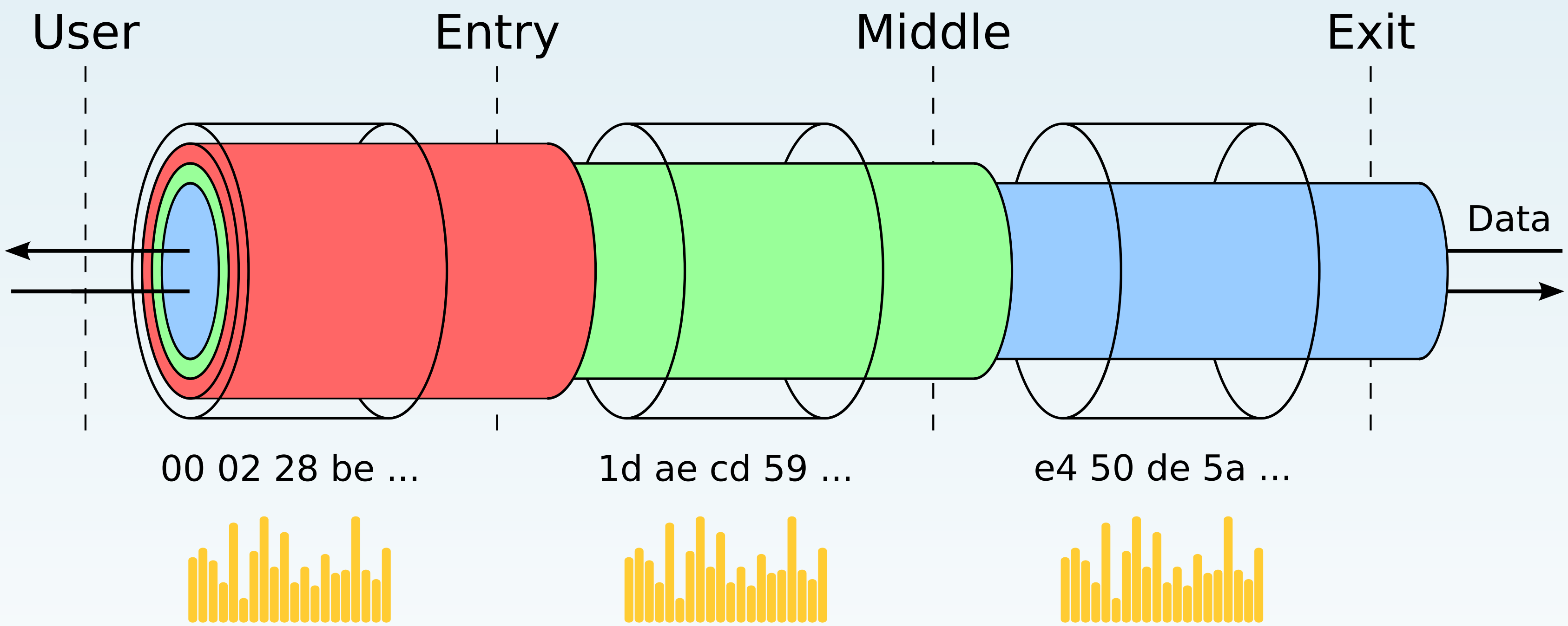


Network Topology (hidden services)

