New Reliability & Performance Challenges in Rearrangeable Networks

A Modeling Perspective

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OVERVIEW

- The changing telecom landscape
- Implications for reliability and performance
- Reliability and performance modeling
- Some solution approaches
- Next steps

THE CHANGING
TELECOM LANDSCAPE

Telecom Networks Are No Longer Fixed Structures

ASSURED NETWORKS

- New technologies developed to enable on-the-fly network rearrangement
- SDN and NFV
  - Inter-router links may be changed based on changing traffic demands
  - Capacity may be added or taken away at other locations
  - Reconfigurable general-purpose boxes enable on-the-fly enable layer 3 redesign and provisioning
- Deliberate rearrangements

Telecom Networks Are No Longer Fixed Structures

- Oh – and by the way, as long as we are talking about rearrangeable networks, remember that network element failures and repairs have always constituted another kind of network rearrangement
- "Accidental" rearrangements
  - TCP/IP responses to network element failures and repairs
  - Now SDN adds more possibilities
    - + May add or remove capacity elsewhere

The Old Order Passeth Away…

ASSURED NETWORKS

- The traditional telecom mantra has always been "make the network infrastructure as reliable as possible"
- This is no longer satisfactory
  - Was always too expensive
  - TCP/IP allows us to live with a certain amount of network element unreliability
    - + How much, precisely?
  - SDN may allow us to live with even more individual network element unreliability
    - + How much, precisely?

…AND NEW PLAYERS COME ON STAGE

ASSURED NETWORKS

- SDN/NFV-enabled rearrangeability is a double-edged sword
- Can respond quickly to changing traffic demands and network element failures
- But the infrastructure is larger and more complex
  - Lots of additional software
    - With little real experience
  - Additional hardware
    - That is in itself cheaper and less reliable

REARRANGEABILITY POSES

NEW CHALLENGES IN

RELIABILITY

AND

PERFORMANCE

Implications for Reliability and Performance

- How do these trends affect
  - Reliability
  - Performance
  - Security
- Acknowledgment: IEEE Study Group SRPSDVE

New Reliability Frontiers

- Reliable infrastructure is nice
- But it is only a means to an end
  - Reliable services
  - Decreased maintainability burden
- Service reliability is driven by
  - Packet delay
  - Packet loss
- These are properties of the network flow

NEW RELIABILITY FRONTIERS

ASSURED NETWORKS

- So it is important to know how the infrastructure contributes to packet loss and packet delay
  - In a fixed network
  - In a rearrangeable network
- How does the flow change when the network is rearranged?

New Performance Frontiers

ASSURED NETWORKS

- Reliability and "performance" are inextricably linked
  - Used to be called "performability"
- All telecom networks are made up of a limited number of shared resources
- Sized so that most "normal" traffic demand is carried without incident
- Disappearance of network elements because of failures simply makes a smaller network
  - A demand that might have been satisfactorily handled if all network elements were working may now result in performance degradation and service failures

