5G for Industry 4.0 operational technology networks

A comparison of the features and application of 5G and Wi-Fi 6 for manufacturing, production and supply chain use cases

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Introduction

Manufacturers, supply chain companies and other enterprises are increasingly looking at mobile networks to provide flexible enterprise grade industrial connectivity. Where once mobile networks were the domain of 'road warriors' these are now displacing wired and Wi-Fi networks as the connectivity of choice across the broad range of industrial use cases due to the ability to deliver an unrivalled balance of capacity, bandwidth, flexibility and security. Wi-Fi is well established within the enterprise IT network environment, but, for the operational technology network that delivers connectivity for the 24x7 production line, warehousing and logistics systems it is necessary to look instead to 5G to support digitisation across the wide range of manufacturing and supply chain use cases.

Whilst Wi-Fi networks provide greater flexibility over traditional wired networks, these networks lack support for mobility and have bandwidth, scalability and signal propagation challenges compared with today's mobile networks. Wi-Fi is often the default choice for flexible enterprise IT, however, 4G and 5G mobile technologies are much better suited to the operational technology network, providing a more suitable technical platform for high volume, high reliability, always on manufacturing, production and logistics solutions in industrial environments. In particular

- Mobile standards for 5G and previous generations from 3GPP ensure a higher level of consistency, interoperability and certification for devices compared with Wi-Fi;
- Mobile networks deliver highest levels of data security and privacy through more advanced encryption techniqes, confidentiality of key exchange processes with SIM and embedded SIM cards, the design of the 'air interface' and robust provisioning and authentication processes;
- The Release 16 features for Ultra-Reliable, Low-Latency Communications deliver latency over the air of 900 micro-seconds to 1 milli-second, substantially better than available even with Wi-Fi 6E;
- 5G networks support Time Sensitive Networking providing support for time-critical functions and interworking between the mobile and wired Ethernet network;
- Quality of Service support is available with 5G networks in the form of guaranteed QoS;
- 5G provides both stand alone and PLMN integrated Non-public network services offering seamless mobility and handover for Connected Industrial Manufacturing facilities, warehouse and logistics;
- Support for a wide range of licensed spectrum with 5G enables a higher certainty of service and bandwidth, with additional support for consistent use of unlicensed spectrum with 5G NRU.

Wi-Fi is sometimes considered as a deployment option for industrial use cases because of perceived ease, cost and wide ranges of device and network products. However, often the decision to use Wi-Fi is made without a complete assessment of the particular demands of Industry 4.0 use cases, or, is based on limited trials that cannot develop to scale for the operational technology network. Recent Wi-Fi technologies including Wi-Fi 5 and Wi-Fi 6 promise the delivery of significant bandwidth gains over earlier generations of Wi-Fi networks. The headline throughput rates are, however, rarely achieved or achievable in Industry 4.0 deployments because of the complex physical environment and user and application demands. And, a Wi-Fi network that is suitable for providing email connectivity will not have the appropriate characteristics to support industrial control processes that are reliant on consistent low latency and high reliability connectivity.

It is also expected that a wide range of solutions for Industry 4.0 mobile network deployments will be available for 5G based on a diversification of the equipment supply industry enabled by 'open networking' and open source initiatives. The O-RAN alliance[1] particularly is actively enabling a wider supplier ecosystem with defined architectures and standards to ensure interoperability between different suppliers and variants of network equipment subsystems. These initiatives will also deliver greater levels of plug-and-play interoperability within the network and between networks and devices.

This paper explores the technical and operational differences between Wi-Fi and 4G/5G mobile networks and then reviews a broad range of manufacturing and supply chain related use cases for the application of these connectivity options. It is hoped that manufacturing and supply chain companies reviewing technology options for Industry 4.0 will see that 5G networks, whether supplied by mobile network operators or standalone, provides the best choice for the Industry 4.0 operational technology network with support over a wide range of use cases. In time it is likely that manufacturing and supply chain companies will consolidate wireless networks and due to the advantages offered by 4G and 5G mobile networks it is expected that these will become the exclusive wireless technology in many manufacturing and supply chain enterprises.

Comparison of Wi-Fi and 5G mobile

Overview

Both Wi-Fi and 5G mobile are based on mature technology standards, with clear product evolutions. Current Wi-Fi deployments will typically be based on Wi-Fi 4 and Wi-Fi 5 and newer deployments Wi-Fi 5 and Wi-Fi 6.

