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RESEARCH ARTICLE

Unlocking Mobility for Wi-Fi-Based Wireless Time-Sensitive Networks

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ABSTRACT Undoubtedly, mobility remains a fundamental asset in wireless communications. Conversely, time-sensitive networking (TSN) represents a vital technology that enables determinism and low latency, fundamental for time-sensitive applications. In our study, we marry these two concepts by introducing a pioneering procedure that facilitates seamless roaming within a Wi-Fi-based Wireless Time-Sensitive Network (W-TSN). Through extensive real-world development and testing, we assess various techniques for optimizing handover moment selection and reducing handover delay. Our findings demonstrate that an integrated approach combining Received Signal Strength Indication (RSSI) and location-based online reduces the need for traditional channel scanning. This approach surpasses the offline and midpoint selection methods, excelling in identifying the optimal handover point and reducing handover delay to less than 20 milliseconds.

INDEX TERMS Handover, IEEE 802.11, openwifi, UWB, wireless time-sensitive networking.

I. INTRODUCTION

With the growing emphasis on technologies such as extended reality (XR), which aims to blur the line between the virtual and real world, the concept of motion-to-photon latency has emerged. This latency refers to the time it takes for user movements to be accurately reflected on a display screen, such as those found in an augmented reality (AR) headset. When the motion-to-photon latency exceeds 20 ms, it becomes difficult for your mind to believe that you are truly immersed in the virtual environment being portrayed [1]. In fact, prolonged exposure to high motion-to-photon latency can lead to unpleasant symptoms such as motion sickness and disorientation [2].

Imagine a scenario where multiple AR headsets are wirelessly connected to a central computer that possesses ample processing power, enabling a top-notch mobile user experience. In this context, the network connecting the headsets to the computer becomes vital. It should offer high reliability and minimize communication latencies below the motion-to-photon latency limit, even during the handover time. This is one of the objectives that wireless time-sensitive networking (W-TSN) should fulfill.

W-TSN is designed to offer a robust network infrastructure that caters to the demanding requirements of time-sensitive applications, enabling not only extended reality (XR) applications but also a wide range of other industrial use cases. These include machine control, automotive systems, distributed monitoring, aerospace, and audio-video streaming [3]. It is actually in this last application where TSN's origins lie. In 2011, the Audio Video Bridging (AVB) task group introduced a set of standards with the objective of developing an interoperable system that would replace analog point-to-point communication methods while ensuring the necessary quality of service (QoS) [4].

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Since its renaming in 2012, the Audio Video Bridging (AVB) task group has evolved into the Time-Sensitive Networking (TSN) task group.[1] This transition expanded the group's focus, aiming to achieve time-synchronized, low-latency streaming services across IEEE 802.1 networks. TSN introduced a set of standards, including IEEE 802.1AS [5] for time synchronization, IEEE 802.1CB [6] for reliability, and IEEE 802.1Qbv [7] and IEEE 802.1Qav [8] for latency management. By offering a toolset that ensures zero congestion and bounded latencies in wired networks, TSN has significantly advanced the deterministic capabilities of networked systems.

With the growing interest of prominent industry vendors, TSN raises a significant inquiry: How can TSN effectively expand itself to the wireless domain to bring a robust network solution? This matter holds particular relevance for the aforementioned time-sensitive applications which stand to gain considerable advantages from the seamless mobility and plug-and-play capabilities of wireless technology. Nonetheless, it is imperative to recognize that these advantages also give rise to challenges associated with the inherently unpredictable nature of wireless communications and their specific procedures.

By using our W-TSN evaluation kit, built on top of the open-source platform openwifi [9], we addressed various wireless challenges specifically related with Wi-Fi-based TSN, including management [10], association [11], application-network integration [12], and mobility with the present work. Within wireless networks, one of the fundamental factors enabling mobility is handover. Consequently, the objective of the current work is to elucidate a Wi-Fi-based TSN-compatible handover management procedure.

Therefore, apart from a general handover procedure proposal, our specific approach centers on the combination of localization within a dedicated network and the utilization of online and offline learning of link quality to fine-tune roaming decisions. This strategy not only eliminates disruptions to time-sensitive traffic but also reduces the latency overhead, both associated with traditional channel scanning methods.

The paper's specific contributions can be summarized as follows:

- A near seamless handover procedure for Wi-Fi-based TSN between Access Points (AP) operating in different channels while Stations (STAs) have a single radio.
- Four different conceptual techniques to determine candidate APs mitigating the adverse impact on time-sensitive applications during handover time.
- The practical implementation and comparison in terms of bandwidth, jitter, and frame loss, of three Ultra-Wideband (UWB) localization-based handover techniques that reduce the need for the station for scanning nearby APs.

[1] http://www.ieee802.org/1/tsn

The remainder of the paper is organized as follows. First in Section II, related work on W-TSN handover is presented. Next, in Section III, the proposed W-TSN handover procedure is described in detail. In Section IV, the hardware handover implementation is explained. In Section V, the results, regarding the handover delay in uplink (UL) and downlink (DL), and handover moment selection are shown. Finally, Section VI, concludes this work.

II. BACKGROUND AND RELATED WORK

Before delving into W-TSN handover, we will first establish the current research context. We will begin by examining general handover optimization standards within IEEE 802.11, followed by a focus on localization-based and link quality-driven optimization. Finally, we will explore research at the intersection of W-TSN and mobility.

Several key standards address the challenges of efficient handover in Wi-Fi networks. IEEE 802.1k allows for the creation of a predefined list of potential target channels for STAs to streamline the channel selection process during roaming, despite relatively lengthy scan times [13]. IEEE 802.1v introduces Basic Service Set (BSS) Transition Management (BSTM), proactively informing STAs of disassociation to seek better APs [14]. Pre-authentication, when used with methods like Pairwise Master Key (PMK) Security Association, enables authentication through the existing AP [15]. IEEE 802.11r, or fast BSS transition, enhances handover through key caching and wired network routing of handshake messages [16]. Cisco's Intracontroller handover transfers the STA's entry from the old AP to the new one via a Wireless Local Area Network (LAN) Controller, typically taking 10 milliseconds, with STA involvement in decision-making [17]. IEEE 802.11be's Multilink Operation allows STAs to associate with new APs while maintaining data flow with the current AP, ensuring a seamless handover experience, but using two radios [18]. Available hardware incorporates some of these techniques to enhance roaming capabilities, but it primarily targets specialized industrial-oriented hardware with closed, proprietary solutions.

In addition to the solutions previously discussed, handover optimization remains a focal point in wireless systems research, serving as a critical response to an acknowledged weakness in wireless. Localization, which capitalizes on the spatial information of network nodes to select the most suitable AP for an STA, stands out as a promising strategy. In [19], an approach to this centers on improving the handover's discovery phase by exclusively relying on localization data, coverage area, and resource metrics. However, a notable limitation in this work is the exclusion of key link quality metrics, such as Received Signal Strength Indicator (RSSI) and Signal-to-Noise Ratio (SNR), from the model. This omission leads to the assumption of ideal propagation conditions, diminishing the real-world applicability of the proposed solution.