e.g. https://facebookcorewwwi.onion/



Encryption

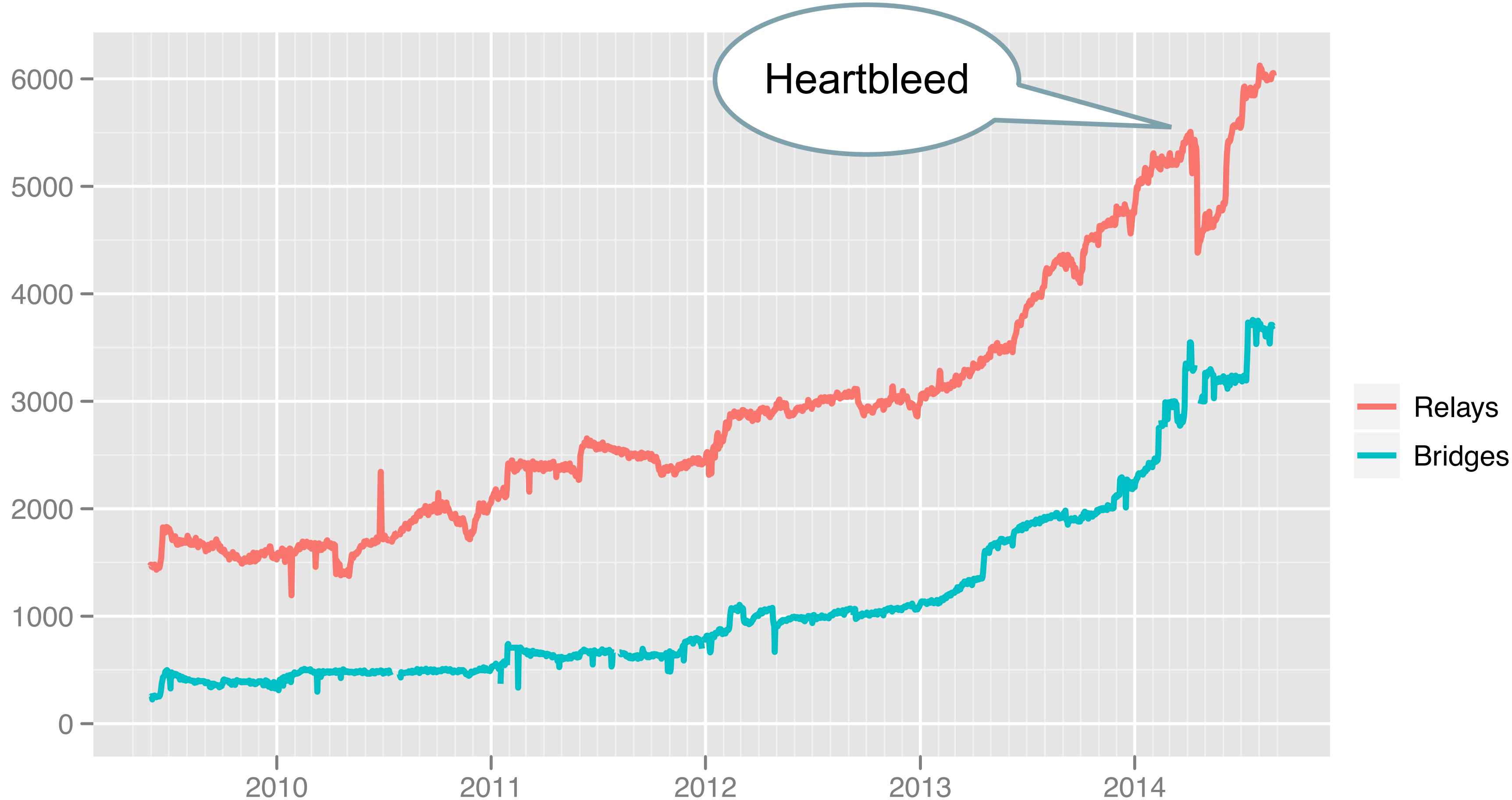


Layered encryption prevents linking of input and output flows based on traffic content

