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Reliability and Resilience in Wireless Networks with Dependent Link Failures

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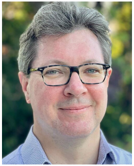

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DFG

Wireless Networks: From Reliability to Resilience

- **Wireless** is the backbone for:
  - Industrial control, mission-critical IoT, cyber–physical systems
  - Public safety, emergency communications, disaster recovery
  - Future 6G: ultra-reliable, low-latency, and resilient-by-design
- **Reliability:** probability that the system is operational at a given time.
- **Resilience:** ability to resist, survive, recover, and adapt under disturbances.
- **Goal:** develop methods to quantify and optimise reliability/resilience under dependent link failures.

Why Independence Assumptions Fail

- Standard network reliability often assumes **i.i.d. link failures**.
- Real networks exhibit strong dependencies:
  - Spatially correlated shadowing and blockage
  - Shared infrastructure (sites, backhaul segments, power supply)
  - Common-cause failures (weather, disasters, jamming, congestion)
  - Cascading failures and overload effects
- Local measurements give **marginal** link success probabilities, but the **joint** distribution is unknown/hard to estimate.
- **Question**: how reliable can the network be, in the **best** and **worst** case, given only the marginals?

Agenda

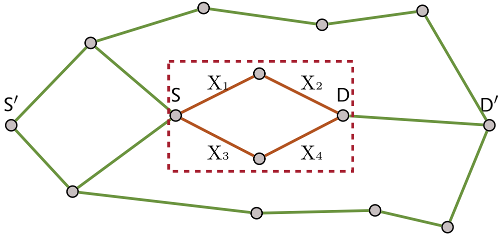
- **Analytical bounds:** worst/best reliability for arbitrary dependency given marginal link probabilities [1]
- **LP and decomposition:** scalable numerical evaluation by LP for large, realistic topologies [2]
- **MC strategies:** load balancing (LB) vs packet duplication (PD) in diamond networks [3]
- **Resilience and power:** multi-connectivity, resilience phases, and power allocation under dependencies [4]

References

[1] Z. Ge and E. A. Jorswieck, "Dependency and Link Diversity Placement for Reliable Wireless Diamond Networks," ICC 2025 - IEEE International Conference on Communications, Montreal, QC, Canada, 2025, pp. 2857-2862, doi: 10.1109/ICC52391.2025.11160844.
[2] Z. Ge and E. A. Jorswieck, "Reliability in Statistically Dependent Networks: Bounds, Linear Programming, and Scalability," in IEEE Trans. on Communications, vol. 74, pp. 2731-2746, 2026,
[3] Z. Ge, S. Jhansale, L. Jueschke, L. Wolf, E. Jorswieck, "Reliability of Load Balancing and Packet Duplication in Dependent Diamond Networks", IEEE VTC fall 2025.
[4] Z. Ge, L. Jueschke, L. Wolf, E. Jorswieck, "Reliable Connectivity Optimization in Wireless Networks with Dependent Link Failures", Asilomar 2025.

Graph Model for Wireless Connectivity

- Represent the network as a directed or undirected graph $\Gamma = (\mathcal{N}, \mathcal{E})$.
- Each edge $e \in \mathcal{E}$ represents a (possibly multi-hop) link:
  - Binary random variable $X_e \in \{0, 1\}$
  - Marginal success probability $p_e = \Pr[X_e = 1]$
- Focus on two-terminal reliability:
  - Source node s, destination node t (- extension to general connectivity)
  - System works if there exists at least one operational path from s to t.



Example network graph with source s, destination t, and diamond network subgraph.