In the study referenced in [20], the authors utilize RSSI zones around the AP to assess the need for handover. They also introduce interleaved scanning for channel assessment, which schedules traffic and scanning in time. However, it is important to note that still, the average scanning time in this approach is 18 milliseconds, during which the STA cannot transmit or receive data, potentially impacting a possible time-sensitive traffic.

An interesting approach known as SyncScan, detailed in [21], introduces continuous AP discovery by aligning scanning timeslots at the STA with AP transmissions. However, again, a notable limitation of this approach arises during the scanning phase, where, although optimization reduces handover delay, it prevents the STA from receiving its own AP's traffic concurrently. It is important to note that this issue is mitigated within the context of TSN, as apart from an accurate network time synchronization, all nodes adhere to a transmission schedule that can accommodate a scanning timeslot. Consequently, the STA avoids receiving time-sensitive data during the scanning process, ensuring smooth operation in practice.

Presently, there exists a limited body of research that addresses the integration of handover and W-TSN systems. Among these initiatives, the work by [22] is particularly noteworthy. Notably, this study diverges from our own approach through its adoption of a decentralized architecture. In this alternative framework, the responsibility for initiating handover decisions rests with the STA rather than being centralized at the Centralized User Configuration/Central Network Controller (CUC/CNC) unit, thus introducing significant disparities when compared to our proposed handover procedure. It is worth noting that this approach employs a single radio at the STA, giving rise to a pivotal consideration. The feasibility of achieving a genuine soft handover is contingent upon the TSN schedule in relation to the speed of channel switching, a metric typically measured in the range of tens of milliseconds under ideal circumstances [23]. In practical terms, this constraint implies that the seamless execution of soft roaming (i.e. with no disconnection as in cellular networks) still may not be practically attainable for real-world implementations and applications.

Another notable work that addresses the integration of mobility with W-TSN can be found in [24]. In this study, the authors assess their zero-delay handover approach through a combination of simulations and real-world experiments. Similar to our own work, this research encompasses multiple phases aimed at achieving seamless handover. However, a key point of differentiation lies in the utilization of redundancy via multiple radios for roaming, in contrast to our approach, which employs a single radio. This pivotal distinction introduces a trade-off between TSN scheduling complexity, the allocation of time resources to manage handover delays, and the handover delay. Nonetheless, it is essential to note that, with control over the hardware, as demonstrated in our research, it is possible to implement optimizations that effectively reduce this handover delay while using a single radio. This, in turn, simplifies the handover procedure, enhances efficiency in terms of time resources utilization, and has minimal impacts on the operation of time-sensitive applications.

One significant distinction between the proposed handover approach in this work and existing methods lies in the time-sensitive nature of the network, which now presents a crucial constraint. While most methods aim to optimize and reduce the time required to complete the handover process, none of the current methods address the critical need to maintain time synchronization and provide a transmission schedule. Furthermore, none of these methods support identifying a set of candidate APs for handover without impacting the time-sensitive traffic of the node performing handover or any other time-sensitive traffic handled by the candidate APs.

Finally, traditionally, the STA has typically been responsible for making the final handover decision. However, in the context of TSN, which is intrinsically driven by the pursuit of determinism and underscores enhanced network control guided by telemetry measurements, a transition towards centralized handover decisions aligns more naturally with the principles of W-TSN.

III. W-TSN HANDOVER

W-TSN, designed as an extension of TSN, must uphold the objectives of TSN, which are high reliability and tightly bounded latencies. This necessitates the avoidance of interference with both its own traffic and other time-sensitive data streams during operation as well as handover time. Considering these factors, we have developed a handover procedure that encompasses three critical aspects: i) Near seamless transition, ii) minimal disruption, and iii) strategic handover.

Prior to describing the W-TSN process, it is crucial to provide an overview of the devices, modules, and topology that play integral roles in this procedure.

A. W-TSN HANDOVER ARCHITECTURE

To achieve the aforementioned objectives while ensuring compatibility with TSN, it is imperative to utilize the TSN architecture. Among these architectures, the centralized approach, depicted in Figure 1 and used in this study, proves to be particularly advantageous for handover scenarios, thanks to its comprehensive network perspective and control advantages. As such, the Centralized User Configuration (CUC) and the Central Network Controller (CNC) jointly manage the computation and distribution of schedules across all TSN nodes. The TSN switches form the core, responsible for handling and forwarding time-sensitive traffic flows. The APs signify the wired network's edge providing wireless communication for the STAs.

As an essential incorporation, we have included a Handover Controller Module (HCM) at the controller side and a Handover Agent Module (HAM) at the STA side. These modules play a pivotal role in the management of handover,

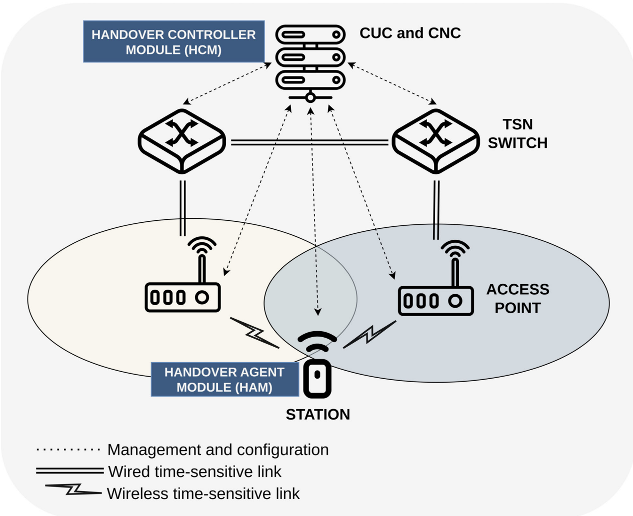

FIGURE 1. **Handover topology.**

as they detect the need for handover and initiate the process accordingly.

As illustrated in Figure 1, in addition to the wired and wireless time-sensitive links, a management and configuration network is presented. This network serves two primary objectives. Firstly, it facilitates the HCM in gathering information concerning the STA link status. Simultaneously, it is employed to provide the STA through the HAM with accurate details for near seamless handover between APs, as described in the following section.