Version / IEEE Standard	When standardised	Bands	Channel width (MHz)	Typical Coverage[2]	Maximum Devices[3]
Wi-Fi 4 IEEE 802.11n	2007	2.4 GHz & 5 GHz	20, 40	< 50 metres indoors < 100 metres outdoors	256
Wi-Fi 5	2013	5 GHz	20, 40, 80,	< 50 metres indoors	512

[1] https://www.o-ran.org
[2] Some Wi-Fi access point equipment supports external antennas enabling coverage to be extended further or focused in specific areas
[3] Per access point based on enterprise grade access points from the Cisco Meraki product line https://documentation.meraki.com/MR/WiFi_Basics_and_Best_Practices/Approximating_Maximum_Clients_per_Access_Point

IEEE 802.11ac			160 (optional)	< 100 metres outdoors	
Wi-Fi 6 **IEEE 802.11ax**	2020	2.4 GHz & 5 GHz 6 GHz (future)	20, 40, 80, 160	< 50 metres indoors < 100 metres outdoors	1024

Table 1. Comparison of Wi-Fi versions

Wi-Fi channel width often appears generous but for any enterprise deployment realistically only 20 MHz channels are usable in the 2.4 GHz band and 80 MHz channels in the 5 GHz band due to the requirement to reuse frequencies for capacity and coverage purposes. As discussed later Wi-Fi channels are also shared for both uplink and downlink traffic, which introduces additional contention for devices with different uplink/ downlink requirements.

5G characteristic		**Value**
Data rate	Peak[4]	Downlink: 20 Gb/s Uplink: 10 Gb/s
	User experience[5] (low band)	Downlink: 100 Mb/s Uplink: 50 Mb/s
Spectral efficiency	Peak	Downlink: 30 bit/s/Hz Uplink: 15 bit/s/Hz
	Average	Downlink: 3.3 ~ 9 bit/s/Hz Uplink: 1.6 ~ 6.75 bit/s/Hz
Area traffic capacity		10 Mbit/s/m^2
Latency	User plane	1 ms ~ 4 ms
	Control plane	20 ms
Connection density		1,000,000 devices per km^2

[4] Achievable using high band (millimetre wave) spectrum
[5] In low band spectrum

Reliability		>= 99.999 % success probability of transmitting a layer 2 PDU (protocol data unit) of 32 bytes within 1ms
Mobility		0 km/hr ~ 500 km/hr
Mobility interruption time		0 ms
Bands **(Licensed)**	Low: < 1 GHz	Wide area coverage (up to 10's of km) across urban, suburban & rural areas
	Mid: 1 GHz to 6 GHz	Dense public network capacity & coverage (up to several km) Particularly in 3.3 – 3.8 GHz 80 - 100 MHz per operator
	High: > 6 GHz	For ultra-high speed and lowest latency 1 GHz per operator in mmWave band Coverage to 100's metres
Bands **(Unlicensed with 5G NR-U)**	3.5 GHz 5 GHz 6 GHz (TBD)	Indoor and outdoor for general coverage and capacity

Table 2. Key characteristics of 5G

Channel widths in 5G are more granular, normally in multiples of 5 MHz and with individual widths typically up to 100 MHz in lower bands and up to 1 GHz in the millimetre wave band. Total contiguous channel widths can range up to 2.4 GHz in the millimetre wave band[6] enabling ultra-high bandwidth for enterprises. Importantly many of the 5G channels are 'duplex' with a pair of identically wide channels each dedicated to uplink and downlink ensuring access for remote devices. Public mobile networks, such as that of Verizon in the US, are already demonstrating the delivery of "ultra-wideband" 5G services[7] reaching up to 4 Gbps showing the ability of mobile networks to achieve real-world throughputs far exceeding that of typical Wi-Fi networks.

[6] "Approaches to 5G Spectrum for Industry 4.0" https://www.gsma.com/iot/resources/5g-spectrum-industry40/
[7] https://www.verizon.com/about/news/fastest-5g-network-world-just-got-bigger-and-better

Raw bandwidth is, however, only one aspect of the enterprise requirement. For use cases including low latency/ high reliability industrial control, real-time location tracking, automated guided vehicles / autonomous mobile robots, and mass deployment of sensors it is only realistically possible to deliver these at scale using mobile technologies. This is due to key differences in the underlying architecture of the radio interface on 5G networks compared with Wi-Fi networks.

5G capability		Application
Data rate		Video capture for safety, security, and plant management Production line high frequency & precision data acquisition and defect monitoring with machine vision Robots, cobots Automated Guided Vehicles and Automated Mobile Robots
Area traffic capacity		Virtual reality & augmented reality Defect monitoring with machine vision
Ultra-reliable, low latency		Robot & cobot control applications Automated guided vehicles & automated mobile robots Plant control, safety, access control and fire systems
Connection density		Connecting 'everything' – tools, machines, cameras, sensors
Mobility		Automated guided vehicles & automated mobile robots Asset tracking
Spectrum	Low	Mining, oil refineries, pipelines, chemical plants, ports and asset tracking/ logistics where connectivity is required across a wide geographic area
	Mid	High quality indoor and outdoor coverage across manufacturing and production sites enabling a combination of sensing, control and video based applications

