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An Evaluation of Broadband Technologies from an Industrial Time Sensitive Networking Perspective

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***Abstract*— In industry, mission-critical assignments require special characteristics for their networks. Chief among these requirements is reliability – proven to be even more desired than other characteristics such as low latency. IEEE 802.1 Time Sensitive Networking (TSN) is a set of Ethernet standards that delivers this high level of urgency to guarantee deterministic messaging and Quality of Service (QoS) for such real-time applications. With the progress made in the wireless broadband technology realm, it would be an opportunistic and fruitful venture to port these TSN standards to the wireless use-case. The choice of broadband technology that would fit this exercise best is an important question. The paper aims to evaluate popular broadband technologies, that is Wi-Fi and the cellular technologies of 4G and 5G, to assess those features that are available in their standards to support or implement the TSN technology in an industrial environment. Along with an overview of TSN and its requirements, the paper aims to review these broadband technologies to determine their readiness for time-sensitive networking. With the aid of results collected from iterative network simulation experiments, our work also shows in what ways the immediate wireless technologies need to be specialised for TSN.**

Keywords—5G, 5GS, 5G-TSN, 802.11, 802.1AS, critical traffic (real-time applications), Industrial Internet of Things, IIoT, LTE, NeSTiNg, Network Function Virtualisation, NFV, network slices, reliability, scheduling, synchronisation, Time Sensitive Networking, TSN, Ultra-Reliable Low-Latency Communication, uRLLC, Wi-Fi.

I. INTRODUCTION

A prime use case of IoT (Internet of Things) is in the industry vertical and is often referred to as Industrial IoT (IIoT). Communication among devices used in industry has traditionally been handled through wired medium connection – standard Ethernet, which makes use of many field-bus technologies. Of these, one technology stands out for its robustness and promise to deliver predictable communications in a manner that would enhance efficiency of the Ethernet infrastructure in place: Time Sensitive Networking. In conjunction with the Open Platform Communications Unified Architecture (OPC UA) protocol's PubSub mechanism [1], which it is commonly applied together with, it is quickly changing the look of the factory floor. Because of TSN's capacity to allow multiple services to be consolidated over the same physical link, and OPC UA's inherent feature of interoperability, they are accelerating the convergence of technologies for data exchange at the plant level.

Though it excels at the determinism that it seeks to deliver, TSN is affected by the same set of issues that affect wireline communications. Ethernet network solutions are affected by: a lengthy installation process for the cabling infrastructure; limited range and mobility for network devices, where the opposite is desirable for IIoT applications like in industrial robots used as automated guided vehicles (AGVs); high cost for cabled infrastructure, in comparison to its wireless counterparts; tedious procedures for the ongoing or routine maintenance, among others. TSN is as well governed by and currently forced to operate within these constraints.

Given the progress made in the wireless broadband technology realm it would be an opportunistic but fruitful venture to port TSN to the wireless use-case. The choice of broadband technology that would fit this exercise best is not a trivial one and should be made with due consideration of the capabilities and features of the present technologies. Efforts have been made on a possible 5G-TSN architecture, for example, although the amount of peer-reviewed literature that has been published to this end is scarce. This paper seeks to investigate the popular wireless technologies to assess their preparedness to host TSN in applications with stringent timing requirements, made use of in industry. The evaluation aims to determine their readiness for TSN. An experiment is also presented to demonstrate that existent wireless infrastructures require special modifications to be truly proficient at delivering time-sensitive communications – an idea which is also shared in [2]–[4].

The IETF's (Internet Engineering Task Force) DetNet, or Deterministic Networking, is another networking standard for Ultra-Low Latency (ULL) networks. Like IEEE's TSN, IETF's DetNet aims for millisecond latencies while affording the network with high reliability [5]. It is as well designed for centrally managed networks, and not the open internet. Unlike TSN, however, it is not limited to OSI model Layer 2, but extends its technologies' support into Layer 3, for networks that require IP routing there [4], [5]. As per [5], DetNet may extend to even higher layers.

Encouraging progress has been made into developing its standards, however, this work is, as yet, lacking. More precisely, in [5], the TSN task group has already published a series of networking standards, while the DetNet task group's documents are presently at the stage of internet drafts, seen in [6], and require further development. That is why the broadband technologies will be compared against the more complete requirements and features of TSN. These have been defined to a further degree, and organisations have already begun releasing industry-compliant TSN devices with use-cases like in [7]–[9]. There are other ULL technologies like Wireless High Performance (WirelessHP), with different goals other than those of TSN and DetNet which aim at deterministic latencies [5]. These other technologies and specifications will not be considered.

