Zero-Delay Roaming for Mobile Robots enabled by Wireless TSN Redundancy

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***Abstract*—Mobile and autonomous robots are among the most critical technology applications requiring wireless connectivity with deterministic performance, including bounded latency with high reliability, even under congested network conditions. Emerging Wireless Time-Sensitive Networking (WTSN) capabilities over Wi-Fi and 5G can enable time synchronization and bounded low latency through time-aware scheduling mechanisms. Such Wireless TSN capabilities have been demonstrated in several industrial/robotic use cases, but under static conditions. Mobility introduces new challenges due to the roaming events and associated network outages owing to signaling between client devices and network infrastructure during these events. In this paper, we show how we can take advantage of the TSN redundancy capability (as defined in the IEEE 802.1CB standard) to eliminate outages or delays due to events like roaming and interference in a mobile robot use case enabled by Wi-Fi 6 TSN. We demonstrate the roaming performance with no delay impact on the applications though simulations of a mobile robot in a factory scenario and experimental results with a mobile robot connected via multiple Wi-Fi 6 radios in a warehouse environment.**

***Index Terms*—Keywords—WTSN, reliability, redundancy, Wi-Fi, multi-link**

I. Introduction

Industrial communication systems that support critical use cases involving tight control loop cycles need to ensure high availability and near zero down times from outages or link loss. Autonomous mobile robots (AMR), which are becoming more prevalent across various domains including home, enterprises and industrial environments, are a key use case that necessarily relies on highly reliable wireless communication networks. As AMR applications explore the latest advances in wireless standards and TSN capabilities for their deterministic communication needs, maintaining consistent network availability is essential, even in mobility-induced events such as roaming and interference, known challenges in wireless networks. In factory and warehouse environments, AMR control and navigation functions may be offloaded to an edge computing infrastructure to achieve higher efficiency, as discussed in [1]. In such scenarios, the wireless network must guarantee low latency with high reliability at all times, especially when the AMR is performing time and safety critical functions, such as manipulation and collaboration with other robots [2].

Recent wireless networks, such as Wi-Fi 6 and 5G, augmented with TSN capabilities have emerged as candidates for addressing the needs of mobile robots and other time-critical applications [3]. Wireless TSN tools such as time synchronization and time-aware scheduling have been demonstrated to enable static robotic use cases in real test beds [4], [5]. Time synchronization and time-aware scheduling have been the main TSN tools applied to wireless networks. By using a single reference clock synchronized across all network devices, the time-aware scheduling capabilities creates protected windows during which only time-sensitive traffic is allowed, thus avoiding congestion delays caused by other traffic flows on the same link. These WTSN features have been studied mainly under static scenarios [4], [5]. However, device mobility imposes new challenges as devices must switch their network association between Access Points (APs) as they move about the environment. Seamless roaming over wireless networks has been a well studied topic [6] given the associated security and performance issues. For instance, in a Wi-Fi network, the mobile station has to exchange multiple management frames (aka four way handshake) as part of the transition between two APs. During this roaming procedure, data communication may be interrupted until the Station (STA), i.e., a device supporting IEEE 802.11 compliant interfaces, completes the re-associate with the new AP, which may result in service interruption for time-sensitive data frames. Enhancements defined by the 802.11r amendment have reduced the steps in the roaming procedure, enabling faster roaming in 802.11. Nevertheless, roaming based on 802.11r still involves (Re)Association Request and Response frame exchanges and mobile stations may still experience delays in the order of a few milliseconds [7]. In addition to the roaming time (i.e. time for completing the re-association), the roaming procedure also involves other aspects that may result in data loss, e.g., the decision of when to trigger the transition, which is typically based on signal strength with the current AP. Data may also be delayed or lost due to buffering and re-routing issues once the connection is moved between APs. The many challenges associated to roaming are especially problematic for time-aware scheduling capabilities where time-sensitive data needs to be served periodically with high reliability and existing Wireless TSN solutions have not been evaluated under mobility conditions.