	High	Very high bandwidth density applications, particularly video for production line quality inspection using machine vision, virtual reality & augmented reality, automated guided vehicles, automated mobile robots and robots/ cobots in manufacturing and production plants

Table 3. Industry 4.0 applications enabled by 5G capabilities

Finally, 5G networks can integrate IoT, 5G NR, industrial devices, legacy 4G LTE and LTE-M devices together under one interoperable umbrella and with a single service provider able to deliver a fully managed service. At a cursory level Wi-Fi networks appear less expensive but require a team of experts to install, maintain, optimise and operate the network inside a large factory floor. The lifetime or total cost of ownership changes as a result, especially when considered against the wider range of use cases that can be enabled reliably over 5G networks. It will be perhaps too radical a move for Industry 4.0 enterprises to immediately exchange Wi-Fi networks for 5G and so a more likely scenario is that Wi-Fi 6 will support the IT domain of a factory while 5G supports the production domain with a plan to make these networks better interoperate in the future.

These topics are explored further below.

Mobility

Fundamentally mobile networks are designed to reliably support user and device mobility. Historically this was implemented to support continuity of voice calls as users moved around, ranging from low speed pedestrians, higher speed automotive uses or high speed train services. As data services have developed the same mobility support is translated to Internet and private network connectivity.

This support for mobility is supported by key features of mobile networks and devices including

- A holistic knowledge of the network composition that allows devices to be provided with key details of neighbouring cells[8] to enable quick and reliable handovers;
- The design of the radio interface that allows the device to measure signal strength and quality for the connected cell as well as surrounding cells so that the device and network can co-operatively work together to choose the best connection;
- The 5G New Radio transmission frame structure which scalably supports large numbers of devices with differing bandwidth, mobility and Quality of Service needs;
- Enhancements to the 5G Ultra-Reliable, Low Latency Communications (URLLC) service which maintain communications continuity (essentially "make" before "break") during handover[9];
- 5G massive MIMO (Multiple Input, Multiple Output) and beamforming which improve the reliability of communications for both static and mobile devices even at the cell edge[10].

Reliable handovers are key to advanced industrial control use cases including autonomous guided vehicles and their smarter equivalent autonomous mobile robots. 5G networks allow these vehicles

[8] Such as frequency, identities and related characteristics
[9] Part of 3GPP Release 16 – explained at https://www.ericsson.com/en/blog/2020/4/reducing-mobility-interruption-time-5g-networks
[10] 5G massive MIMO is explained at https://www.qualcomm.com/news/onq/2019/06/20/how-5g-massive-mimo-transforms-your-mobile-experiences, MIMO is also offered in Wi-Fi products

to have totally reliable operation throughout a manufacturing plant, or its associated warehousing, even in situations that challenge Wi-Fi networks. Access point switching in Wi-Fi networks is a slow and much less reliable process and can take upwards of 30 milliseconds to complete[11] even where high-end networks and devices implement optional Wi-Fi standards including IEEE 802.11 k,r,u and v. Without these advanced features[12], which remain rarely implemented even in high-end equipment, Wi-Fi access point "roaming" can take over 200 milli-seconds during which time communications in uplink and downlink remain interrupted.

For a number of use cases location positioning is also important. 5G introduces a range of positioning capabilities, with dedicated support in the form of a Location Management Function[13]. 5G Release 16 supports accurate positioning based on uplink/downlink propagation time and angle based estimates from radio link and antenna measurements from both the network and the device. This is is further enhanced in Release 17 for the location of assets and moving objects within factories with planned 'sub-metre' level accuracy and and end to end positioning latency of under 100 milli-seconds.

In summary, for any use case which requires both continuous low-latency connectivity along with mobility, 5G represents the best solution. This is particularly true in critical control and safety related use cases.

Device capacity

For those use cases which involve a high density of connected devices it is particularly important to understand the comparative scalability of Wi-Fi and mobile networks. This can affect applications such as plant monitoring, which could require thousands of deployed sensors, or mass tracking of components, assemblies and products through production lines and warehousing where tens or even hundreds of thousands of devices may need connectivity.

The Wi-Fi 802.11 protocol allows for up to 2,007 devices to be associated with an access point at any time[14]. When Wi-Fi encryption is employed (as it should to protect data and operations) the practical number of devices that can be associated[15] on a given access point will typically have a limit in the order of hundreds of devices, generally determined by the processing and key storage capability of hardware based crypto engines within each access point. For example recent enterprise grade Cisco Meraki Wi-Fi 5 access points support a maximum 256 client devices per radio band and 512 devices per access point[16].

