Impact of Multi-Connectivity on Channel Capacity and Outage Probability in Wireless Networks

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1. Introduction

Multi-connectivity (MC) refers to a setting in which a user is simultaneously connected to a network through multiple connections. We investigated the impact of MC on the expected channel capacity under failures as well as the outage probability: the probability that a user is disconnected from the network.

- How does multi-connectivity affect per-user throughput and outage probability of a cellular network?
- How does a multi-connected network behave under different failures (targeted, random, line-of-sight)?

In this research, we assumed that each user in this network connects to exactly k base stations (BS) that provide the highest signal-to-noise ratio (SNR).

2. System Model

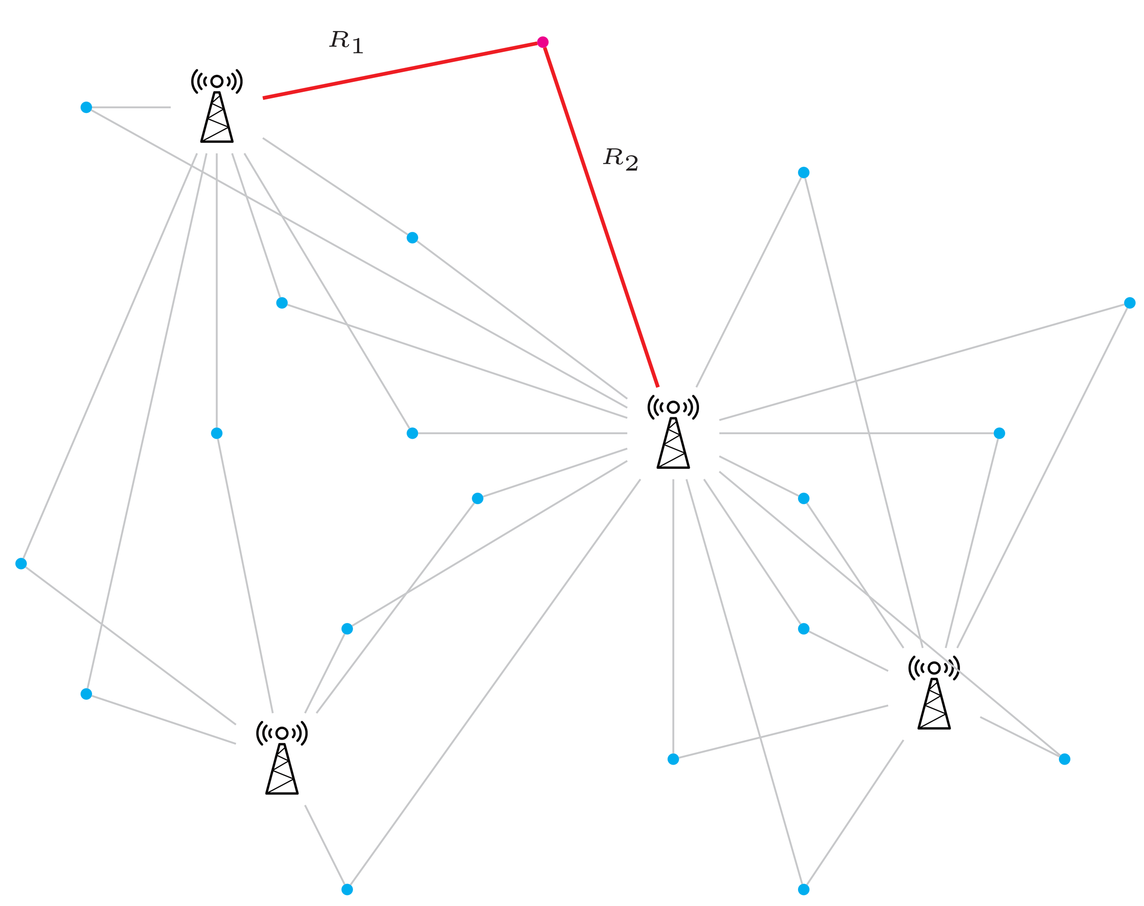


Figure 1: Example of 2-connectivity

Red user: connected to two base stations at distance R_1 and R_2.