This paper is organised as follows: Section 2 outlines the features of TSN, detailing its requirements; Section 3 provides a brief review of the features of the key broadband technologies, describing which ones are desired, and which areas fall short; Section 4 presents a summary of the findings of the investigation; Section 5 details an experiment that shows how present wireless equipment handles TSN; Section 6 concludes this paper with a discussion on the level of preparedness of the conventional networks discussed for TSN.

II. REQUIREMENTS FOR TSN

TSN aims at delivering deterministic messaging in order to provide guaranteed Quality of Service (QoS) for supporting real-time applications. To make such a guarantee, there are certain requirements that need to be satisfied. They comprise the following:

A. *Support for multiple services*

This means allowing several services with different kinds of traffic to be consolidated over the same architecture [10]. Usually, the traffic from these services falls under one of two types: critical control traffic versus best-effort (or background) traffic[1]. TSN is able to differentiate between the two for better QoS. The next requirement arises as a direct consequence of this.

B. *Low transmission latency*

This ranges from under 1 ms to 10 ms for equipment control in industrial environment [11]. In TSN, this appears to be governed by three things:

1) Scheduling: Arranging frames for different services or communications in their own schedule-compliant queues. This guarantees an upper-bound limit for latency of transmissions [7]; it works to ensure that critical messages will always be delivered without interruption at their appointed times. TSN handles this through IEEE 802.1 Qbv [12].

2) Allowing for frame pre-emption*:* this sets a minimal latency in the presence of more critical transmissions by allowing them to interfere with, and cut off, non-TSN traffic mid-transmission. Afterward, the interrupted session continues where it left off, accomplished through standard IEEE 802.1Qbu [13]. Although this may not be a strict requirement for all as some vendors like [8] are able to implement time-sensitive communications without utilising any frame pre-emption capabilities in their equipment. It is also interesting to note that another kind of pre-emption exists in cellular communications, which shall be discussed later.

3) A steady dedicated bandwidth *for communications:* usually IIoT applications do not run bandwidth-intensive operations. A capacity of 100 Mbps is sufficient to cover a wide range of cases, comparable with the data-rates that can be averaged by most fieldbuses as seen in [14]. For the strict requirements of equipment control on the factory floor, a dedicated connection that can supply a few kilobits per second up to 1 Mbps is sufficient.

These three, in conjunction, set and maintain the QoS at a specific level. As reported in [9], TSN assures the end-to-end latency of the network no matter the workload at the time, heavy or light.

With these different services running and communication streams flowing, there are various devices that will be involved, whose number only looks to increase what with the converging of IoT in industry and the boom of 4IR. The next requirement accommodates their orchestration.

C. *High precision time synchronisation*

This is to do with having one common time for all participating network elements. They need to be in sync for their activities to be well-coordinated. In fact, this is where time-sensitive networking begins, because without this there wouldn't even be room for the scheduling of any kind of services. In [15], Ethernet TSN uses IEEE 802.1AS, which is a profile of IEEE 1588v2 PTP. It is normally capable of syncing the slave clocks to the master clock with great accuracy: within the order of sub-microseconds for hardware synchronisation, and that of a millisecond for software synced devices. TSN works like 1588 hardware synchronisation.

D. *Vendor-neutrality and versatility*

The technology should not care for, or is not specific to, a particular vendor, that is, it is vendor-agnostic. It can be applied by different manufacturers. Whereas other fieldbus solutions are mutually incompatible [16], worth mentioning is the fact that TSN is at present highly interoperable – it can integrate with, and work alongside several other fieldbuses and automation technologies. Furthermore, in [9], TSN is an IEEE communication standard that allows interoperability between standard-conformant industrial devices from any vendor. Vendors everywhere should conduct interoperability testing to ensure an open platform for data exchange within control systems.

