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Network coding for a survivable and secure Internet

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Lecture overview

- Survivability mechanisms
  - 1+1 path protection
  - Network Layer Packet Redundancy (NLPR)
- How to utilise network coding to provide survivability
  - Network layer
  - Comparison with existing approaches
- Secure packet transport using network coding

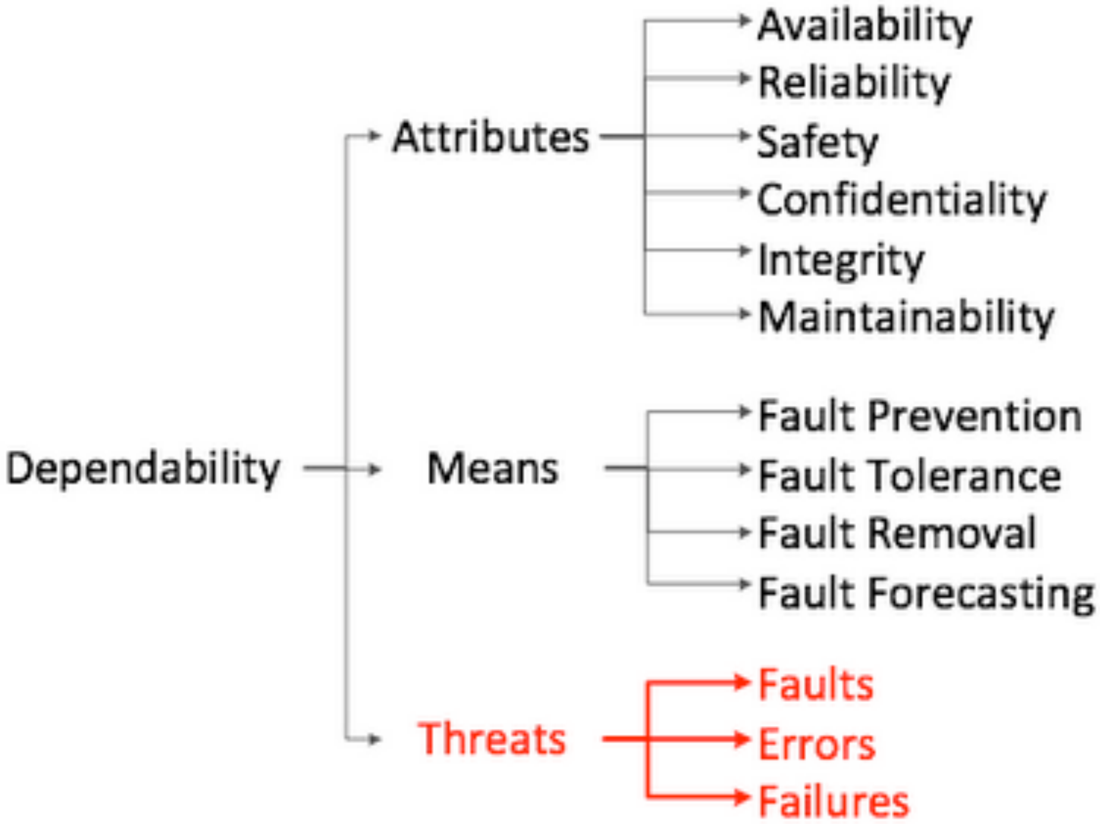
Unified view on QoS

- Quality of Service (QoS) includes
  - Performance
  - Survivability
  - Security
- Aim for a unified view on QoS
- Cost is also an essential part
- *Network coding as a mechanism to provide cost-efficient QoS in communication networks*

Network survivability

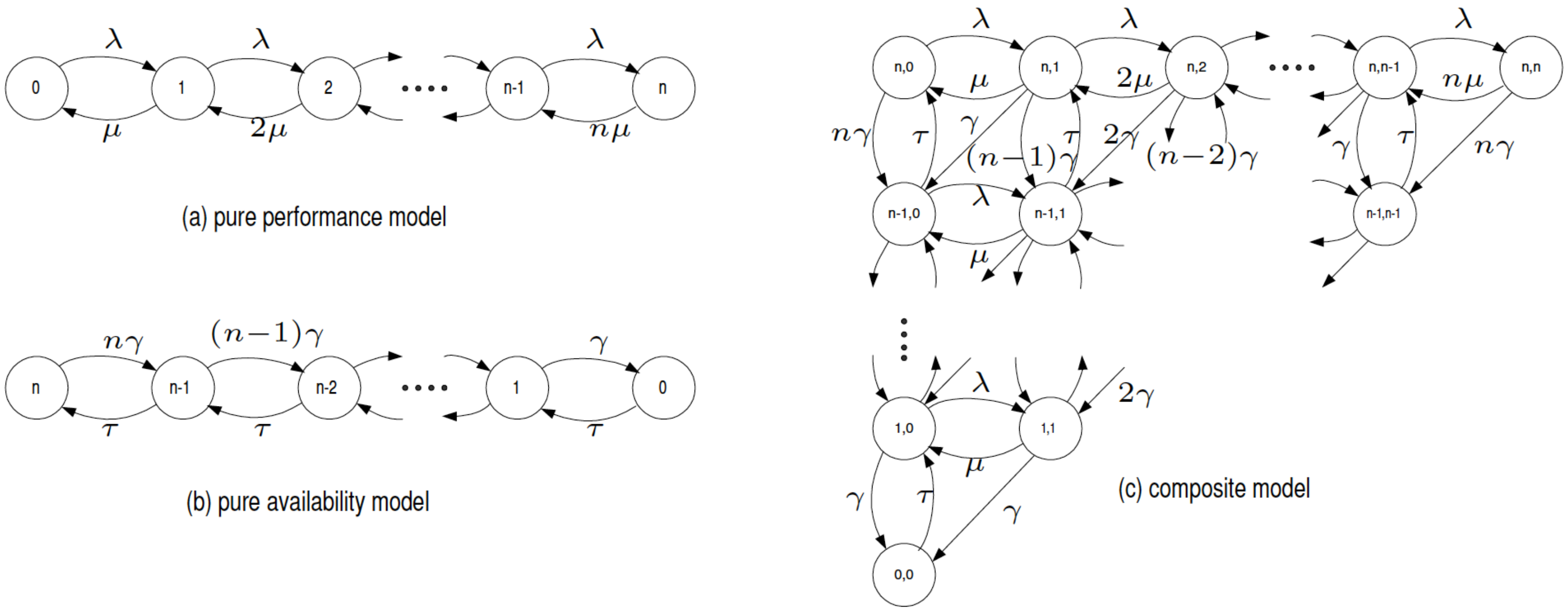
- A networks ability to handle failures
- Can be measured as the fraction of available resources after the occurrence of failures
- Related terms
  - **Dependability:** Trustworthiness of a system
  - **Resillience:** Ability to provide service in the presence of faults