To ensure seamless connectivity and operation of the TSN functions even during existing roaming procedures that may incur unavoidable delays, we leverage the TSN link redundancy protocol defined in the IEEE 802.1CB standard and mobile devices equipped with multi-radio capabilities. An implementation of 802.1CB redundancy over Wi-Fi 5 has been described [8] and evaluated under unmanaged interference in a static network. In this paper, we extended the 802.1CB over Wi-Fi 6 TSN capable network and demonstrate how the multi-radio redundancy capabilities can achieve zero-delay roaming and ensure seamless operation for mobile robots. We evaluate the wireless redundancy capabilities in simulation and real experiments in warehouse scenarios.

The rest of the paper is organized as follows. We begin in Section II by providing a brief overview of the state of the art in terms of Wireless TSN capabilities and discuss challenges introduced due to mobility and multi-link radio devices. In Section III, we describe our implementation of TSN redundancy over Wi-Fi 6 multi radio devices and discuss how to apply it to significantly reduce roaming related performance loss. In section IV, we provide performance results using mobile robots in virtual (simulation) and real warehouse environments. Finally, we provide future directions and conclusions in Section V

II. Wireless TSN and Mobility Challenges

In this section we review the state of the art in Wireless TSN capabilities and their applications to industrial systems. We discuss the challenges imposed by mobility of devices in maintaining seamless connectivity and time-sensitive performance.

A. *Wireless TSN Capabilities*

The IEEE 802.1 Time-Sensitive Networking (TSN) task group develops standards to enable deterministic communications within IEEE 802-based Local Area Networks (LANs) [9]. TSN standards can be seen as a “tool-box”, where tools can be chosen depending on the network scenario, underlying link layer and use case requirements. Several TSN tools have been extended from wired (Ethernet based on IEEE 802.3) to wireless media, including IEEE 802.11 (Wi-Fi) and 5G [10] [3]. Time synchronization based on the 802.1AS generalized Precision Time Protocol (gPTP) and time-aware scheduling based on the IEEE 802.1Qbv standard have been the main features implemented over Wi-Fi and 5G wireless links. The main benefit of these features is the bounded low latency that can be achieved when time-aware scheduling is applied to all devices in the network, synchronized to the same reference clock, to create protected (time) windows for time-sensitive traffic. The time synchronization and time-aware scheduling capabilities applied over Wi-Fi have been demonstrated in several testbeds. In [11], we have applied 802.1AS time synchronization and 802.1Qbv time-aware scheduling over Wi-Fi 5 devices to enable a collaborative robotic use case. The two Universal Robots, UR3s, perform a joint lift and controlled movement of a custom metrology bar. One robot operates as leader and provides position and orientation information at 125Hz to guide the follower’s velocity-based controller to the next position. The real-time position information is mapped to a higher priority queue which is controlled by a time-aware schedule. Other traffic in the network, including background traffic that is added to create congestion, is mapped to a best effort traffic queue. The results demonstrate a successful operation of the use case under background traffic with the proper configuration of the time-aware schedule for the Wi-Fi network.

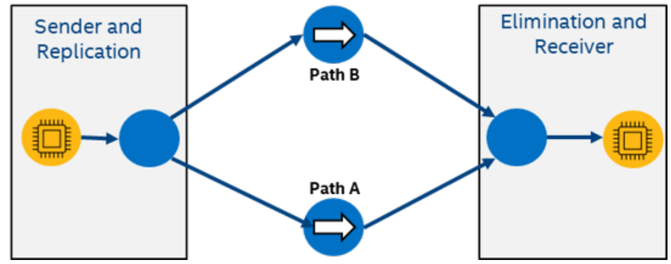

Fig. 1. Frame Replication and Elimination For Reliability (FRER) over a wired connection.