New Performance Frontiers

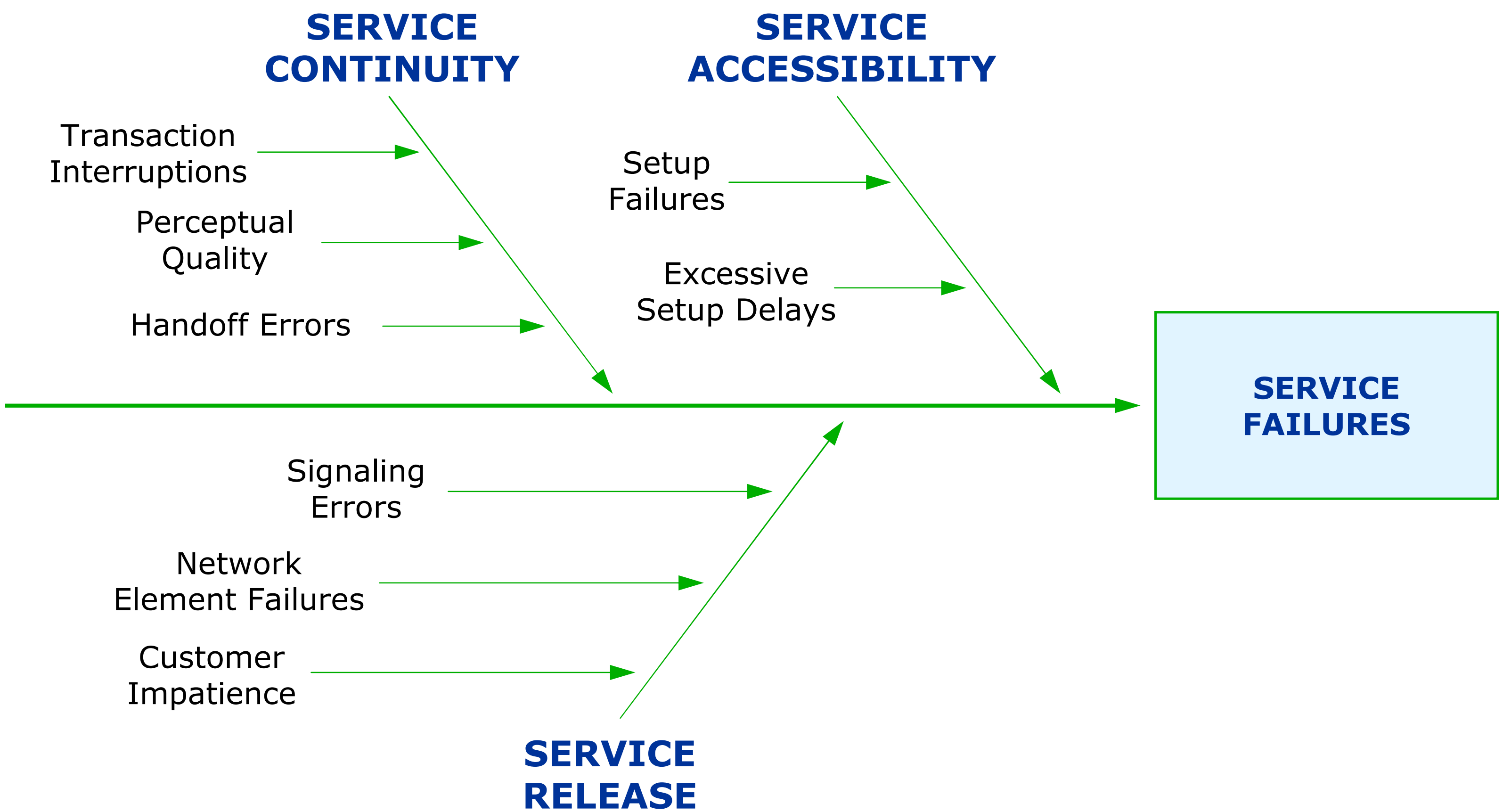
- Rearranging a network introduces a transient in the packet flow
- Performance may temporarily degrade until a new equilibrium is reached
  - Probably short-lived
  - Unless rearrangement is a response to large network element losses

NEW CHALLENGES

ASSURED NETWORKS

- Factors affecting (service) reliability
  - Variable network structure
  - Less reliable individual network elements
  - More complicated control schemes
  - New and untried software
- Factors affecting performance
  - Variable network structure
    - Potential for additional delays in executing rearrangements
  - Less reliable individual network elements