Reliability is what such communications is predicated on. It equates to a high success rate for packet delivery, and

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[1] Critical control traffic is time-sensitive traffic which is often regarded as real-time communication, while best-effort (or background) traffic is a non-real-time communication, which means it is less "urgent". This kind of distinction is important where mission-critical applications such as those employed in health systems or in industrial automation are in play.

efficiency. Increased efficiency is the direct result of a "predictable" network [8], which is come by through synchronisation and low transmission latency, as mentioned, and also built upon by a layer of seamless redundancy (IEEE 802.1CB [17] – Frame Replication and Elimination for Reliability). By this standard, copies of frames are sent out at the same time as the intentional frames, but on different paths split up from the original stream. The original becomes a compound stream composed of member streams, all headed to one destination. Upon successful arrival of the intentional frames, and after all streams are re-joined, these duplicates are erased or "eliminated" on the last work node to the destination. From [17], it is worth noting that 802.1CB does not manage the creation of these multiple paths over which the duplicates are transmitted.

Reliability is therefore an implicit underlying requirement of a time-sensitive communication. For industrial automation, a near-lossless reliability of 99.999% may be required.

III. REVIEW OF THE TECHNOLOGIES

A review of the current wireless broadband technologies follows to see how capable they are at supporting TSN. It will consider what features are available in their standards that allow them to implement the TSN body of standards in the industrial environment.

A. Requirement 1: Allowing multiple services

Most wireless technologies partially satisfy the first requirement.

The current Wi-Fi standard, IEEE 802.11ac or Wi-Fi 5 [18] can haul all types of traffic; its architecture includes different access categories (AC): voice, video, best-effort, and background. Where it falls short though is in the extent to which it differentiates between the urgency of these different classes of traffic – it does not have a specific AC for time-sensitive communication [2]. The ACs help Wi-Fi stations apportion the network resources appropriately depending on the service for better QoS. But this is only supported once a device has successfully engaged the channel to transmit. In as far as access priority and what device or communication should be serviced first, Wi-Fi routers or stations make use of approaches like the Virtual Collision Handler in 802.11e (2005 version) to grant access to high priority traffic. Although experiments have evidenced that there are still some serious shortcomings in Wi-Fi in catering to time-sensitive traffic such as starvation from resources [19]. This will be covered more in requirement 2.

4G (LTE) as well can carry different types of traffic in its packet-switched network. It makes some distinction between the services being offered – voice, video, web-surfing or some other data function – treating them all as different types of data calls. It is thus aided in providing a specific level of QoS, but at the expense of efficient utilisation of its radio resources; the studies on end-to-end QoS in LTE, [20] revealed that current approaches in LTE, even with parameters like the QoS Class Identifier (QCI), mean that mobile network operators are forced to make a trade-off between the performance they offer and the QoS they guarantee their clients. Even if the telco resorts to sending numerous copies of the packet, this works counter-actively to ensuring QoS because flooding the channel like this degrades its performance. This is why the QoS offered by a circuit-switched call in 3G may in some situations be more assured than that of a packet-switched call. The authors also believe that this reason suggests why this older technology persists in the design of telcos today.

5G has the potential to handle things quite differently. It is a technology that should deliver highly convergent networks once fully operable in most territories. One of its core features, network function virtualisation (NFV), allows it to implement network slicing: a network service of a particular traffic can be deployed in its own network slice. As if in a virtual private network (VPN) environment, a service of one slice should not affect the operation of those in other slices. This allows 5G to assign a specific level of QoS for different kinds of traffic, by giving mobile operator clients a dedicated connection to the network operator resources, but without them having to lease out specific portions of spectrum as is the case in LTE. It would fully meet requirement 1.

Cisco hails the next generation of Wi-Fi, that is, its 802.11ax specification known as Wi-Fi 6, and 5G as complementary technologies built from the same foundation [21]. From here on out, future iterations of Wi-Fi will be discussed alongside 5G. Even before its ratification in mid-2020 it was envisioned to support many industries with mission-critical services like health, energy, and as relates more to our discussion, manufacturing automation. 5G is expected to handle all kinds of traffic like the current Wi-Fi 5 standard, but it goes further in this regard in that it will add some enhancements that will work to support real-time applications for better QoS.

B. Requirement 2: Low latency

Latency times vary drastically along different wireless technologies. As one would expect, the more current the technology, the faster its transmission speeds. Scheduling plays a big part in determining the overall latency of a network. It is at the heart of a time-sensitive communication, and so it will be treated in depth.

