Technology: WLAN IEEE 802.11n, Wi-Fi 4

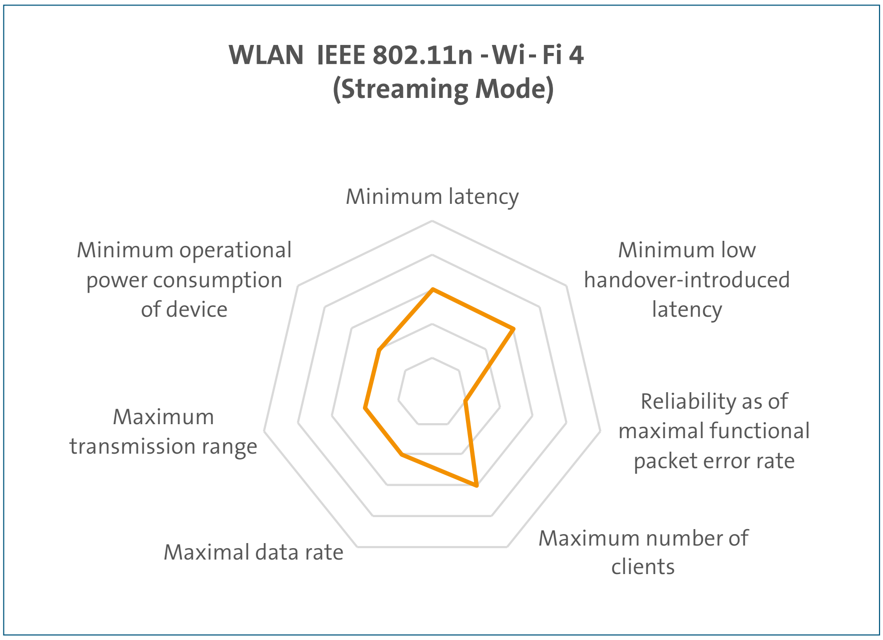
Abstract

Starting with the first products end of the 90s, Wireless LAN (WLAN) more commonly known as Wireless Fidelity (Wi-Fi) technology has seen a fast and continuous evolution, primarily by increasing the speed of data transmission from a few megabit per second in to the range of several gigabit per second.

Wi-Fi 4 or IEEE 802.11n is an extremely widespread technology and standard that can be found in a multitude of different devices. Its key characteristics are the simplicity and ease of use that comes with drawbacks due to its channel access mechanism, handover / roaming behavior and operation in the ISM bands.

The Wi-Fi 4 standard was completed in 2009 and this technology is until today widely used on the factory floor. As Wi-Fi generally was designed for quasi stationary environments like offices or consumer applications its fundamental design decisions reflect this. So, mobility in Wi-Fi 4 is bound to interruptions in connections. Thus, in empirical latency and reliability data from industrial environments, always numerous long latencies above 100ms appear [LucasEstan18, Lyczkowski 20]. Thereby, each time a client device scans for available access points extra latency is added.

Technology Briefly



Note: Scale value "5" = best performance; scale value "0" = not specified. Source: SEW-Eurodrive

The properties in this diagram have been defined by consensus within WCM-Working Group 2.

In addition to a consensual definition, the property values refer to requirements described in reference use cases. This is done to ensure a degree of comparability between wireless communication systems.

The reference use cases have been described by the WCM-Working Group 1, providing specific requirements for:

- Realtime / Ultra low latency communication (e.g. discrete manufacturing)
- Streaming/high data rate (e.g. video streaming)
- Massive Industrial Internet of Things (mIIoT) / Sensor Networks (e.g. valve status)

Property Definitions

Minimum Latency

Nominal achievable latency for the given reference use case and the associated functional packet error rate (FPER) property.

- Assuming that all clients are able to fulfill this latency requirement at the same time
- The latency is measured from reference input interface to reference output interface of the wireless communication system (e.g. Layer2/3)
- The latency and FPER of the spider diagram need to be achievable at the same time as they are linked together

Minimum Handover-Introduced latency

Minimum latency added to the nominal latency when a handover of a single device occurs for the given use case. Handover assumes operation of all devices of the usecase with the associated FPER.