B. HANDOVER PROCESS

To streamline the W-TSN handover process, we have segmented it into four distinct states as shown in Figure 2. For clarity in understanding the procedure, we have chosen a two-part explanation. Initially, we will establish and define the proposed states, followed by a detailed description of each state transition. The states are as follows:

1) Before HO: In this state, the STA is connected to an AP, featuring an allocated transmission schedule tailored to meet its specific traffic flow demands. In this state, there is no need for a handover process.
2) AP candidates determined: in this state, the HCM together with the HAM, employ one of the time-sensitive, impactless methods—such as localization, coordinated beaconing, and coordinated probing, as detailed in the subsequent section. Through these techniques, the STA assesses the link quality to potential APs, and determines if it is necessary to perform handover.
3) Handover Prepared: In this state, the handover decision has been finalized, and in alignment with the chosen target AP, the resources along the new path, including the schedule, are prepared for utilization. At this stage, both the TSN and the STA are in a state of readiness, anticipating the handover trigger.
4) Handover Done: At this state, the STA has transitioned to the target AP and it is able to communicate with the TSN using its new transmission schedule. Subsequently, the STA will revert to State 1.

The first state change, as seen in Figure 2, itAP Candidates Determination, is dedicated to the identification of potential APs to which the handover could take place. In the second state shift, *Preparation*, the system assembles the essential elements required for a near seamless transition. Finally, in the third state change, *Trigger*, the handover process is initiated, ensuring a seamless and uninterrupted transition toward the selected AP.

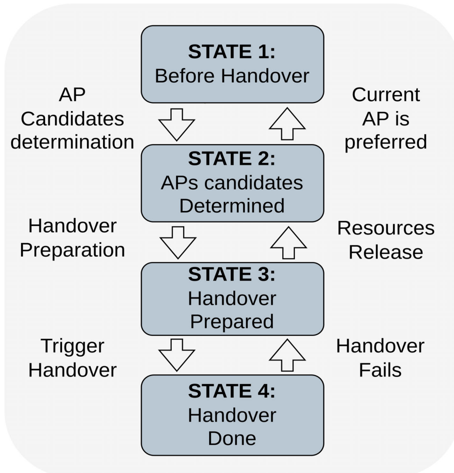

FIGURE 2. **W-TSN handover state diagram.**

Let's delve into each of these stages change in the following subsections:

1) DETERMINING CANDIDATE APS

When the need for handover is identified, for reasons such as signal strength deterioration, load distribution requirements among APs, or STA localization/mobility, the selection of candidate APs must be carried out without disrupting time-critical traffic. For this, we propose using one or a combination of the following methods:

- **Localization**: Through localization, the STA can pinpoint its exact location and inform the HCM of it via the present AP using the management and configuration link. Either a Wi-Fi-based localization system using fine timing measurement (FTM) or an external localization system such as UWB-based can be used. In the first case, to prevent affecting other time-critical traffic, the exchange of FTM requests must be planned within the overall W-TSN. By leveraging these methods, the HCM can identify one or more candidate APs that can be chosen as the target for handover based on the position of the STA, the location of the APs, and telemetry information indicating the signal quality for STA-AP pairs at particular locations.
- **Coordinated beaconing and scanning** Time-sensitive STAs can only scan for potential APs when they are

not sharing any time-sensitive data in the UL or DL. STAs can be given the ability to scan for nearby APs while no time-sensitive data exchanges are occurring by appropriately scheduling beacon transmissions across APs at a specific time. In addition, this specific time should be known by all STAs. In this manner, the STA can gather data about potential APs and provide it to the HCM. Similar to current Wi-Fi handover protocols presented in Section II, the STA can be informed about nearby APs and their operational channel to limit the number of channels that need to be scanned.

- **Coordinated probing** To gather data regarding potential APs, the STA would directly transmit probe requests in a fixed shared time slot across APs. This will prevent interfering with ongoing time-sensitive traffic. The information from probe requests that candidate APs receive is sent to the HCM to determine the group of candidate APs. As an alternative, probe responses could be returned to the STA, allowing it to gather the data on its own. Such probe responses can also be transmitted over the AP the end node is currently connected to, minimizing the amount of time the STA needs to remain on a different channel. As in the previous approach, by informing the end node about nearby APs and their operational channel, the number of channels to send probes on can be reduced.
- **Overhearing** STAs on different Basic Service Sets (BSS) operating on the same channel in dense installations can overhear one another, a phenomenon known as overlapping BSS. Information about the region or zone where an end station is located can be collected by listening to traffic and logging details such as the STA involved in the communication, received signal strength, etc. The HCM can then be informed of this information. This allows for the identification of possible APs on various channels inside or close to that region.

2) HANDOVER PREPARATION

The HCM, after obtaining the set of candidate APs, will decide the target AP the STA must handover to and, optionally, the timing at which the handover should take place. To prepare for handover, the necessary resources must be set up in the target AP and along the new path via the TSN switches in order to prevent interfering with other time-sensitive flows handled by the target AP and guarantee the timings of the new flow(s) from the STA that will wander to the AP. The HCM, knowing the STA's application requirements, will compute transmission schedules for the impending traffic flow path as part of this preparation. Such schedules concern the target AP, the STA performing handover, and the TSN switches along the new route. The CUC/CNC communicates the allocation of resources at the target AP and switches by using the management and configuration links, either to be executed immediately or at the predetermined time when the handover should be executed.

Also, resources that will be no longer required after the completion of the handover procedure should be considered. When the exact timing of handover has been defined, the release of resources can already be communicated along with timing, which takes into consideration sufficient margin to verify the successful completion of the handover or to cancel the release upon detection of failure of the handover. In case no exact timing of the handover has been defined, the communication to release resources will only take place upon successful completion of the handover procedure. Further, to avoid the overhead related to the association and authentication to a new AP, the HCM can already provide all necessary information about the STA to the new AP, hence performing the association and authentication on behalf of the STA.

Figure 3 illustrates a handover scenario within the TSN schedule framework. The diagram depicts schedules for both the initial and target APs, featuring designated time slots for connected devices, particularly the STA. Notably, during the handover preparation phase, an unused time slot appears in the target AP schedule, serving as a crucial element for a smooth transition. Upon the handover trigger, the STA shifts from the initial AP's allocated slot to the corresponding slot in the target AP. Despite potential variations in cycle lengths between the initial and target schedules, strict adherence to the STA's time-sensitive traffic flow requirements is required. Post-handover success, resources are liberated at the initial AP. More details on the handover process are described in the next section. This approach ensures that the STA smoothly transitions from the initial AP to the target AP, mitigating potential traffic contention.

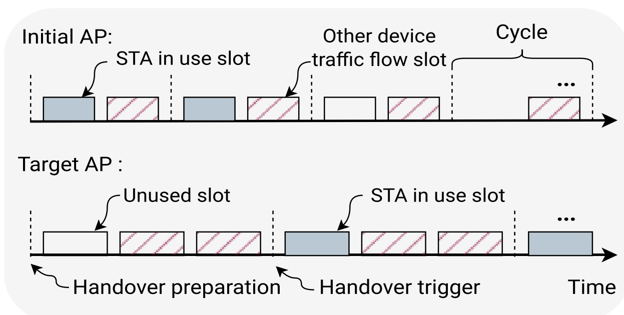

FIGURE 3. W-TSN handover schedule example.