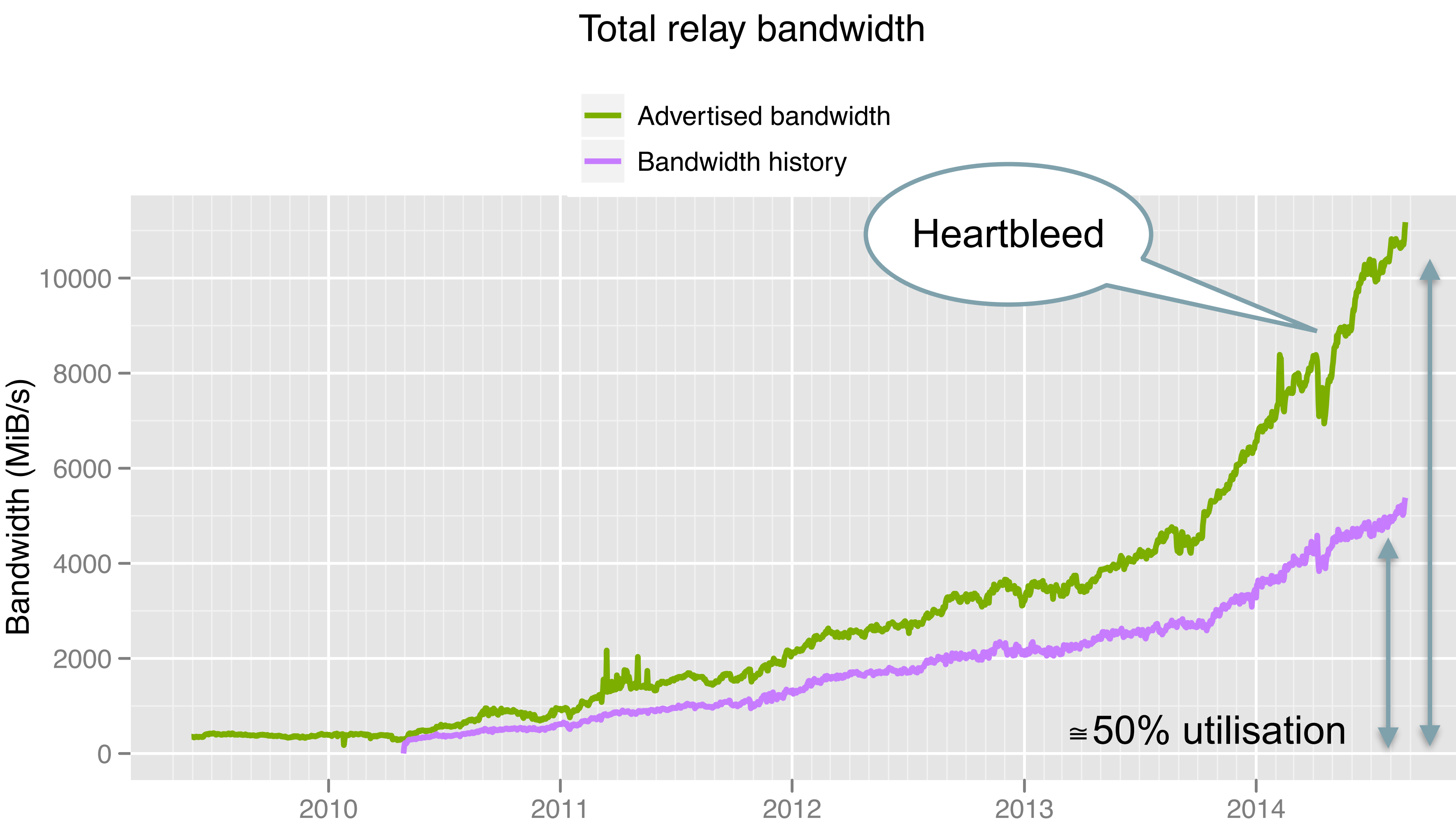
Distribution of network information

- Tor nodes publish their information (descriptors) to the directory authorities
- Directory authorities negotiate a consensus listing all available Tor nodes, and sign under keys of all participating directory authorities
- Directory mirrors (most Tor nodes) connect to directory authorities to retrieve consensus
- Tor clients connect to mirrors to receive up-to-date consensus, or bootstrap by connecting to directory authority directly
- Tor clients verify digital signatures on consensus