3. Measures

Shannon's channel capacity:

$$C_j = W \log_2(1 + SNR_j), \tag{1}$$

$$W = \frac{\overline{W_{tot}}}{\lambda_{BS} D_{BS_j}}, \tag{2}$$

$$SNR_j = \frac{pR_j^{-\alpha}}{\sigma} = \begin{cases} cR_j^{-\alpha} & R_j \geq 1, \\ c & R_j < 1, \end{cases} \tag{3}$$

for $c = \frac{p}{\sigma}$ and where R_j is the distance to the j^{th} base station.

$$C_{sum}^k = \frac{\overline{W_{tot}}}{\lambda_{BS} D_{BS}} \sum_{j=1}^{k} \log_2(1 + SNR_j), \tag{4}$$

as we assume D_{BS} is independent of j.

Outage probability: $\mathbb{P}(D_U = 0)$.

4. Expected C_{sum}^k

Theorem 1. *In the high SNR regime, the sum of the channel capacities, $\mathbb{E}(C_{sum}^k)$, approximated with:*

$$\mathbb{E}(C_{sum}^k) = \frac{\overline{W_{tot}}}{\lambda_U} \frac{\alpha}{2\ln(2)} \left(\ln(\phi) + \gamma + 1 - \left(H_k + \frac{\lambda_{BS}\pi}{k} \right) \right), \tag{5}$$

is decreasing in k.