3) HANDOVER TRIGGER

Once the handover process advances to State 3, the handover manager module will initiate handover for the STA via the current AP. This initiation encompasses important information, such as the new AP's channel, transmission schedule, whether pre-association has already been carried out at the target AP, and, if specified, the timing for executing the handover. In the absence of precise timing instructions, the receiving STA will promptly commence the handover procedure.

The process involves the following steps at the STA:

1) In order to mitigate undesired UL transmissions throughout the procedure, the STA will enact a transmission gating system and systematically queue frames. While a comprehensive elucidation of the gating system is beyond the scope of this paper, a detailed exposition can be referenced in [12].
2) The new transmission schedule is set up and the STA switches to the new channel.
3) The transmission gates are reopened at the STA according to the new schedule.
4) Once the gates are opened, the STA can immediately continue to perform time synchronization and time-sensitive communication via the target AP using the provided schedule. For time synchronization, Precision Time Protocol (PTP) defined within IEEE1588, is the preferred time approach in TSN and transparent and boundary clocks are the most relevant clock modes in PTP [25]. For both cases TSN handover will work as follows.
   - With a transparent clock, the STA can continue executing the time sync procedure with the end-to-end transparent clock.
   - With a boundary clock, the STA can proceed with the sync procedure, but now with the new boundary clock, which is synced with the old boundary clock in the old AP. As part of the trigger, the IP address or MAC address of the target AP can be communicated, such that the STA can anticipate the new clock it will interact with.
5) In case of association with the target AP has not yet taken place, the association process with the new AP will be performed using the provided schedule.

4) HANDOVER FAILTURE

From a theoretical point of view, the occurrence of a handover failure is dependent on specific conditions, such as the inability to establish the target link. This may be attributed to factors like a failed wireless association or unfavorable channel conditions. Nevertheless, from a practical perspective, incorporating handover failure mechanisms becomes imperative to safeguard time-sensitive traffic flows. Detecting such failures is straightforward, as both the HCM and the HAM anticipate the initiation of traffic to and from the new link within a defined timeframe.

Upon encountering this scenario, two alternative approaches are proposed. 1) The STA attempts to revert to the previous AP, whose time resources are maintained as outlined in Section III-B2 and resetting the handover process to enter State 1, as depicted in Figure 2.2) Should this initial approach prove unsuccessful, the STA initiates a bootstrapping process. Notably, this process should be designed not to disrupt existing time-sensitive flows for already associated clients, as detailed in our prior work [11].

IV. W-TSN HANDOVER PRACTICAL IMPLEMENTATION

In this section, we will focus on the practical implementation and testing of the described methods in Section III. The objective is to realize a seamless W-TSN handover experience, with particular attention to two key aspects: i) swift and efficient switching between APs by optimizing delays in network and STA processes that deal with AP switching, and ii) making handover decisions on optimal space/time moment considering wireless channel dynamics. These two aspects will be described in the next subsections. For this implementation, we have been focused on the wireless part of the W-TSN Evaluation Kit, which can be seen in Figure 4 [9].

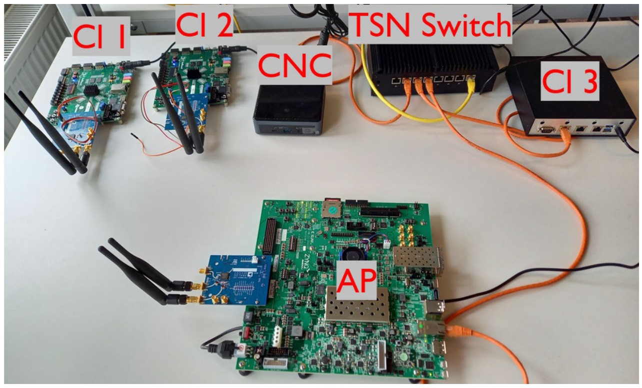

FIGURE 4. Wired-wireless TSN evaluation kit.

The Evaluation Kit offers a range of topology options for developing and testing both wired and wireless TSN. It is capable of accommodating an increased number of APs, as demonstrated later in our handover development and testing. Furthermore, the kit integrates essential TSN features, including PTP-based time synchronization mechanisms, a TSN gating system within the wireless nodes, and comprehensive management implementations.

A. HANDOVER DELAY OPTIMIZATION

Handover delay can be defined as the time elapsed from the reception of the last frame from the old AP to the receipt of the first frame from the target AP with no other traffic [26]. Minimizing this delay requires attention to two distinct components: the wired part, responsible for updating the traffic flow path, and the wireless part, which handles the channel update at the STA. In this section, our primary focus will be on the latter component, as it tends to consume more time [21].

Once the handover agent module (HAM) within the STA receives instructions from the controller's HCM, it initiates the handover process using the user-space command *Sdrctl*. *Sdrctl* is a user-space utility designed as an nl80211 test mode command, facilitating communication with the openwifi[2] driver. This tool enables control over FPGA and transceiver settings, including channel selection, clear

[2]https://github.com/open-sdr/openwifi

channel assessment (CCA) threshold, transmission schedule, data rate, and various other parameters.

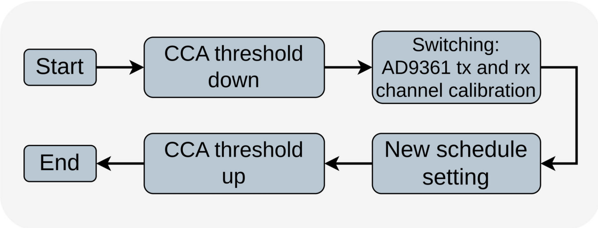

FIGURE 5. W-TSN STA handover flow diagram.

Therefore, as illustrated in Figure 5, HAM leverages *Sdrctl* to execute a sequence of actions. Initially, it reduces the CCA threshold below the channel noise level, hence prompting the STA to perceive the channel as occupied. The CCA threshold helps devices decide whether a channel is considered busy or idle. As such, reducing the CCA threshold will virtually prevent the STA from transmitting during handover time. Subsequently, the new frequency is configured for the transceiver, next, the new transmission schedule is set, concluding with reversing the CCA threshold. Both the new frequency and new transmission schedule, are received from the HCM as described in Section III-B3. By completing the entire handover operation with just a single instance of netlink communication between the user space and the driver, we effectively optimize the processing delay associated with this operation. This optimization, as we will demonstrate in the Results Section V, leads to a reduction in the overall handover delay.

