PROJECT NO: 3-023

Frictionless Ticketing for Public Transport

Appendix 1: Technical evaluation

JULY 2022

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LA TROBE UNIVERSITY | Centre for Technology Infusion

About this Appendix

This project is a collaboration between Transport for New South Wales, iMOVE and The Centre for Technology Infusion with the objective to evaluate emerging technologies that can deliver frictionless ticketing for public transport.

This Appendix provides details and substation of the findings in the main report. To keep the main report readable, we have included full reports of technology reviews in this Appendix. This report should not be read in isolation.

It includes:
- A literature and technical assessment of technology options
- Technology profiles for 5G, UWB, Biometrics and SLAM
- A scan of global transport websites
- Synopsis of relevant background articles

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Acronyms

3GPP	3rd Generation Partnership Project
ACMA	Australian Communications and Media Authority
AFDO	Australian Federation of Disability Organisations
AI	Artificial Intelligence
AoA	Angle-of-Arrival
AoD	Angle of Departure
API	Application Programming Interface
APPs	Australian Privacy Principles
AR	Augmented reality
ARK	Autonomy Research Kit
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
ATCS	Advanced Train Control Systems
BIBO	Be In Be Out
BICO	Be In, Check out
BLE	Bluetooth Low Energy
BPSK	Binary Phase Shift Keying
BS	Base Station
CAPEX	Capital Expenditures
CBP	Customs and Border Protection
CCC requirements	Car Connectivity Consortium requirements
CCCS	Command Control and Communications Systems
CCOPS	Community Control Over Police Surveillance
CIBO	Check In Be OUT
CiCo	Check-in/Check-out
CRC	Cyclic Redundancy Check
D2D	Device to Device
DAFE	Digital/Analog Front End
DL	Downlink
DL-AoD	Downlink Angle-of-Departure
DoI	Diffusion of Innovations
DPA	Data Protection Act
DSP	Digital Signal Processing
EER	Equal Error Rate
EKF	Extended Kalman Filter
ELS	Enhanced Location Service
EME	Electromagnetic Energy
ERM	Electromagnetic compatibility and Radio spectrum Matters
ETSI Standard	European Telecommunications Standards Institute Standard
FAR	False Acceptance Rate
FCC	Federal Communications Commission
FEC	Forward Error Correction
FIVE	Face in Video Evaluation
FMR	False Match Rate
FNMR	False Non-Match Rate
FPGAs	Field-Programmable Gate Arrays
FP-Node	Floor Plane Node
FRMCS	Future Railway Mobile Communication System
FRR	False Rejection Rate
FRSs	Face Recognition Systems
FRVT	Face Recognition Vendor Tests
FTM	Fine-Time-Measurement
FWG	Functional Working Group
GDPR	General Data Protection Regulation

GNSS	Global Navigation Satellite System
HF	High Frequency
HRIP Act	Health Records and Information Privacy Act 2002
IaaS	Infrastructure as a Service
ICNIRP	The International Commission on Non-Ionising Radiation
ICP	Iterative Closest Point
IEEE	Institute of Electrical and Electronics Engineers
IJB	IARPA Janus Benchmarks
IMU	Inertial Measurement Unit
IoT	Internet of Things
IPS	Indoor Positioning System
IR	Impulse Radio
IR-UWB	Impulse Radio Ultra-Wide Band
iSims	Integrated SIM
ITS	Intelligent Transportation Systems
ITSp	Intelligent Transportation Spaces
LF-RFID	Low frequency radio frequency identification
LFSR	Linear Feedback Shift Register
LMF	Location management function
LoRa	Long-Range
LS	Least Squares
LTE	Long Term Evolution
Maas	Mobility as a Service
MAC	Media Access Control
MBOA	Multiband OFDM alliance
MEC	Multi-access Edge Computing
MIMO	Multiple-Input Multiple-Output
M-MTC	Massive Machine-Type Communication
MN	Moving Networks
MSK	Minimum-Shift Keying
MSL	Mining Systems Laboratory
MT	Maximum-Throughput
MTA	Metropolitan Transit Authority
MB	Multiband
navCOM	Navigational Command
navMSG	Navigational Message
NDT	Normal Distributions Transform
NFC	Near Field Communication
NG-RAN	Next Generation Radio Access Network
NIST	National Institute of Standards and Technology
NLoS	Non-line-of-sight
NR	New radio
OFDM	Orthogonal frequency division multiplexing
oGLs	Object-level graphlets
OOK	On-off Keying
OPEX	Operating expenses
OTDOA	Observed time Difference of Arrival
PaaS	Platforms as a Service
PAM	Pulse Amplitude Modulation
PDCN	Physical Disability Council of NSW
PDoA	Phase-difference-of-Arrival
PE	Pose Estimation
PHY	
POS	Point-of-sale Systems
PPB	Pilot Parliaments Benchmark
PPIPA	Privacy and Personal Information Protection Act