Root Cause Analysis

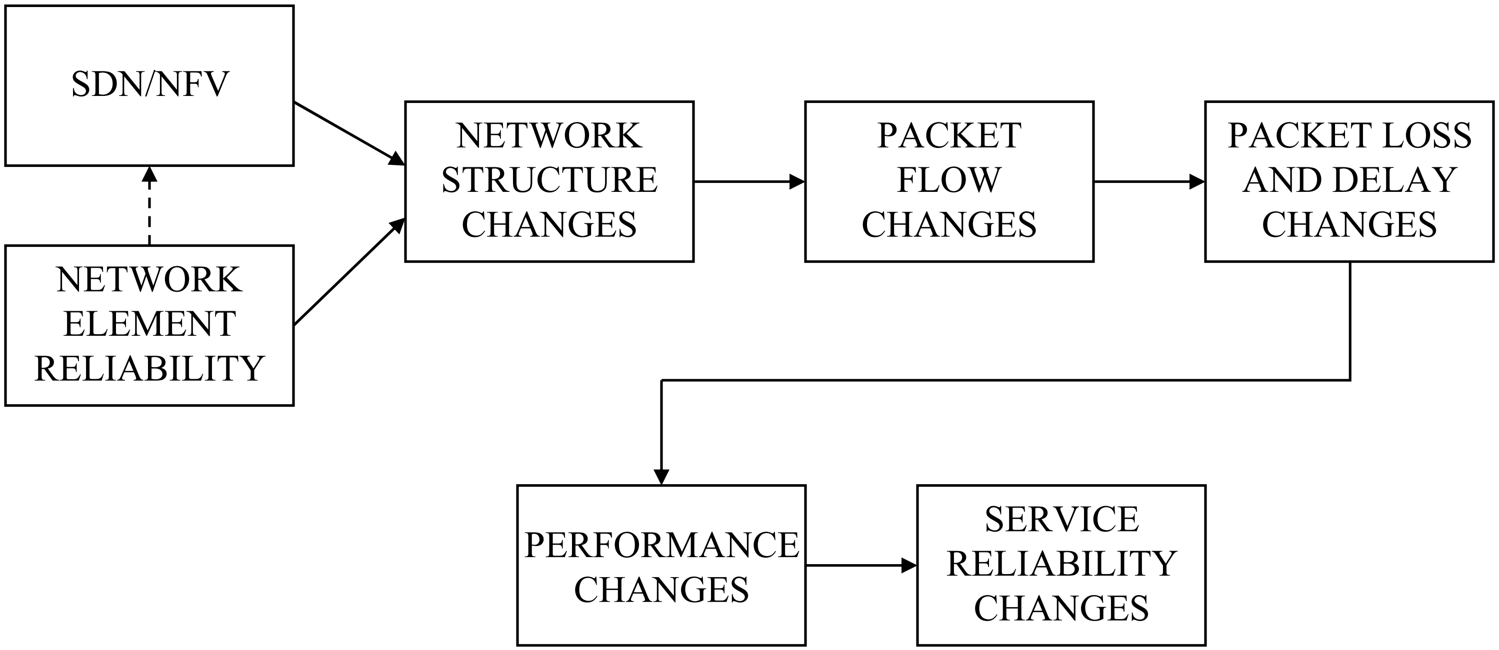


Root Cause Analysis

ASSURED NETWORKS

- Every one of these is a result of
  - Packet delays
  - Packet loss
- But….packet delay/loss are performance issues, no?
- Sure, but they manifest themselves as service failures

BOTTOM LINE


SDN/NFV
NETWORK ELEMENT RELIABILITY
NETWORK STRUCTURE CHANGES
PACKET FLOW CHANGES
PACKET LOSS AND DELAY CHANGES
PERFORMANCE CHANGES
SERVICE RELIABILITY CHANGES

MODELING RELIABILITY AND PERFORMANCE

Rearrangeable Networks

ASSURED NETWORKS

- So the key concept needed to understand reliability and performance in rearrangeable networks is <u>network flow</u>
- Rearrangements are represented by changes to
  - Network capacity matrix
  - Routing matrix

THREE PERSPECTIVES

- Develop limit theorems for the flow in a Ford-Fulkerson network
  - Strong law of large numbers
  - Central limit theorem
- Queueing networks with unreliable servers
- The Gale-Hoffman feasibility theorem in networks with unreliable elements

MAX FLOW NETWORK

- Original problem: given a source, a destination, and the capacities of each link, what is the maximum flow possible from the source to the destination?
- Later modifications added
  - Multiple sources and destinations
  - Finite capacities at the nodes also
  - Multiple commodities

Max Flow Network

- When the capacities change, the flow changes too
- Limit theorems tell us if there is any regularity to this behavior
  - Help with capacity provisioning

IMPORTANCE

- Given the point-to-point demands and the network element capacity processes, the central limit theorem would tell you the (approximate) distribution of the occupancy on each network element
  - Utilization (occupancy) as a function of BW while also accounting for reliability
- In equilibrium, the throughput at each destination node represents the success probability (service accessibility) for streams directed to that node