Problem Statement: Extremal Reliability

- Let $\mathbf{X} = (X_e)_{e\in\mathcal{E}}$ be binary edge states with $\Pr[X_e = 1] = p_e$.
- Joint distribution $\Pr[\mathbf{X}]$ is unknown, but must be consistent with the marginals $\{p_e\}$.
- Network works if system state is in a set $\mathcal{S}_{ok}$ determined by connectivity between s and t.
- We seek **sharp bounds**:

$$R_{min} = \min_{\Pr[\mathbf{X}]\in\mathcal{P}_{marg}} \Pr[\mathbf{X} \in \mathcal{S}_{ok}], \quad R_{max} = \max_{\Pr[\mathbf{X}]\in\mathcal{P}_{marg}} \Pr[\mathbf{X} \in \mathcal{S}_{ok}],$$

  where $\mathcal{P}_{marg}$ is the set of all joint distributions with given marginals.
- Captures **worst-case** and **best-case** reliability over all dependency structures.

Series Systems: Intuition from Bernoulli Vectors

- Consider n Bernoulli RVs $X_1, \dots, X_n$ with marginals $\Pr[X_i = 1] = p_i$.
- Series system: works if $\bigwedge_{i=1}^{n}(X_i = 1)$.

Then the following bounds hold:

$$\left(\sum_{i=1}^{n} p_i - (n-1)\right)_+ \leq \Pr\left[\bigwedge_{i=1}^{n}(X_i = 1)\right] \leq \min_i p_i .$$

- **Upper bound:** attained by fully positive dependence (co-monotone structure).
- **Lower bound:** attained by as negative as possible dependence (counter-monotone structure).
- This is the first building block for network-level reliability bounds.

Parallel Systems: Intuition from Bernoulli Vectors

- Consider n Bernoulli RVs $X_1, \ldots, X_n$ with marginals $\Pr[X_i = 1] = p_i$.
- Parallel system: system works if $\bigvee_{i=1}^{n}(X_i = 1)$.

Then the following bounds hold:

$$\max_i p_i \leq \Pr\left[\bigvee_{i=1}^{n}(X_i = 1)\right] \leq \left(\sum_{i=1}^{n} p_i\right)^1 .$$

- **Upper bound:** attained by as negative as possible dependence (counter-monotone structure).
- **Lower bound:** attained by fully positive dependence (co-monotone structure).
- This is the second building block for network-level reliability bounds.

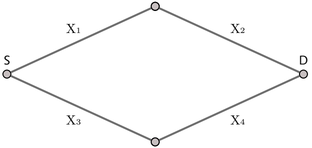
From Series/Parallel to General Graphs

- Network reliability can be expressed via minimal paths P_k:

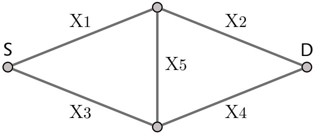
$$\text{system works} \iff \bigvee_k \bigwedge_{e \in P_k} (X_e = 1).$$

- Within each minimal path, use the series-type bounds.
- Across paths, combine using union/intersection techniques to obtain network-level worst/best bounds:
  - worst-case reliability tightly characterised by path structure
  - best-case reliability often considerably larger than the i.i.d. value when paths share edges.
- Analytical expressions available for important patterns: series, parallel, bridge, and diamond subgraphs.

Toy Example: Diamond and Bridge Networks



Diamond network with four links and marginals p_1, p_2, p_3, p_4.



Bridge network with five links and marginals p_1, p_2, p_3, p_4, p_5.

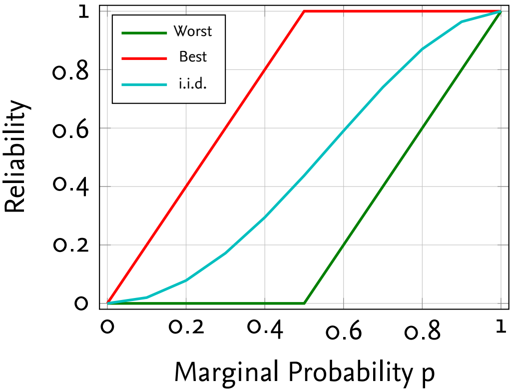
Deconstruct into two parallel paths with two serial links to obtain

$$\max(p_1 + p_2 - 1)_+, (p_3 + p_4 - 1)_+ \leq \Pr_{\text{success}} \leq (\min(p_1, p_2) + \min(p_3, p_4))^1$$