For several reasons Wi-Fi 5 cannot support requirement 2 of a guaranteed end-to-end latency. Chief of these stems from the fact that Wi-Fi operates in unlicensed frequency bands and all sorts of other communications seek to make use of the same frequencies. There is usually contention for the channel in order to successfully relay frames. It involves its random access since a Wi-Fi station has to first determine what moments the channel is idle before it can begin transmitting. Transmissions are of variable length, some being rather long with an upper bound of 5 ms [2]; traditional Wi-Fi stations cannot interfere with an ongoing transmission once it's begun. This opportunistic use of frequency causes frames to be dropped due to collisions. There is frequent need for retransmission attempts [4]. Another cause is from interference. Wireless LAN (Local Area Network) signals are subject to interference from the transmissions of a range of devices, which affects the network performance. In the case of mission-critical services that are administered in controlled settings like that of a factory-floor, this can be kept in check through the employ of certain methods. If the interference is from other parties, that is, from outside the factory, oftentimes the plant is big enough for them to decay. If on the other hand the source is in-plant communications, other methods can be used to mitigate or solve the disruption. Interference from multipath effects and electrical disturbances can be eliminated by methods such as OFDM (Orthogonal Frequency Division Multiplexing) and MIMO (Multiple-Input Multiple-Output) for the former, and galvanic isolation for the latter [22]. In any case, because of higher packet loss, packets have to be retransmitted more often in wireless media [4]. Ultimately, all these factors increase the PPDU[2] duration, or packet duration, and account for overall higher latency times, especially at moments when the network is congested. To put it plainly, if packets arrived at a Wi-Fi STA (station) at a constant bit rate, it can incorporate one of several of the Wi-Fi standard's schedule-based packet transmission mechanisms to transmit the packets [2]. But as described, this is not the case – packet flow is at times irregular. Apart from worst-case latency, jitter and reliability do not remain at constant values and do vary in congestion periods. This makes following a strict schedule out of the question. A look at common MCS[3] value lists will specify the theoretical throughput of a Wi-Fi STA as opposed to its actual throughput. In [11], an example of latency in Wi-Fi 5 (802.11ac) revealed that a single user transmission from 9 STAs will take approximately 1.3 ms. Adame et al. [23] contend that Wi-Fi 7 (802.11be) could overcome the limitations caused by BSSs (base station subsystems) under a common administrative domain, which affect TSN operating in license-exempt bands.

Going by the ideas of [24], managing the communication delay from sources of queueing and packet transmission requires a twofold solution: firstly, to stop the transmission activities of non-TSN frames when a TSN frame shows up; then, to reduce the channel access times, and protect transmissions from collisions.

Frame pre-emption is the ability to interrupt the normal flow of scheduled packets mid-transmission and allowing another packet flow to take precedence before re-engaging the scheduled flow. It is not inherently present in Wi-Fi. As mentioned, it is at present not possible for a Wi-Fi station to stop another Wi-Fi station from transmitting [2]. This feature would have to be included in the device by the manufacturer, of which most manufacturers would not willingly do [25] unless it is required by standards bodies. As noted in the minutes of the IEEE Wireless Next Generation Standing Committee Meeting [25], manufacturers would have to support this solution by making Wi-Fi stations that would voluntarily give up the opportunity to transmit in the presence of a TSN transmission.

Summing up on requirement II for Wi-Fi communications, transmission times vary, and the ultra-low latency needed for industry automation in mission-critical IoT can only be achieved through modifying the Wi-Fi stations to make them able to navigate between the different types of traffic queues. The few works [2], [24] found to this end have only theorised how this can be realised, none going so far as to venture into it practically. Until a practical solution is found and developed the average latency remains variable during congestion, and so Wi-Fi does not meet requirement 2.

The work [26] identified that the LTE authentication mechanism is a source of delay in the network. They noted that the delay from authentication is significant to cause degradation and service failures; the accessibility of the LTE network may thus affect its QoS. Apart from that, unless there is a dedicated connection, network delays often vary because of the constant management of resources which seeks to balance the network load with its performance output for best overall use of resources, focusing on many objectives besides time sensitivity. Service pre-emption is quite possible and is regularly managed by base stations to support a subscriber making calls that deem a certain level of quality. Their call connection is assigned to a base station that would service that particular connection more optimally. QCI and the 3GPP defined mechanism, Allocation Retention Priority (ARP), are used to prioritise packets and service flows [27]. A Technical Advisory Note to the Government of Canada [27] supports this: the state of a pre-emption flag, whether it is enabled or disabled, dictates whether a service flow can pre-empt a lower priority service flow, or whether it can itself lose those resources assigned to it to honour the request of a higher priority service flow. The particular lower priority service may be allowed to run if it can do with the limited resources available, albeit at a lower quality than normal, which is known as service degradation. In the event there are higher priority services already running in the network, it is also possible to deny any lower priority service requests totally. Despite these capabilities, LTE still falls short of meeting the first requirement with a latency averaging 50 ms.

