Arnold's Bifurcation Principle Applied to Radio Link Failure and Beam Failure Early Warning in Cellular Networks (4G/5G/6G)

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Abstract

Mobile phone connections drop for two related reasons: a narrow mmWave beam gets blocked, or a link of any kind simply fades out because the phone has moved into a weak-coverage spot. Both problems are handled today by mechanisms that only react after the signal has already gone bad. This paper describes one small, fixed, dedicated hardware controller – not a piece of software – that watches the ordinary signal-quality numbers a phone or base station already measures, and raises a warning before either kind of failure happens. We show, on two separate synthetic examples, that the same fixed controller gives an early warning before both the mmWave beam failure and the general radio link failure mechanisms would fire on their own. We explain in plain terms why this only works well as dedicated hardware and not as software running on a shared processor. All results here are from simulated data; the next step is testing on real network measurement logs.

1 Introduction

Every mobile phone connection depends on keeping a good enough signal between the phone and the tower. Two specific failures are well known in the telecom industry:

1. **Beam failure**: In newer mmWave 5G, the phone and tower use a narrow directional beam. If something blocks it – a person walking past, a passing vehicle – the beam can fail in under a second. The industry's standard fix, called Beam Failure Detection and Recovery, only counts the failure after the signal has already gone bad several times in a row [1].

2. **General radio link failure (RLF)**: This can happen on any generation of network, in any frequency band, whenever the signal fades for long enough – for example, driving into a tunnel or a weak-coverage pocket. The standard mechanism here is a timer called T310: the phone counts consecutive bad readings, starts a timer, and declares the link failed only if the timer runs out without the signal recovering [2].

Both mechanisms share the same weakness: they are reactive. They wait for the signal to already be bad before doing anything. This paper applies **Arnold's Bifurcation Principle** – the same fixed, training-free method already used in our earlier work on hemodialysis vascular access, drone wind-gust safety, and cardiac arrhythmia warning – to both of these telecom problems at once, using the exact same underlying logic for both.

*Patent Pending.

2 The Simple Idea Behind the Method

Think of a phone's signal quality as something that is normally quick to bounce back from small dips – a bit of interference, a brief reflection off a wall – and quickly returns to normal. As a real problem approaches (a blocker moving into the beam path, or the phone drifting into a coverage hole), the signal gets slower and slower at bouncing back from these small dips, even before it actually fails. This slowing-down effect is a well-studied warning sign in many kinds of systems approaching a collapse [3], and it can be measured directly from how strongly one signal reading resembles the reading just before it (a statistic called lag-1 autocorrelation). Our method tracks this statistic, on a short rolling window of recent readings, with no historical data and no training required.

3 Why Dedicated Hardware, and Not Software or Firmware

It is tempting to think this could just run as a small piece of software or firmware on the phone's or base station's existing processor. We explain plainly here why that is the wrong choice for this application.

Software and firmware share the same processor as everything else on the device. That means:

- **It has to wait its turn.** The processor is already busy handling many other urgent radio tasks. Our monitoring logic would have to be scheduled in alongside all of that, and under heavy load, it may simply not run in time to catch a fast-moving failure.
- **It can be interrupted.** A more urgent task can always push our monitoring task aside, exactly when a fast failure is developing and speed matters most.
- **It can be corrupted or fail to update correctly.** Firmware is code that lives in memory and can be overwritten. A bad update, a memory fault, or a software bug can silently disable the safety warning, and nobody may notice until it has already failed to catch a real event.
- **It depends on the same power and clock domains as everything else.** If the main processor is reset, busy, or in a low-power state, the monitoring stops with it.

A small, dedicated hardware block avoids every one of these problems. It has its own fixed logic, wired directly to always run, with nothing to schedule, nothing to interrupt it, and nothing to overwrite. It draws very little power because it does one simple, fixed job. This is why we describe our invention specifically as a dedicated hardware controller, and not as firmware or software, anywhere in this paper.

4 Method

For each case study, we take a normalized signal-quality stream (RSRP or SINR, depending on the case) and a second, correlated proxy signal derived from the same measurements. On a rolling window of the most recent readings, we compute:

- the lag-1 autocorrelation of the primary signal (the early-warning statistic),
- the rolling variance of the primary signal, and
- the lag-1 autocorrelation of the second proxy signal.