PPM	Pulse Position Modulation
PR	Pseudo Random
PRSs	Positioning Reference Signals
PTC	Positive Train Control
PWD	People with Disability
PWM	Pulse Width Modulation
RAT	Radio Access Technology
RF	Radio frequency
RFICs	Radio Frequency Integrated Circuits
RFID	Radio frequency identification
RRLT	Redundant Radio Localization and Tracking
RS	Reference signal
RSRP	Reference Signal Received Power
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RSU	Road Side Infrastructure/Units
RTLS	Real-time Locating System
RTT (1)	Return Travel Time
RTT (2)	Round-Trip-Timing
RU	Radio Units
SaaS	Software as a Service
SAFD	Scale-aware Face Detection
SBAS	Space Based Augmentation System
sGLs	spatial-level graphlets
SLAM	Simultaneous Location and Mapping
SON	Self-Optimising Networks
SRD	Short Range Devices
SRS	Sounding Reference Signal
SSLS	Sub-sampling Least Squares
TAM	Technology Acceptance Model
TDoA	Time-difference of Arrival
TfNSW	Transport for New South Wales
TG	Task Groups
TH-BPSK	Time-Hopping Binary Phase Shift Keying
TH-PPM	Time-Hopping Pulse Position Modulation
ToF	Time-of-Flight
TWR	Two-way Ranging
UAVs	Unmanned Aerial Vehicles
UDN	Ultra-Dense Networks
UE	User Equipment
UGV	Unmanned Ground Vehicle
UHF	Ultra-high frequency
UHF-RFID	Ultra-high frequency radio frequency identification
UL-AOA	Uplink angle-of-arrival
UL-TDOA	Uplink Time Difference of Arrival
U-MTC	Ultra-reliable Machine-Type Communication
URA	Uniform Rectangular Array
URLLC	Ultra-Reliable Low Latency Communications
URS	User Requirements Specification
UTAUT	Unified Theory of Acceptance and Use of Technology
UWB	Ultra-wide band
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

WAN	Wide Area Networking
WCG	Weighted Centroid Geometric
WHO	World Health Organisation
WiWo	Walk-in/Walk-out
WLAN	Wireless Local Area Network
WM5G	West Midlands 5G
WMM	West Midlands Metro
WPAN	Wireless Personal Area Network

1: Technology profiles

Summary

In this chapter, we review the four technologies in the use cases of frictionless payment in public transport including 5G, Biometrics, Simultaneous localisation and mapping (SLAM), Ultra-wide band (UWB) in terms of:

- Technical features
- Industry standard and protocols
- Regulatory institutes
- Key players/market leaders
- Existing vendors/product
- Future roadmap

Key findings for each technology type

Real-time positioning systems based on UWB technology are currently mature. UWB owns the advantages of low power consumption, high data rate, resilience, penetration, cheap infrastructures, and high accuracy. The accuracy of UWB can be to measure distance and location to an accuracy of 5 to 10 cm.