Number of relays



The Tor Project – https://metrics.torproject.org/



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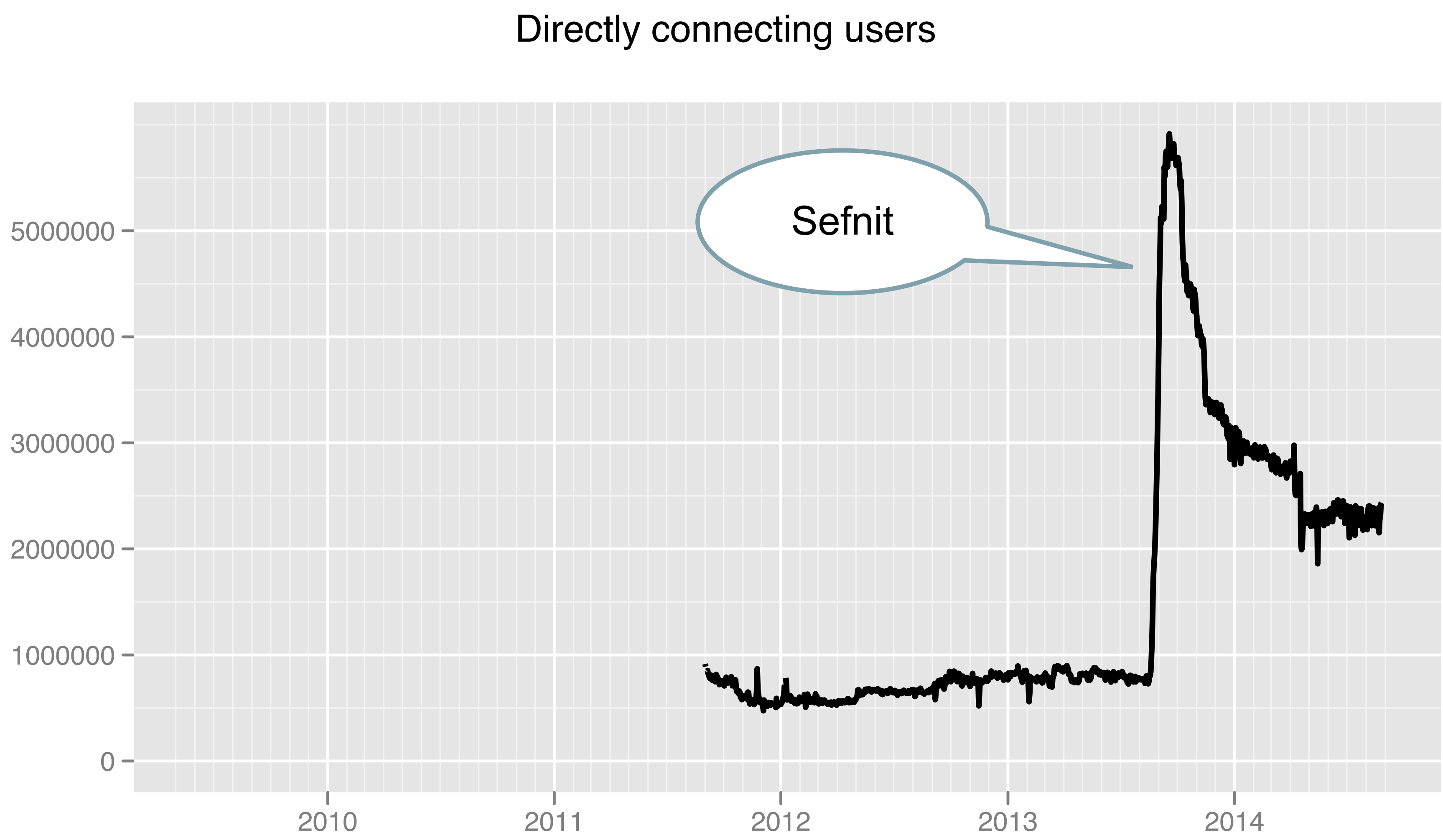