5. Failure Models

1. Random failures
Every link fails with a probability p.

2. Overload failures
BSs fail with a probability proportional to their degree.

3. Distance failures
Links fail when the distance between the user and the BS is higher than a certain threshold.

4. Line-of-sight failures
Links fail because they are not in the BS's line-of-sight (LoS).

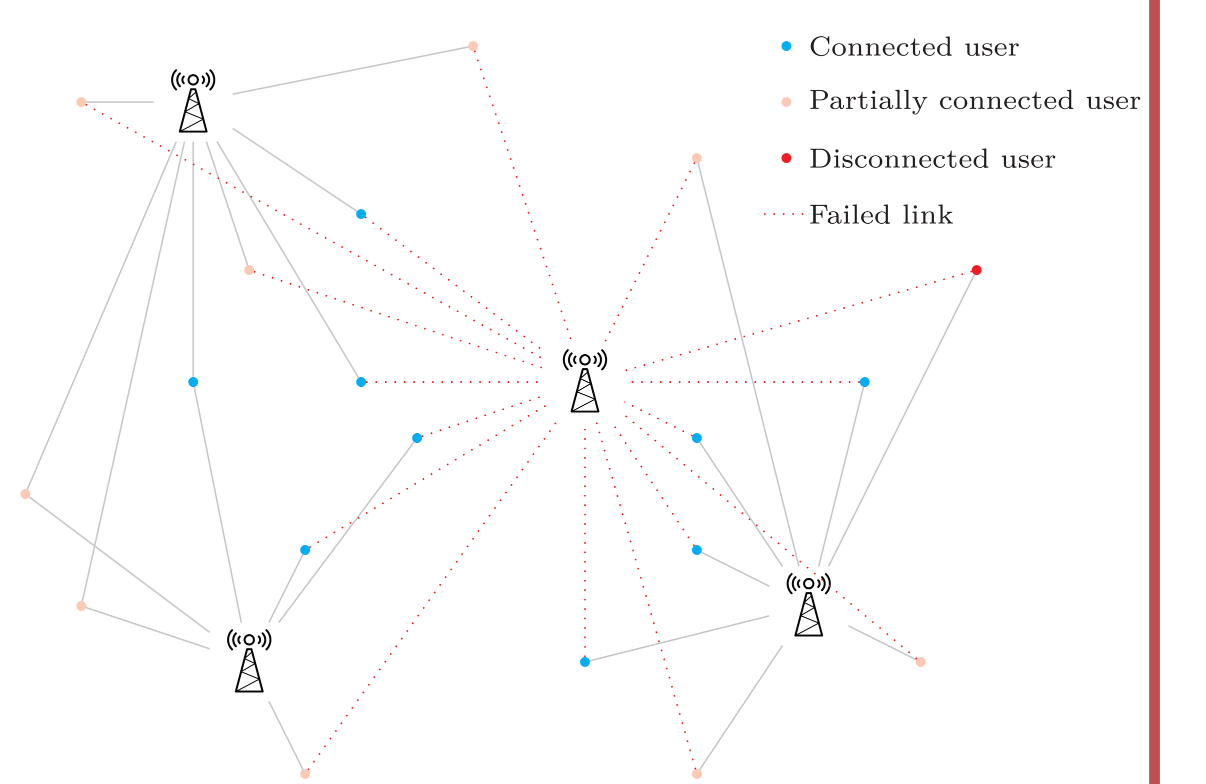
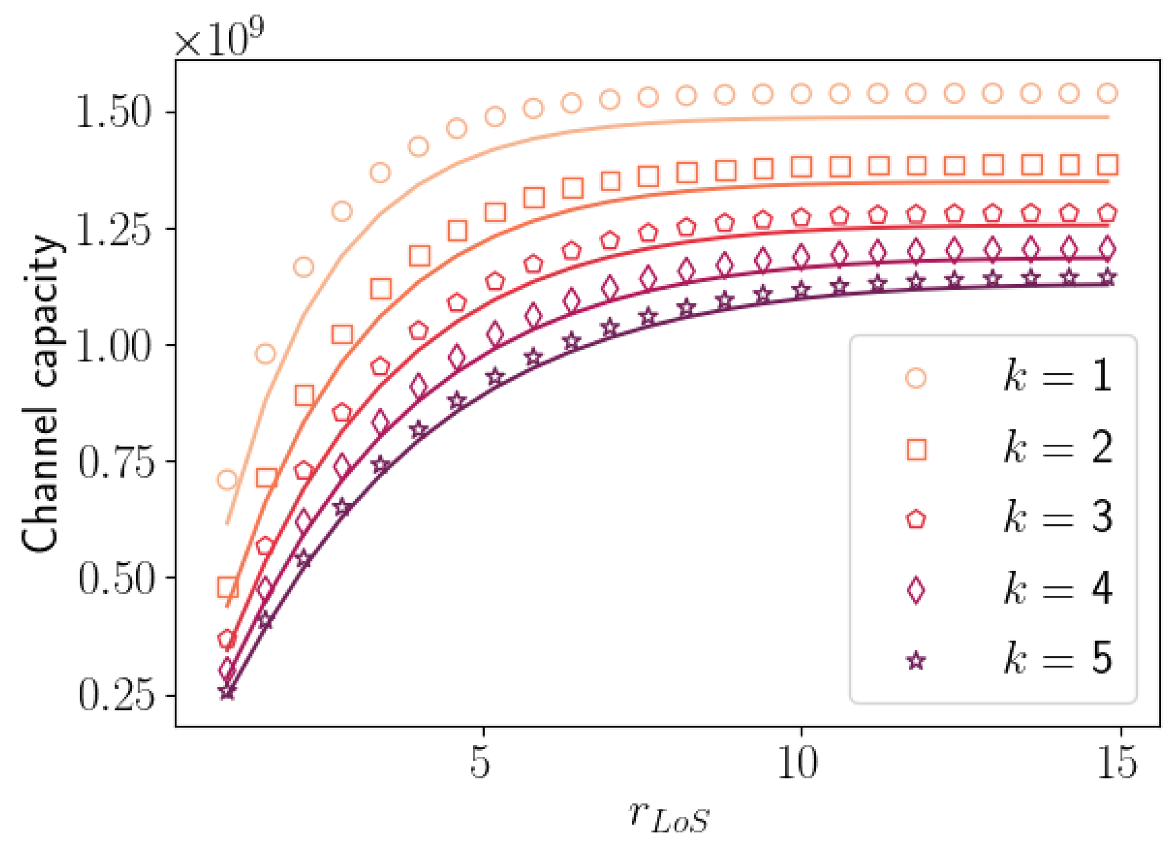
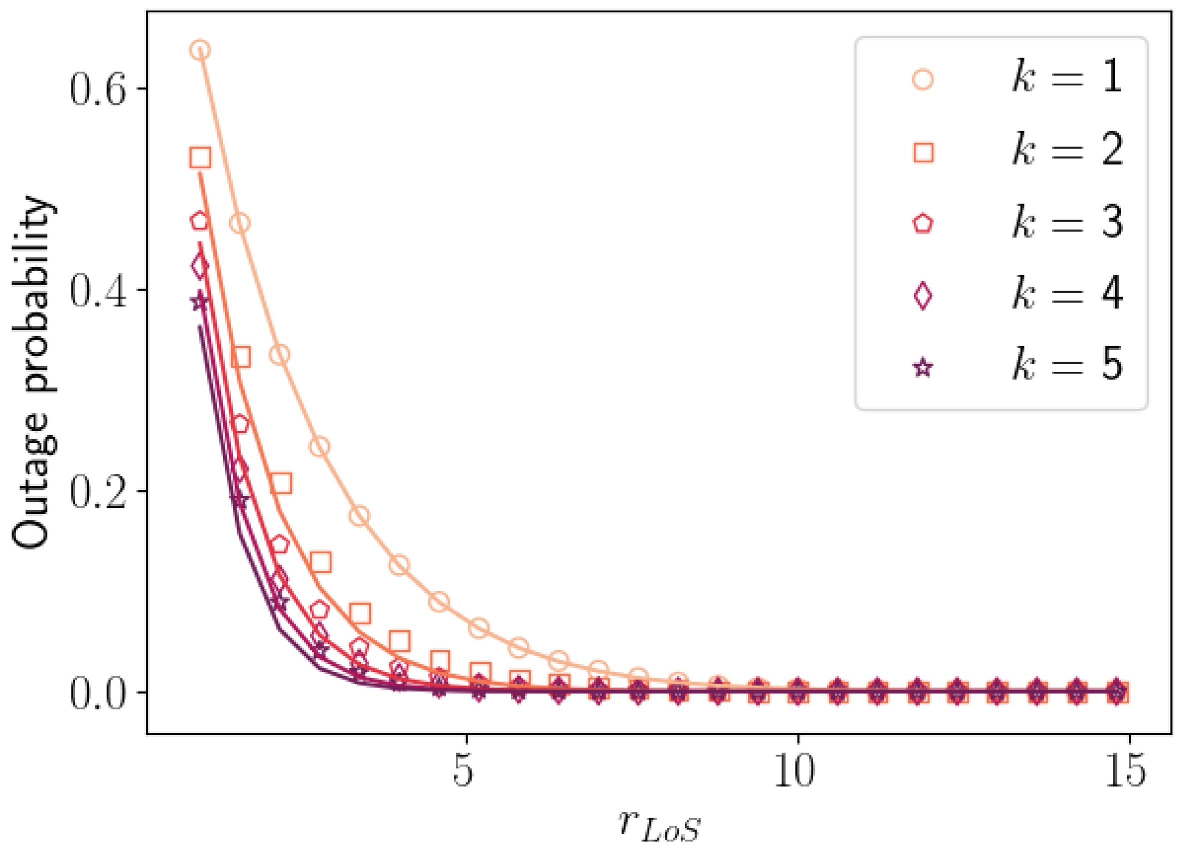