No historical corpus or training step of any kind is used. The estimator starts working from the very first readings of a brand-new connection.

5 The k-of-n Quorum

A single reading crossing a threshold is not, by itself, treated as a reliable warning, since ordinary noise can cause a brief, meaningless crossing. We require agreement between multiple independently-derived channels before raising an alarm. With $n = 3$ channels and indicator functions $\nVdash_i(t) \in \{0, 1\}$ for channel i,

$$\text{Alarm}(t) = \nVdash \left[\sum_{i=1}^{n} \nVdash_i(t) \geq k \right], \quad k = 2,\ n = 3. \tag{1}$$

This same rule, and the same code, is used unchanged in both case studies below.

6 Case Study A: mmWave Beam Failure

We generated a synthetic beam-quality (RSRP) stream in which a blocker gradually approaches, causing the signal's natural recovery to slow down well before the beam physically fails. Figure 1 shows this stream alongside the point where the industry-standard Beam Failure Instance (BFI) counter would declare failure. Figure 2 shows our precursor statistic rising ahead of both the true failure and the reactive counter. Figure 3 shows the resulting early-warning lead time, and Figure 4 shows the three-channel quorum voting behind it.

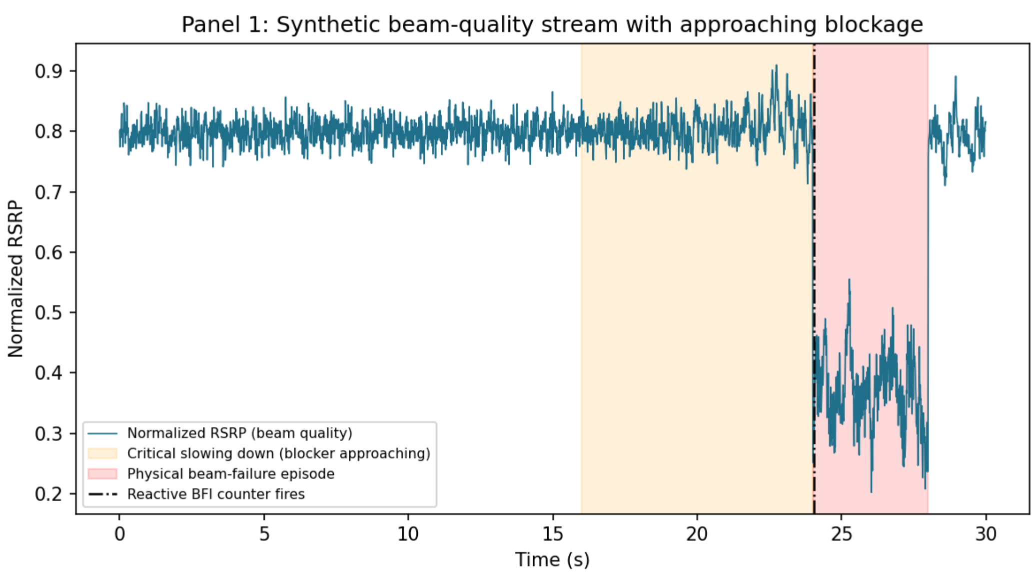

Figure 1: Case Study A: synthetic beam-quality stream approaching a physical beam-failure episode, with the reactive BFI counter's trip point marked.