Network survivability



Network survivability

Example



(a) pure performance model

(b) pure availability model

(c) composite model

Reference:

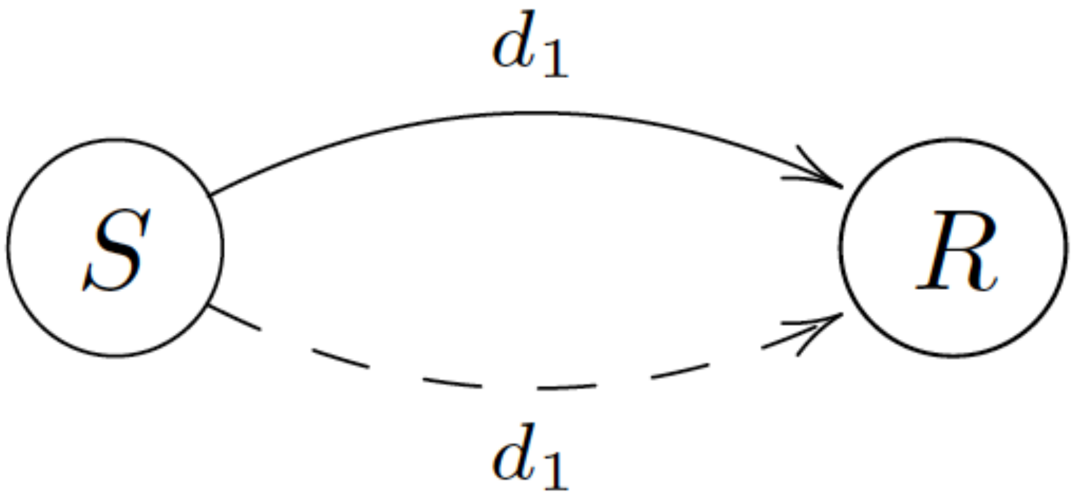
Y. Liu, S. Trivedi: A general framework for network survivability quantification

Survivability mechanisms

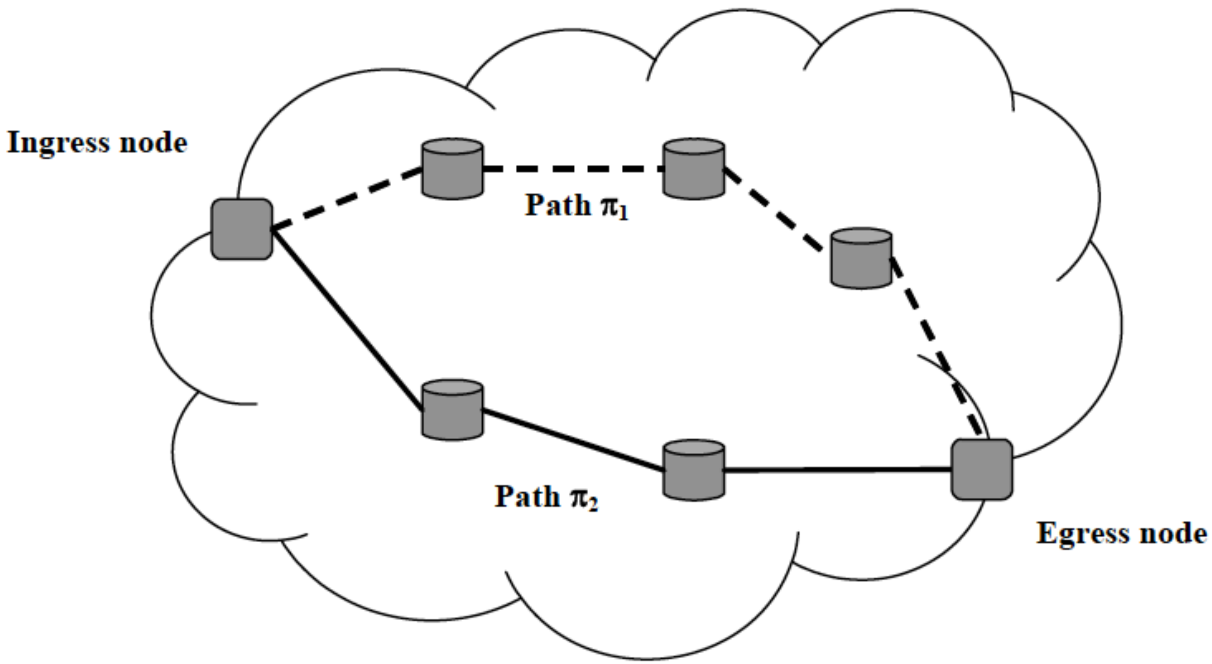
- Protection strategies
  - Predetermined capacity reserved for back-up paths
  - Fast
  - Requires much extra capacity
- Restoration strategies
  - Dynamic resource allocation in the case of failure
  - Slow
  - Requires little extra capacity