5G possesses potential to be used for frictionless ticketing. 5G New radio (NR) provides a few enhanced parameters for positioning accuracy estimation than previous mobile generations, particularly with regards to time-and angle-based positioning method. According to Qualcomm, 5G Positioning is meeting centimetre-level absolute accuracy requirement of down to 0.3m (Qualcomm, n.d.).

Biometric authentication compares data for the person's characteristics to that person's biometric "template" to determine resemblance. In this topic, facial recognition, fingerprint, voice recognition and vein recognition are mentioned in the report respectively, and they are different forms of biometric authentication. According to the National Institute of Standards and Technology (NIST) Face Recognition Vendor Tests (FRVT) latest results, IDEMIA's Facial Recognition Ranked #1 in NIST's FRVT Test. In ideal conditions, facial recognition can have near-perfect accuracy which is 99.97%. Accuracy will be lower in reality, and the result depends on the factors like light, camera and end-users' distance etc.

China, Japan, Korea, and America are leading globally when it comes to facial recognisition. China is using facial recognition in subway and railway stations for payments and verifying passenger's identities at the entrance gate. But in the USA, 32 airports are currently using facial recognition for identity verification. Despite considerable public debate about the ethical use of facial recognition and privacy, biometric authentication is known and used by more and more people. According to Visa's survey result, more than 65% of consumers are already familiar with biometrics, 86% of customers are interested in using biometrics to verify their identity or to make a payment and 70% of consumers believe that biometrics are easy to use (Visa, 2021).

SLAM is a method used for a device to build a map and localise in that map at the same time. Using a SLAM mobile map app, we can walk through a location, creating a digital mapping, eliminating the need for lengthy setups or prior high-definition maps. In a train station, people can use mobile phones, smart cards, or body cam type of devices to navigate to the entry of the station, and the device will be able to buy a ticket frictionlessly. The algorithms of SLAM to detect the indoor maps are also diverse in the complexity and accuracy. There are still some challenges of using SLAM in the frictionless payment, e.g., the cost of the Light Detection and Ranging (LIDAR) devices, high computational cost for image processing, point cloud processing, and optimisation, etc.

1.1 Ultra-Wide Band

1.1.1 Introduction

As the name suggests, Ultra-Wide Band (UWB) uses a wide channel bandwidth (500 MHz) between 3.1 GHz and 10.6 GHz and short two nanosecond (2 ns) pulses to accurately measure the Time-of-Flight (ToF) between two devices, such as smartphones, wearables, keys, tags, door locks, and anchor points. When in proximity, these devices begin ranging using ToF measurements that calculate the roundtrip time of the communication. One device can therefore calculate the relative location of the other instantly (with refresh rates at 100 times per second) and continuously, with movements being monitored in real-time. Meanwhile, angle of arrival techniques ensure that the system knows the precise location and direction of a device, ensuring that devices such as door locks can determine what side of the door a user is standing, and fully understand user intent. UWB was used historically for accurate ranging and radar information.

UWB is not a new technology and was originally used for military communications, as seen in Figure 1. UWB was authorised for commercial use by the Federal Communications Commission of the United States in 2002, allowing operation on the unlicensed 3.1 GHz to 10.6 GHz spectrum (Pozyx, n.d.). Initially positioned as a data transfer technology in a similar vein to Wi-Fi, for various reasons including power restrictions, UWB was unable to succeed.