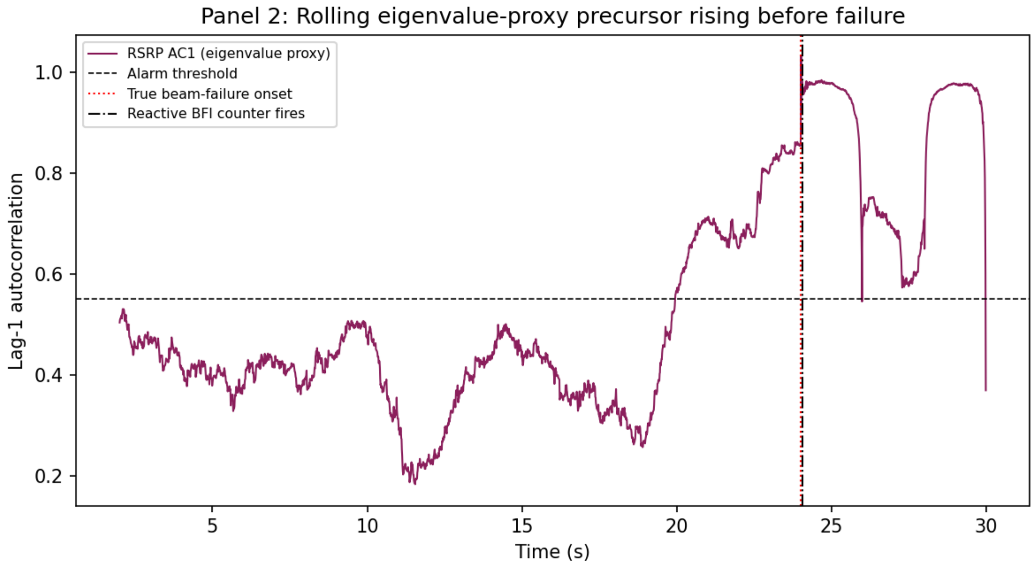

Figure 2: Case Study A: rolling precursor statistic crossing its alarm level before both the true failure and the reactive counter.

7 Case Study B: General Radio Link Failure

Using the identical estimator code, unchanged, we generated a second synthetic scenario: a phone drifting into a general coverage hole, unrelated to mmWave beams. Here the comparison mechanism is the T310/N310 timer procedure rather than the BFI counter. Figure 5 shows the signal stream and the timer's eventual trip point. Figure 6 shows the precursor statistic rising ahead of both. Figure 7 shows the resulting lead time, and Figure 8 shows the quorum vote.

8 One Controller, Two Problems: Why This Matters

Figure 9 shows the point of running both case studies side by side: it is the exact same hardware logic, with no changes and no retraining, applied to two completely different existing telecom mechanisms. The controller itself has no built-in idea of what a "beam" or a "cell" is – it simply watches whatever numeric stream it is connected to. This is what we mean by domain-blind: the same chip design that applies here has, in companion papers, also been applied unchanged to hemodialysis vascular-access pressure, drone flight-sensor data, and cardiac rhythm signals.

9 Prior Work

Autoregressive filtering has already been used in a granted patent to forecast the next RSRP reading in software [4]; that is a different use of similar mathematics, forecasting a future value rather than watching for a slowing-down warning sign. Separate work uses trained machine-learning models [11, 9, 10] or an extra sub-6 GHz sensing channel [6, 7] to guess at upcoming mmWave blockage, and a recent survey covers the wider push toward AI-based beam management [8]. A separate sensing-assisted patent uses new joint radar-and-communication signals for the same purpose [5]. General critical-slowing-down early-warning methods have also been studied for network-wide cascading