One of the 3GPP's takes on 5G TSN involves extending the 5G system (5GS) to connect to the IEEE TSN network as just another among its IEEE TSN-capable bridges [28]. This integrated system architecture would render the entire 5GS, from end to end, to be seen as a single logical (or virtual) IEEE TSN 802.1AS time-aware bridge. To support TSN in this way, 5G would need modifications to its radio access network (RAN) and core elements. It is currently still limited in these specific areas as presented in [28]: features to provide for the enhanced scheduling in TSN that has transmission windows as small as 10-20 µs accessed in the time domain (this currently sits at 100 µs or larger in the 5GS RAN); features to ensure the radio performance in terms of latency, reliability and capacity. The views of Mannweiler et al. [28] posit that enhancements are needed to guarantee availability of radio resources in 5G cells that would fulfil these latency and jitter requirements. Jitter in this regard can be understood to

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[2] PPDU is an abbreviation inside an abbreviation for PLCP (Physical Layer Convergence Protocol) Protocol Data Unit. It is what's used to measure a unit of information that is transmitted among peers in a packet-switched data networks. Some texts may refer to it as simply the Physical Layer PDU, or more painless still, the packet duration.

[3] MCS index value is a unique number used to specify these three values – number of spatial streams + modulation type + coding rate, for a Wi-Fi STA.

influence predictability. And, as stated earlier, there is a direct relation between predictability and reliability, and the overall efficiency of a network. A predictable network environment fosters efficiency [8] – which is a key goal of time-sensitive communications. Additionally, time sensitive traffic classes need to be accommodated in 5G QoS profiles, as outlined in the meeting in [3]. Some of the enhancements for 5G TSN integration are included in 3GPP's Release-16, which was only finalised in July 2020, with further enhancements expected in Release-17 (projected for 2021, though the pandemic has highly increased its risk of being delayed). For this reason, it is expected that 5G will fully meet the needs of the second requirement since these capabilities enable 5G to support ultra-reliable and low latency communications (uRLLC). It (5G) has the potential to deliver traffic with low latency links that assure an interval of under 1 ms. Furthermore, in place of frame pre-emption, 5G offers the option to run such time-sensitive communication efforts on their own dedicated connections using network slices. Although the radio frequency channel would still be shared amongst all users, so congestion periods would bring up similar problems as in LTE and other broadband technologies if the number of these users increases beyond the efficiency point of the channel.

Most non-wireline approaches readily meet the bandwidth requirement: Wi-Fi's present standard (Gigabit Wi-Fi) peaks out at 1300 Mbps theoretically, though the actual speed is reported to be around 200 Mbps, so still it surpasses the stated average; the maximum download speed in LTE is circa 300 Mbps; 5G is the most acclaimed of these, expected to achieve download speeds of 10 Gbps.

C. Requirement 3: High precision time synchronisation

Another reason that reduces Wi-Fi's ability to support time-sensitive communications is its inability to accommodate precise time synchronisation. However, [29] noted that the 802.1AS standard does include a proposal for clock synchronisation for wireless 802.11 in section 12 of its standards document [30], by using 802.11 Timing Measurement (TM). The task of making sure that all Wi-Fi stations have their clocks synchronised to the same time is one that involves heavy coordination of all participating elements. Following the example in Ethernet, this could involve either hardware synchronisation of these stations, or a software synchronisation embedded in their programs (which is generally not as precise as hardware synchronisation, as discussed earlier). Although this would be a hurdle for legacy networks, the protocol could easily be configured in newer range devices.

Still, there remains the task of selecting a "Grandmaster device". This would be the sole device in the network which is responsible for propagating its own time to all other clocks in order to have a synced network. Ethernet TSN has a framework for this – the Best Master Clock Algorithm [30] (BMCA)[4]. In non-wireline channels, this choice depends on the type of the wireless network in question.