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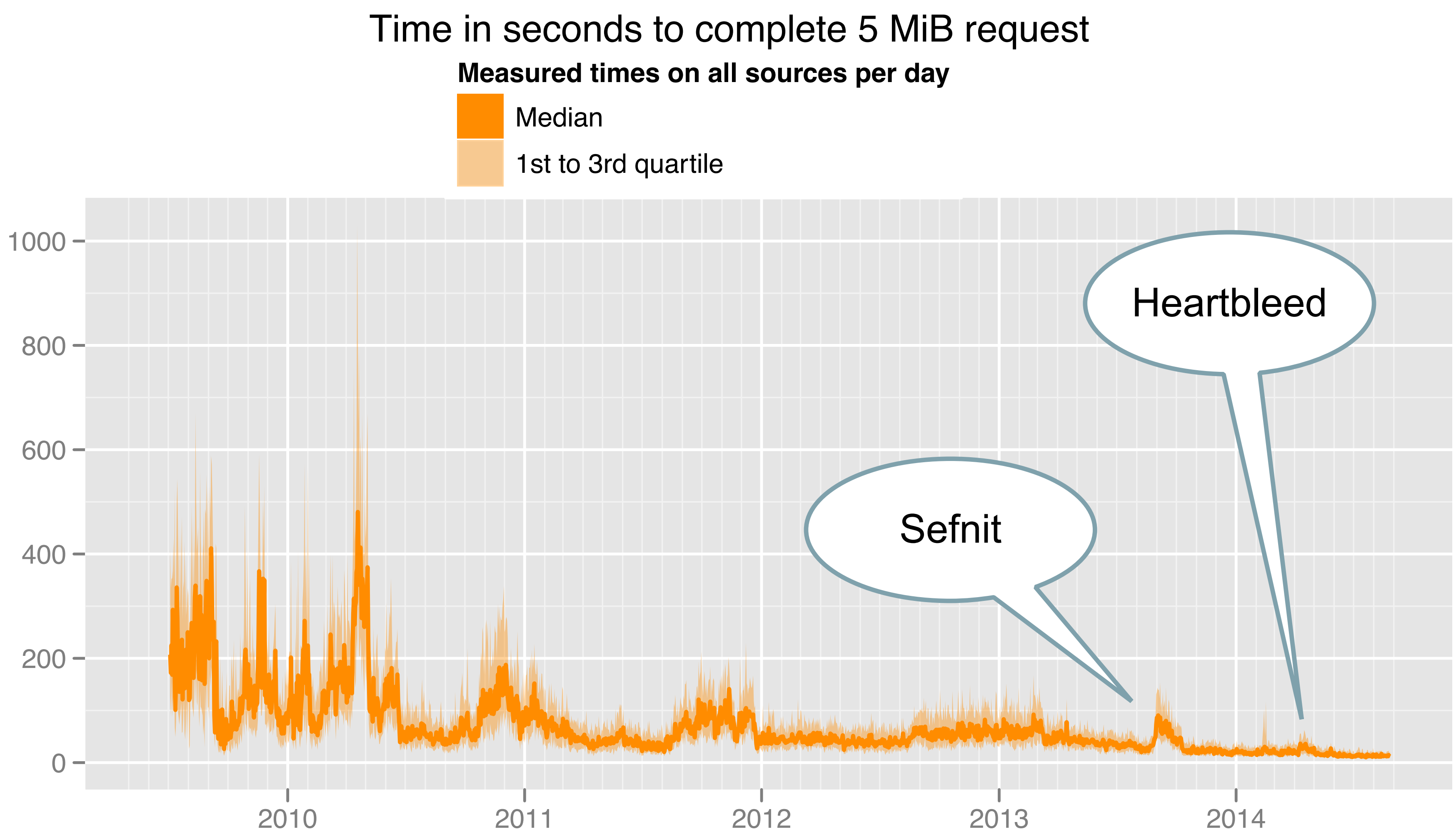

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Challenge 1: Source routing

- Clients choose complete path based on information in consensus
- Cryptography enforces that network traffic must follow the path chosen
- If first and last Tor node selected is compromised then user can be de-anonymised
- If attacker has compromised proportion of Tor network bandwidth **p**, then proportion of paths de-anonymised ≅ $\mathbf{p^2}$ (e.g. 1% of bandwidth de-anonymises 0.01% of paths)