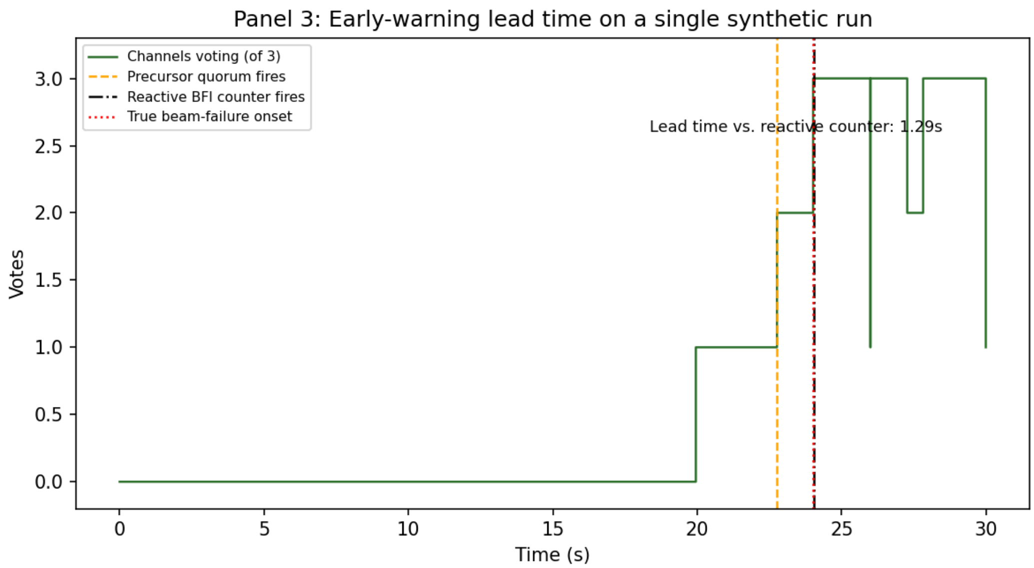

Figure 3: Case Study A: early-warning lead time on a single synthetic run. This is one run, not an averaged result (see Scope and Limitations).

failures [12] and for other types of networks [13], though not for cellular radio links specifically, and not as a dedicated hardware controller. None of this prior work describes a small, fixed, training-free hardware block that runs the same, unchanged, across both beam failure and general radio link failure.

10 Scope and Limitations

- **Simulation only.** Both case studies use synthetic signal generators, not real network measurement logs. The lead times shown are single runs, not averaged results across many trials or real deployment conditions.
- **Real-world confounds not modeled here.** Multipath reflections, fast phone rotation, handover boundary effects, and interference from nearby cells can all change the signal in ways not represented in these simulations.
- **The reactive-mechanism settings used here** (BFI counter thresholds, T310/N310 timer values) are illustrative values chosen to match the general shape of the real 3GPP mechanisms, not values taken from a specific commercial device.
- **Instantaneous blockage is a hard case.** This method depends on detecting a gradual slowing-down in how the signal recovers from small fluctuations, in the time window before a failure. If a blockage is near-instantaneous – a sudden, sharp fade with no gradual approach – there may be little or no warning signature for the precursor to detect, and the lead time over the existing reactive mechanism could be minimal or even negative in such cases. Increasing the measurement sampling rate can help in some of these cases: a blockage that appears instantaneous at a coarse sampling interval may reveal a short but real transition period once sampled finely enough, giving the precursor a brief window to work with. This does not help for a true physical discontinuity, such as a fiber cut or a hard connector break,