Industrial automation and robotics applications usually have very high reliability requirements, and some include functional safety requirements, which are challenging to meet over wireless links [12]. The TSN tool box also includes a redundancy feature defined by the IEEE 802.1CB Frame Replication and Elimination for Reliability (FRER) specification, which enables data path duplication for higher reliability against link and device failures. The IEEE 802.1CB FRER function provides increased reliability for a time-sensitive stream by replicating every packet in the stream and sending it over multiple redundant paths. Fig. 1 illustrates how the FRER function works between two end systems. An end system may be classified as a talker, a listener, or both. The talker identifies and replicates packets of time-sensitive streams over two or more disjoint paths - Path A and Path B in this example. During this process, a Redundancy-tag (R-tag) containing a sequence number is inserted into the packets. At the listener side, the FRER function uses a sequence recovery mechanism to eliminate duplicate packets by examining the sequence information embedded in the R-tag and reconstructs the original stream. The FRER functions at both the end points isolate the underlying network operations and provide protection to applications from outages and potential link and device issues as the likelihood of these events happening in both the links at the same time is reduced. It should be noted that implementing FRER would require two or more redundant physical connections or paths between the talker and listener. The 802.1CB FRER capability has been extended to operate over Wi-Fi as described in [8]. The 802.1CB redundancy capability was enabled over dual Wi-Fi 5 radios to demonstrate resiliency against unmanaged co-channel interference (e.g. from rogue or malicious devices) in a static scenario, which is a potential issue due to the operation in unlicensed spectrum. 802.1CB over multiple wireless links is also expected to play a key role in addressing the mobility related issues in wireless networks, as discussed next.

B. Mobility Challenges

Roaming is an important function of wireless networks that enables mobility. As a wireless device, such an AMR, moves around performing its tasks, it will move in and out of the coverage range of several APs. Without lack of generality, consider an AMR equipped with Wi-Fi radio within a factory where several APs are deployed, as illustrated in 2. As the AMR moves, the STA automatically roams from one AP to another in an attempt to maintain seamless connectivity to the LAN infrastructure. The Wi-Fi roaming procedure involves multiple steps, which can be grouped in three main phases:

- **Roaming trigger event and scanning:** the first phase mainly covers the decision of when to trigger the roaming procedure. Typically, STAs use signal strength information with the current AP to infer the communication range and decide whether it is moving outside of the coverage of the AP. The decision is an implementation specific feature, not specified in the 802.11 standard. Another important step is identifying other neighboring AP candidates that may be considered roaming candidates, which may be done by using active or passive scanning, both defined in the 802.11 specification. As the name suggests, STAs can passively collect AP information (e.g. by listening to beacon frames) or may actively send a Probe request frame and wait for Probe responses sent by the APs that may accept the connection.

- **Basic Service Set (BSS) transition:** Once the STA decides to roam, it needs to start the BSS transition procedure, which includes multiple frame exchanges to performance authentication, security key negotiation and re-association as defined in the 802.11 specification, known as four-way handshake [7]. During this phase, the data connection with the previous AP is suspended, thus data packets must wait in the queue until the new connection is established. This is a known issue in 802.11 roaming, and enhancements have been defined in the 802.11r amendment, known as fast BSS transition, to reduce the number of required steps, therefore reducing connection suspension time. The 802.11r enhancements have been evaluated in [7]. The simplified BSS transition procedure leverages AP neighbor reports to help STAs build a list of candidate APs, avoiding the need for active scanning, and includes only two frame exchanges, one with the current AP to indicate the imminent roaming and one re-association frame exchange with the target AP to complete the transition [13]. Despite the enhancements, the delay incurred due to the roaming procedure with 802.11r is still expected to be in the order of single digit milliseconds in the best case, to tens of millisecond depending on the STA and AP vendor specific implementations.

- **Routing reconfiguration:** Once the BSS transition at the 802.11 link layer has been completed, the routes in the network may need to be updated. For instance, IP packets generated towards the STA need to be routed to the new AP for transmission to the STA in the downlink direction. Although this process is automatically handled by higher layer routing protocols in most enterprise LANs, there is a possibility that buffered packets in the old AP may be lost.

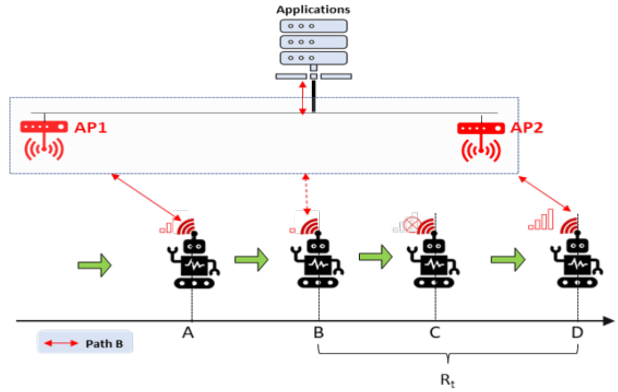

Fig. 2. Traditional standard roaming procedure.