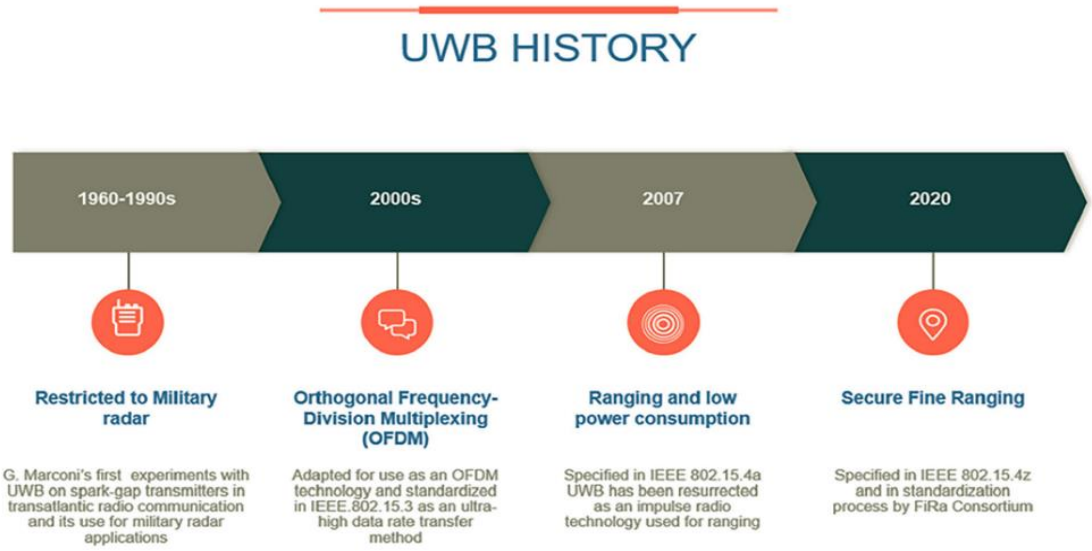

Figure 1. UWB History

As a new emerging technology in the 21st century, UWB has the capability to provide accurate localisation functions to enabled devices. This report will discuss the technical specifications of UWB by investigating the fundamental structure of UWB such as pulses, bandwidth, and localisation methodologies. With the advent of modern digital processing capabilities of UWB technology, regulations and standards are also presented to ensure future prototypes may be presented in a consistent manner.

The report will list the current key players/market leaders and existing vendors to provide an understanding of the current directions and landscape. We will be able to see how UWB technology is currently being used in different fields with the purpose of embedding the localisation function for security and access control purposes. The future roadmap of UWB is also presented within the report to provide a vision towards the capability of UWB to be used across all devices in the future, presented by FiRa Consortium.

UWB is a technology for the transmission of data using techniques which cause a dissemination of the radio energy over a very wide-ranging frequency band, while maintaining a very low power spectral density. The low power spectral density limits the interference potential with conventional radio systems, and the high bandwidth can allow very high data throughput for communication devices, or high precision for location and imaging devices. This fundamental structure maintains the security aspect of the technology while offering localisation data (ETSI, 2021).

1.1.2 Technical features

Pulses

The primary use case of UWB technology is to provide distance measurement between two devices in a secure and accurate manner. Rather than modifying the amplitude, frequency or the phase of the sinusoidal radio wave, the initiator sends very short pulses across the wide spectrum frequency. In the case of UWB, the pulses are responsible for carrying the information. A corresponding receiver then translates the pulses into data by listening for a familiar pulse sequence sent by the transmitter. Pulses can be sent once every two nanoseconds.

Bandwidth Range Definition

The UWB is specified as a band of operation signal from 3.1 to 10.6 GHz. Wireless systems typically use a central frequency and a few MHz either side to define a channel bandwidth band. UWB uses at least 500 MHz to 1.3 GHz. This means that if the user chooses to use 3.1 GHz as the transmission frequency, the user can also go up to 3.6 GHz and transmit the pulses within that range of frequency.

Noise Elimination

The UWB stays under the noise floor limit with a functioning power of less than one milliwatt, as seen in Figure 2. As mentioned before, the UWB spectrum covers the frequency from 3.1 GHz up to 10.6 GHz. While employing such spectrum, the technology would function underneath the noise level threshold. As shown in the graph below, each technology such as GPS and Bluetooth may function at different power level in conjunction with frequency (GHz). As UWB operates at a very high frequency with low power level, it neither crosses the noise floor region nor other radio technology. This makes UWB very resilient.