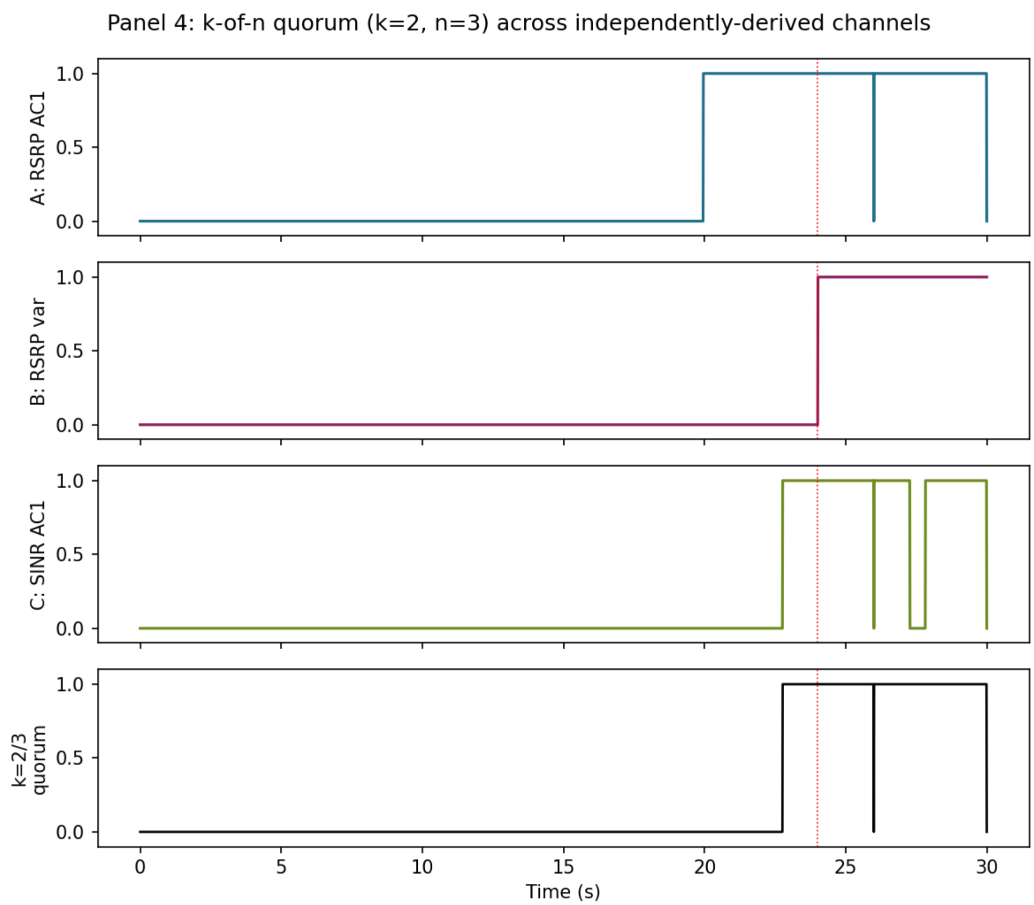

Figure 4: Case Study A: the three-channel quorum vote behind the alarm.

where no gradual transition exists at any sampling rate. A higher sampling rate is also not free: it increases power draw, works against the ultra-low-power design goal in Section 4, and typically raises measurement noise, which may require re-tuning the rolling-window size and alarm threshold. The method is expected to help most on gradual-onset failures, not truly instantaneous ones.

- **No physical hardware has been built yet.** The next step is testing this same fixed logic against real measurement logs from real phones and base stations.

11 Anticipated Questions

Q1: Why is validation only on simulated data? Real network measurement logs were not available at the time of writing. The simulation shows how the method behaves; the next step is testing it on real logs.

Q2: Could ordinary signal noise or fast movement cause a false alarm? Yes, this is possible, which is why the method requires agreement across three independently-derived channels rather than acting on a single reading.

Q3: Does this replace the existing BFI counter or T310/N310 timer? No. It is designed to run alongside these existing mechanisms, giving extra warning time, not to replace the

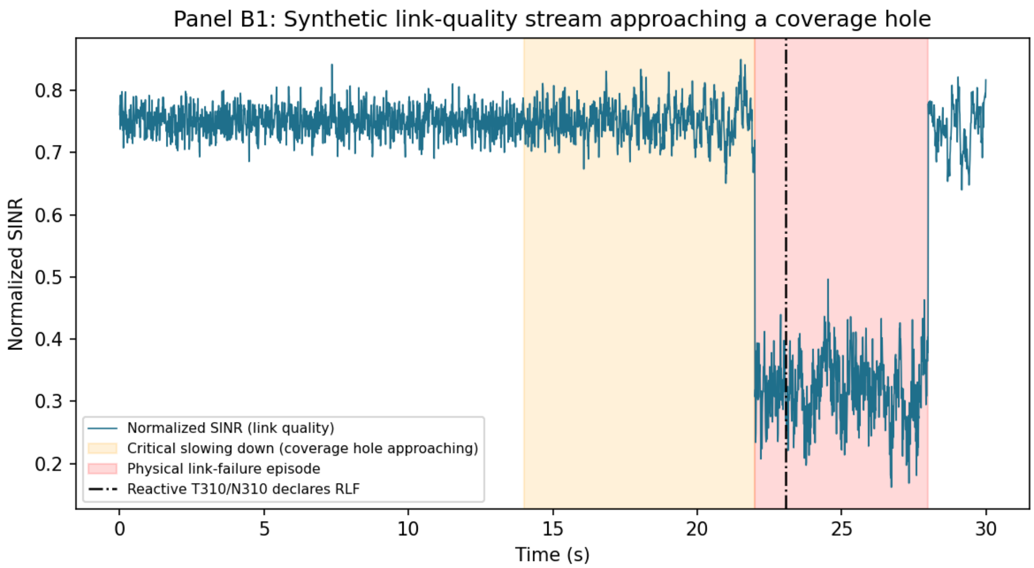

Figure 5: Case Study B: synthetic link-quality stream approaching a general coverage hole, with the reactive T310/N310 mechanism's trip point marked.

standardized fallback.