B. HANDOVER MOMENT SELECTION

Now that we have introduced an optimal channel switching procedure, the next critical aspect is to execute the handover at the precise spatial moment. This directly correlates with the techniques detailed in Section III-B1. Traditionally, achieving an optimal handover location involved setting an RSSI threshold to trigger channel scanning, a process that may be limited by the controller based on network configuration. However, channel scanning can be incompatible with TSN, as it temporarily disrupts the STA's ability to transmit or receive time-critical traffic from the current AP as demonstrated with the related works in Section II. To circumvent this issue, alternative mechanisms described in Section III-B1 have been proposed. In our exploration, we have chosen to investigate the use of localization as a means to avoid scanning and facilitate localization-dependent applications.

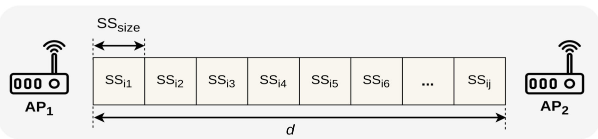

FIGURE 6. Spatial slots (SS) distribution.

Integrating an Ultra-Wideband (UWB) localization tag with the STA offers the ability to pinpoint the STA's location in relation to the surrounding APs. To correlate STA localization with channel quality, RSSI values are continually monitored and relayed as monitoring traffic to the handover module at the TSN controller. The controller leverages this data to construct a one-dimensional Radio Environmental Map (REM), partitioning the space between APs into Spatial Slots (SS) that encapsulate the recorded RSSI values as shown in Figure 6. Dividing the space into SS offers the advantage of mitigating the impact of localization system accuracy limitations. Consequently, the SS_{size} is chosen in consideration of both the localization system accuracy and the anticipated spatial coherence of the environment. The RSSI values on each SS are updated every t_s seconds as in Equation 1:

$$\mathrm{SS_{ij}} = \alpha \cdot \mathrm{RSSI_{ij}^{NEW}} + (1-\alpha) \cdot \mathrm{RSSI_{ij}^{OLD}} \tag{1}$$

where α will control the importance of new RSSI values, i represents the AP and j is the SS index.

Utilizing the REM methodology, the network controller determines the optimal AP for the STA to connect to. This approach is not constrained by a single dimension; instead, it can be expanded into a two-dimensional framework if the need arises. This approach has given rise to three distinct flavors of localization-based W-TSN handover: i) middle point, ii) offline learning, and iii) online learning.

- **Middle point:** This handover method was developed as a baseline reference approach. It relies on the STA's position, where it defines a geometric middle point between the APs and establishes a threshold zone to prevent the well-known "ping-pong" effect when STA is equally served by both APs. Consequently, when the STA crosses this middle threshold zone, the HCM instructs the STA to switch AP. However, this method lacks a mechanism to account for the spatial variability in signal propagation. Given the inherent imperfections in signal propagation and the influence of environmental phenomena like reflection, refraction, and diffraction caused by obstacles, leading to multipath effects, the ideal handover point in space will likely not align with the geometric midpoint between the APs. As a result, the use of this method is restricted, and it is only applied in this study as a reference scenario.
- **Offline learning:** This handover method draws inspiration from REM network planning techniques and is structured into two distinct stages [27]:
  - The learning stage where the STA is required to traverse the environment while associating with each available AP. This process enables the controller's handover module to compile a comprehensive REM by collecting the RSSI values associated with each AP within every SS_{ij}.
  - The working stage where the network controller utilizes the acquired REM knowledge in conjunction with the current STA SS position to make informed decisions regarding STA handover, ensuring it connects to the most suitable AP.

This method leverages offline learning to enhance handover decisions based on the learned radio environment. It also better accounts for the propagation variability as the best AP for each SS is considered. However, as a drawback, if the environment changes, while in the working stage, the learned REM might not be applicable anymore. This limitation not only affects handover but also poses challenges for effective network planning. Despite this drawback, this method is valuable in scenarios where significant environmental changes are not expected, making it a practical approach. This consideration led us to conduct testing and evaluation.

- **Online learning:** In contrast to the previous method, the online learning approach eliminates the need for a dedicated learning stage. Instead, the HCM maintains the REM of each AP, which is continually updated with RSSI values as the STA moves within its coverage area. As an initial handover point, the geometric middle is chosen. However, once enough Spatial Slots are filled within each AP's REM (SS_{ij}), the recorded values are utilized to iteratively fit an RSSI-distance logarithmic model. The Equation 2, shows the model, representing the two APs shown in Figure 7:

$$\mathrm{RSSI}_{\mathrm{AP_i}} = a_i - b_i \cdot \log_{10}(x) + X_{\theta i} \tag{2}$$

where i represents each AP with $i = \{1, 2\}$, x, the distance, a, and b represent the received signal power loss and are determined through the least-squares fitting procedure. The fitting process also yields the standard error X_θ, which is a zero mean Gaussian random variable that reflects the random variation in the path loss due to multipath. This standard error is used in calculating the 95% confidence interval, which is also considered when the optimal handover SS is selected.

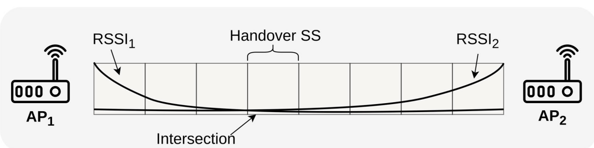

FIGURE 7. Online learning.

The HCM then, by solving the given equation system, identifies the intersection point of the models as seen in Figure 7. Based on this intersection, the HCM iteratively selects the optimal handover SS for the STA, ensuring an informed and efficient handover decision. This online approach offers the distinct benefit of seamless adaptation to evolving environmental conditions for the constant update of the handover SS. Nevertheless, a drawback of this method is its similarity to the midpoint approach, where only one SS is chosen for the transition. This could overlook the intricacies of wireless multipath scenarios. Despite this limitation, its practical use is broad, especially in dynamic scenarios where both the STA and the environment are subject to frequent changes.

V. RESULTS

A. SETUP DESCRIPTION

The proposed W-TSN handover procedure has been implemented and tested using the openwifi IEEE802.11/Wi-Fi baseband chip/FPGA design. As shown in Figure 8, on the mobile wireless client side, we have employed a Xilinx Zedboard equipped with the AD-FMCOMMS4-EBZ transceiver, serving as the STA. This is connected via Ethernet to an Intel Next Unit Computing (NUC) end node, which employs the Robot Operating System 2 (ROS 2) to drive a 4WD Rover Zero 3. Each AP in our setup utilizes a Xilinx ZC706 board along with an AD-FMCOMMS4-EBZ transceiver. These APs are connected through Ethernet to a Qotom Q818GE Linux TSN Switch, which in turn is connected via Ethernet to another NUC, functioning as the CNC/CUC.