For i.i.d. links, we obtain

$$\Pr_{\text{success}} = 1 - (1 - p_1 p_2) \cdot (1 - p_3 p_4) \tag{1}$$

Toy Example: Diamond Network Illustration



Reliability bounds and the i.i.d. case for the diamond network

Diamond and Bridge Networks

- Bridge/diamond graphs appear as basic motifs in larger topologies.
- Analytical worst/best bounds reveal:
  - When adding a bridge link increases reliability significantly.
  - When dependencies limit the benefit of additional links.
- These motifs guide both:
  - **Network design**: where to place additional links.
  - **Algorithm design**: how to decompose larger graphs.

Characterization for Bridge Network

Proposition 1

Given a network graph with $\mathcal{P}$ disjoint paths from source to destination, if one path consists of L links with the L largest marginals, $p_1, p_2, \ldots, p_L$: $\min_{i\in\{1,\ldots,L\}}(p_i) \geqslant \max_{K\in\mathcal{E}\setminus\{1,\ldots,L\}} p_K$, then the worst-case reliability cannot be improved by adding "bridge" links between paths.

Proposition 2

Given the network graph with $\mathcal{P}$ disjoint paths from source s to destination d. For placing an edge between two arbitrary nodes v_1, v_2 of two different paths $\mathcal{P}_1, \mathcal{P}_2$, denote the equivalent probability for the linear path from the source to v_1 by p'_1, from the source to v_2 by p'_3, from v_1 to the destination by p'_2, and from v_2 to the destination by p'_4. If

$$(p'_1 < p'_2 \wedge p'_3 < p'_4) \vee (p'_2 < p'_1 \wedge p'_4 < p'_3) \quad (2)$$

holds, the additional edge does not improve the best-case reliability.

LP Formulation of Extremal Reliability

- Let $\mathbf{x} \in \{0,1\}^{|\mathcal{E}|}$ index all possible edge states.
- Decision variables: $p(\mathbf{x}) = \Pr[\mathbf{X} = \mathbf{x}]$.
- Objective (worst or best reliability):

$$\min / \max \sum_{\mathbf{x} \in \mathcal{S}_{ok}} p(\mathbf{x}).$$

- Constraints:

$$\sum_{\mathbf{x}} p(\mathbf{x}) = 1,$$
$$\sum_{\mathbf{x}: x_e = 1} p(\mathbf{x}) = p_e, \quad \forall e \in \mathcal{E},$$
$$p(\mathbf{x}) \geq 0, \quad \forall \mathbf{x}.$$

- Linear program in $2^{|\mathcal{E}|}$ variables: exact but not scalable.

Motivation for Graph Decomposition I

- Even though LP could be transformed to dual problem, where optimization variables are linear, but then constraints grow exponentially.

$$\begin{aligned} \max\ (\min) \quad & \mathbf{y}^{\mathsf{T}}\mathbf{b}, \\ \text{s.t.} \quad & \mathbf{y}^{\mathsf{T}}\mathbf{C} \leq (\geq)\ \mathbf{s}_0, \end{aligned} \tag{3}$$

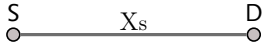
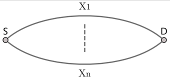
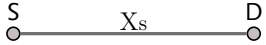
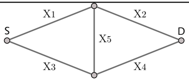
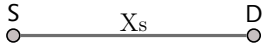
where $\mathbf{y} = [\mu, \lambda_1, \ldots, \lambda_n]$ contains the Lagrange multipliers for the constraints, the vector $\mathbf{b}$ contains the total probability and the marginals $[1, p_1, \ldots, p_{2^n}]$.

- Improvements in complexity by removing redundant constraints

Motivation for Graph Decomposition II

- Real topologies can easily have 20–30 links or more.
- Direct LP would require 2^{30} variables and constraints.
- But many networks contain:
  - long series chains,
  - pure parallel structures,
  - repeated motifs such as bridges and diamonds.
- Idea: **recursively reduce** these subgraphs to equivalent single links with effective marginal success probabilities and reliability bounds.
- Remaining core graph is much smaller; exact LP is then feasible.