Considering an AMR scenario where time-critical tasks may depend on maintaining low bounded latency data communication over the wireless link, it is obvious that existing roaming procedures can potentially disrupt the time-sensitive applications, depending on the application data transmission cycle and latency requirements. For applications that operate at very short cycles, for instance under 10 milliseconds, the roaming process may delay the time-sensitive data delivery beyond the expected deadlines. It should be noted that the low signal strength condition that typically triggers the roaming process may also disrupt application if it causes re-transmissions in the 802.11 layer or data loss. In Fig. 2, as the AMR moves from point A to point D, it roams from AP 1 to AP2. At point B the AMR is still connected, but the weak signal level may have already created disruption in the time-sensitive stream before the roaming procedure has started. Therefore, it is important to consider transmit power limits and coverage range when deploying AP in industrial networks to ensure signal resilient connections are always available. Several tools exist across the industry to plan and optimize the deployment of APs to ensure high reliability. Nevertheless, the roaming procedure is a fundamental aspect as it is required in any type of deployment.

The roaming procedure may also impact the TSN features as the STA switches association between APs. The 802.11 Timing Measurement (TM) or Fine Time Measurement (FTM) procedures that support 802.1AS time synchronization will need to be re-established with the new AP. Given the TM/FTM sessions happen periodically (e.g. default period is approximately 125 msec), no additional overhead is expected to maintain time synchronization, as the mobile STA only needs to ensure the next TM/FTM session is performed with the new AP. The APs are part of the overall TSN-capable LAN, and all APs should be synchronized to the same reference clock, therefore maintenance of time synchronization should be seamless as long as the roaming transition delay is smaller than the TM/FTM session periodicity. In the case of 802.1Qbv, the roaming delay may play a more important

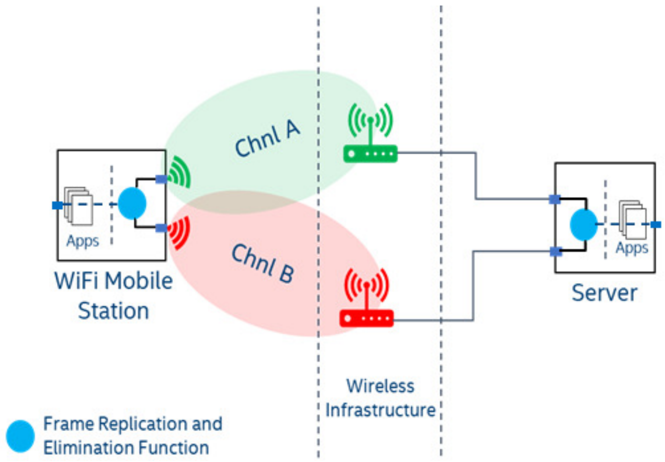

Fig. 3. Frame Replication and Elimination For Reliability (FRER) over Wi-Fi

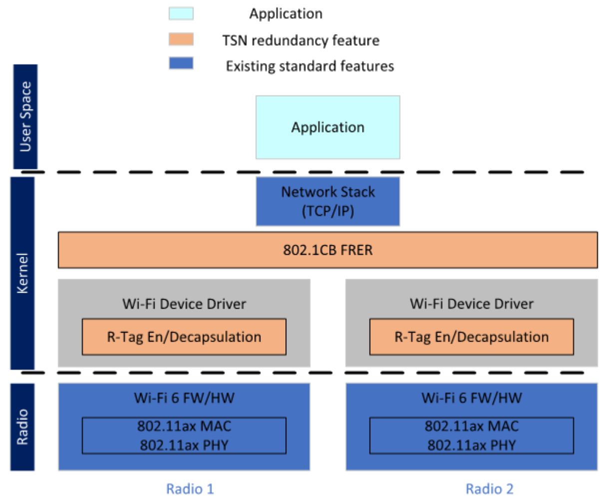

Fig. 4. Enabling Redundancy over WiFi-6 TSN Stack.

role as discussed previously, depending on the 802.1Qbv cycle time and duration of the protected windows for time-sensitive traffic. Furthermore, the configuration of 802.1Qbv resources at multiple APs needs to be performed seamlessly by the Central Network Configuration (CNC) entity. Configuration enhancements may be required to handle dynamic changes caused by roaming in wireless networks.