Figure 2: Example of overload failure, links fail with probability $p = 1 - D_U^{-\beta}$.

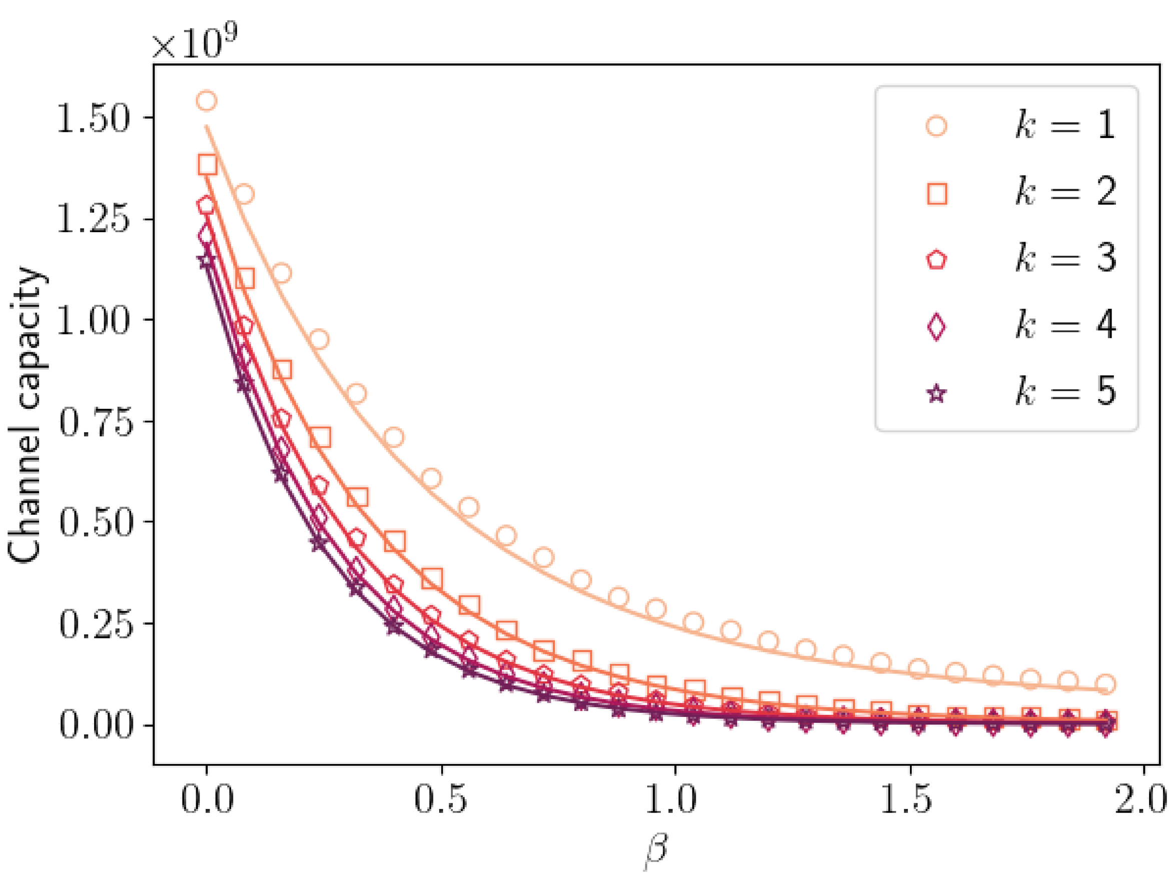
6. Results



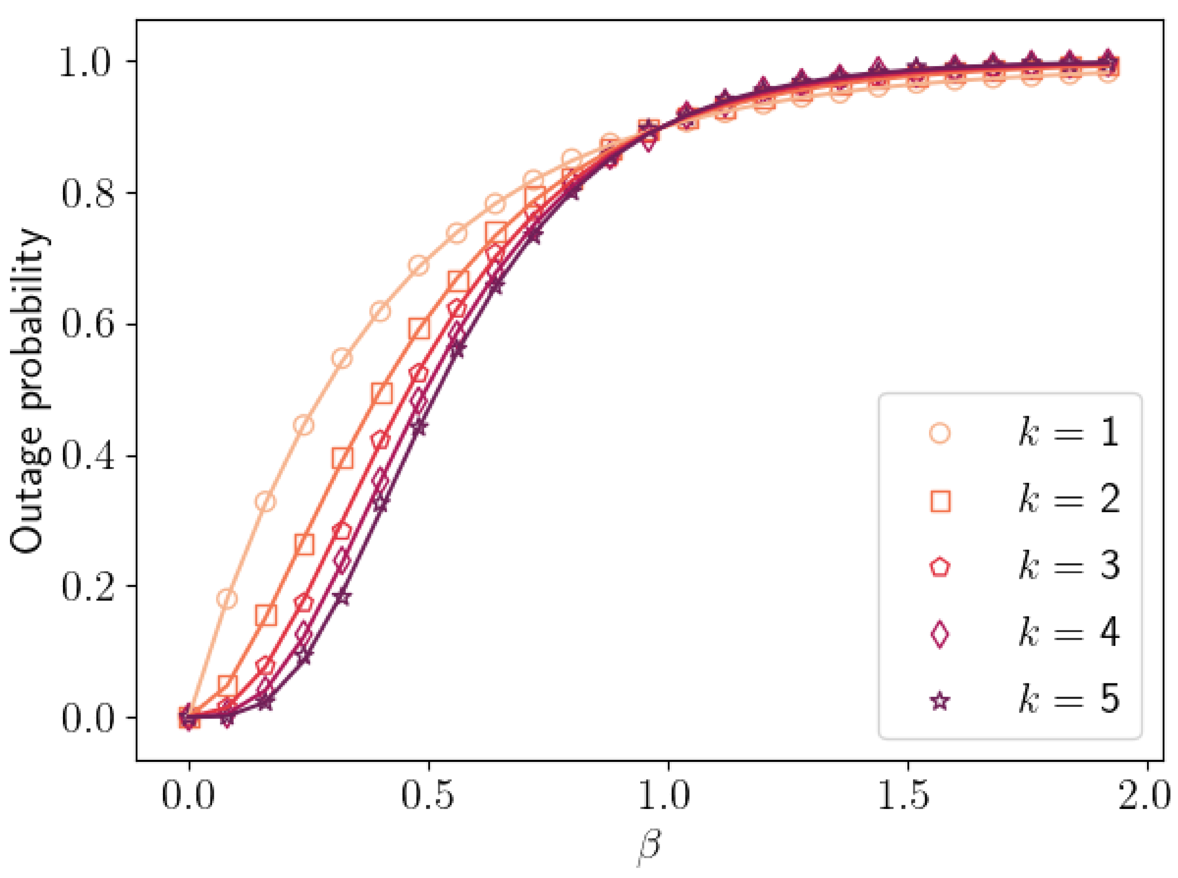
(a) Impact of r_{LoS} on $\mathbb{E}\left(C_{sum}^k\right)$ - LoS failure



(b) Impact of r_{LoS} on outage probability - LoS failure



(c) Impact of β on $\mathbb{E}\left(C_{sum}^k\right)$ - overload failure



(d) Impact of β on outage probability - overload failure

Figure 3: Simulated (circles) and calculated (line) expected channel capacities and outage probabilities. $\lambda_{BS} = 10^{-2}, \lambda_U = 0.1, \alpha = 2$, on a 1500x1500m area, so 225,000 users.

7. Conclusion

We have shown that multi-connectivity will not lead to higher per-user throughput, with the remark that there are many ways in which multi-connectivity can be used to benefit the user.
Moreover, while multi-connectivity negatively affects the per-user throughput, higher degrees of multi-connectivity always increase reliability for the user, as the outage probability decreases.
For future work, it is interesting to investigate different methods of dividing the channel capacity in multi-connectivity (e.g. packet-splitting or load-balancing), as this may lead to different conclusions.

References

[1] L. Weedage, C. Stegehuis, and S. Bayhan, *Impact of multi-connectivity on channel capacity and outage probability in wireless networks*, 2021. arXiv: 2104.09823 [cs.NI].

[2] C. Stegehuis and L. Weedage, *Degree distributions in AB random geometric graphs*, 2021. arXiv: 2104.03711 [math.PR].