Mobile IoT technologies have been introduced within 4G networks, and form the basis for the 5G massive machine-type communications (mMTC) service. Work from Ericsson to evaluate the performance of LTE-M determined that a single wide-area cell can support 1 million devices per square kilometre from just 3.24 MHz of bandwidth, and the same connection density is carried through to 5G networks[17] and smaller cells. Indeed 5G is expected to support up to 1 million connected devices, and with millimetre wave support can provide exceptional levels of bandwidth and low-latency services to production and warehousing areas. Mobile IoT and 5G mMTC also

[11] Field Trial Results - https://www.cablelabs.com/field-trial-results-show-wi-fi-certified-vantage-devices-offer-significant-improvement-network-performance
[12] Devices should be certified 'Wi-Fi Agile Multiband' https://www.wi-fi.org/discover-wi-fi/wi-fi-agile-multiband . Certified products: https://www.wi-fi.org/product-finder-results?sort_by=certified&sort_order=desc&certifications=73
[13] https://www.ericsson.com/en/blog/2020/12/5g-positioning--what-you-need-to-know
[14] Further detail at https://www.extremenetworks.com/extreme-networks-blog/how-many-devices-can-my-access-point-support/
[15] Or connected, whether or not the device is transmitting or receiving data
[16] https://documentation.meraki.com/MR/WiFi_Basics_and_Best_Practices/Approximating_Maximum_Clients_per_Access_Point
[17] https://www.gsma.com/wp-content/uploads/2019/04/The-5G-Guide_GSMA_2019_04_29_compressed.pdf

support power saving features to enable device batteries to last several years, suiting applications such as smoke detectors, location trackers and periodic metering.

Overall therefore mobile networks using 5G or 4G LTE-M or NB-IoT are better able to support much higher connection densities than Wi-Fi. Importantly 5G also introduces a more flexible air-interface frame structure which provides better tailored downlink/uplink and bandwidth availability to devices, and, the common availability of separate uplink and downlink frequencies ensures devices are able to transmit with minimal delay even whilst other devices are receiving data.

Interference and reliability

Any wireless communication signal will be subject to some degree of interference, which affects both the reliability of communications as well as the realisable throughput speed. In denser networks interference can come from various sources

- Neighbouring or nearby networks and connected devices which are operating on the same frequency or set of frequencies as the current network
- Neighbouring or nearby networks and devices which are operating on nearby frequencies that have some degree of overlap with the current network
- Interference from other devices on the current network
- Interference caused by the device itself, particularly 'multi-path' interference where signals are reflected from objects and features of the environment such as walls, floors and ceilings
- Other noise sources including background radiation, noise from electrical switches and motors

One key advantage of mobile networks is that they are principally operated in licensed or controlled spectrum and this means the licensed network operator can better manage the interference environment, backed where needed by local regulators and law enforcement.

Predominantly Wi-Fi networks are operated in shared or unlicensed spectrum where any user can deploy networks provided they use approved equipment and settings. In many situations this can lead to higher levels of interference between networks. Additionally some Wi-Fi networks also experience external interference from non Wi-Fi equipment operating in the same frequency band, for example Bluetooth and microwave oven equipment. 5 GHz Wi-Fi has another very specific source of interference which relates to weather radar systems, and specifically there are three sub-bands in the USA and Europe which 5 GHz Wi-Fi must detect and avoid to prevent potential disruption to radar systems at airports and military sites[18].

In the 2.4 GHz band there are only three available non-overlapping 20 MHz Wi-Fi channels (for the US and China) and four minimally overlapping 20 MHz channels in Europe, Middle East and Africa and Japan. This means that any extensive 2.4 GHz Wi-Fi network has little freedom to select an unused channel particularly in the case of neighbouring networks so interference is common and achievable data rates reduced. 5 GHz Wi-Fi is easier to deploy than 2.4 GHz Wi-Fi as there are, dependent on country and the proximity to weather radar, up to six available 80 MHz channels and up to twelve available 40 MHz channels[19].

[18] http://www.multicap.be/en/technology/dynamic-frequency-selection-dfs
[19] The actual number of usable channels can depend on proximity to airfields or military installations where part of the 5 GHz spectrum may already be used for weather radar. https://blogs.cisco.com/networking/winning-back-the-weather-radio-channels-adds-capacity-to-5ghz-wi-fi-spectrum

For both network technologies where there is a higher level of interference there will be a corresponding reduction in the maximum possible throughput. This is particularly pertinent to 2.4 GHz Wi-Fi since there is usually a level of interference present. But, there is one other important factor to consider and that is the radio access mechanism. Wi-Fi networks use an approach known as 'Carrier Sense Multiple Access' which means that any device or access point wishing to transmit data will monitor the channel frequency until it is free from transmissions and then start its own transmission[20]. As more Wi-Fi devices are connected to a channel, and, as more data is transmitted, the chance of a collision happening multiplies and this contention leads to an exponential increase in transmission latency and decline in total available bandwidth. Mobile networks on the other hand use 'control channels' separate from the uplink and downlink data transmissions, and these control channels ensure client devices can better co-ordinate their transmission under the control of the base station, use the available bandwidth more efficiently, and can achieve the required Quality of Service. In particular the new 5G frame structure allows devices to share available 5G bandwidth even better by a combination of time and frequency division multiplexing. The 5G frame structure also complements 'network slicing' functionality which enables controlled access between network and devices according to specific application requirements including security, data isolation and service level agreement.