Reliability as of maximal Functional Packet Error Rate, where Functional PER:

Percentage of data that is delivered later than the nominal latency for a given reference use case due to errors on the channel, late channel access, scheduling, or whatever other reason.

- Assuming that all clients are at the maximum range and at line of sight
- Assuming that all devices have to fulfill the same latency requirement (provided by the minimum latency property)
- Assuming that all clients fulfill the same FPER requirement
- FPER and latency of the spiderdiagram need to be achievable at the same time as they are linked together

Maximum number of clients

The maximum supportable number of clients for the given reference use case. This means the number of clients servable by one access point/base station/node in a meshed network/relay.

- Assuming that all devices in that scenario have the same communication requirements
- The available spectrum for the property is defined by the maximum bandwidth supported by the technology.
  It needs to be in line with the data rate property
- Per default the frequency regulation of Germany is referenced

Maximum Data Rate

The maximum/peak user data rate (payload) achievable per device for the given reference use case. Assuming that all devices in that scenario have the same communication requirements.

Minimum Operational Power Consumption of Device

Mean power consumption in Watt [W] for the given reference use case.

- This references the power consumption of a known device/node for that use case
- The time duration for the averaging is defined by the use case

Maximum Transmission Range

Maximum distance from a single transmitter to a single receiver

- Assuming maximum allowed transmission power (EIRP)
- Assuming typical receive antennas for the application
- The frequency band is also defined by the application
- Assuming line of sight communication

The “Technical Parameters” chart in the “Detailed Technology Description” section provides further information on these properties and other Key Performance Indicators (KIPs).

A brief description of the reference use cases can be found in the Appendix.

Disclaimer: This graph is based on the information provided by the authors of this chapter – a list of authors can be found at the end of the publication – available at the time of publication. It reflects an approximate performance of the communications system at a high level, based on the requirements specified in reference use cases.

This performance may of course vary depending on the degree of customization possible in defining the specific requirements for each industrial application and on the specific implementation. Thus, dialogue between the industrial user and wireless experts is encouraged to explore all possibilities.

Technology Briefly

Starting with the first products end of the 90s, Wireless LAN (WLAN) technology has seen a fast and continuous evolution, accompanied by an ever-increasing number of devices in use. The technology is based on the standards developed by the standardization group IEEE 802.11. The Wi-Fi Alliance (WFA), a vendor organization, supports interoperability and market development and is responsible for the popular Wi-Fi naming and numbering.

Wi-Fi 4 is WFA's designation for the standard 802.11n. Wi-Fi 4 is presumably the most widespread version on the factory floor and thus marks the base line for many comparisons.

Wi-Fi 4 can operate in the bands 2.4 GHz and 5 GHz, which are available globally (2.4 GHz) or nearly globally (5 GHz). Within these bands Wi-Fi 4 is bound to OFDM and CSMA mechanism for channel access resulting in best effort behavior with steep performance declines in case of many devices with high data rates or many small packets sent.

IEEE 802.11 physical layer evolution

Release Date	Standard	Wi-Fi Alliance naming	Frequency Band	Max. Data Rate at PHY Layer
1999	802.11b	–	2.4 GHz	11 MBit/s
1999	802.11a	–	5 GHz	54 MBit/s
2003	802.11g	–	2.4 GHz	54 MBit/s
2009	802.11n	Wi-Fi 4	2.4 + 5 GHz	600 MBit/s
2012	802.11ad	-	60 GHz	8.6 Gbit/s
2013	802.11ac	Wi-Fi 5	5 GHz	6.9 Gbit/s
2013/2016	802.11af/ah	-	< 1 GHz	35 – 234 MBit/s
2021	802.11ax	Wi-Fi 6/6E	2.4/5/6 GHz	9.6 GBit/s
2024 envisaged	802.11be	Wi-Fi 7	2.4/5/6 GHz	46 GBit/s

Table 1: IEEE 802.11 physical layer evolution.

Table 1 provides a brief overview on the current evolution of Wi-Fi.

A perspective on the technological evolution of Wi-Fi is provided in Table 2.