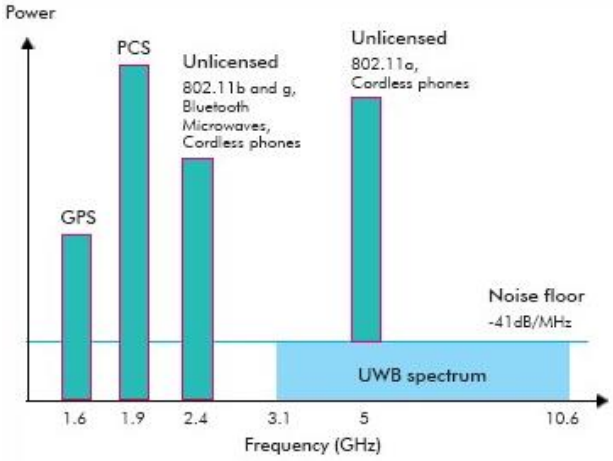

Figure 2. UWB Operating below the "noise floor" (ITU Strategy and Policy Unit, 2021)

Localisation

Distance and location can be achieved by just one token and one anchor. However, for the best accuracy, there are three different methods for the UWB technology to accurately pinpoint the location of the initiator through the anchors. The methodology (Figure 3) is chosen based on the infrastructure. As the initiator is

placed within the region and starts sending out pulses, the anchors can measure the distance through three different methods: (Gary Explains, 2020)

- Two-way Ranging (TWR): The Two-Way Ranging method determines the ToF of the UWB radio frequency (RF) signal and then calculates the distance between the nodes by multiplying the time by the speed of light. The TWR process is applied between the Tag and demanded Anchor, just only one Anchor may be involved in TWR at given time
- Time-difference of Arrival (TDoA): Opposite to that of the first method, the sensor would emit a signal where the different anchors would receive at different time frames according to the distance in-between. The sensor position is calculated based in the time difference. The method has the lowest energy consumption and is useful for localisation of things in large numbers.
- Phase-difference-of-Arrival (PDoA): Similar to that of the method above, the phase difference between the received signals at different anchors is measured and the angle of the signal received is calculated between the sensor and anchor. This method is useful for real-time localisation of things in large numbers.
- Single Anchor velocity and position tracking: This system requires an Inertial Measurement Unit (IMU) and a single UWB anchor. The main requirement is to measure the velocity using the IMU. The system uses the velocity to update the current location of the tag via a speed estimator to leverage the range changing pattern. The estimated speed coupled with orientation estimation from the IMU can provide a velocity estimate to keep the system observable (MIST Lab, 2020).