Therefore, in any industrial use case where there is a requirement for real-time or near-real-time control such as automated mobile robots, it is the mobile network that is best able to deliver the required Quality of Service including guaranteed uplink/ downlink bandwidth and latency.

Channel/ carrier aggregation for high bandwidth services

High bandwidth services, often associated with high definition video transmission, put major demands on networks for bandwidth. High bandwidth is of even greater importance when image and video processing is required in real-time or near real-time for control purposes, for example in automated visual quality analysis on production lines or in navigation and collision avoidance systems for automated mobile robots. High bandwidth can also be required for high frequency real-time data capture, virtual reality and augmented reality.

Both Wi-Fi and mobile networks allow carrier spectrum to be aggregated to support higher bandwith operation. There are some differences, however,

- It is possible on 2.4 GHz Wi-Fi to aggregate (known as "channel bonding") two contiguous 20 MHz channels to form a combined 40 MHz channel. However the limited bandwidth available in the 2.4 GHz band means there is only really one or two such 40 MHz channels that can be used so this has very limited application, for example in small offices. For most industrial deployments therefore 20 MHz channels would be the practical norm;
- As overviewed earlier, 5 GHz Wi-Fi can have contiguous channels bonded up to 40 MHz, 80 MHz or 160 MHz. In practice 80 MHz is the maximum that should be used for an extensive Wi-Fi network because there are insufficient contiguous blocks of spectrum available to enable 160 MHz channels (with reuse). Also, bonding and therefore wider channel reuse are dependent on client device capabilities, national spectrum regulations as well as the earlier noted proximity to weather radar systems so this can also impact the ability to use 80 MHz channels or even 40 MHz channels[21];

[20] IEEE 802.11ax introduces 'BSS Coloring' which avoids the additional latency waiting for communications relating to nearby access points. https://www.rfwireless-world.com/Terminology/What-is-BSS-Coloring-in-WLAN-802-11ax.html

[21] Cisco best practices on high density deployments https://documentation.meraki.com/Architectures_and_Best_Practices/Cisco_Meraki_Best_Practice_Design/Best_Practice_Design_-_MR_Wireless/High_Density_Wi-Fi_Deployments

- Wi-Fi 6 should in time support the 6 GHz band, designated Wi-Fi 6E, enabling up to seven 160 MHz bonded channels or fourteen 80 MHz channels depending on regulation. This will permit wider area use of higher bandwidth channels;
- 4G LTE currently supports carrier aggregation of up to 100 MHz[22] dependent on spectrum availability. Both intra-band and inter-band contiguous and non contiguous configurations are supported across TDD and FDD spectrum;
- 5G enables up to 1 GHz of spectrum to be aggregated, as with 4G LTE this can be non-contiguous or even split across multiple bands e.g. logically combining sub 6 GHz and millimetre wave bands over 6 GHz. With a guideline 1 GHz spectrum allocation for operators in the millimetre wave band[23] mobile networks can reliably deliver in excess of 250 MHz of carrier bandwidth throughout a manufacturing plant using a conservative four cell reuse pattern. Importantly the highest levels of wireless uplink bandwidth can be enabled over 5G to support critical Industry 4.0 use cases in machine vision for quality inspection and process control, real-time data acquisition and automated guided vehicles/ automated mobile robots;
- As a further development 4G LTE and 5G can also support parallel use of the same radio spectrum for devices, allocated, in real-time, according to whether the device is better connected using 4G or 5G. This is achieved through a combination of antenna technology along with decision making in network equipment which dynamically allocates available spectrum as required to support 4G and 5G connectivity. This more efficient use of spectrum provides improvements to customers in terms of higher bandwidth delivery and provides a smooth transition path for 4G LTE based Private Networks moving to 5G.

In summary, 5G better offers manufacturing and supply chain enterprises the ability to deliver high bandwidth wireless connectivity across a wide area, and with the added benefit of supporting high speed mobility for those use cases requiring it.

Over the air security and privacy

Manufacturing and supply chain enterprises need to be sure that their communications are secure and private, particularly where there is proprietary information being communicated and crucially where critical control functions are being delivered over the network.

The flexibility afforded by wireless networks also introduces risk, particularly because wireless signals can extend outside of the physical bounds of the enterprise or into areas where there is less control or oversight. Therefore strong wireless security is a must have for Wi-Fi and mobile networks. Over time security mechanisms have improved on both types of network and security best practices available on Wi-Fi and mobile networks are both able to deliver suitably robust networks.