1+1 path protection

- Protection strategy
- Duplicate packet on redundant path
- R will receive two identical data packets in non-failure state
- Costly



1+1 path protection

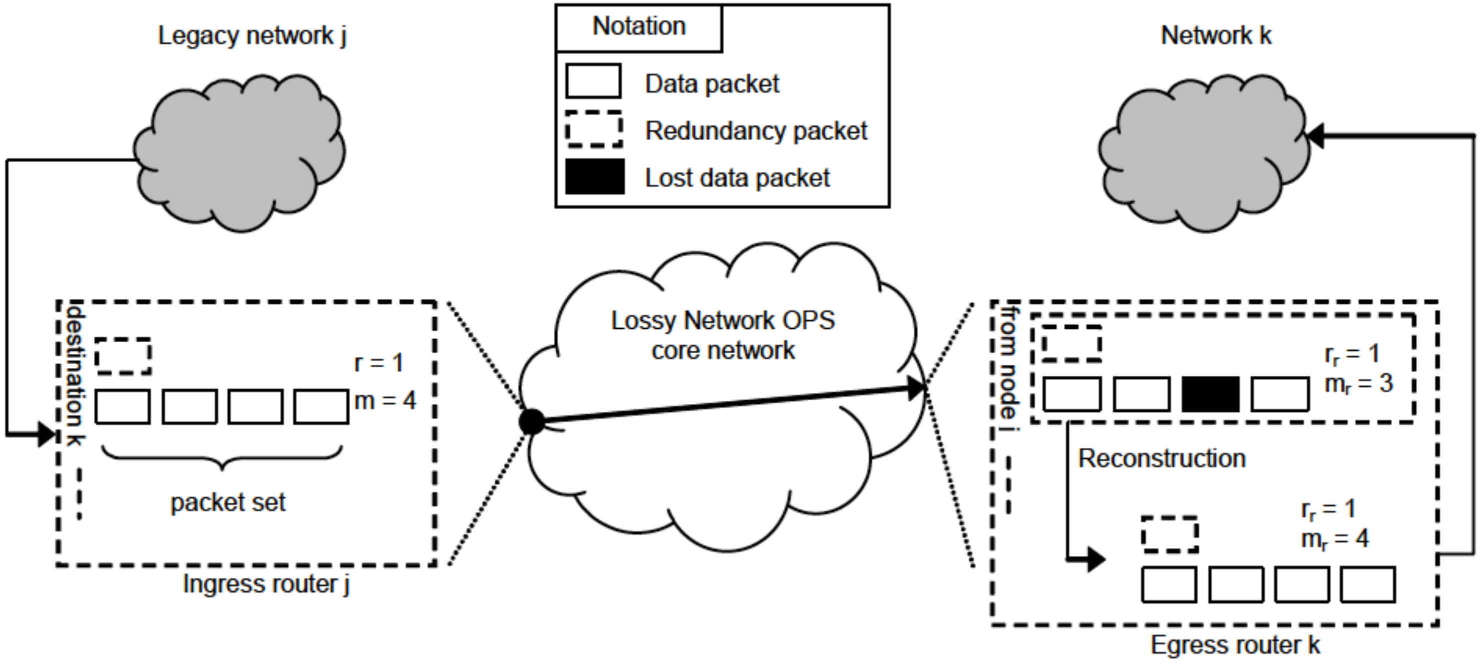


Shared packet redundancy (SPR)

- A set of redundancy packets are added to a set of data packets
  - Ingress node
- Packets may be lost in the network
  - Failures
  - Buffer overflow
  - Contention (Optical Packet/Burst Switching)
- Packets may be reconstructed
  - Egress node

Shared packet redundancy (SPR)

