IEEE P802.11  
Wireless LANs

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| Proposed Additions and Revisions for Gap Analysis of Automotive TIG Technical Report Draft | | | | |
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Abstract

This document proposes modifications to Section 4 of document 802.11-25/1295.

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1. **Gap Analysis**

While IEEE 802.11 standards continue to evolve, several key gaps remain for automotive applications’ requirements identified in Section 3, highlighting specific gaps that prevent optimal automotive service delivery [7, 8, 19]:

**Service Discovery for Automotive Services**:

Section 3 identifies automotive service discovery requirements, for example, for sensor data sharing with certificate validation, fast network discovery within 100ms for drive-thru scenarios, capability advertisement for both download and upload services, and authentication support.

IEEE 802.11u [9] provides Generic Advertisement Service (GAS) and Access Network Query Protocol (ANQP) for service discovery, but such multi-frame exchanges (GAS Initial Request/Response, GAS Comeback Request/Response) add further latency, e.g., require 200-500ms in congested environments, which may exceed the automotive timing requirements. For example, HD map dowloads in drive-thru scenarios require that the connection establishment within 100ms.

IEEE 802.11ai [12], Fast Initial Link Setup (FILS) Discovery mechanism aims to reduce the discovery process duration via various mechanisms including: FILS discovery frames which may be transmitted more frequently than beacon frames, non-AP STAs sending probe requests including the list of APs they already know about and therefore do not wish to hear from, each AP reporting on other APs within the same ESS it knows of via any of its operating radios, and others. However, these features are not known to be widely adopted. Furthermore, when it comes to the periodicity of FILS discovery messages, it is important to avoid band polution, esp. as beacons grow in size and the needed transmission time.

IEEE 802.11be[10] Multi-Link Operation (MLO) enables simultaneous operation across 2.4/5/6 GHz bands. For Multo-Link Device (MLD) STAs operating in any MLO mode, such as Simultaneous Transmit Receive (STR), Multi-Link-Mulit-Radio (MLMR), or extended-Multi-Link-Single-Radio (eMLSR), the avaialability of two radios, even if one radio is only good for scanning and receiving low-MCS packets, potentially accelerating discovery through parallel scanning via these multiple radios each scanning in a different band. Note that for a STA that aims to set up a MLMR or STR link between itself and an AP, it needs to be ensured that the multi-link aspect does not add latency waiting for two channels in two different bands to be identified. For example, the STA might proceed with association and establishing link security via one link, as soon as a channel has been identified in a first band, and later, add a second link upon identifying a second channel in a different band via another radio.

Also note that due to its short range, the use of 6 GHz for offloading has inherent limitations.

IEEE 802.11bn's[11] proposed coordinated spatial reuse and ultra-low latency features remain in development and are not optimized for automotive discovery scenarios where vehicles need rapid identification of upload-capable versus download-capable infrastructure.

Service discoverymechanisms For example, the work done in IEEE AI/ML studies directed to this objective can be helpful. See [18]

**Autheticated and Seccure Connetion Establishment performance**:

Section 3 requires fast connection establishment, such as within 30 seconds for stationary map downloads and 100ms for mobile scenarios. Authentication overhead can possibly add 220-500ms due to vehicle certificate validation chains that could result in connection establishment latency to exceed these targets.

IEEE 802.11ai [12], Fast Initial Link Setup (FILS) authentication reduces the overhead and latency of association and EAP-based authentication using information from a prior full authentication between a STA and an AP via a smaller number of exchanges., representing a significant improvement over traditional authentication procedures.

However, FILS based authentication is not widely adoped. Furthermore, it is important to evaluate the effectiveness of FILS authentication in vehicular environments, both for their scalability if multiple vehicle STAs concurrently attempt to authenticate and establish a secure link with an AP. Note that the more challenging RF enviorment for vehicular offloading, such as vehicle STA mobility up to 40 km/h, as well as dense-deployment interference scenarios common at parking areas and charging stations where multiple vehicles compete for access can cause authentication frames loss and thus, authentication failures or added latency. Such added authentication latency could be significant for high-mobility STAs like vehicles, and drive the overal connection establishment latency to exceed the required latency KPIs.

The standard can be enhanced to address parallel multi-channel scanning requirements essential for rapid discovery in automotive applications. Pre-authentication mechanisms could also be optimized for predictable vehicular routes to known service locations to leverage route planning data for faster connection establishment.

Furthermore, priority-based association mechanisms for handling multiple simultaneous vehicle connections at busy parking facilities could be specified to decrease connection delays when vehicles arrive concurrently.