III. TSN Redundancy Over Wi-Fi Multi-Radio Devices

The Wi-Fi roaming procedure follows a "break before make" approach that incurs in suspension of the data connection as discussed in the previous section. One approach to avoid roaming induced delays in the data connection is to enable a "make before break" roaming, in which data communication is maintained while the roaming procedure is being executed. This can be achieved by adapting the 802.11 specification to leverage new Multi-Link Operation (MLO) capabilities being introduced in the 802.11be amendment. The reliability and latency enhancements enabled by multi-link techniques under development in 802.11be has been evaluated in [14]. Despite the promising results, the 802.11be specification is not yet finalized and MLO capabilities are only expected to be available in future Wi-Fi 7 products. In this work, we consider the existing computing platform capabilities to support multiple Wi-Fi Network Interface Cards (NICs) connected via the main PCIe bus to maintain multiple associations and enable the "make before break" roaming capability. In addition, we leverage the 802.1CB FRER functionality to maintain seamless application data connections and deliver time-sensitive data without being impacted by roaming delays. We have implemented the 802.1C FRER over dual Wi-Fi 6 NICs in a compute platform that can be used by AMRs.

In Fig. 3, we show the network architecture when multi-radio capabilities are enabled in the mobile STA. We consider two Wi-Fi 6 radios that are configured to operate simultaneously in non overlapping channels. The FRER function is introduced at the link layer above the multiple Wi-Fi radios so that the capability is transparent to the higher layer applications. Next, we describe the FRER implementation and how it was used in combination with the multi-radio capability to ensure roaming with no perceived delay for time-sensitive applications.

A. *Wi-Fi 6 TSN Software Stack with Redundancy Capability*

In this work, we have extended the IEEE 802.1CB implementation over Wi-Fi 5 TSN discussed in [8] to operate with a new Wi-Fi 6/6E Wireless TSN software stack. The new stack is enabled by a custom Wi-Fi 6/6E driver that supports the TSN features and the latest off the shelf Wi-Fi 6/6E NICs from Intel (AX210). The new stack also implements an enhanced 802.1AS time synchronization capability over 802.11 FTM, which provides higher time synchronization accuracy compared to the 802.1AS implementation over 802.11 TM over Wi-Fi 5 [8]. The FRER function is introduced over the Wi-Fi 6 driver and it works by inserting a redundancy tag (R-tag) between the 802.11 layer and the IP header. The Wi-Fi driver has been modified to recognize the new header including the R-tag and properly encapsulate/decapsulate the R-tag in the 802.11 frames. Fig. 4 shows the 802.1CB FRER layer and support introduced in the Wi-Fi 6 software stack.

B. *Enhanced Roaming procedure with TSN redundancy*

The 802.1CB FRER capability over dual Wi-Fi 6 radios enables two distinct data paths that can operate simultaneously. Of course, the APs have to also support the dual radio capabilities, which is typical in most commercial APs. The APs deployment has to be planned accordingly to ensure robust coverage at any location within a factory/warehouse environment, considering frequency planning and coverage for the redundant links. In other words, an AP deployment layout should consider a redundant set of channel assignments laid out in such a way that the infrastructure is able to provide disjoint redundant paths (links) for the STA in support of the 802.1CB FRER capability. There are several challenges related

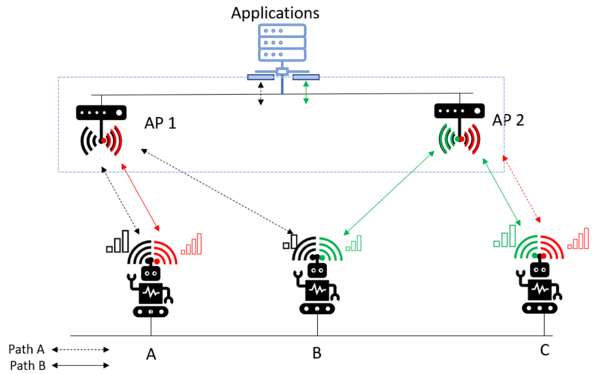

Fig. 5. Enhanced roaming procedure with redundancy.