Context of OPS networks



Shared packet redundancy (SPR)
Context of OPS networks

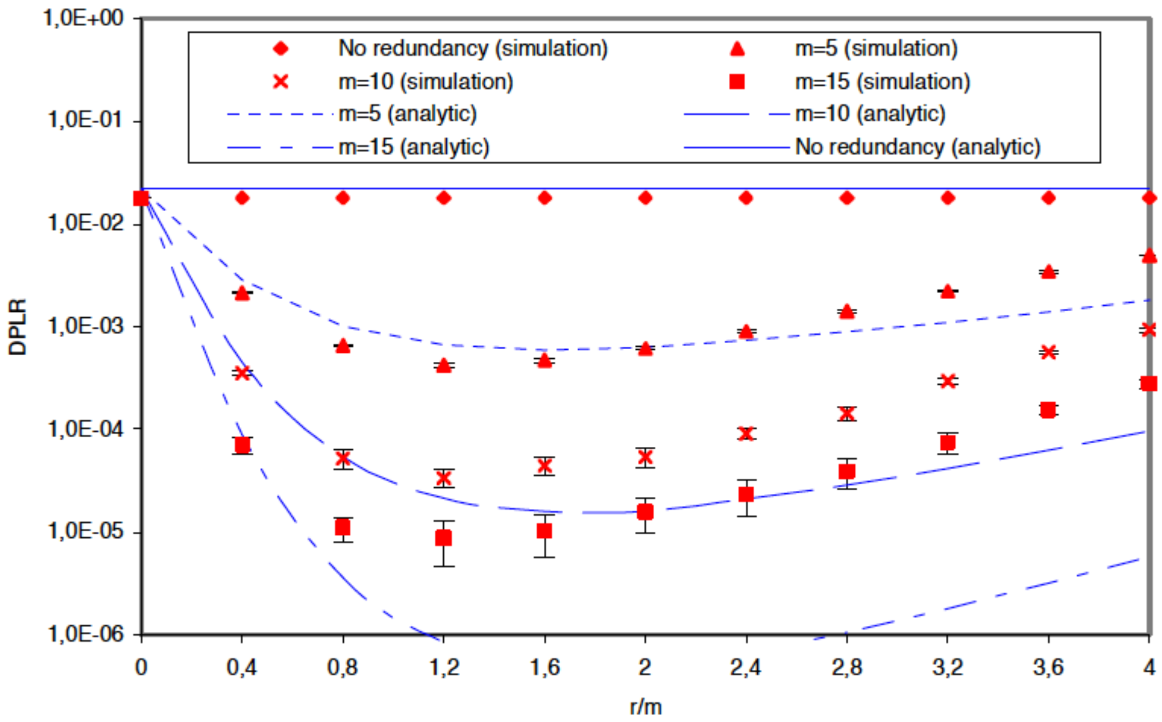
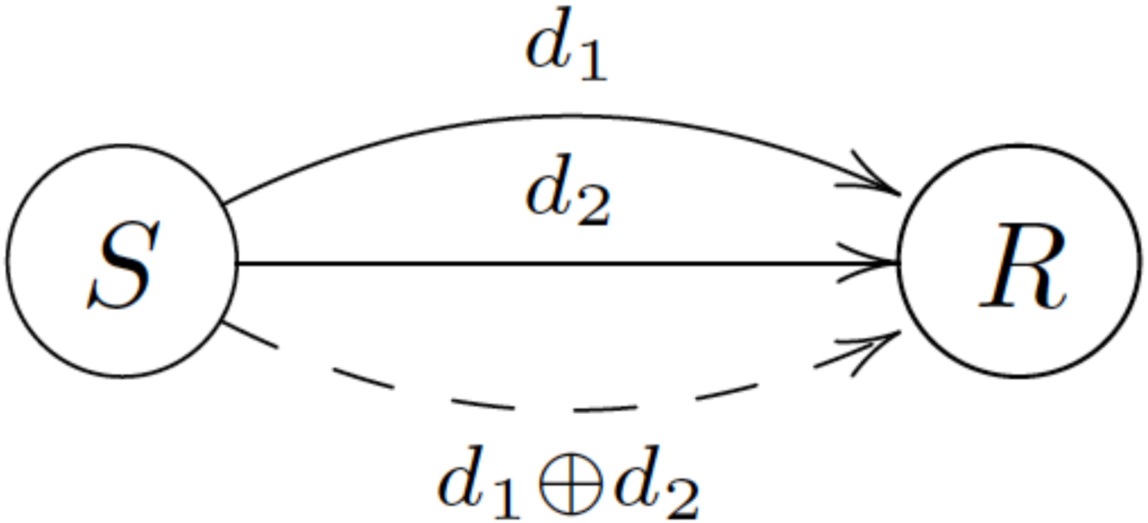


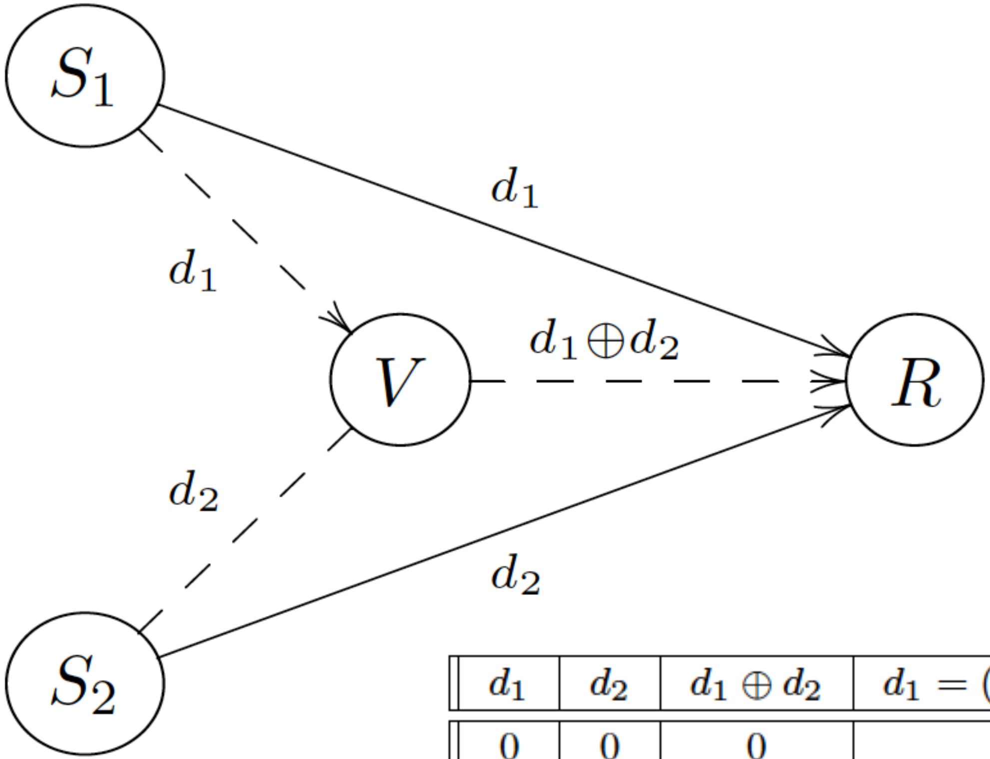
Fig. 4. The DPLR as a function of the product r/m for various values of the parameter m. ρ_D=0.2, G=7, AM=Poisson, PLD=Deterministic, RPSM=BTB.