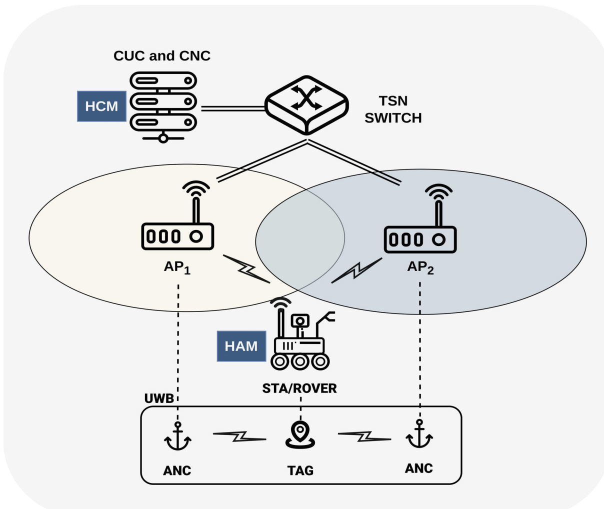

FIGURE 8. W-TSN test setup.

The UWB localization system comprises both Anchors (ANC) at known fixed positions and a mobile TAG, which is attached to the Station (STA) board via a Universal Serial Bus (USB) interface. The UWB hardware is built on the Wi-PoS platform, with localization precision within the 5-centimeter range. This system is further bolstered by a sub-GHz wireless infrastructure for seamless communication, as outlined in a study by [28]. This setup was developed and tested within a warehouse-style environment of 12 × 25 meters, featuring metallic shelving units but devoid of any obstructions between the APs.

Lastly, the management and configuration of the network is established using a ZeroMQ PUB/SUB model, illustrated in Figure 9, facilitating message exchange between the HCM and HAM. On one front, the HCM can initiate an AP handover when necessary. Conversely, the HAM

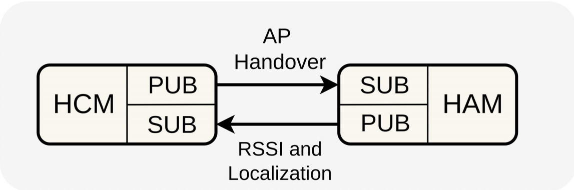

FIGURE 9. ZeroMQ model.

disseminates messages to the HCM, encompassing its real-time coordinates and the prevailing RSSI value.

B. HANDOVER SPEED

To assess the improvements outlined in Section IV-A, we conducted an uplink traffic test. The experiment platform can be viewed in Figure 10. It is worth noting that we did not implement any specific TSN scheduling scheme in the gating system, ensuring that we measure only the handover delay and not any possible additional delay due to time slot access delays. For this measurement, the STA/Rover remained stationary at the central point between the APs. The distance separating the APs, 'd', is 6 meters. and to avoid external interference, the APs operated on Wi-Fi 6E channels (specifically, 5975 MHz and 5995 MHz). Additionally, we manually configured the handover triggers at 50-ms intervals and the traffic consisted of 100k pings generated every 1ms going from STA to CNC, where only ping requests are considered.

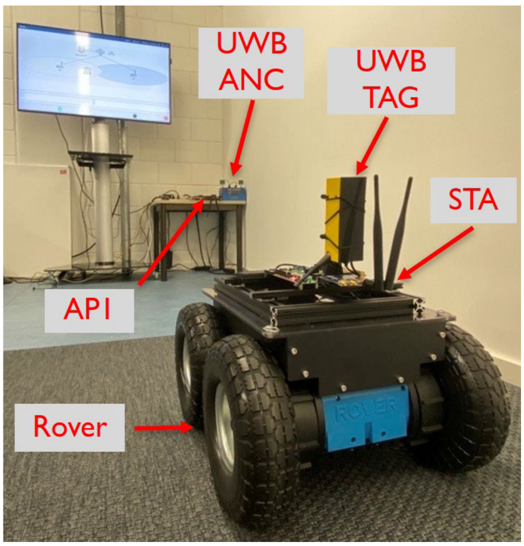

FIGURE 10. Experiment platform.

To avoid the need for time synchronization between the APs and the STA for measuring handover delay, which could introduce additional traffic and require precise synchronization, we internally assessed the interframe arrival time of pings within the STA. The STA driver has two interrupt functions: one is called upon receiving a frame for transmission from higher layers, and the other notifies higher layers when a frame has been successfully transmitted.

By comparing the frame arrival times in both interrupt functions, we were able to measure the impact of handover delay on traffic. Figure 11 presents the results. The three curves in the graph represent the cumulative distribution function (CDF), of frame interarrival times for the following scenarios: no handover, slow handover (handover before the introduced modifications), and enhanced handover (handover with modifications). As reported in the literature, typical handover results in delays exceeding 100 ms [23]. However, in the case of enhanced handover, the frame interarrival time was reduced to as low as 13 ms.

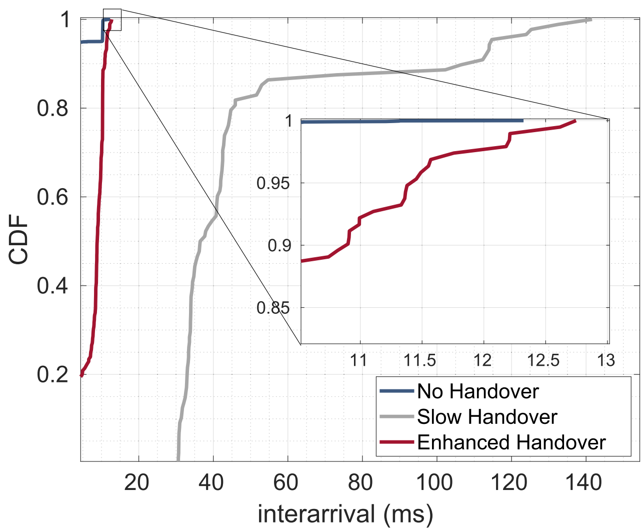

FIGURE 11. Uplink handover delay CDF.

To provide an application-focused perspective on the handover delay of the proposed enhanced handover solution, we conducted end-to-end tests. These tests encompassed both UL and DL scenarios, involving UDP traffic flowing between the CNC/CUC and the Rover in Figure 8. To quantify the handover delay, we employed the frame interval time, utilizing 100k UDP frames transmitted at a generation rate of 1 ms. Furthermore, we manually initiated handovers at 50-ms intervals, from the HCM, to update both the wired and wireless segments of the TSN. The results of these tests can be seen in Figure 12.