Peer-to-Peer anonymity networks

- Alternative to source-routed is peer-to-peer
- Clients connect to first node in the network, but do not have complete control of the path selected
- Advantage is that load balancing is easier and clients don’t need to know full network
- Disadvantage is route-capture: first malicious node will only route to other malicious nodes
- If attacker has compromised proportion of network bandwidth **p**, then proportion of paths de-anonymised ≅ **p** (e.g. 1% of bandwidth de-anonymises 1% of paths)

Managing consequences of source-routing

- Source routing brings advantages, but has costs
- Clients must know of all nodes
  - Consensus means that only one directory authority is contacted
  - Mini-descriptors reduce size of information downloaded and diff's have been proposed
- Clients are provided enough information to load-balance correctly, through probing nodes and adjusting probability of selection
- Still a problem for network growth

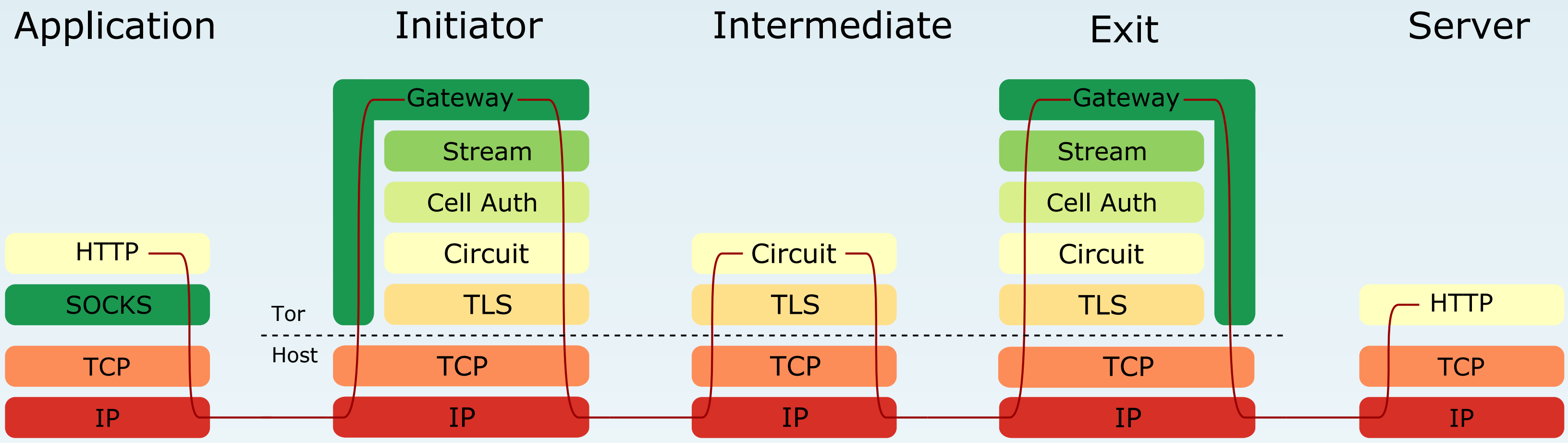
Challenge 2: congestion control

- Tor network is perpetually congested
  - ~50% utilisation on average
  - IP networks normally 3–5%
- Tor nodes cannot drop packets when congested
  - Counter-mode encryption used
- Links between nodes use TCP, so take advantage of TCP congestion control
  - Down-side is head of line blocking
- End-to-end congestion control achieved through Tor implementing sliding windows