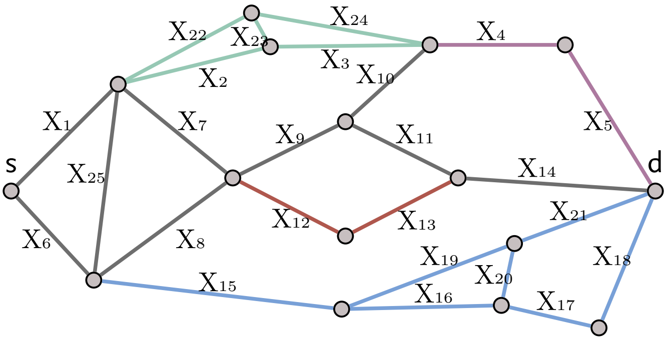
Network Decompositions

structures	replaced	iid	worst-case	best-case
		$p_s = \prod_{i=1}^{n} p_i$	$p_s^{wc} = \sum_{i=1}^{n} p_i - (n-1)$	$p_s^{bc} = \min p_i$
		$p_s = 1 - \prod_{i=1}^{n} (1 - p_i)$	$p_s^{wc} = \max p_i$	$p_s^{bc} = \sum_{i=1}^{n} p_i$
		SDP method	see Proposition 1	see Proposition 2

Network Decomposition Algorithm

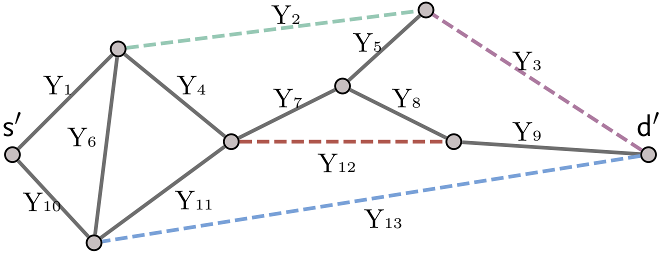
- Iteratively apply the following reductions:
  1. Detect and replace maximal **series** chains by a single equivalent link.
  2. Detect **parallel** groups and replace by an equivalent link.
  3. Identify **bridge and diamond** subgraphs and reduce using analytical bounds or local LP.
  4. Repeat until no further reductions are possible.
- Keep track of:
  - transformed link marginals,
  - propagated worst/best reliability bounds.
- Final reduced graph: small enough to solve the LP exactly.

Example Networks I



The initial example model with 25 edges.

Example Networks II



The initial example model after decomposition. The dashed lines represent the new links, and the marginals correspond to the effective probability of the simplified links.

Further Comparisons

Structure	Nodes	C. Pr.	Marg.	Links	L.a.D.	LP	Bounds
Example network	16	–	0.4	25	13	(0, 0.8)	(0, 1)
Figure 3 from [5]	5	–	0.75	7	7	(0.5, 1)	(0.5, 1)
"Euro Aug. 2010" from [6]	9	–	0.7	12	1	(0.1,1)	(0.1,1)
Fig.1 in [7]	8	–	0.3	12	12	(0, 0.6)	(0, 1)
randomly generated	15	0.3	0.6	27	13	(0.2,1)	(0.2,1)
randomly generated	150	0.01	0.8	114	19	(0,0.8)	(0,0.8)
randomly generated	15	0.4	0.8	46	46	–	(0.6, 1)

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[5] E. K. Mutar, 'Estimating the reliability of complex systems using various bounds methods,' International Journal of System Assurance Engineering and Management, vol. 14, pp. 2546–2558, December 2023.
[6] S. Knight, H. X. Nguyen, N. Falkner, R. Bowden, and M. Roughan, 'The Internet topology zoo,' IEEE Journal on Selected Areas in Communications, vol. 29, no. 9, pp. 1765–1775, 2011.
[7] J. Wilson, 'An improved minimizing algorithm for sum of disjoint products (reliability theory),' IEEE Transactions on Reliability, vol. 39, no. 1, pp. 42–45, 1990.