In Figure 12, we initially showcase two baseline measurements conducted without any handover (No HO) for both the DL and UL scenarios. Subsequently, we present the enhanced measurements for DL and UL traffic under the handover condition, revealing median values of 12 and 16 ms, respectively. It is important to take into account that these results are influenced not only by handover delay but also by the inherent variable processing delays at various points in the network, including the STA, AP, switch, and CUC/CNC or Rover, hence are higher than the results presented in Figure 11. In conclusion, while the significance of a low handover delay is evident, it is crucial to contextualize it

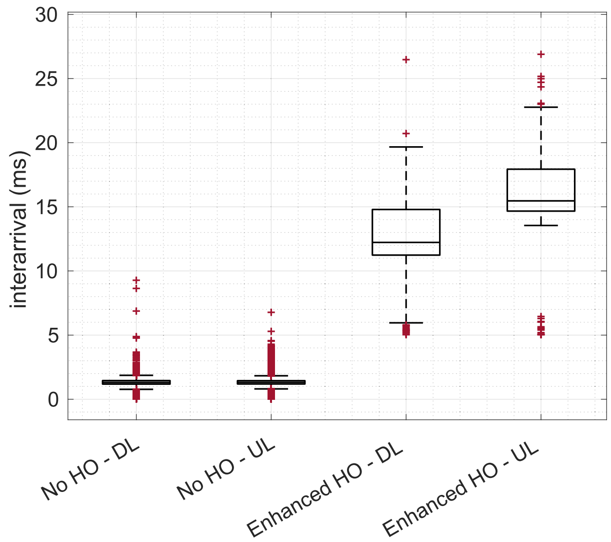

FIGURE 12. End-to-end handover delay.

within the traffic dynamics. Depending on the application frame generation rate, there is a possibility that a frame may need to be transmitted during handover. In the case of uplink (UL), illustrated in Figure 5, the CCA threshold mandates the frame to wait in the buffer, causing a delay in its transmission. Conversely, in the case of downlink (DL), the frame may face the risk of being lost. This underscores the imperative to minimize handover delay, particularly in scenarios where the timely transmission of frames is critical.

C. HANDOVER MOMENT SELECTION

To evaluate and compare the handover moment selection methods outlined in Section IV-B, we opted for a realistic experimental approach. In this context, we established a specific movement pattern for the Rover, as illustrated in Figure 8. The Rover follows a predefined path, traversing between the APs at a constant speed for a duration of 150 seconds in each test run. The rest of parameters are summarized in Table 1.

TABLE 1. Measurements parameters.

Parameter	Value
Measurement time	150 s
APs distance (d)	6 m
APs frequencies	5975 & 5995 MHz
Data rate	26 Mbps
Bandwidth	20 MHz
iperf traffic	UL&DL at 5Mbps
Rover speed	0.4 m/s
SS_{size}	30 cm
α	0.8
t_s	40 ms

While the primary objective of this experiment is to assess handover performance, it is essential to consider the performance throughout the entire trajectory between the APs from an application perspective. Therefore, the following results measure various performance metrics, including throughput, packet loss, and jitter in both the UL and DL using end-to-end *iperf* traffic. To prevent automatic adjustments in the transmission rate made by the Linux Minstrel algorithm, we set the transmission rate to a constant 26 Mbps in all wireless nodes.

	Cycle: 2048 us			
	512 us	512 us	512 us	512 us
AP$_1$:	**PTP**		**iperf**	**C&M**
AP$_2$:	**PTP**	**iperf**		**C&M**
STA$_1$:	**PTP**	**iperf**		**C&M**
STA$_2$:	**PTP**		**iperf**	**C&M**
	Q0	**Q1**	**Q1**	**Q2/Q3**

FIGURE 13. W-TSN transmission schedule.

The transmission schedule employed for the W-TSN is detailed in Figure 13. This schedule consists of a cycle with a duration of 2048 μs, divided into time slots of 512 μs. The first time slot, assigned to queue 0 in all nodes, is dedicated to time synchronization traffic, which utilizes PTP, as previously described. If the roaming delay, is small enough, there are no visible affections on time synchronization. The second and third time slots are allocated for UL/DL *iperf* UDP traffic between the STA connected to one of the APs, respectively, utilizing queue 1. The final time slot, which involves queues 2 and 3, is designated for configuration and management (C&M) traffic, as depicted in Figure 9.

Considering the 26 Mbps fixed physical data and the applied schedule, we configured the *iperf* traffic for both the uplink (UL) and downlink (DL) to operate at a realistic 5 Mbps.

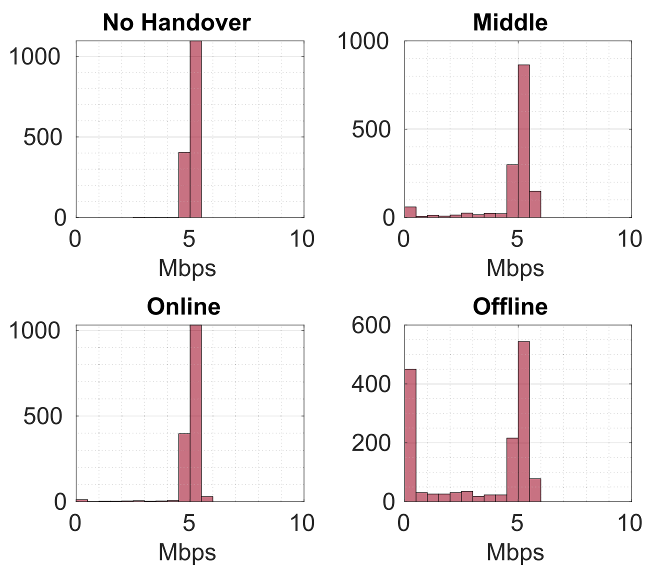

FIGURE 14. Downlink throughput distribution.

Figure 14 illustrates a DL throughput comparison across four examined scenarios. The initial scenario, *No Roaming*,

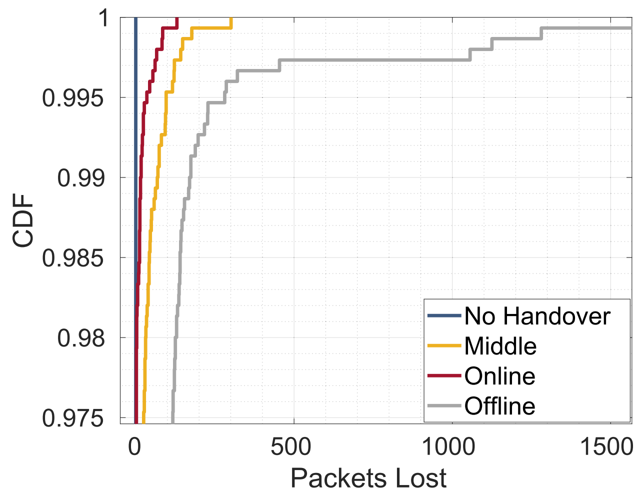

FIGURE 15. Downlink packet loss CDF.

serves as the reference case and involves a stationary STA associated with an AP. Subsequently, the following three scenarios, namely *Middle*, *Online*, and *Offline* are aligned with the mechanisms elaborated upon in Section IV-B. In this Figure, it is evident that the reference scenario, along with the *Online* approach, effectively maintains a higher level of requested bandwidth compared to the *Middle* and *Offline* approaches.