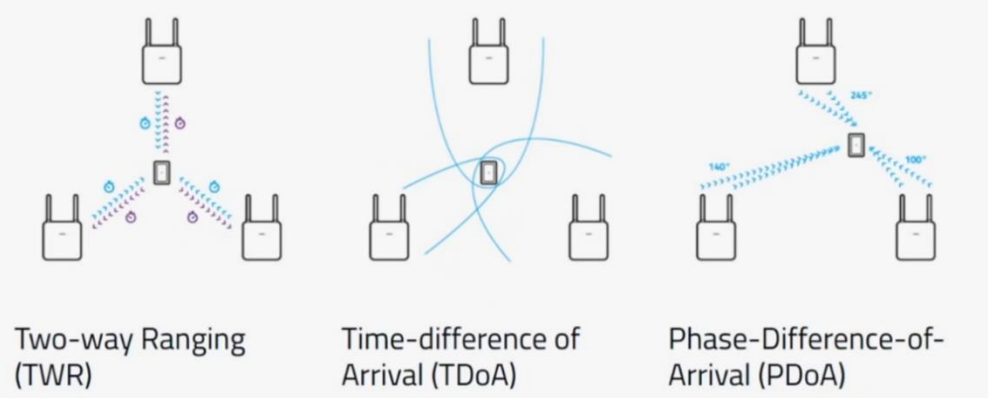

Figure 3. UWB Methodology

Security

The distinctive ToF measurement of UWB allows the technology to provide a robust security interface for all users. With the capability to quickly determine the precise distance, any attempt to intercept or redirect an UWB signal through relay attack will be mitigated. This makes it significantly harder for the hacker to interfere. UWB also fits into a broader security-by-design approach that embeds it in a secure element that protects data stored on users' devices and comes with added levels of security on the physical layerencryption introduced in IEEE 802.15.4z standard (Dachs, 2020).

Differences vs radio frequency identification (RFID)

Baptiste Pestourie (2020) has summarized the two technologies as shown in Table 1

Table 1. Differences UWB vs. RFID

	Accuracy		Refresh rate	Range	Communication performance	Power consumption	Cost	Typical use case
	Line of Sight	Non Line of Sight						

Active RFID	60 - 100 cm	> 1 M	0.1 - 10 Hz	~ 90 m	Extremely low data rates ~1 kbps	~0.4 uA	2-3$	Budget and low power system with little data exchange
UWB	~10 cm	< 50 cm	~1000Hz	10 - 30 m	High data rates, up to 21.6 Mbps)	transmission 600 uA, rest 15 uA	~20$	High performance IPS in industrial environement

The plot in Figure 4 for each system contains distance estimation results for all the base stations of that system. Observing the plots, ultra-high frequency RFID (UHF-RFID) system performs worse as it is the most affected by multipath and Non-line-of-sight (NLOS) conditions. Low frequency RFID (LF-RFID) system has the shortest tag detection range while the distance estimation performance is significantly better compared to UHF-RFID but not quite close to the superior performance of the UWB system. In the case of UWB system, estimated distances, most of the times, are larger than the real distances which is the ideal behaviour (Gharat, 2017).

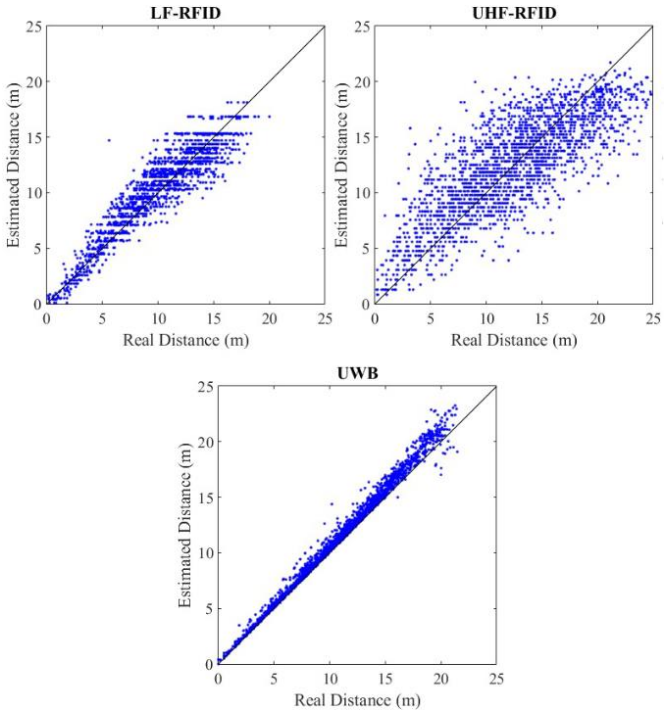

Figure 4: Plots of real distances versus estimated distances for LF-RFID, UHF- RFID and UWB based systems

Cumulative distribution functions (Figure 5) for 2D positioning errors of all the three systems are shown in figure below. LF-RFID system keeps positioning error below 2m for 74% of the test points while UHF-RFID achieves this task for only 20% of the test points. UWB system achieves sub-meter accuracy for nearly 87% of test points compared to 42% in the case of LF-RFID system.