The current version of Wi-Fi has no system in place for this level of synchronisation. Literature to this end has seen a team, Cho et al. [31], try to harness Ethernet's synchronisation capabilities in the IEEE 1588 protocol and, by means of a gateway, extend it to the wireless sensors of their wireless network. Mildner [29] arrived at this same conclusion, that since there aren't at present any implementations of the previously mentioned 802.1AS proposed method for wireless clock sync, it requires one to fall back on clock sync mechanisms for wired Ethernet.

All generations of mobile radio access networks require precise frequency information and synchronisation for duties involving the efficient spectrum use and to perform handover between base stations [32]. This is accomplished through popular methods like Synchronous Ethernet (SyncE) in LTE [32], [33]. With regards to timing synchronisation, these mobile technologies work with at least microsecond accuracy at the base station. IEEE 1588v2 is prevalently used to achieve this accuracy, in conjunction with other methods like satellite-based timing (GPS for example). LTE techniques such as TDD (Time Division Duplex), MIMO, MBSFN (Multi Broadcast Single Frequency Network) each have varying requirements for synchronisation [33]. In [33], the degree of precision required for Time of Day (TOD) synchronisation is to some microseconds – it may be 1.5 µs or more depending on the application used, with MIMO techniques demanding as little as 0.5 µs. While in 5G, achieving high position accuracy requires that base station clocks are tightly synchronised to under 100 ns [32]. 5G is still being extended to provide tighter synchronisation for real-time capabilities. 3GPP has stated that the support for time synchronisation for the UE's is an enhancement that is only expected in Release-17 [34]. Similar methods as in LTE are used for synchronisation, that is, satellite-based timing, and packet network-based timing (IEEE PTP). Both these broadband technologies fulfil requirement 3.

D. Requirement 4: Vendor-neutrality and versatility

Wireless technologies are accommodated by a range of telcos, device manufacturers and vendors.

As regards Wi-Fi, the standards are defined by IEEE and the technology is managed by a body of companies, the Wi-Fi Alliance. In all existing versions they have allowed various manufacturers to produce equipment for the technology, using

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[4] The BMCA compares among several attributes, to determine which device should be the Grand Master: Priority 1 (which may be chosen based on proximity to the network, or how likely a device is to be removed versus those that are fixed), Class (the role of device), Clock Accuracy (the time source accuracy), offsetScaledLogVariance (or clock variance), and others, ultimately ending with the port number and MAC address of the clock as the final decider attribute. This last mentioned attribute, offsetScaledLogVariance, characterises precision and frequency stability.

their certification as a stamp of approval to ensure that devices meet expectations for interoperability among other things.

Cellular communication technologies are serviced by a network of mobile network operators (MNOs) around the world. These technologies are mostly only interoperable in as far as clients of different vendors and telecom companies may communicate with one another. There are restrictions however in intermixing the equipment in their architectures, say using components of the core of one network in another, depending on the design and layout of the particular operator (the reason why open standards are rising). It is possible to varying degrees and different dimensions. Some networks are being designed to use equipment from different generations of technology, which is not the same as inter-vendor compatibility. For example, a 5G network provided by the ABC network, using equipment from a vendor, Nokia-Siemens, to partially implement 5G as a non-standalone (NSA) 5G network that has an Evolved Packet Core (EPC) from LTE connected to both eNodeB (LTE) and 5G New Radio RAN (as is the case in 5G NSA Option 3). 5G is regarded as the ultimate convergence technology, so reasoning suggests that more platforms will seemingly converge and interoperate on it. Though this will have to be seen in future trials.

IV. ANALYSIS

A summary of results of the evaluation on the preparedness of the broadband technologies for a time-sensitive communication follows.

A. Analysis of Reliability

In TSN, the communication should have low-latency time guarantees in conjunction with being thoroughly robust or reliable. A measure of the total packets successfully delivered is a good way to assess how reliable a packet-switching technology is. The wireless technologies discussed so far are used in various environments for all kinds of tasks, and by different groups of subscribers or clients. Some of these tasks are urgent, while others fare well enough with a higher delay (best-effort traffic). A fair comparison involves a day-to-day scenario where the wireless technology is being made use of by a considerable number of different services at the same time. Different services have to be considered since not all these technologies are utilised strictly for stringent IoT services. Such a comparison will help assess how the wireless technology behaves when critical services are mixed with non-critical ones.