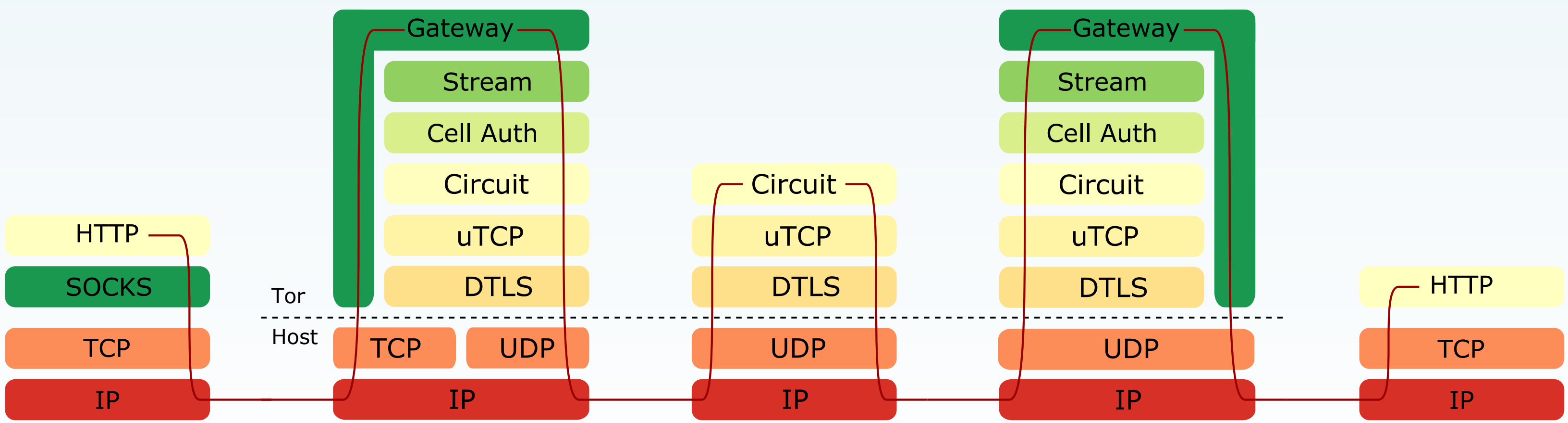
Potential changes in congestion control

- Replace TCP with UDP and bring congestion control explicitly into Tor
    - Also avoids problem of limited number of TCP sockets
    - Use latency-based congestion control (LEDBAT/µTP) to back off before packet loss
    - When multiplexing different circuits on one link, don’t block all circuits when there’s packet loss on only one
    - Also needs new crypto (DTLS?)

Tor over TLS/TCP (current)



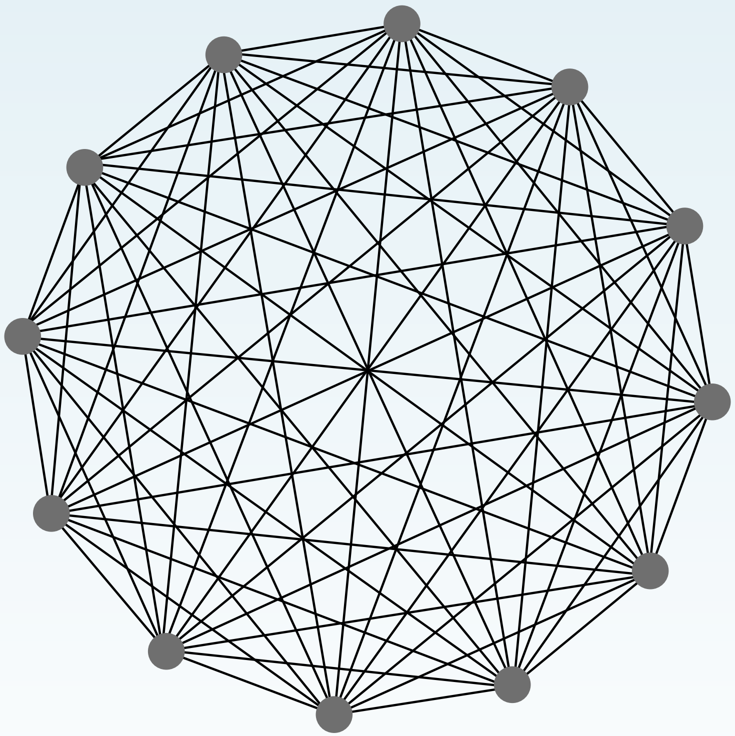
Tor over μTP/DTLS/UDP (potential change)