- Enterprise Wi-Fi security based on WPA2 (or WPA3), AES and RADIUS authentication (typically with the same username / password used for IT network access) provides a high level of security suitable for protecting the enterprise Wi-Fi network. This overcomes weaknesses of the 'pre-shared key' or password approaches (or even weak default settings including no security) used for home and small business Wi-Fi networks[24];
- The SIM card or eSIM used on mobile networks from 2G onward supports well proven authentication and over the air encryption, protecting traffic from eavesdropping and

[22] See https://www.3gpp.org/technologies/keywords-acronyms/101-carrier-aggregation-explained , https://www.rfwireless-world.com/5G/5G-NR-Carrier-Aggregation-basics.html and https://www.ericsson.com/en/news/2020/10/5g-carrier-aggregation
[23] Reference https://www.gsma.com/spectrum/wp-content/uploads/2020/03/5G-Spectrum-Positions.pdf
[24] Wi-Fi 'Personal' security is not recommended for enterprise deployments

tampering. Initiatives like the GSMA's IoT Safe[25] further leverage the SIM / eSIM for secure IoT data communications using highly trusted SIM capabilities;

- 5G release 16 supports USIM based (either a physical UICC or eUICC provisioned by an operator) authentication as well as EAP/AKA based authentication for non-public (or private) networks. In 5G, communication between user equipment and the core network is under the control of core network functions and the data and control plane communication is protected by encryption and integrity protection;
- With 5G networks there is introduction of a new authentication framework, based on the Extensible Authentication Protocol (EAP), bringing in the additional flexibility as supported in enterprise grade Wi-Fi.

Related to the topic of encryption and security is the migration of the Wi-Fi authentication protocol to WPA3 with 'Simultaneous Authentication of Equals', this is not backwards compatible with the previous Pre-Shared Key mechanism in earlier Wi-Fi devices and networks and so leads to a disruptive upgrade.

From a use case perspective Wi-Fi networks are strongly associated with IT network access for mobile workers, using the inbuilt Wi-Fi of laptops, tablets and smartphones for business applications including email, document development and review, and video conferencing. The SIM based security of mobile networks is arguably better suited to embedded devices in the Operational Technology (OT) network along, naturally, with wide area mobility for smartphones and tablets. 5G extends the mobile security model into the established IT authentication and encryption area providing an effective solution for both OT and IT networks.

Device identity

A major difference between 5G and Wi-Fi is in the area of device identity. Wi-Fi devices are identified through a 'MAC' or (media access control) address. The Wi-Fi MAC address consists of 12 hexadecimal coded characters and is equivalent to a 48-bit hardware address. This physical layer hardware identity is used for packet routing, and higher level protocols such as IP can then be routed in local network equipment based on the association between the device IP address and the MAC address. The MAC address can be used to support quality of service measures such as prioritisation or bandwidth controls in Wi-Fi networks as well as IP address allocation strategies such as "pinning"[26] the local IP address for a specific device. The MAC address on some devices can be overridden by an application or the device operating system so is not guaranteed to be globally unique; it should not, as a result, be totally relied on for authentication or security measures and there is a risk to quality of service management in the case this is administered using MAC addresses that are readily spoofed or cloned. As mentioned earlier in the security and privacy section, authentication using the extensible authentication protocol (EAP) is advised for enterprise deployments.

The SIM card, as used in 5G, 4G and earlier mobile networks, and its flexible embedded alternative the eSIM, enable a much richer form of identity based on 'secure element' technology. These offer a tamper resistant, microprocessor backed platform incorporating secure storage and application execution environment. The SIM / eSIM enables identity in the form of a unique serial number (integrated circuit card identifier or ICCID of 18 to 22 digits) and international mobile

[25] Full details on IoT safe at https://www.gsma.com/iot/iot-safe/
[26] Commonly IP addresses are allocated by network routers using the dynamic host control protocol (DHCP), but IP addresses can be reserved where it it beneficial to know the address is fixed e.g. for specific equipment or sensors

subscriber identity (or IMSI, up to 15 digits). Together with the communication module hardware identifier (international mobile equipment identifier or IMEI) this complementary set of identifiers are used for network authentication and authorisation. Only valid combinations of the SIM / eSIM and hardware device identifiers are given access to the network and used as the basis for the application of policies including quality of service and access to network slices. More generally the SIM / eSIM

- Incorporates a secure place for storing security credentials and keys that can be used for network access and encryption as well as useful storage for application level credentials and keys;
- Ensure that data can be secured from where it is generated to where it is processed – from chip / device to cloud or on premises servers;
- Provides choice between a removable SIM module that can be installed or swapped into new equipment or a fixed eSIM that is soldered into a communications module;
- Total confidence that only devices with the correct security credentials can access network resources;
- eSIMs can be provisioned with multiple 'profiles' to support different networks, for example enabling different data sovereignty requirements across private and public networks.