1+1 path protection with SPR



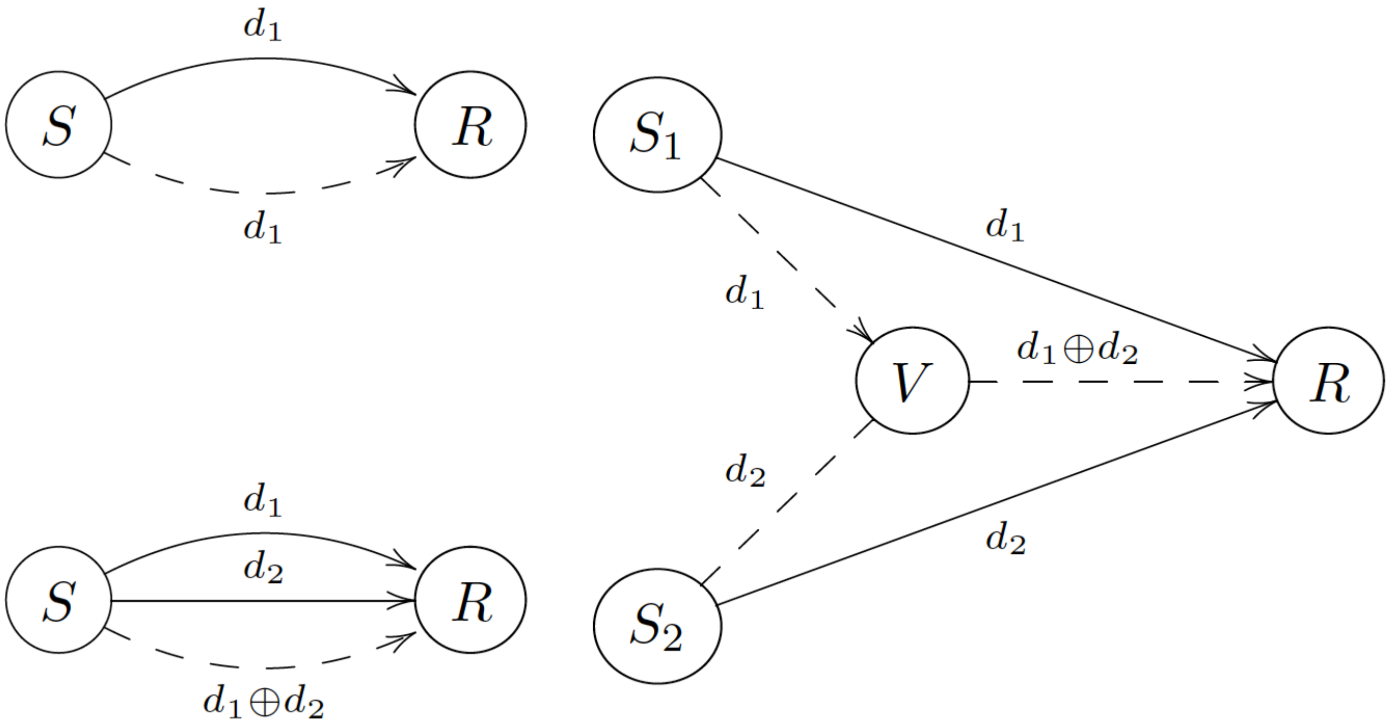
d_1	d_2	$d_1 \oplus d_2$	$d_1 = (d_1 \oplus d_2) \oplus d_2$	$d_2 = (d_1 \oplus d_2) \oplus d_1$
0	0	0	0	0
0	1	1	0	1
1	0	1	1	0
1	1	0	1	1

1+1 path protection with NC



d_1	d_2	$d_1 \oplus d_2$	$d_1 = (d_1 \oplus d_2) \oplus d_2$	$d_2 = (d_1 \oplus d_2) \oplus d_1$
0	0	0	0	0
0	1	1	0	1
1	0	1	1	0
1	1	0	1	1