Feature	Wi-Fi 4	Wi-Fi 5	Wi-Fi 6	Wi-Fi 6E
Bands (GHz)	2.4, 5	5	2.4; 5	6
Modulation	OFDM	OFDM	OFDMA	OFDMA
Symbol modulation (highest)	64-QAM	256-QAM	1024-QAM	1024-QAM
Channel width (MHz)	20, 40	20, 40, 80, 160	20, 40, 80, 160	20, 40, 80, 160
MU-MIMO	No	downlink	downlink, uplink	downlink, uplink
DL/UL MU OFDMA	No	No	Yes	Yes
Target Wake Time	No	Partial (IEEE 802.11e)	Yes	Yes
BSS Colouring	No	No	Yes	Yes
Extended range	No	No	Yes	Yes

Table 2: Comparison of main features across Wi-Fi 4, Wi-Fi 5, Wi-Fi 6 and Wi-Fi 6E.

High-level Technology Description

Topology

Wi-Fi is an infrastructure-based technology consisting of independent access points (APs) or APs orchestrated by one controller. Sometimes the APs are also called Base Stations (BS). The entire 802.11 standards family targets wireless local area networks (WLANs). Anyway, the decision on changing the connection from one AP to another is based in the client device.

Within typical industrial settings applications run on a device i.e. industrial PC with direct Wi-Fi connections or an industrial PC / controller being connected to an industrial grade Wi-Fi client. This is shown as client in the figure 1. The application running on the client communicates with an application server. That server is connected via Ethernet to the APs. Thus, performance evaluations are typically based on that same network architecture including the Ethernet links.

Interfaces

The functionality defined in IEEE 802.11n (or whole 802.11 family) corresponds to the lowest layers of the ISO / IEC basic reference model of Open Systems Interconnection, namely Layer 1 (Physical Layer) and Layer 2 (Data Link Layer). Corresponding interfaces for the communication with higher layers are specified. Usually, IP and TCP or UDP are used on Layer 3 and 4, but also other protocols are possible.

From a hardware point of view, products (System-on-a-chip – SoCs-modules) with different hardware interfaces are on the market. Types of interfaces depend on the intended applications, and support PCIe and SDIO.

Most devices provide typical network management interfaces like Simple Network Management Protocol (SNMP) or web-based management systems.