Application of Wi-Fi and 5G to key manufacturing use cases

In the following tables there is a review of key use cases identified by the GSMA IoT manufacturing forum and published at https://www.gsma.com/iot/manufacturing/benefits-use-case/ - this review considers how the use case is delivered over Wi-Fi and what difference can be made when connectivity is migrated to 5G.

Edge computing is important to mention in connection with 5G as this particularly enables ultra-low latency, and the ability to retain data at the manufacturing or warehouse site when edge computing resources are deployed locally to the enterprise. In addition other edge computing use cases are enabled for off-site devices and users with the support for compute nodes to deployed within the core mobile network.

Product Build & Quality

Use Case	Wi-Fi	5G
Remote expertise via augmented reality / virtual reality	Higher resolution and/ or stereo vision may only be possible using a single user	Enables higher bandwidth density for improved video resolution, reduced visual lag and supports more users in any given area.

	dedicated Wi-Fi access point for performance[27]. Noticeable visual lag when moving around site between access points.	Also enables seamless mobility thoughout and beyond the manufacturing site.
Automation with robots and cobots	Lack of low latency/ ultra-reliable operation limits use for real-time/ near real-time control applications. Connectivity interruptions in the case of mobile robots/ cobots.	Extends capabilities into real-time or near-real-time control to improve throughput, quality and safety. Higher density of robotic/ cobot equipment supportable in a given area. Higher resolution video and additional camera angles supported. Reliable factory floor / plant wide mobility for moving robots / cobots.
Smart, connected tooling	Number of supportable tools/ equipment is limited per access point and its coverage area. Challenge of securing the network connectivity for tools or equipment having no user interface. Difficult and costly to provide seamless coverage around the indoor/ outdoor environment.	Low latency/ high reliability enables settings to be updated in real-time/ near real-time, and also data recording and tool control in real-time/ near real-time. Massive scale deployment of smart tools at high density is supported, with high security leveraging the SIM/ eSIM. Seamless mobility (factory floor wide/ manufacturing plant wide) can be achieved. High battery standby times are enabled via power optimisation features.

[27] Review at https://venturebeat.com/2019/08/02/siggraph-2019-showed-why-wireless-vr-all-but-demands-5g-or-wi-fi-6/

Defect monitoring with machine vision	Large numbers of high resolution video cameras result in congestion of the Wi-Fi network, reducing the number that can be supported by any given access point, limiting the resolution/ frame-rate and leading to variable delays in processing. These factors reduce effectiveness for manufacturing/ production quality and throughput. Provision of high bandwidth coverage suitable for widespread use of machine vision across the manufacturing or production site is difficult and costly.	Defect monitoring is augmented with closed-loop control processing using the ultra-reliable, low-latency features of 5G. Video transmission latency is reduced via the additional available bandwidth (especially in mmWave bands) and higher definition imaging supported to enable improved sensitivity and rejection of defects. Larger numbers and densities of cameras can also be deployed across the whole manufacturing or production facility.
End-to-end traceability	Limited numbers of 'things' can be traced simultaneously across individual Wi-Fi access points due to hardware and protocol constraints. Variable delays due to access to the wireless resource, and when 'things' are mobile affect real-time and near real-time traceability Providing wireless coverage throughout a manufacturing and production plant is complex and costly, and wide area 'national' coverage is cost prohibitive.	5G enables higher scalability of traceability solutions. Supporting higher device densities, more and higher resolutions of CCTV cameras used for tracing, and guarantees over communications when using ultra-reliable, low latency communications. The seamless mobility support in 5G ensures continuous traceability throughout the manufacturing plant and warehouse and beyond into national / international settings[28].

Factory Efficiency

Use Case	Wi-Fi	5G

[28] Dependent on coverage

Predictive maintenance	Diverse monitoring requirements across a range of manufacturing machines, robots, cobots and production equipment places demands for bandwidth and number of devices to be connected which exceed the capabilities of Wi-Fi networks. Providing reliable coverage able to meet the challenges of total bandwidth and number of connected devices across the manufacturing plant or production facility is neither technically possible or cost effective over Wi-Fi.	Larger numbers of simple and complex sensors can be supported on 5G networks, and with higher data rates available there is support for greater frequency sampling and higher precision sampling for key data such as low and high volume voltage, current, temperature and noise sampling. When using lower data rate sensors 5G networks support the massive deployment of such sensors allowing more points to be monitored throughout the production line, factory facility (energy, water and HVAC), warehouse, and transportation functions.
Asset tracking	Battery consumption and battery life are poor with Wi-Fi based asset tracking solutions making them suitable only for short-term tracking of larger objects or larger, powered equipment and vehicles, typically used in an indoor only environment. Limitations around the number of devices that can be connected simultaneously to a single Wi-Fi access point mean that few assets can be tracked in any given area. Wide area tracking including outdoor, regional, national/ international has very limited possibilities.	Tracking is extended beyond the factory floor or production plant to a national / international footprint via public mobile networks. 5G optimisations enable efficient massive scale deployment of tracking solutions, support for multi-year battery life and application control over duty cycle. Additional data can readily be sent, including environmental data. Devices can also be 'woken' from the network for active tracking. CCTV cameras for asset monitoring can also be deployed at a large scale and supporting high resolution imaging.