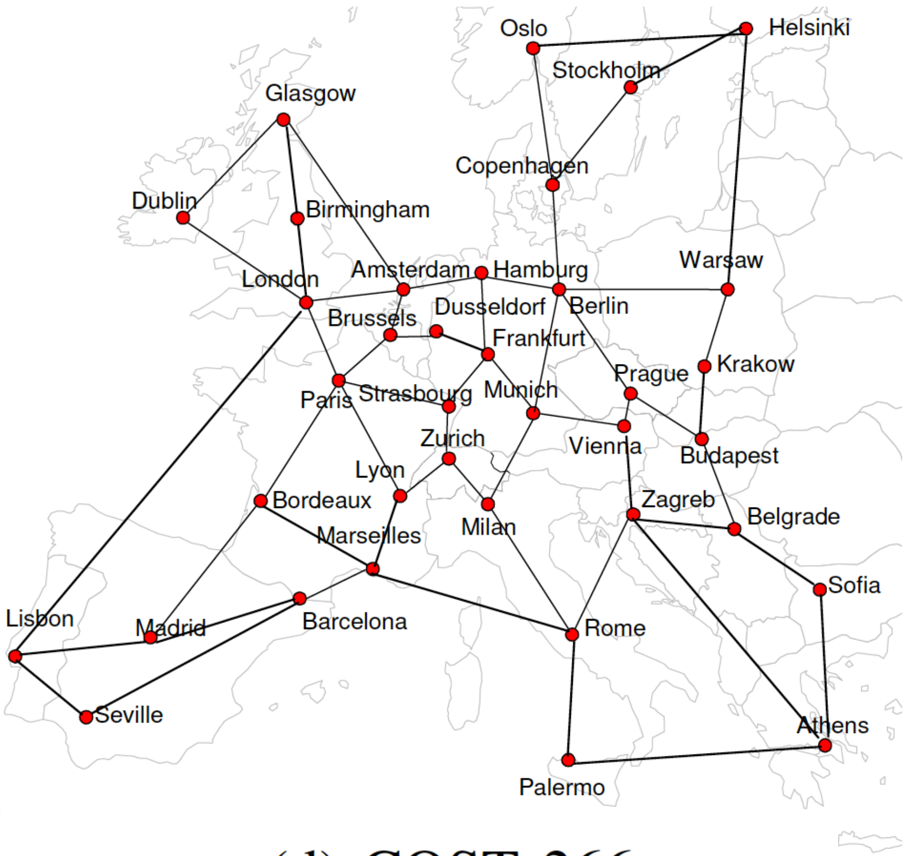
Three approaches to 1+1PP



Cost-efficiency

- The schemes are evaluated on cost-efficiency
- Amount of resources used to provide 1+1PP
- Two approaches
  - Analytical model
  - Simulation of realistic network topologies
- Network cost relative to unit cost
- Challenge
  - Accurate analytical model
  - Computing resources required for simulation model

Sample network topology



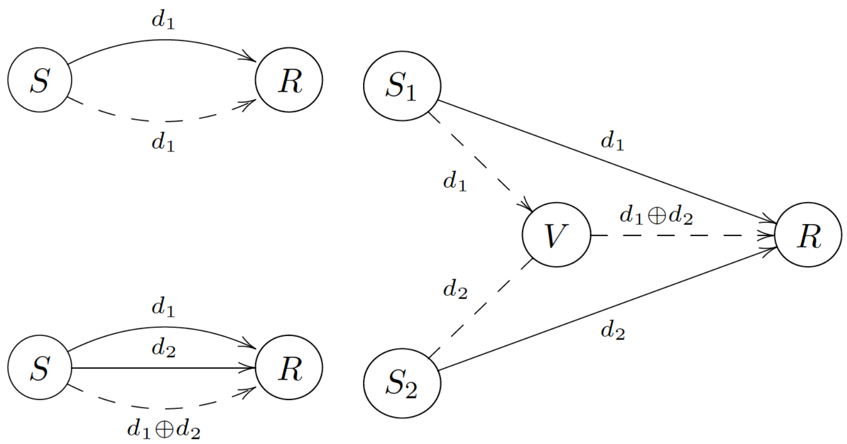
(d) COST 266

Cost model

$$c(p_{S,R,1}) = c(p_{S_1,R,1}) = c(p_{S_2,R,1}) = \pi$$

$$c(p_{S,R,x}) = (1+b)^{x-1} c(p_{S,R,1}) = (1+b)^x \pi$$

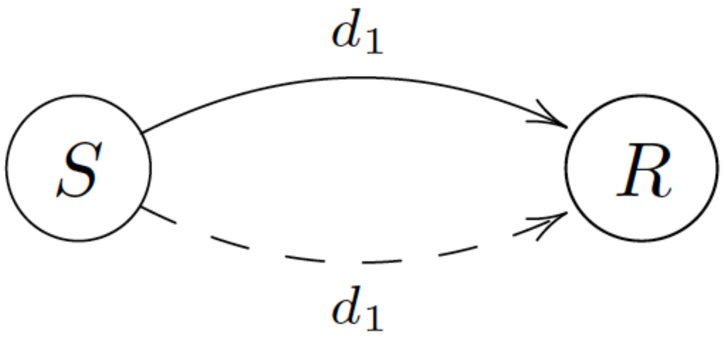
Symbol	Description
S	Source node
R	Receiver node
V	Coding node
d_i	Data packet i
$p_{A,B,x}$	Path between node A and B with cardinality x
$c(p_{A,B,x})$	Cost of path $p_{A,B,x}$
b	Relative cost increase for next path
k	Relative distance from source nodes S_1 and S_2 to coding node V
C_Y	Total cost of providing 1+1 path protection with scheme $Y \in \{T, NR, NC\}$
C_Y^D	Total cost of sending data packets
N_Y	Relative cost of providing 1+1 path protection with scheme $Y \in \{T, NR, NC\}$



Cost model T1+1PP

$$C_{\mathrm{T}} = c(p_{S,R,1}) + c(p_{S,R,2}) = (b+2)\pi$$

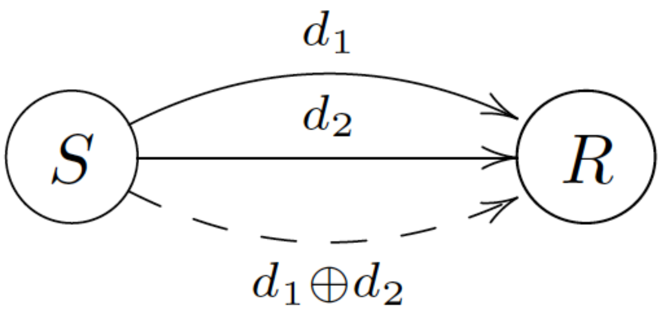
$$C_{\mathrm{T}}^{D} = \pi$$



Cost model NR1+1PP

$$C_{\mathrm{NR}} = \sum_{i=1}^{3} c(p_{S,R,i}) = \sum_{i=1}^{3} (1+b)^{i-1}\pi = (b^2+3b+3)\pi$$