Challenge 3: Clique topology

- Any Tor node can (almost) be at any position in a path selected by a client
- TCP links are kept up unless idle
- As a result any node must be able to connect to any other node, and many nodes will stay connected to almost **every** other node
- Problems include
  - Tor nodes in censored countries are not useful
  - IPv6 only nodes cannot be used
  - Not optimal for mixing traffic of different users

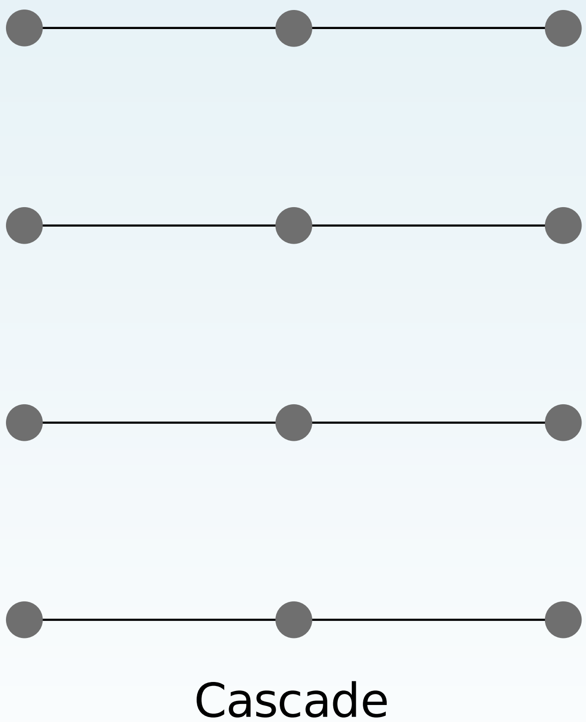
Alternative topologies: clique



Free Route

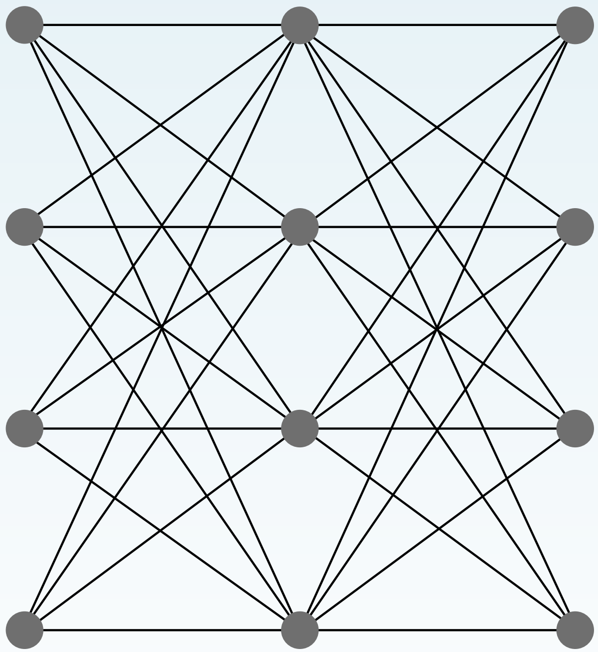
- $O(n^2)$ links
- Node may be at different stage of different paths

Alternative topologies: cascade



- O(n) links
- Easy to trace traffic

Alternative topologies: stratified



- $O(n^2)$ links, but less than clique
- Node always at same point in every path
- Optimal design, for some reasonable metrics
- Tor approximately does this already

What is needed next

- More **bandwidth** (both exit and middle)
- More **development effort** on Tor and surrounding projects, e.g.
  - Censorship resistance
  - Safe user experience (browser, chat, mail)
- Principles and tools for **scaling, enhancing performance and security** of source-routed overlay networks
- Techniques for safely **measuring networks** and rolling out **significant design changes**