Power and heat management	Extending Wi-Fi coverage to all parts of a plant, for both indoor and external sensors, and power and heat equipment is very difficult and costly. This limits the comprehensiveness and effectiveness of any solution based on Wi-Fi connectivity. Low power, battery operated sensors used for monitoring are also limited by Wi-Fi power consumption. And, sensor density is limited by the relatively low limits on the number of connected devices per access point.	In a high sensor / controller density environment 5G efficiently enables a much larger number of devices to be supported. Ultra-reliable low latency communications are a key advantage of 5G – ensuring control actions are performed in real-time or near real-time and with total confidence. High quality coverage can also be delivered reliably, indoor and outdoor, seamlessly using the three complementary spectrum regions.
Machine vision for plant management	Extending reliable high-bandwidth coverage across the manufacturing or production plant is a challenge for Wi-Fi networks, especially if this requires coverage of the building exterior and outside spaces. Video resolutions and frame rates may need to be reduced due to limited available bandwidth and the need to support other devices and services across the same Wi-Fi infrastructure.	5G enables an increased density of higher resolution CCTV to be deployed, improving the range and accuracy of machine vision applications. When machine vision identifies a situation that requires action the ultra-reliable low latency communications support within 5G ensures immediate and guaranteed response such as shutting down equipment that might risk an employee's safety. The low, medium and high frequency band support within 5G, and multiple antenna (MIMO) / beamforming support helps ensure full indoor, outdoor and building fabric site coverage for these applications.
Automated guided vehicles (AGVs) and automated	Poor mobility support on Wi-Fi networks limits the useful	5G networks provide improved support for mobility and

mobile robots (AMRs) for manufacturing – workstation replenishment and movement of work in progress	deployment range of AGVs and AMRs. Vehicle speed may need to be reduced to safely deal with delayed 'handovers' between access points. Applications must also deal with handover related connectivity loss – impacting the efficiency of orchestrating fleets of AGVs and AMRs. Coverage across the manufacturing and production plant is more difficult to deliver due to a lack of low spectrum band Wi-Fi. Also, band reselection is simplistic making it more likely connectivity is lost particularly in areas such as automated lifts/ elevators and as vehicles move between production areas. Wi-Fi also lacks low-latency guaranteed communications which impacts the support for real-time and near real-time control applications.	coverage, enabling AGVs and AMRs to remain continuously connected with supervisory systems whilst the vehicles move throughout the manufacturing facility and warehouse – even whilst in lifts/ elevators. The increased bandwidth available on 5G also enables additional camera perspectives to be relayed, and with lower latency and higher resolution permitting better decision making for traffic co-ordination and safety. This is also very important for LIDAR data transmission. Control actions have rapid and guaranteed delivery with ultra-reliable, low latency communications to achieve maximum efficiency and safety of operation.

Closing remarks

Industry 4.0 use of mobile networks is increasingly of interest to manufacturers and supply chain companies and it is clear that as enterprises drive to increase adaptability in their operations they achieve significant benefits when using 5G or 4G mobile technologies.

Wi-Fi networks are commonplace within enterprise IT networks, particularly for flexible workspaces featuring laptops, tablets and smartphones. But as explored within this document there are a number of technical and scalability challenges which limit the usefulness of Wi-Fi networks for the wider manufacturing and supply chain operational applications, particularly when device numbers and breadth and capability of applications are scaled up.

Therefore manufacturing and supply chain companies are encouraged to introduce 5G mobile connectivity for their adaptable production environments. Whether this is to support rapid reconfiguration of the production line, support for automated guided vehicles or autonomous mobile robots, reliable continuous tracking of components or supplies, or any of the other use cases analysed earlier, mobile networks deliver the breadth of capabilities that mean the enterprise is best able to achieve the benefits of Industry 4.0 investments.

The substantial capabilities introduced with 5G including network slicing, new authentication framework, key exchange and encryption, edge computing, massive bandwidth and open networking initiatives provide, ultra-reliable low-latency and massive device scale deliver the greatest flexibility for Industry 4.0. And in the future, 5G developments such as time sensitive networking support[29], will deliver even more capabilities to support the migration of wired networks to wireless.

Revision history

Version	Date	Author	Description
01		Steve Doyle (GSMA)	

[29] See https://www.ericsson.com/en/blog/2018/12/5g-meets-time-sensitive-networking

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