Q4: What is the intended hardware target? A small, low-power, dedicated hardware block that reads the signal-quality measurements a phone or base station already produces, requiring no new sensor.

Q5: Why does the same design apply to both beam failure and general link failure? Because the underlying method only looks at how a numeric signal recovers from small fluctuations. It does not need to know what the signal represents, so the same fixed design works on either problem without modification.

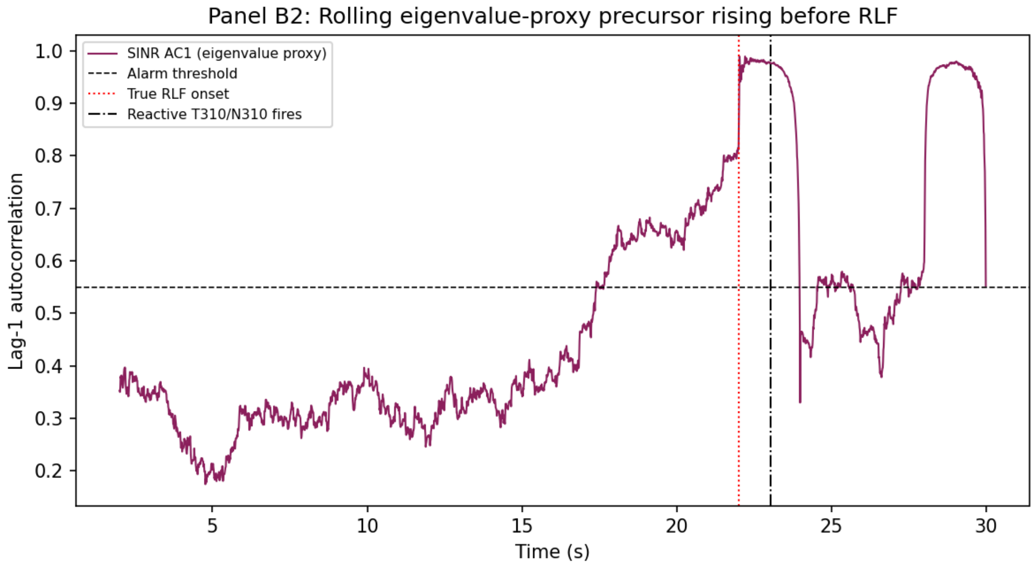

Figure 6: Case Study B: rolling precursor statistic crossing its alarm level before both the true failure and the T310/N310 timer.

12 Conclusion

Using one unchanged piece of fixed hardware logic, we have shown, on two separate synthetic examples, an early warning ahead of both the mmWave Beam Failure mechanism and the general Radio Link Failure mechanism used in cellular networks today. We explained plainly why this only works reliably as dedicated hardware, not as firmware or software sharing a processor with other urgent tasks. All results here are preliminary and based on simulated data; testing against real network logs is the necessary next step.