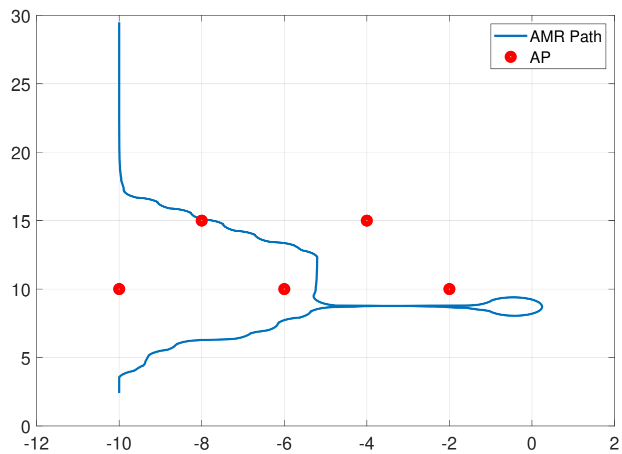

Fig. 6. AMR environment scenario. Navigation task involves and AMR moving along blue path from bottom left corner to top left corner.

to wireless propagation and coverage planing in industrial scenarios, which are outside the scope of this work. In this paper, we focus on evaluating the TSN redundancy capability as an approach to maintain seamless connectivity during roaming events.

Once the TSN redundancy capability is enabled, the application packets are always duplicated over disjoint links. Only one of the links is used for performing roaming at any given time as the STA moves around, while the redundant link maintains data communication with the current AP. Once the roaming is complete and data connection re-established, the other link can also roam to the new AP. A roaming scenario is illustrated in Fig. 5, where the AMR connects initially to two channels (as two independent BSSs enabled by AP A). As the AMR moves and the signal strength to the first AP drops it starts roaming in one of the radios to one of the channels in AP 2 (green channel), while maintaining one data link (black channel) with AP 1, as shown in position B. At position C, the AMR has switched both channels to AP 2. The TSN redundancy function maintains packets flowing throughout the process and even if one of the connection is interrupted/dropped in one of the links, a redundant packet can still reach the server. Next, we present experimental results using the TSN redundancy in simulations and real experiments.

IV. Wireless TSN Testbed and Experimental Results

In this section, we provide a series of experimental results demonstrating the use of Wireless TSN redundancy to ensure zero-delay roaming in AMRs. To demonstrate a scalable warehouse scenario, we first perform a detailed numerical simulation analysis. Following this, we detail a physical experimental AMR test bed and report real world measurements demonstrating redundancy features.

A. Simulation Analysis

We conduct a larger scale analysis of TSN redundancy through numerical experiments in a simulated mobile robotic factory use-case. Using the open-source MuJoCo simulation platform [15], we construct a factory-like environment in which an AMR navigates through a prescribed path, leveraging on-premise Edge compute to perform compute intensive localization functions (referred to as SLAM). As previously described, a Wi-Fi network is utilized to communicate between the client device located on the robot and the AP connected with the Edge infrastructure—see [2] for details on this setup. Our numerical simulations use a system-level simulation of a Wi-Fi 6 network with 802.1CB redundancy features in conjunction with the MuJoCo physics simulation environment. We model Wi-Fi fast roaming procedure is modeled assuming an data connection interruption of 10 msec, which is compatible with lab experiments performed between Intel Wi-Fi client and a third party AP implementing 802.11r. The roaming event is triggered based on the signal strength.

In Figure 6 we present the AMR navigation task setup, where the red line indicates the prescribed path to be followed by the AMR, starting from the bottom left corner and concluding in top left corner. We consider in our numerical experiments a maximum speed of 4 m/s. The SLAM workload that is offloaded over the Wi-Fi network consists of a 41 KB payload in the uplink and 32 byte payload in the downlink, occurring every 8 ms. The red markers further indicate 5 APs deployed in the network each operating with 80 MHz channel bandwidth.