PD versus LB for the Diamond Network

Question: When to apply packet duplication and when load balancing?

- PD and LB strategies:
  - PD: send same packet over both paths; success if at least one path succeeds.
  - LB: split rate between paths; success may require both to be operational.
- We focus again on the **diamond network**: two two-hop paths in parallel between s and t.
- Each hop has a marginal success probability depending on SNR and effective rate.
- The diamond network is the elementary motif inside larger path-redundant topologies.

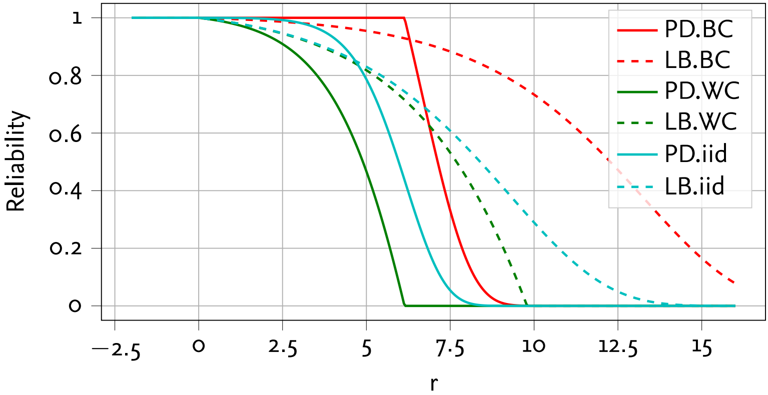
Rate Mapping and Marginal Success Probabilities

- Let r denote the effective end-to-end rate.
- Under PD: Each path carries rate r. Individual hops see rate r and SNR ρ_e.
- Under LB: Rate r is split across the paths (e.g. r/2 per path). Lower per-hop rate increases marginal success probabilities.
- Rayleigh fading, closed-form expressions relate r, ρ_e, and $p_e^{(PD)}$, $p_e^{(LB)}$:

$$\exp\left(-\frac{2^r - 1}{\rho_e}\right) = p_{ep}^{(PD)}, \quad \text{and} \quad \exp\left(-\frac{2^{\frac{r}{2}} - 1}{\rho_e}\right) = p_{el}^{(LB)}. \quad (4)$$

- These marginals are then plugged into the reliability-bounds framework (worst, i.i.d., best).

Reliability vs Rate: Crossovers



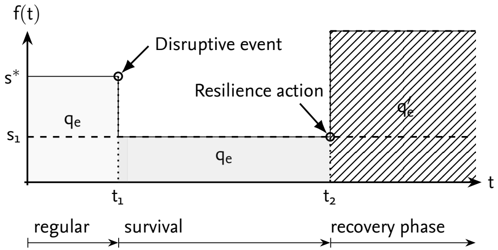
Reliability of PD and LB over effective rate for SNR=20.

Goodput Analysis

- Define goodput: $G(r) = r \cdot p_{succ}(r)$.
- Compute goodput-optimal rate for PD and LB under different dependency assumptions.
- Results:
  - In the **best-case**, PD and LB can achieve the same optimal goodput.
  - Under **i.i.d.** and **worst-case** dependencies, the favourable strategy depends strongly on SNR and target regime.
  - LB can dominate in goodput even when PD is more reliable at some rates.
- Again, there is no "one-size-fits-all" MC strategy when dependencies are taken into account.

Resilience Over Time: Phases and Service Level

- Resilience phases:
  - **Regular phase:** nominal operation with target service level s^*.
  - **Disturbance and survival phase:** performance degrades to s_1.
  - **Recovery phase:** multi-connectivity actions restore service.
- Detection delay ΔT and resilience actions affect the total power consumption and time under degraded service.
- Reliability bounds enter as the probability that MC can sustain required rates in each phase.