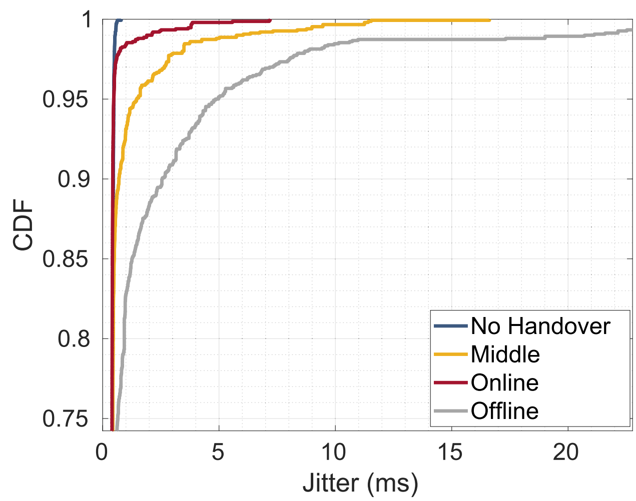

FIGURE 16. Downlink jitter CDF.

The results obtained for DL throughput align with the findings presented in Figures 15 and 16, depicting packet loss and jitter, respectively. It is evident that the *Online* method consistently outperforms the other approaches in these metrics as well.

As anticipated, the results pertaining to throughput, packet loss, and jitter in the DL exhibit a similar pattern to those observed in the UL as depicted in Figures 17, 18, and 19. Of particular note is the suboptimal performance of the *Offline* approach, which is elaborated upon in Section IV-B.

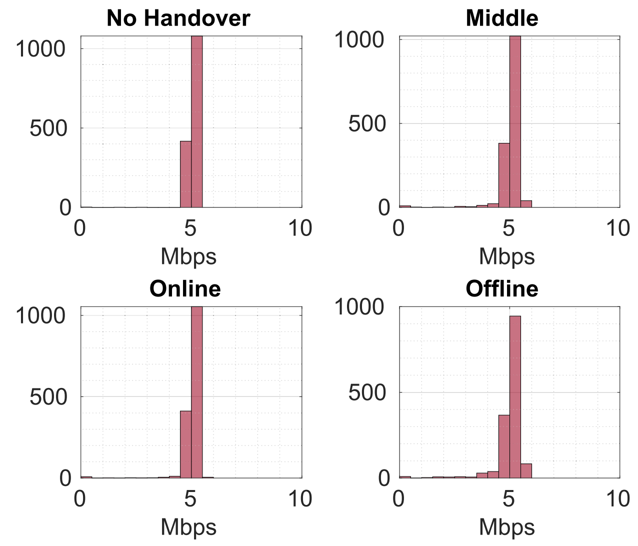

FIGURE 17. Uplink throughput distribution.

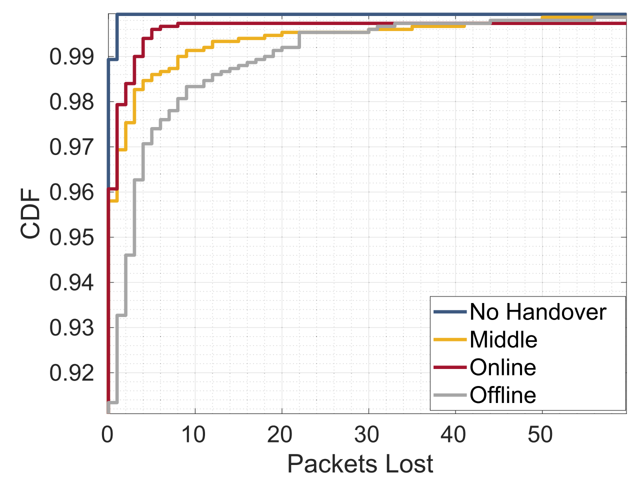

FIGURE 18. Uplink packet loss CDF.

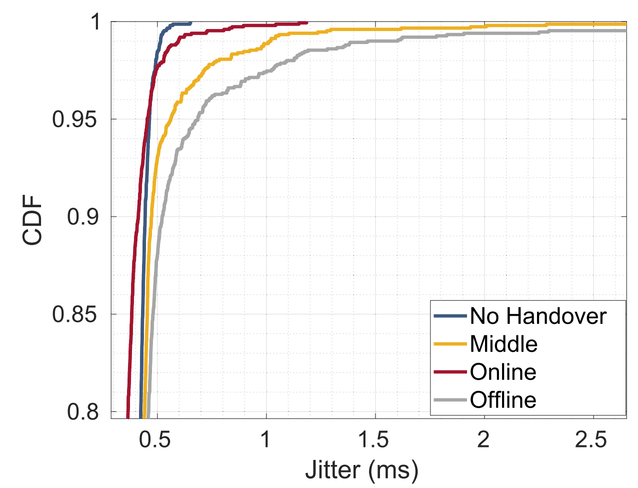

FIGURE 19. Uplink jitter CDF.

The *Offline* mechanism initially constructs a REM using the best RSSI information from the APs' REMs. This approach results in multiple potential handover points within the general REM. Contrary to expectations, the outcome of this strategy, as indicated by the results, deteriorates overall link quality instead of enhancing it.

VI. CONCLUSION AND FUTURE WORK

Our study addresses the crucial challenge of achieving near semaless W-TSN handovers for access points (APs) operating on different channels with a single-radio station (STA). We emphasize the potential of this approach to minimize time-critical traffic disruption for other STAs and reduce self-traffic disturbances during handovers.

Recognizing the challenge of determining the right handover moment for controllers and STAs, conventional channel scanning methods, like those in IEEE 802.11, are unsuitable for W-TSN. Thus, our research introduces alternative techniques, primarily focusing on a localization-based method. Our solution employs Ultra-Wideband (UWB) localization and Radio Signal Strength Indicator (RSSI) data to build a robust Radio Environment Map (REM). This REM learns from the environment, identifying optimal handover points for the STA, enhancing the W-TSN mobility performance. Furthermore, the achievement of a handover delay of under 20 milliseconds, which notably falls below the motion-to-photon latency, not only addresses these technical challenges but also opens up avenues for transformative technologies, such as Extended Reality (XR), to enrich the user experience through seamless integration with wireless systems.

In future research, we will expand our two-dimensional REM to accommodate more APs. We explore alternative models, considering variables like Channel State Information (CSI) and packet loss rates for improved precision. Additionally, we are aligning our efforts towards implementing coordinated beaconing and probing strategies. Furthermore, our focus extends to the integration of traffic balancing mechanisms and the incorporation of machine learning techniques into our handover modeling. This collective approach aims to foster more efficient and reliable wireless communication in dynamically evolving environments.

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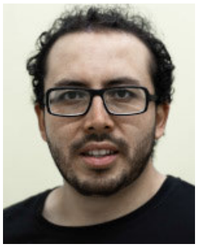

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