In Figure 7, we present the network uplink latency (which contains the highest volume load) in the case in which the client device is equipped with redundancy capability over dual radios and the case in which it can connect to only a single AP at a time (single radio). It can be observed that, in the latter case, large spikes in uplink latency occur during the periods in which the device is re-associating to a new AP during roaming. Further observe that such latency spikes, reaching around 16 ms, far exceeds the control duty cycle of 8 ms of the AMR control loop, and can thus cause performance degradation. The latency performance using redundant links, on the other hand, maintains a 7 ms latency even during roaming periods due to the uninterrupted connectivity enabled by 802.1CB

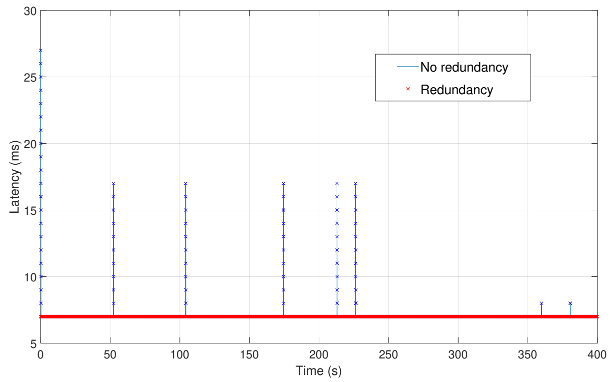

Fig. 7. Packet latencies for uplink packets during AMR navigation task with and without redundancy capabilities. Without redundancy, large spikes in latency that exceed the control duty cycle are observed during roaming periods, while latencies remain at 7 ms with redundancy enabled.

redundancy.

B. *Warehouse measurements*

We have also performed experiments in a real warehouse environment using a Mobile Robot as shown in Fig. 8. We set up the network with two APs labelled as AP1 and AP2. Given the TSN redundancy capabilities are not available in off the shelf APs, we have used Intel NUCs equipped with Wi-Fi 6 client NICs (Intel AX210) operating as AP in what is known as Soft-AP mode. The APs are connected to a single Application server over Ethernet. As it was not feasible to modify or upgrade the Mobile Robot available for the experiments, we have used another Intel NUC equipped with two Wi-Fi 6 NICs (Intel AX210) to enable the TSN redundancy capability and mounted the NUC on top of the Mobile Robot. A closer snapshot of the AP and Mobility Robot with top mounted NUC is shown in Fig. 9. The time-sensitive application is modeled by a downlink data stream (60 Byte packets at 100 Hz) between the Application server. The traffic was generated using *iperf* and measurements were done using *tcpdump*.

Given our need to use clients devices in Soft-AP mode in order to implement the TSN redundancy capability, our experiments also have some limitations. The APs (Soft-APs) can only operate with a single radio. In our experiments, they are configured to operate in 20 MHz at the 5GHz band with 1 dBm transmit power. AP1 uses channel 157 (5785 MHz) and AP2 uses channel 149 (5745 MHz). This configuration is enough to enable an overlaping coverage between both APs, which will be important to take advantage of the redundancy capabilities. Also, we do not have fast roaming (802.11r) capabilities implemented in the APs, which will result in higher roaming delays. Commercial APs may be optimized low latency traffic forwarding within its protocol stack compared with a Soft-AP, which is used for testing and not as a commercial-grade AP product. However, we believe the testbed limitations do not affect the main goal of the experiments which is to validate the network behavior with and without the redundancy capability in roaming scenario.

Fig. 8. Roaming experiment scenario with Mobile Robot in a warehouse environment

Fig. 9. AP implemented as a NUC operating as soft-AP and Mobile Robot with mounted NUC

Refer again to Fig. 8 which illustrates the roaming test scenario. The top part of the figure shows the Mobile Robot with a single radio a straight path between both APs. The Wi-Fi radio uses active scanning to identify new APs and as the signal strength with AP 1 degrades, it drops the connection with AP 1 and establish a new association with the AP 2. When redundancy is enabled (bottom part of the figure), the Mobile Robot has a strong signal strength with AP 1 but it is outside the range of AP 2. As it moves, the second radio is able to connect with AP 2 while the first radio is still connected with AP 1. Due to the 802.1CB FRER function running at the higher layers data packets continue to be delivered and duplicate packets are eliminated during the periods where both connections are active.