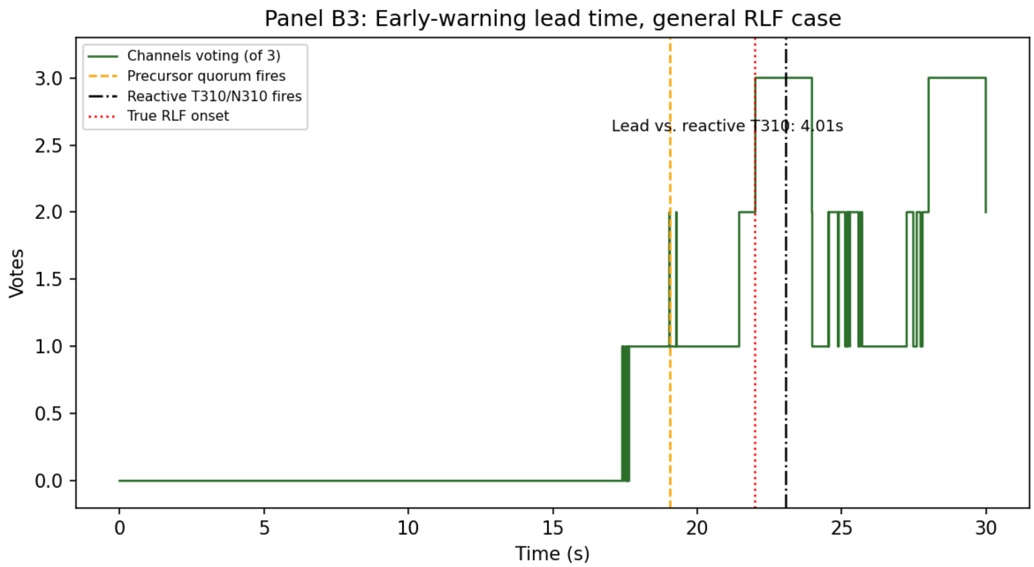

Figure 7: Case Study B: early-warning lead time on a single synthetic run. This is one run, not an averaged result.

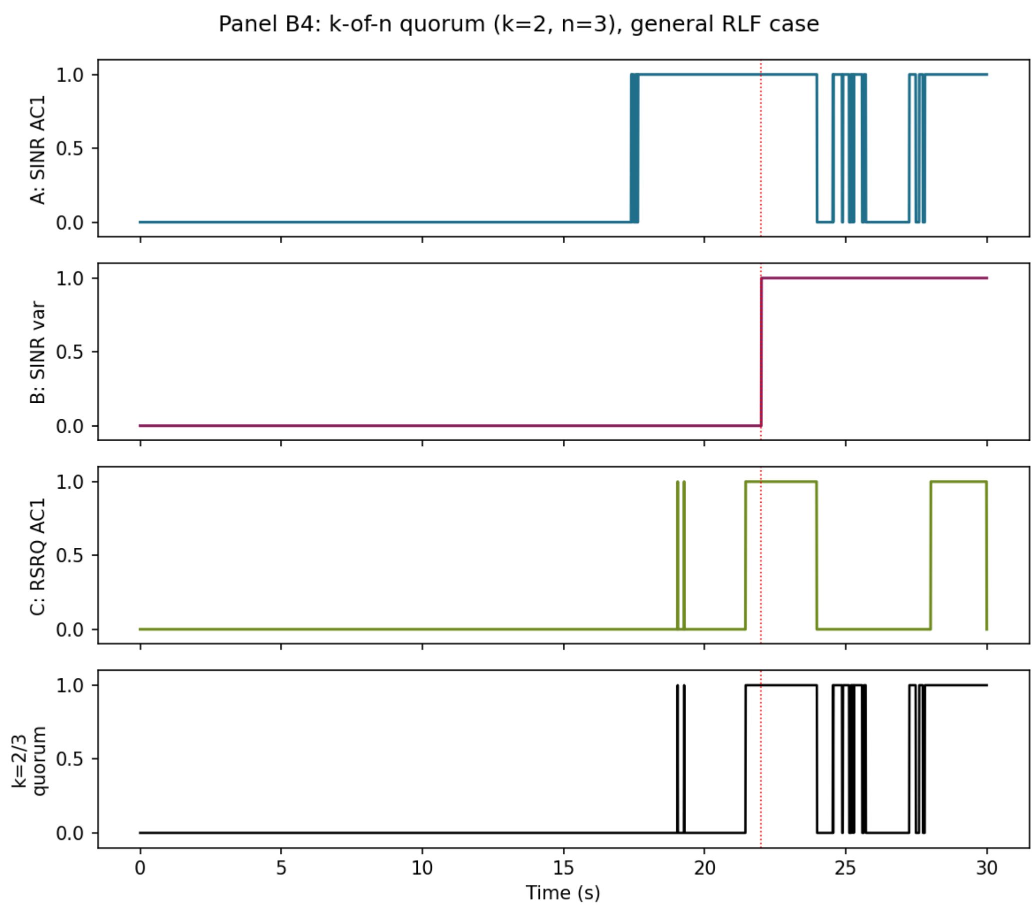

Figure 8: Case Study B: the three-channel quorum vote behind the alarm.