IMPORTANCE

ASSURED NETWORKS

- Why would anyone want to know this?
  - Avoid underprovisioning
    - + Inferior service reliability
  - Avoid overprovisioning
    - + Overspending
- Even if a network designer does not follow recommendations for reasons not covered in the model, knowledge of where the baseline is is important

STRATEGY

- Capacity changes in network elements governed by well-behaved stochastic processes
- Show that the map from capacity (and offered load) onto flow is continuous
- Transfer limit theorems from the network element capacity processes onto the flows

MAX FLOW NETWORK
LIMIT THEOREMS

- The approach is to consider

$$\Psi_{ab}(t) = \min_{k=1,\ldots,r} \sum_{(i,j)\in\chi_k(a,b)} C_{ij}(t)$$

  as a functional of the (matrix-valued) CTMC $C(t)$

- If this functional is measurable, we can apply the results of Kemeny and Snell to obtain SLLN and CLT for $\Psi_{ab}(t)$

Max Flow Network
Strong Law of Large Numbers

- Assume a stationary distribution for the capacity matrix Markov chains

$$\pi_k^{(i,j)} = \lim_{t\to\infty} P\left\{C_{ij}(t) = k\right\}, \; k = 1, \ldots, N_{ij}$$

- $\{\Pi_K : K \in \mathcal{M}_{N\times N}\}$ is the stationary distribution of $\{C(t)\}$ formed from the (i, j) stationary distributions above

$$\Pi_K = \lim_{t\to\infty} P\left\{C(t) = K\right\} = \lim_{t\to\infty} \prod_{i,j=1}^{N} P\left\{C_{ij}(t) = K_{ij}\right\} = \prod_{i,j=1}^{N} \pi_{K_{ij}}^{(i,j)}$$

Max Flow Network
Strong Law of Large Numbers

- Then $\lim_{T\to\infty}\frac{1}{T}\int_0^T \Psi_{ab}\left(C\left(t\right)\right)dt = \sum_{K\in\mathfrak{M}_{N\times N}} \Psi_{ab}\left(K\right)\Pi_K$

- Central limit theorem is similar but the notation is horrible

QUEUEING NETWORKS
BASIC MODELS

- Jackson network
  - Exogenous Poisson arrivals
  - Exponential service times at the nodes
  - Finite buffers
  - Lossless links
  - Markovian routing
  - Product-form solution
    - Nodes behave as though they were independent M/M/*c* queues

Queueing Networks
Basic Models

ASSURED NETWORKS

- Other tractable network models with product-form solutions
  - BCMP network
  - Gordon-Newell network
  - Networks whose nodes have the "M$\Rightarrow$M property" (Muntz)
- Beyond these, simulation is most often used to study performance

Queueing Networks

- Standard solution approach for the Jackson network
  - Solve the traffic equation
    - Get the total offered load at each node
  - Product-form solution for the network
    - Network behaves as if the nodes are independent

Jackson Network as a Packet Network Model

ASSURED NETWORKS

- Lossless links?
  - Redraw network to incorporate finite link capacity
- Poisson arrivals?
  - Good description of voice traffic
  - Not so much for data traffic: more long-range dependence than Poisson

Jackson Network as a Packet Network Model

ASSURED NETWORKS

- Markovian routing?
  - Address-based routing is not
  - Various restricted Markovian routing schemes to approximate address-based routing
    - Edge nodes only I/O
    - Packet touches a given router at most once

Jackson Network with Unreliable Elements

- Allow the numbers of servers in the queues at the nodes to vary
  - Variable capacity of network elements
  - Driven by reliability
- So make each node a M/M/c_t queue

Erlang Delay Model with Unreliable Servers

- Start with an M/M/c/b queue, b, $c < \infty$
- Let $C(t)$ be a stochastic process with discrete state space $\{0, 1, 2, \ldots, c\}$ and continuum parameter space (time)
- The M/M/c_t/b_t queue has
  - Poisson arrivals
  - Exponential service
  - Finite buffer space $B(t)$ at time t
  - $C(t)$ is the number of servers active at time t