We have measured the time difference between consecutive packets arriving at the Mobile Robot (inter packet arrival time). In ideal conditions, the inter packet arrival time should be constrained, mostly under 10 msec given the continuous flow of packets (60 Bytes at 100 Hz) used in the experiment. Fig. 10 shows the inter packet arrival times for the entire experiment with and without redundancy enabled. As expected, redundancy capability is able to maintain the inter packet arrival constrained without experiencing any significant delays. The single radio (no redundancy) case has significantly higher variation in the inter packet arrival times. Also very high delays are observed due to the roaming procedure. Fig. 11

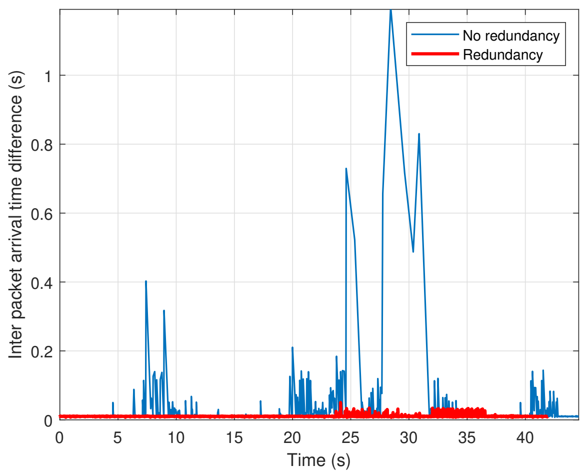

Fig. 10. Inter packet arrival time as measured at the mobile robot NUC while traversing the path between two APs. Without redundancy multiple large spikes are observed causing packets to be lost.

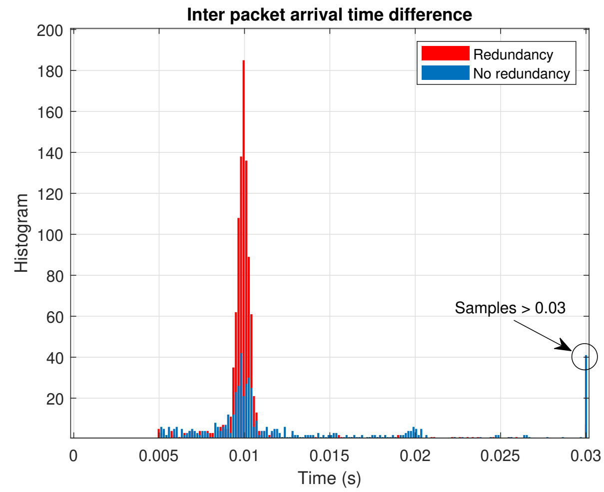

Fig. 11. Inter packet arrival times with and without redundancy enabled. We observe most packets arriving near 10ms intervals with redundancy, however a large group of packets arrive with significant delays greater than 30ms when redundancy is not enabled.

shows the histograms for the inter packet arrival times for the period around the roaming event (between 20 and 40 seconds in Fig. 10). As can be noted, most samples are grouped tightly around 10 msec when redundancy is enabled. In the single radio case, a large number of samples experience layers higher than 30 milliseconds as highlighted in the figure. We also observe that 7.3% of packets were lost due to re-routing issues in the case of single radio experiment, while no packets were lost when redundancy was used.

Even though the delays experienced with a single radio device may be smaller when using a commercial AP implementation, the data connection interruption is unavoidable with current roaming procedures for a single radio device. The TSN redundancy capability implemented at the higher layer is able to remove the effect of roaming as long as there one connection active at any point in time.

V. Conclusion

Mobile Robots are pervasive in industrial environments and require deterministic low latency wireless connectivity. Advances in wireless technologies and wireless TSN capabilities are promising, but the challenges imposed by roaming procedures are still to be addressed. In this work, we consider TSN redundancy based on the 802.1CB standard as an approach to minimize delays associated with roaming procedure in a Wi-Fi network. We discuss a TSN redundancy implementation using Wi-Fi 6 and provide a performance evaluation using simulation (for a large scale scenario) and a real test bed in a warehouse environment. The results validate the expected benefits of leveraging dual radios with TSN redundancy operating at a higher layer to minimize the effects of roaming and maintain consistent low latency performance. As future work, we plan to explore new Wi-Fi chipsets with multi-radio capabilities and multi-link operation enhancements defined by 802.11be, as well as commercial AP implementations for the TSN redundancy capability.

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