Resilience phases and service level vs. time.

Multi-Connectivity Strategies

- Consider N parallel paths from s to t.
- Two main strategies:

  Packet duplication (PD): same data is transmitted over multiple paths; success if at least one path succeeds.

  Load balancing (LB): traffic is split across paths; each path carries a fraction of the rate.
- Trade-offs:
  - PD improves reliability but increases resource usage.
  - LB improves spectral efficiency but may require all paths to succeed.
- Under dependent failures, the ranking between PD and LB is not obvious.

System and Power Model

- Rayleigh fading links with SNR depending on transmit power q_e.
- Effective rate on link e under strategy s:

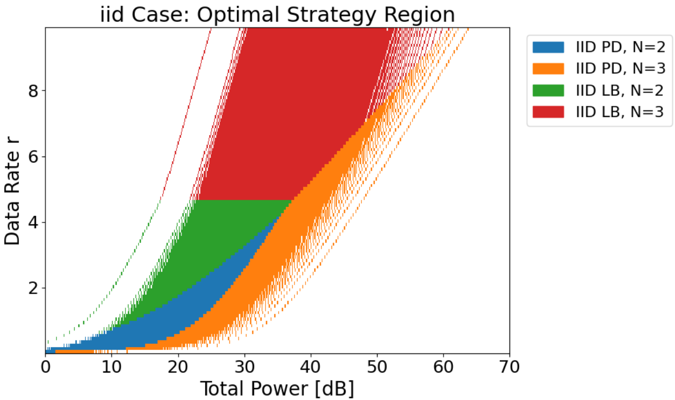
$$R_e^{(s)} \quad \Rightarrow \quad p_e^{(s)} = \Pr\left[\log_2(1+\alpha_e q_e) \geq R_e^{(s)}\right].$$

- Marginal success probabilities $\{p_e^{(s)}\}$ feed into the reliability-bounds framework.
- Total discounted power over resilience phases:

$$P_{tot} = P_{regular}(\Delta T, q_e) + P_{survival/recovery}(N, q_e, q_e', \delta),$$

with discount factor δ capturing horizon.
- Objective: choose MC strategy, number of paths N, and powers to meet reliability constraints with minimal total power.

Optimality Regions - Numerical Results



The optimal strategy for different parameters.

Summary of Contributions

- Analytical worst/best reliability bounds for networks with dependent link failures, given only marginals.
- LP formulation of extremal reliability and a scalable graph decomposition algorithm for large topologies.
- Resilience-aware power and MC design: joint optimisation of strategy, number of paths, and power.
- Detailed comparison of packet duplication and load balancing in diamond networks and as building blocks in larger graphs.
- Overall: a **toolbox** for designing resilient multi-connected networks under uncertainty about dependencies.

Open Problems and Future Work

- From two-terminal to all-terminal resilience analysis.
- Integration with:
  - O-RAN and AI-native RAN control loops,
  - network slicing and service orchestration.
- Joint optimisation of:
  - reliability, latency, and energy,
  - topology design, MC strategy, and scheduling.
- Automated mapping from observed network state to recommended MC strategy (PD/LB, number of paths, power allocation).

Take-Home Messages

- Dependencies matter: i.i.d. reliability can be misleading.
- With only marginal link statistics, we can still obtain sharp worst/best reliability bounds.
- LP + decomposition allows evaluation of realistic, large topologies.
- Multi-connectivity is powerful but needs:
  - strategy selection (PD vs LB),
  - power control and resilience-aware design.
- **Design checklist:** measure marginals, bound reliability, decompose the topology, and adapt MC strategy.

Publications – Questions?

1. Z. Ge and E. A. Jorswieck, ”Dependency and Link Diversity Placement for Reliable Wireless Diamond Networks,” ICC 2025 - IEEE International Conference on Communications, Montreal, QC, Canada, 2025, pp. 2857-2862, doi: 10.1109/ICC52391.2025.11160844.
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