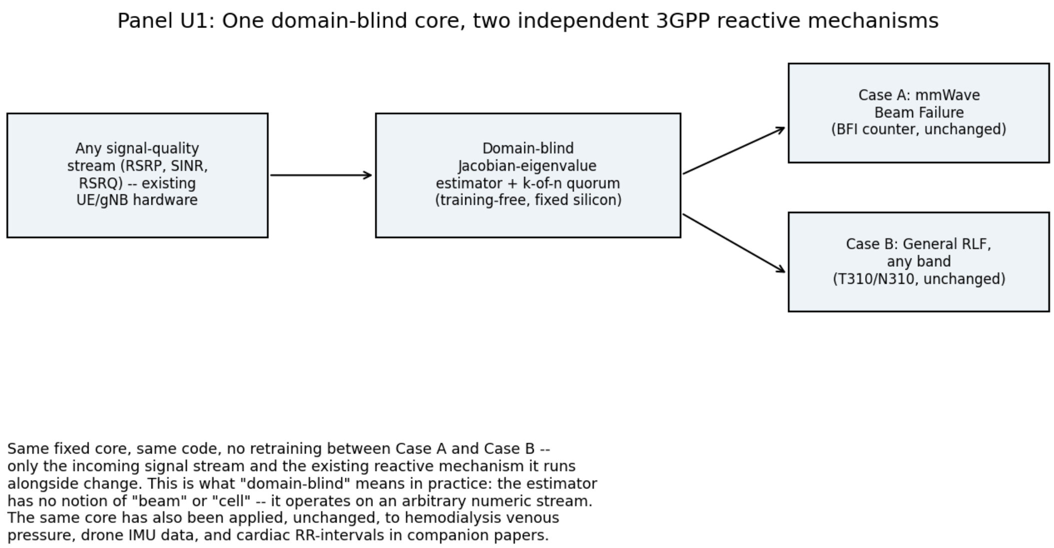

Figure 9: One fixed hardware core, applied unchanged to two different existing 3GPP reactive mechanisms.

References

[1] 3GPP TS 38.213, "NR; Physical layer procedures for control," 3rd Generation Partnership Project, Technical Specification (Beam Failure Detection and Recovery procedures).

[2] 3GPP TS 38.331, "NR; Radio Resource Control (RRC) protocol specification," 3rd Generation Partnership Project, Technical Specification (Radio Link Failure, T310/N310/N311 procedures).

[3] M. Scheffer, J. Bascompte, W. A. Brock, V. Brovkin, S. R. Carpenter, V. Dakos, H. Held, E. H. van Nes, M. Rietkerk, and G. Sugihara, "Early-warning signals for critical transitions," *Nature*, vol. 461, pp. 53–59, 2009.

[4] U.S. Patent No. 12,028,727 B2, "Managing feedback information to enable reference signal received power prediction."

[5] U.S. Patent Application Publication No. 2025/0088890 A1, "Method and system for sensing-assisted beam refinement and prediction for communications," filed Sep. 7, 2023, published Mar. 13, 2025.

[6] Z. Ali and H. Hallen, "Early Warning of mmWave Signal Blockage and AoA Transition Using sub-6 GHz Observations," *IEEE Communications Letters*, 2019. arXiv:1905.00594.

[7] "Guard Beam: Protecting mmWave Communication through In-Band Early Blockage Prediction," arXiv:2208.06870, 2022.

[8] "AI/ML for Beam Management in 5G-Advanced," arXiv:2309.10575, 2023.

[9] "Multi-Head DNN-Based Federated Learning for RSRP Prediction in 6G Wireless Communication," 2024–2025.

[10] "Physics-informed Diffusion Models for Multi-scale Prediction of Reference Signal Received Power in Wireless Networks," arXiv:2512.21475, 2025.

[11] "Intelligent Propagation Model Method for RSRP Prediction Based on Machine Learning," 2021.

[12] D. Zhou and A. Elmokashfi, "Network recovery based on system crash early warning in a cascading failure model," *Scientific Reports*, vol. 8, article 7327, 2018.

[13] M. Pirani and S. Jafarpour, "Network Critical Slowing Down: Data-Driven Detection of Critical Transitions in Nonlinear Networks," arXiv:2208.03881, 2022.