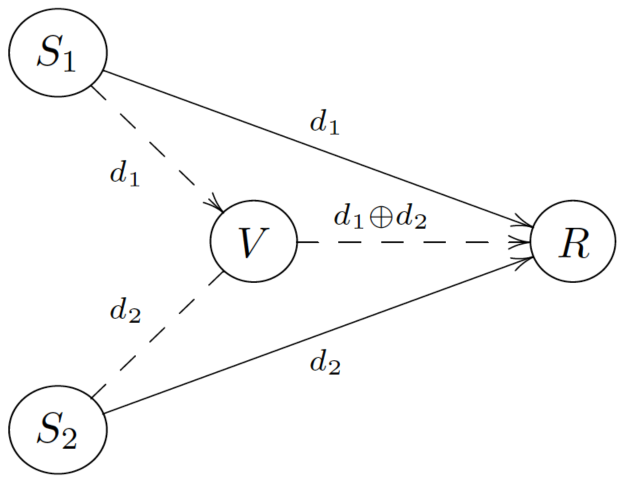
$$C_{\mathrm{NR}}^{D} = 2\pi$$



Cost model NC1+1PP

$$C_{\mathrm{NC}} = c(p_{S_1,R,i}) + c(p_{S_2,R,i}) + c(p_{S_1,V,i}) + c(p_{S_2,V,i}) +$$
$$+ c(p_{V,R,i}) = \pi + (1 + b/2)\pi + k(1 + b/2)\pi + k(1 + b)\pi +$$
$$+ (1 - k)(1 + b)^2\pi = ((1 - k)b^2 + \frac{5 - k}{2}b + k + 3)\pi.$$

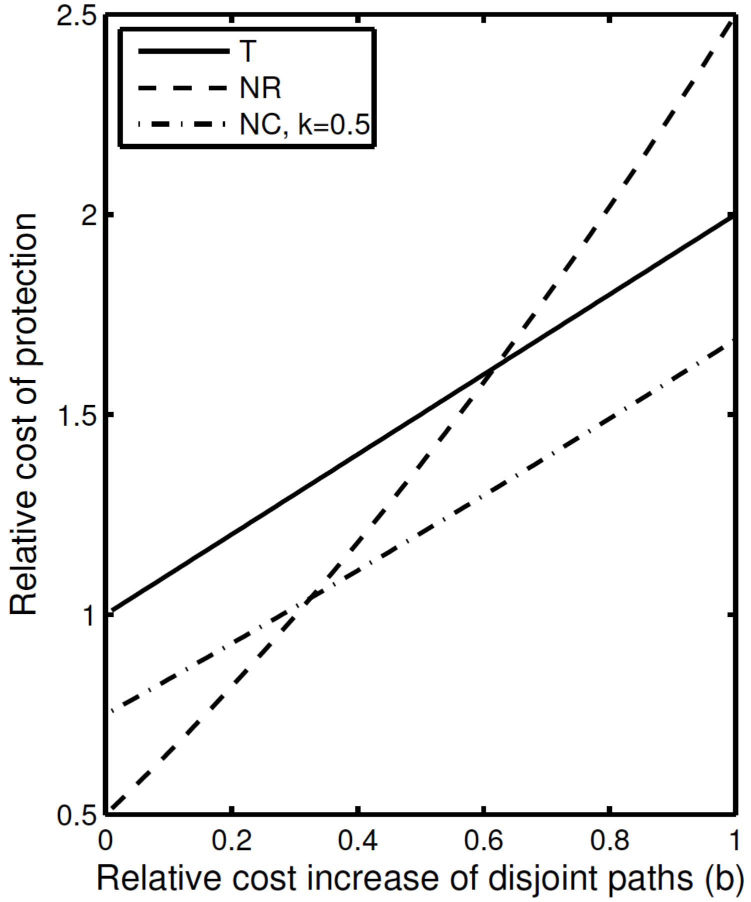
$$C^D_{\mathrm{NC}} = 2\pi$$



Cost comparison

$$N_Y = \frac{C_Y - C_Y^D}{C_Y^D}$$

Results


2.5
2
1.5
1
0.5
0
0.2
0.4
0.6
0.8
1
T
NR
NC, k=0.5
Relative cost of protection
Relative cost increase of disjoint paths (b)

ILP formulation

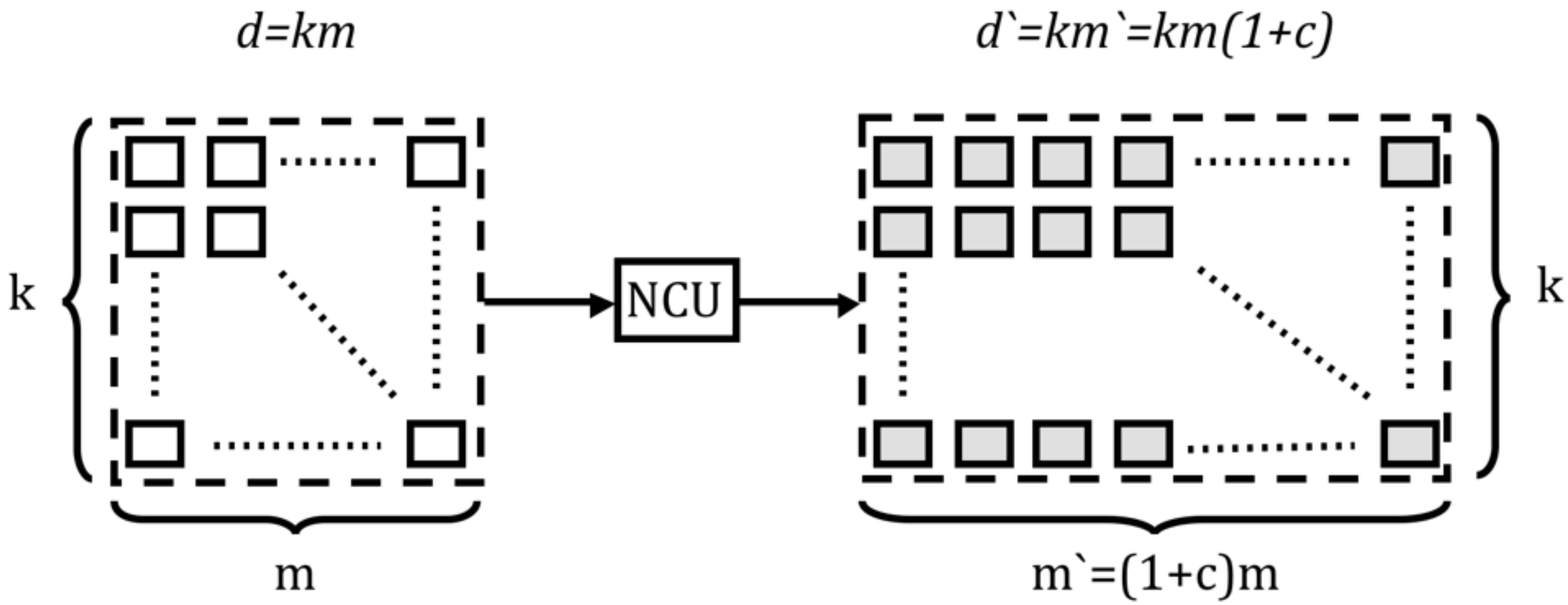
$$\min \left\{ \left[\sum_{\forall i \in E} \sum_{\forall d \in D} c_i \left(x_i^d + y_i^d - \sum_{\forall j \in V} \frac{z_i^{d,j}}{2} \right) \right] - p \cdot q^d \right\}$$