IEEE 802.11be[10] MLO could enable faster connection establishment across multiple bands simultaneously, but it can be further improved by integrating with fast connection establishment technique such as FILS for automotive scenarios.

Features introduced in 802.11u, which was used to create WFA Passpoint capability can also help facilitate authentication and subsequent secure link establishment. To ensure that a STA, such as a vehicle only selects an AP it can successfully authenticate with, and thereby reduce the expected overal AP discovery latency, the use of interworking capability with other external entities such as enterprise networks, together with the use of ANQP process which allows STAs to query the APs pre-association, helps vehicle STAs to identify which APs are operated by service providers the vehicle STA has credentials to successfully authenticate with, and/or has authenticated with before. This becomes even more helpful for moving vehicles, as they have more stringest discvery latency requirements, and yet often fall out of range of their currrent AP and need to expeditiously identify the next suitable AP they are in range of.

**Mobility and Handover Support**:

The fast and seamless roaming requirements are discussed in section 3. For example, continuous sensor reporting and resumable map downloads, with vehicles traversing multiple AP coverage areas while maintaining upload sessions for processed environmental maps (~1-2GB) and time-sensitive event reports need fast and seamless roaming. Sustained streaming services over WLANs also impose roaming latency limitations depending on vehicle speed, and steaming service QoS.

IEEE 802.11r [13] Fast BSS Transition (FT) provides PMK caching and 4-way handshake optimization for STAs as they roam among APs within the same ESS that belong to the same mobility domain, typically achieving 200ms handover targets for intra-ESS scenarios. However, this performance may not meet the stringent timing requirements for continuous time-sensitive vecular data transfer, such as sensor uploads identified in Section 3, where seamless transitions are essential for maintaining time-sensitive event reporting capabilities. FT further allows for additional information sharing about a target AP, such as measuremenet reports, neighbor list, and other helpful information. The standard's focus on intra-ESS scenarios for FT, and its authentication improvements being limited only to mobility domains defined within a single ESS presents challenges for automotive applications where vehicles traverse different operator networks, requiring inter-ESS roaming capabilities beyond the current scope.

IEEE 802.11k [14] Radio Resource Measurement provides neighbor reporting and load information that serves as a foundation for handover decisions. The use of AI/ML to improve roaming has been discussed in [18] The standard could be enhanced with mobility prediction algorithms for anticipating access point transitions based on vehicle speed and trajectory data. Current handover mechanisms could benefit from QoS state preservation for ongoing bulk transfers or prioritized time-sensitive traffic during roaming events.

MLO mechanims could improve roaming experience by allowing a single link maintained with current AP, while another link is established with the target AP. However, this capability is not supported in IEEE 802.11be and might not be supported in 802.11bn either.. IEEE 802.11bn introduces seamless roaming enhancements with reduced handover latency targets and enhanced fast BSS transition mechanisms including coordinated roaming through target AP MLD and context transfer capabilities for APs within a seamless mobility domain (SMD). However, these standards require broader inter-ESS capabilities for automotive applications where vehicles regularly traverse different operator networks, and would benefit from vehicular-specific coordination algorithms that account for the rapid topology changes and mobility prediction based on vehicle trajectory characteristic of automotive environments.

**Multi-vehicle Coordination:**

In section 3, efficent aggregation requirements of similar sensor reports from multiple vehicles is required to reduce upload redundancy, and multicast delivery mechanisms for common map elements are needed to minimize redundant unicast traffic in high-density scenarios

IEEE 802.11bc [15] Enhanced Broadcast Service provides improvements for broadcast traffic delivery with enhanced reliability mechanisms, addressing some aspects of group communication required in automotive scenarios. However, the standard would benefit from faster service detection mechanisms, as beacon-based service advertisement with ~1 second intervals may not meet automotive timing requirements for 100ms connection establishment in drive-thru scenarios. Additionally, automotive applications require enhanced security mechanisms for broadcast/multicast traffic in dynamic vehicular environments, including secure group key management and authentication for vehicles joining and leaving broadcast services, as well as verification of map data authenticity in collaborative scenarios.

IEEE 802.11be coordinated spatial reuse and multi-link coordination capabilities could improve efficiency in dense vehicular environments. IEEE 802.11bn coordination features include Multi-AP Coordination (MAPC) framework and coordinated beamforming that could enable sophisticated multi-vehicle management. However, these enhanced coordination features might be difficult to adopt in outdoors environment with fast channel variations and semi-stationary or moving vehicles and might require automotive-specific algorithms for collaborative automotive scenarios.