THE M/M/C_T QUEUE

ASSURED NETWORKS

- $C(t)$ is an integer-valued step function
- So if you are willing to ignore the transient the departure process is a (nonhomogeneous) Poisson process
  - At time t_0 in an equilibrium regime, this is simply a M/M/$C(t_0)$ queue
  - During the intervals of constancy of $C(t)$ the departure process is homogeneous

Jackson Network with Unreliable Elements

- As a model for a packet network
  - Nodes are routers
    - + Input and output buffers
  - Links are transport
    - + Non-blocking
      - Re-draw the network
- At each fixed *t* in equilibrium regime, you have a Jackson network with node capacities $C_1(t)$, …, $C_N(t)$
  - Ignoring transient effects
  - Product-form solution at *t*

Jackson Network with Unreliable Elements

ASSURED NETWORKS

- Flow in the network is $\{X_1(t), \ldots, X_N(t)\}$ where $X_i(t)$ is the number of packets in service at node *i*
  - Ignoring the transient

$$P\left\{\left(X_1(t),\ldots,X_N(t)\right)=\left(k_1,\ldots,k_N\right)\right\}=\prod_{i=1}^{N}P\left\{X_i(t)=k_i\right\}$$

- Packet delay and packet loss are handled similarly

THE GALE-HOFFMAN THEOREM

Gale-Hoffman Feasibility Theorem

- Multiple demands (sources and destinations) are given
- Finite, known link capacities
- Nodes are nonblocking

Gale-Hoffman Feasibility Theorem

- A flow in the network is feasible if for every set A of nodes, the total demand out of A does not exceed the capacity $C(\bar{A}, A)$ from outside A into A
- Total demand out of A is $\sum_{\substack{i \in A \\ j \in \mathcal{N}}} d_{ij}$
- Total capacity from $\bar{A}$ into A is $C\left(\bar{A}, A\right) = \sum_{\substack{i \in \bar{A} \\ j \in A}} c_{ij}$

Gale-Hoffman Feasibility Theorem

- To account for network element reliability, we again make the network element capacities into random processes
  - Matrix of stationary Markov processes
- Probability that a flow whose demand set is *A* is feasible is then

$$\alpha(t) = P\left\{d(A) \le c\left(\bar{A}, A; t\right)\right\} = P\left\{\sum_{\substack{i \in A \\ j \in \mathcal{N}}} d_{ij} \le \sum_{\substack{i \in \bar{A} \\ j \in A}} c_{ij}(t)\right\}$$

Some Open Questions

ASSURED NETWORKS

- Suppose $\{X_1, X_2, \ldots\}$ is a sequence of random variables, $S_n = X_1 + \cdot \cdot \cdot + X_n$, satisfying a law of large numbers $S_n/n \to A$ (strong or weak)
  - Not assuming any other structure about $\{X_1, X_2, \ldots\}$ (*e. g.*, renewal or Markov)
  - $f : \mathbf{R} \to \mathbf{R}$, $Y_i = f(X_i)$, $T_n = Y_1 + \cdot \cdot \cdot + Y_n$
  - Find conditions for convergence of T_n/n
- Same question for central limit theorem

SOME OPEN QUESTIONS

- Generalize the Gale-Hoffman theorem to the case where some or all nodes may be both origin and destination nodes
  - Edge routers
- Incorporate routing matrix changes into the models
  - Interplay between capacity changes and routing changes
    - + TCP/IP
    - + SDN

SUMMARY AND CONCLUSIONS

- We examined how flows in some kinds of networks are affected by unreliable network elements and capacity changes stemming from SDN actions
  - SLLN and CLT for flows in FF networks
  - Queueing networks
  - Probabilistic feasibility in flow networks

Summary and Conclusions

- Computational challenges remain
  - Packet delays and losses
  - Downstream service reliability figures of merit
    - Accessibility
    - Continuity/Fulfillment
    - Release

NEXT STEPS

ASSURED NETWORKS

- Make the queueing network models rigorous
  - Clean up the transient issue
  - Include the interplay between capacity changes and routing changes
  - Stability under non-Poisson arrivals
  - Markovian routing approximations to address-based routing
- Make this into a practical engineering tool

SHAMELESS PROMOTION