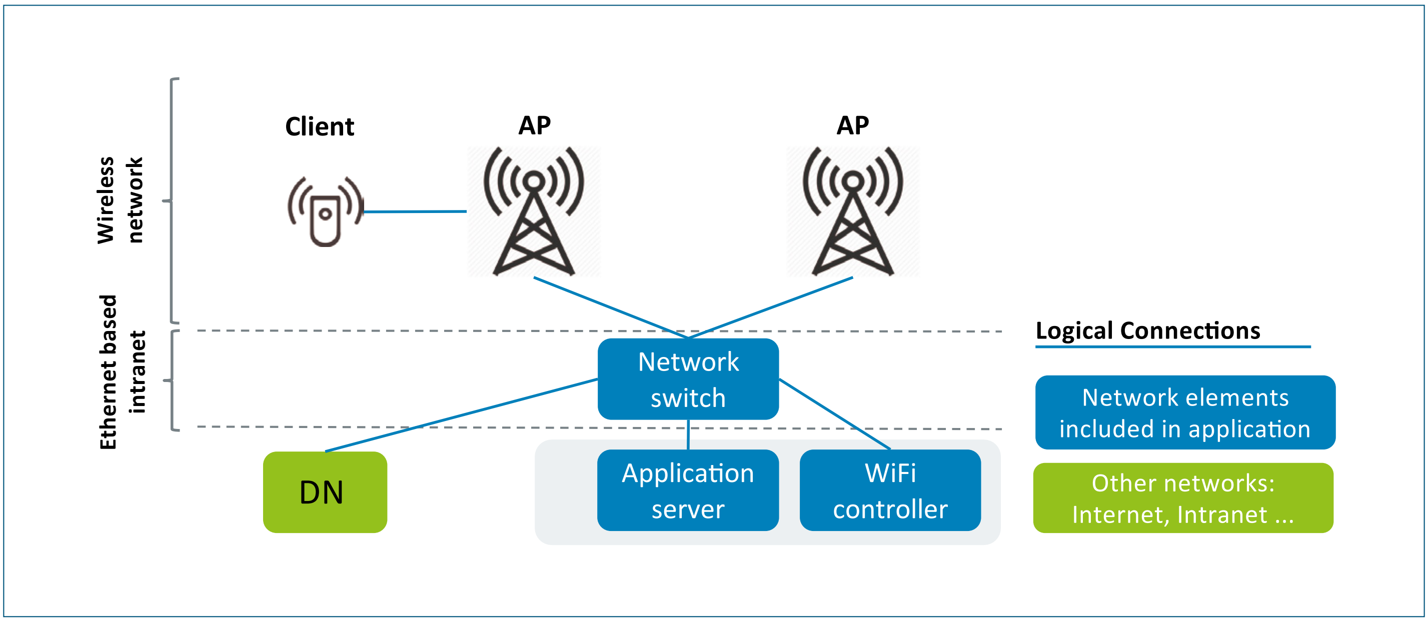


Figure 1: Architecture of Wi-Fi4-Applications.

Source: modified from VDMA e. V., Fraunhofer-Institut IIS “5G im Maschinen- und Anlagenbau”

Time Behaviour

Wi-Fi 4 relies (as all generations before) on the channel access scheme Listen-before-Talk (LBT), based on CSMA. Therefore, the start of transmissions is not deterministic and comes with random delay and jitter. Nevertheless, the requirements of some industrial applications regarding time behavior can be met.

Spectrum

Wi-Fi 4 can operate in the globally available 2.4 GHz ISM band and 5 GHz band with channels of 20 and 40 MHz.

Coexistence

The basic mechanism of all Wi-Fi systems to ensure coexistence with other systems in a band is Listen-BeforeTalk (LBT). LBT ensures a reasonable grade of coexistence in many environments and is sufficient for many applications. Nevertheless, especially in dense environments (environments with many clients and APs in small areas) and for applications with challenging requirements on QoS, LBT can lead to a degradation of service.

Besides LBT, Wi-Fi comprises additional mechanisms to improve coexistence with other Wi-Fi systems, which rely on specific mechanisms of the Wi-Fi protocol. Some of these mechanisms are dedicated to reserve the channel for a certain amount of time or the duration of a transmission in order to avoid interference.

Maturity

The 802.11n standard is from all perspectives mature. A wide variety of devices is available on the market.

Detailed Technology Description

Technical Parameters

Parameter	General KPIs
Protocol	IEEE 802.11n
Frequency bands	2.400 – 2.485 GHz 5.470 – 5.725 GHz 5.150 – 5.350 GHz
Un-licensed frequency band	Yes
International coverage	Generally very good, but with various exceptions
Real-Time capability	No
Network topology	Base station
Handover (mobility) support	Intermitent
Voice support	No
Localization support	Yes
Coexistence mitigation mode	CSMA/CA
MiMo capability	Yes
Typical range BS - MS	15 – 40 m
Typical range mesh	15 – 40 m per hop
Typical latency BS - MS	5 – 30 ms @ 99% (including handovers optimal environment) >100 ms @ 99% (including handovers, industrial environment) 3 ms @ 70%
Typical latency with one hop in a mesh	15 ms (industrial environment)
Typical data rate	50 Mbps
Maximal number of active clients	255 according to standard <20 as best practice 100 according to technical documentations . Datasheets
Maximal lifetime when using a battery	2 bis 2.5 W (nominal power consumption)
Expected interference immunity	Medium
Likelihood of coexistence	Data hungry, robust
Signal bandwidth	20 or 40 MHz
Coexistence relevant bandwidth	leer
Localization accuracy	< 100 cm - 20 m
Technology maturity level	Mature
Product availability	2010
Standardization	IEEE
Standard availability	2010
Required Infrastructure on site	Access Point

Parameter	General KPIs
Streaming Mode	
Nominal latency	4 – 200 ms
Handover introduced latency	> 50ms
Cycle time	> 1 ms
Roundtrip time	9 – 400 ms
Maximal Functional Packet Error Rate	10^{-2}
Maximum number of clients	<20 as best practice
Telegram size	
Maximal data rate MS downlink	< 1500 byte
Maximal data rate MS uplink	< 50 Mbps
Data payload per MS uplink (net)	50 Mbps
Maximal RF power [EIRP] downlink	50 Mbps
Maximal RF power [EIRP] uplink	23 dBm
Required SNR	23 dBm
Mean power consumption in usecase	1 bis 2.5 W (nominal power consumption)
Maximum transmission range	40 m

Technology Description

General

The 802.11 n standard builds on its predecessors and originally focused on low mobility best-effort use cases. Thus, Wi-Fi 4 focused on enhanced bandwidth and coverage. Thereby Wi-Fi 4 is intended for usage in the 2.4 and 5 GHz bands.

