Performability-Aware Network Slicing for Mission-Critical Smart Grid Communications

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Introduction: The increasing complexity of smart distribution grids requires ultra-reliable and low-latency communications (uRLLC) to ensure real-time information delivery for monitoring, protection and control operations. Performability; a combined measure of a system's performance and reliability, is critical in these scenarios, especially under fault conditions [1]. For example, during a short-circuit fault, protective relays must communicate within milliseconds to isolate the affected section and avoid cascading failures. The integration of beyond 5G technologies introduces new paradigms in network slicing, enabling differentiated service guarantees. However, the challenge lies in designing performability-aware slicing strategies that can allocate resources efficiently and maintain service continuity under dynamic traffic loads and potential grid-induced failures. Thus, this thesis aims to address the following research questions.

- What are the essential requirements for communication services to support mission-critical protection operations in smart distribution grids?
- How can radio resources be optimally allocated in support of mission-critical protection operations while ensuring co-existence with bandwidth-intensive applications such as enhanced Mobile Broadband (eMBB), to ensure guaranteed performance during grid failures?
- How can we quantify the performance of the failure states of the combined power grid and the communication network, considering centralized and decentralized deployments?

Methodology: The initial thesis work begins by investigating the different message types for grid protection and control and classifies them into 5G use cases. Therein, we model the smart grid communication network as a sliced infrastructure where mission-critical protection traffic coexists with other resource-intensive services. To support this, we design and evaluate a network slice orchestration model that leverages network function virtualization to provide scalable, programmable communication tailored to smart distribution grid requirements. Our work involves the following main contributions:

- Three multidimensional Markov models are developed to assess the transient performance of network slicing for resource allocation with and without traffic priority.
- An optimization algorithm and a scheduling mechanism that supports the coexistence of traffic such as mission-critical uRLLC and bandwidth-heavy eMBB traffic while maintaining stringent quality-of-service guarantees.
- A two-tier admission control mechanism that integrates long-term intent admission control of service requests and short-term flow admission control, enabling differentiated handling of mission-critical and non-critical traffic.
- Two discrete event simulations that enable the evaluation of the performability, and a set of algorithms to allocate network resources aiming at achieving end-to-end latency requirements and availability demands of service requests in smart distribution grid.

Results and discussion: Through analysis and simulations, we reveal the behavior of a sliced network with heterogeneous traffic during the transient period and demonstrate the importance of traffic priority as well as the necessity of service adaptation. By implementing flow-level admission control for non-mission-critical traffic, enforcing prioritization, and allocating certain levels of reserved capacity for mission- critical traffic, we can ensure the service level objectives of latency-sensitive smart distribution grid protection traffic are met while the network utilization is efficient. Decentralized deployments offer minimum latency levels and faster fault recovery at the expense of increased resource overhead, whereas centralized architectures achieve better observability.

Future work: Future research extending this work could be directed at on-demand slice instantiation and automated failure recovery, adaptive slicing ensuring robustness against network congestion and component failures.

Conclusion: To summarize, this thesis contributes with models and simulation tools that enable the assessment and evaluation of the performability of end-to-end NFV-supported network services, and proposes a set of algorithms that efficiently allocate network resources aiming at achieving end-to-end latency requirements and availability demands of service requests in smart distribution grid protection and control.

References

[1] Beaudry. "Performance-related reliability measures for computing systems." IEEE Transactions on Computers 100.6 (1978): 540-547.