**QoS and Traffic Management:**

Section 3 identifies different automotive traffic types requiring sophisticated prioritization. For example, bulk map downloads (8GB background transfers), dynamic map updates (50MB with sub-second requirements), large sensor uploads (5GB collaborative datasets), streaming services at various quality tiers, and time-sensitive event reports requiring adaptive QoS based on vehicle context.

IEEE 802.11e[16] Enhanced Distributed Channel Access (EDCA) provides basic QoS through four access categories (AC\_VO, AC\_VI, AC\_BE, AC\_BK) with differentiated channel access parameters. The standard establishes a foundation for traffic prioritization in wireless networks through access category-based medium access control. Furthermore, HCF (Hybrid Coordination Function) Controlled Channel Access (HCCA), by allowing contention-free periods of channel access during Transmit Opportunities (TXOPs) for QoS STAs allows to better serve time-sensititve traffic based on Traffic Specifications (TSPECs). Additionally, Stream Classification Services (SCS), especially their augmented variation enabled as of 802.11be allow for STAs to request from a supporing AP detailed data packets treatment for different traffic streams, including data rate and delay bound, thereby enabling APs to plan their resource allocation so that they can better serve their STAs. Additionally, for packets out of such traffic stream,

IEEE 802.11be also introduces enhanced QoS features with the aid of multi-link QoS coordination, potentially enabling more sophisticated traffic management across multiple bands. IEEE 802.11bn's proposed ultra-low latency mechanisms and deterministic access could also further address time-sensitive prioritization requirements. However, these standards require integration with automotive-specific traffic classification systems to optimize QoS mechanisms for vehicular applications, esp. for mobile and semi-mobile scenarios, wherein the limited time a STA is associated with an AP further contributes to traffic time sensititvity. .

**Session Management and Resumption:**

As described in section 3, some WLAN offloading use cases, such as the resumable vecular data downloads (e.g. 8GB full-region map refreshes,) and uploads (e.g. integrity-checked sensor uploads) can survive mobility-induced interruptions across different operator networks. Such disruptions may be roaming-induced, or result from harsher outdoors RF conditions during frame exchange between an external AP and a vehicle STA.

IEEE 802.11r provides security context maintenance during handovers within extended service sets. But current standards assume stationary clients with infrequent interruptions, differing from vehicular scenarios with frequent handovers. The standards would benefit from also encompassing high-mobility STAs such as vehicles (which may be moving at above 3 km/h speed) use cases and assess FT’s performance during such scenarios. For example, enhanced state preservation during handovers, service resumption with coordination across operator networks, and integrity checking, and context maintenance during mobility events.Furthermore, 802.11bn seamless roaming aims to mitigate roaming-induced disruptions through better coordination between current and target AP, including context trasnfer.

IEEE 802.11be MLO could provide a more robust connection between AP and STA and thus reduce interruptions through alternate links, while IEEE 802.11bn enhanced reliability features and context transfer capabilities could reduce disruption/resumption frequency. However, these standards require session state preservation mechanisms for seamless continuation of large transfers across different access points to fully address automotive mobility requirements. Such session state preservation may benefit from help from upper-layer protocols.

**Infrastructure Resource Allocation:**

Section 3 discussed the requirement of automotive-specific resource allocation supporting various and sometimes asymmetric traffic patterns. For example, map downloads and streaming services need sustained downlink capacity while sensor uploads demand burst uplink capability, along with dynamic capacity advertisement and multi-AP coordination for vehicles in motion.

IEEE 802.11ax[17] introduces Orthogonal Frequency Division Multiple Access (OFDMA) for improved resource allocation efficiency, enabling more granular bandwidth allocation compared to previous standards. This provides a foundation for sophisticated resource management in dense wireless environments.

However, current implementations would benefit from enhanced capabilities to dynamically advertise available uplink capacity for sensor data uploads, reserve downlink bandwidth for map distribution to multiple vehicles, and provide edge computing integration for real-time sensor data processing. The standard could be enhanced with automotive-specific resource allocation mechanisms that account for the asymmetric nature of vehicular traffic patterns and coordinate resource allocation across multiple access points to optimize coverage for vehicles in motion.

IEEE 802.11be enhances OFDMA with improved efficiency, coordinated spatial reuse, and multi-link resource coordination, potentially enabling more sophisticated resource management. IEEE 802.11bn deterministic access mechanisms could enable predictable resource allocation for automotive services. However, these standards require automotive-specific mechanisms for advertising uplink capacity, coordinating the vehicular data distribution and sharing, and integration with automotive service classification and priority management systems to address the automotive use cases’ requirements identified in Section 3.

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