

Resource Allocation for Handoff in Hybrid V2X Communication

Sachin Sharma (2022CTZ8387)

Centre for Automotive Research and Tribology

Indian Institute of Technology Delhi

Supervisor's: Prof. B. K. Panigrahi and Prof. Manav Bhatnagar

ABSTRACT

Vehicular networks (VNs) have emerged as a key enabling technology for intelligent transportation systems by supporting reliable vehicle-to-everything (V2X) communication. However, the high mobility of vehicles leads to frequent handoffs (HOs), which introduce significant challenges such as increased signaling overhead, resource congestion in overlapping regions, and degradation of network connectivity. In particular, the large number of vehicles simultaneously performing HO in coverage-edge regions leads to severe load imbalance and inefficient resource utilization. Therefore, this thesis investigates various mechanisms to improve HO management, connectivity, and resource allocation in hybrid V2X communication systems through analytical modeling and optimization frameworks.

This thesis first investigates the joint optimization of connectivity probability and required resource blocks (RBs) for efficient HO management in hybrid V2X communication systems. Frequent HOs create excessive signaling and resource loading in overlapping regions of base stations, which reduces network efficiency and increases convergence time for resource allocation. To address this challenge, a game-theoretic Flexible Resource Allocation framework is proposed to dynamically redistribute RBs among vehicular clusters connected to a next-generation base station (g-NB). Closed-form expressions for the optimal transmit power are derived under the cellular vehicle-to-everything standard of 5G networks, and the impact of connectivity probability on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) links during HO is analyzed. Furthermore, the effects of non-uniform vehicle speeds and the time complexity of the algorithm are investigated.

Although dynamic RB allocation can alleviate load imbalance during HO, conventional cluster-head (CH)-based HO mechanisms still suffer from significant latency and contention in dense vehicular environments. In overlapping regions, a single CH often becomes a bottleneck due to heavy traffic and limited channel access, resulting in increased HO delay and potential HO failures. To overcome this limitation, this thesis proposes an evolutionary game-theoretic framework that enables the selection of multiple handoff agents (HOAs) in the overlapping region. These HOAs form cooperative HO clusters that distribute HO signaling tasks and reduce channel contention among vehicles. The variability of V2V and V2I links is captured using a queueing-theoretic model to analyze the buffering of HO data at HOAs. Furthermore, optimal RB allocation is performed to minimize the total waiting time in HO clusters, thereby improving HO efficiency and network stability in dynamic vehicular environments.

Despite the advantages of HOA-based cooperative HO mechanisms, dense vehicular deployments introduce additional challenges such as hidden-node (HN) contention and protocol-level timing inefficiencies. These issues become particularly severe in overlapping HO regions, where multiple vehicles attempt to access the wireless channel simultaneously. To address this problem, a HN-aware distributed HO framework is developed based on multiple HOAs. The spatial distribution of vehicles is modeled using a Matérn Cluster Process with Holes (MCP-H), which captures realistic vehicular dispersion while incorporating safety-driven spatial exclusion regions. Cluster member (CM) association with HOAs follows a minimum-distance rule, while spatial statistics are used for performance evaluation. The HOA to CM role selection is formulated as a constrained evolutionary game-theoretic problem that accounts for g-NB resource limitations, contention delay, and protocol timing constraints. The resulting evolutionary dynamics converge to an Evolutionarily Stable Strategy, enabling adaptive load distribution among HO clusters and improving HO reliability in high-density scenarios.

In addition to improving HO coordination and load distribution, reducing the frequency of HO events is also essential for improving network performance in high-mobility scenarios. Conventional V2I communication relies on continuous connectivity with base stations to deliver real-time content, which leads to frequent HO events and increased signaling overhead. To mitigate this issue, this thesis proposes a cache-enabled HO framework in which vehicles store pre-fetched data at the user equipment, allowing them to access cached content even when leaving the coverage area of a base station. A game-theoretic optimization framework is developed to determine the optimal transmit power of gNBs for proactive data distribution. Closed-form expressions for optimal transmit power are derived to jointly consider HO rate and average throughput under dynamic channel conditions. Simulation results confirm the effectiveness of the proposed approach in improving throughput and reducing unnecessary HO operations in high-mobility VNs.