In such a setting with high channel usage, Wi-Fi has a high rate of dropped packets. It cannot help but perform sub-optimally because it gives no prioritisation to time-sensitive traffic – as mentioned, there is no AC or special class assigned for real-time traffic. And current methods discussed above aren't enough to evade resource starvation when there is heavy traffic involved. Consider the case of a medium to large-sized network with many users: transmissions from all devices access the network in whatever capacity they are able to, and transmission times cannot be predicted. They vary wildly in situations where variable-sized frames are present. All this greatly impacts determinism of the network. Poor predictability correlates to poor efficiency and reliability. Wireless technologies like Wi-Fi support 802.1CB for redundancy for increased reliability [4], [29]; however in [4], having frames travelling on multiple disjoint paths could cause them to be received out of order, and it would fall upon either the endpoints or switches to reorder them. Bush and Mantelet [4], have further stated that, because of the retransmission processes in wireless, there are other aspects that would need to be considered to incorporate this 802.1CB redundancy in this wireless TSN design. One such outstanding aspect they mention is the buffering of packets as they wait to be reordered upon receipt – Wi-Fi has not seamlessly integrated 802.1CB into its architecture as of yet.

The 4G LTE network boasts reliability of 99.99% in favourable conditions. This figure drops a digit in the same setting just described.

5G standards cite a reliable channel with high success rate for packet delivery (approximately 99.999%), although there hasn't been much room to thoroughly benchmark this against enough applications as its roll-out in different territories is underway.

Table I shows certain requirements of real-time applications, most of which were identified in [11], specifically for the case of equipment control in industry. It also shows a summary of the technologies under review and their preparedness or capability to satisfy these requirements, compiled with data extracted from the sources in the review including [35] for delay and jitter analysis in LTE.

TABLE I. STATE OF PREPAREDNESS OF WIRELESS TECHNOLOGIES

	Intra BSS latency (ms)	**Jitter variance (ms)**	**Packet loss**	**Data rate (Mbps)**	**Precise Synchronisation (ms)**
	[11]				[36]
Robotics and Industrial automation - Equipment control [11]	< 1 ~ 10	< 0.2 ~ 2	Near-lossless	< 1	< 1
Wi-Fi 5	No	No	No	✓	✓
4G/LTE	No	No	No	✓	✓
5G	Expected	Expected	✓	✓	✓

The next table with data extracted from [37] shows some performance requirements for uRLLC 5G (certain attributes such as connection density and service area dimensions have been excluded).

TABLE II. PERFORMANCE REQUIREMENTS FOR LOW-LATENCY AND HIGH-RELIABILITY SCENARIOS

Scenario	Max allowed end-to-end latency (ms)	Comms service availability	Reliability	User experienced data rate (Mbps)
Discrete Automation	10	99.99%	99.99%	10
Wi-Fi 5	No	No	✓	✓
LTE	No	Variable	No	✓
5G	Expected	Expected	✓	✓
Process Automation - remote control	60	99.9999%	99.999%	1 ~ 100
Wi-Fi 5	No	No	No	✓
LTE	✓	No	No	✓
5G	✓	Expected	Expected	✓
Process Automation - monitoring	60	99.9%	99.9%	1
Wi-Fi 5	No	No	✓	✓
LTE	✓	✓	✓	✓
5G	✓	✓	✓	✓

We ran experiments to investigate the workings of a setup involving TSN-aware switches and a TSN-unaware Wi-Fi access point, described in the next section.

V. SIMULATION

To highlight that it is critical that all components of a network need to support TSN, including the wireless portion, simulations on a network with wired TSN switches and a wireless non-TSN access point were performed.

Three setups were designed to be used: one with best-effort traffic only; another solely with TSN traffic; and finally, one with both TSN and non-TSN traffic. In the first setup, a non-TSN talker sends best-effort traffic to a listener through two switches and finally an access point which sends the packets to a wireless listener. In the second setup, a TSN talker uses the same interconnection to transmit critical traffic to another listener, using the access point to send data wirelessly for the final leg of the transmission. The last setup (see Fig. 1) has both talkers sending traffic to the wireless listeners to see how well it accommodates a combination of control traffic and background traffic with wireless elements present in the network. The single TSN-unaware access point was placed at a point in the setup after the second switch, to provide a bottleneck for both traffic flows. Up until the access point, all communication was passed through Ethernet. This is to demonstrate the necessity of having TSN-capable wireless components. The critical traffic consists of 354-bytes TSN frames, meanwhile, the best-effort traffic comprises 1400-bytes long non-TSN frames. The experiment was repeated for a range of scenarios that differed in frame send intervals and some set link speeds. The highest bandwidth speeds tested for were 1 Gbps Ethernet and 693.3 Mbps Wi-Fi (802.11ac). The mean numbers of packets delivered successfully was recorded, along with the losses incurred.