Symbol	Description
x_i^d	$\in \{0,1\}$, if link $i \in$ the working path for demand d
y_i^d	$\in \{0,1\}$, if $i \in$ the protection path for d
$z_i^{d,j}$	$\in \{0,1\}$, if $i \in$ the coding path with coding node j for d
v_j^d	$\in \{0,1\}$, if j is the coding node for d
w_j	$\in \{0,1\}$, if j is a coding node in the network G
q^d	$\in \{0,1\}$, if demand d is routed
$d_{d_2}^{d_1}$	$\in \{0,1\}$, if $d_1 \neq d_2$, if d_1 and d_2 are coded together
r_j^d	$\in \{0,1\}$, if j is the target of d
N	$\in \mathbb{N}, 0 \leq N \leq \lvert V \rvert$, maximum number of coding nodes
p	$\in \mathbb{Z}^+$, large, penalty if demand not routed
c_i	$\in \mathbb{R}^+$, cost of link i
f_i	$\in \mathbb{R}^+$, available free capacity along link i

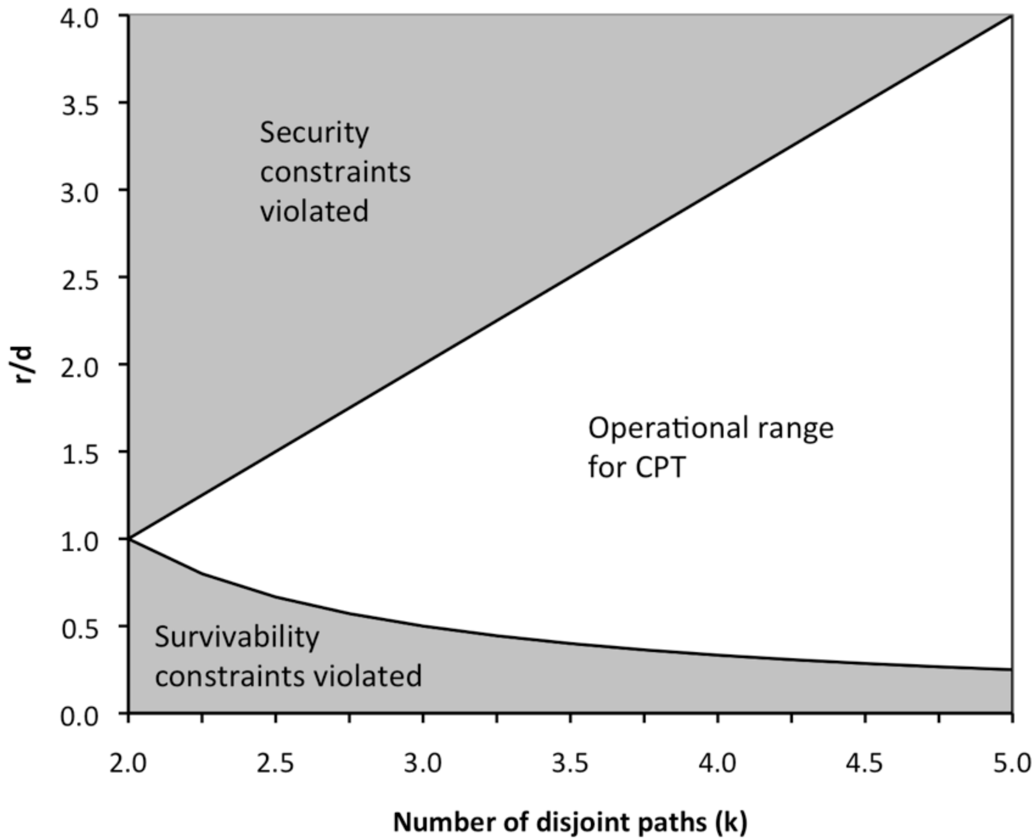
Secure networking with NC

- Network coding may be utilised to provide secure data transmission
- Protects against eavesdropping of a single link
- All incoming data packets to an ingress node are coded and transported over the network
- A number of coded packets is required to obtain data information

Coded packet transport



Coded packet transport



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Summary

- How to utilize NC to provide
  - 1+1 path protection
  - Secure data transport
- Cost-advantages over traditional 1+1 path protection
- May also utilize other networking advantages of NC
  - Cost-efficient provision of multicasting