Channel Access

The channel access in Wi-Fi 4 uses a CSMA / CA channel access and thereby employs LBT. The CSMA / CA works with the distributed coordination function (DCF) that defines back off times after which LBT is performed. Further, a ready to send / clear to send (RTS / CTS) approach is available to minimize collisions. When using RTS / CTS, first a RTS frame is sent that is acknowledged by the AP with CTS that grants a contention free transmission. Further, a point coordination function can be used to coordinate the channel access of each station.

OFDM and MIMO

Wi-Fi 4 employs OFDM (orthogonal frequency division multiplexing). With OFDM and OFDMA, the channel is divided in so-called subcarriers (also called tones). In OFDM, all subcarriers are dedicated to one device, which means that exactly one device can transmit at a time using the complete channel (see figure 2).

MIMO (multiple input multiple output) is only supported up to the order of 4 using multiple antennas for separating data streams and multi-user MIMO is not part of Wi-Fi 4. Significant enhancements for MIMO are present in Wi-Fi 6.

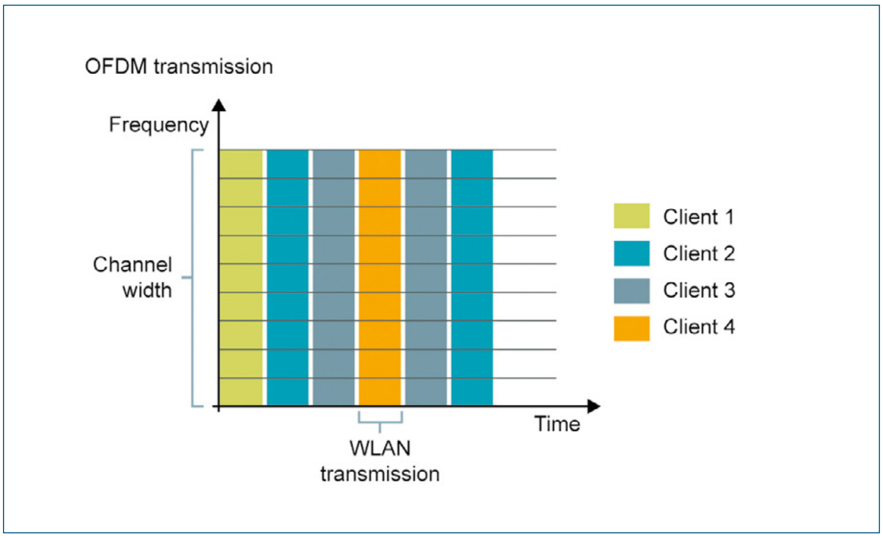


Figure 2: OFDM communication. Source: Siemens AG

Application Reference

Application Specific Technology Description

Wireless access to machine data

Current situation and pain points:
Many machines are already equipped with a router for remote maintenance or condition monitoring / predictive maintenance. In many cases this router only connects to the machine builder (internet connection via e.g. LTE) and is totally separated from the production network because of IT-Security reasons. Often a substantial amount of data points is gathered in this device. Though this data would be particularly useful in case of setting in operation, debugging or other local monitoring of the machine, it is not directly accessible. Furthermore, even physical access to the machine is often limited for external service technicians (e.g. access restrictions due to safety regulations or hazardous substances). Therefore, service technicians face various hurdles when trying to locally connect to the machine.

Wireless solution:
A direct Wi-Fi connection to the machine provides easy and physically flexible access to the machine data e.g. even on a mobile tablet PC. If IT-Security restrictions apply this wireless access can still be limited by the machine operator. Furthermore, a wireless connection can be essential when servicing machines with large dimensions. A wireless connection is much easier and more flexible than using a long Ethernet cable. This wireless approach also avoids hazards caused by a long cable in connection with moving parts and eliminates the typical tripping hazard caused by cable loops on the floor.