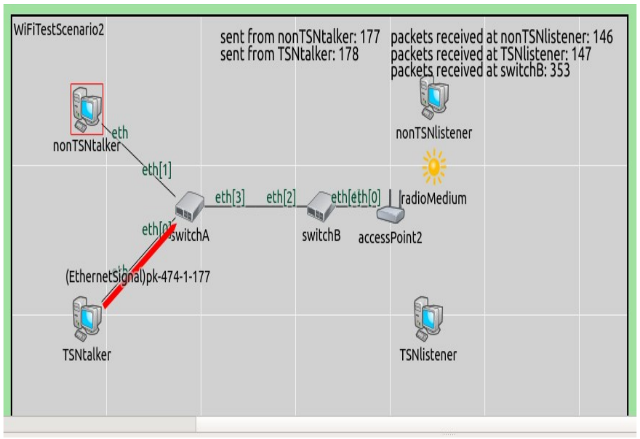

Fig. 1. TSN Simulation Setup

The packet delivery and losses were measured at different points in the network. The measurements indicate that all losses in the simulated network happen due to the TSN-unaware wireless access point. The plot in Fig. 2 shows a summary of the results for the losses measured after the access point, with respect to the traffic generated. The results tell that to minimise losses and thus maximise delivery of the critical TSN traffic, whether in the case with only TSN traffic present or for mixed traffic, the overall traffic (incl. TSN traffic) must be a small fraction of the total capacity of the channel. Our simulation reveals that if the channel is use to less than about 6%, the losses are marginal, under 3%.

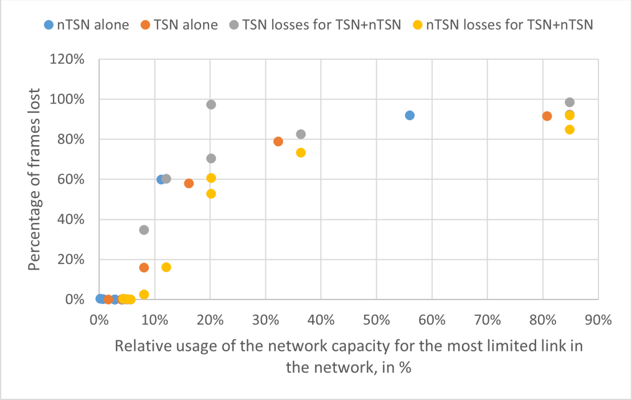

Fig. 2. Frames Lost in each network setup type vs Relative Network Usage. “nTSN alone” refers to non-TSN scenario, i.e. the model with no TSN traffic. “TSN alone” refers to the scenario with only TSN traffic. “TSN losses” and “nTSN losses” refer to the counts of the frame losses in TSN and best-effort traffic, respectively, in the model where both TSN and best effort traffic are present.

VI. CONCLUSION

Our findings suggest that, at present, 5G is the sole wireless technology whose specifications will presumably possess all the features that are requisite for time-sensitive communications. The 5G is most-readily adapted to suit mission-critical IoT, industrial automation and other application scenarios requiring determinism. As viable as 5G is, this work further helps to contextualise how 5G is still a way from the mark of completeness. Furthermore, some authors believe that even future versions of Wi-Fi such as Wi-Fi 7 (802.11be) will not be able to guarantee fully deterministic communications, since other wireless networks may make use of these same bands. However, many of the limitations of the present-day Wi-Fi can be mitigated in the future iterations to make it well-suited for time-sensitive networking.

The authors in [4] support that the road towards realising wireless TSN begins with leveraging the state-of-the-art hardware for their present wireless capabilities before finally transitioning into an ecosystem with innate end-to-end TSN capabilities. The simulation experiment was conceived with design considerations that followed this methodology. Further, it was built on the NeSTiNg framework which [38] developed and used to simulate TSN. The following work however modifies their original setup to accommodate wireless transmissions. As regards Wi-Fi, our simulated setup incorporated TSN-aware switches and a TSN-unaware access point; all packet losses in TSN traffic occurred at the TSN-unaware link.

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