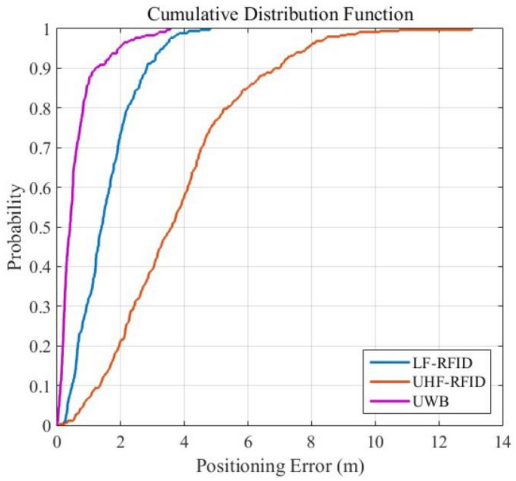

Figure 5: Cumulative distribution function for positioning errors of LF-RFID, UHF-RFID and UWB systems

Table 2 below compares the localization performance of all the three systems. The overall localization performance of LF-RFID system is considerably better than that of UHF-RFID system, in the challenging environment considered for the evaluation. Although the performance of UWB system is far superior compared to the two RFID based systems, it must be taken into consideration that these two systems are implemented using off-the-shelf components while the UWB system uses components from the evaluation kits consisting of a tag with an external antenna and an external power supply.

Table 2 Localization error performance comparison

	LF-RFID	***UHF-RFID***	***UWB***
Mean error (m)	1.53	3.78	0.58
Standard deviation (m)	0.91	2.12	0.62
CDF at 50% (m)	1.41	3.61	0.41
CDF at 90% (m)	2.82	6.84	1.10
Maximum error (m)	4.81	13.05	3.56

Further evaluation can be found in a comprehensive review by Li (2019). A variety of technologies for indoor localisation are evaluated. The merits and defects of these technologies are compared by Li, (Li, 2019) of which we highlight Li's findings about RFID and UWB in Table 3 below.

Table 3 Comparison of indoor localization technologies (UWB and RFID)

System	Advantages	Disadvantages
UWB	High accuracy, strong anti-jamming capability, good security	High construction cost
RFID	Low cost; real-time localization	Sensitive to environment

1.1.3 Industry standards and protocols

UWB Alliance and FiRa Consortium

UWB Alliance was established in 2018 in order to develop UWB technology and Institute of Electrical and Electronics Engineers (IEEE) 802.15.4z standard. Companies like Apple, Hyundai, Kia, Zebra, Decawave, Alteros, Novelda and Ubisense are among the founding members of the alliance. The alliance is aimed to develop

worldwide the ultra-broadband technologies and to work out the requirements and regulations for promoting the use of this technology in various industries, products and solutions. The alliance is dedicated to the promotion of UWB industry through fostering the protection and advancement of the regulatory environment for UWB technologies.

FiRa Consortium, on the other hand, is a member-driven organisation that is dedicated to the development and widespread adoption of seamless user experiences using the secured ranging and positioning capabilities of Ultra-Wideband. The company aims to promote the use of UWB in access control, location-based services and device-to-device fields. The company also helps built on to the IEEE 802.15.4/4z which will be mentioned below (Businesswire, 2020).

IEEE and ETSI

UWB technology is based on **IEEE 802.15.4 standard**, which is used to combine sensors and actuators into a single wireless network. Currently, IEEE 802.15 working group specifies wireless personal area network (WPAN) standards. Task groups (TG) in IEEE 802.15 leverage UWB technologies for 802.15.3 high-rate and 802.15.4 for low-rate communication protocols such as Zigbee and WirelessHART (Hsu, 2021).

The IEEE 802.15.4z version of this standard is designed to significantly expand the range of UWB applications (RealTrac, 2019). The IEEE 802.15.4z amendment put forth in 2019 enhances the ultra-wideband physical layer with additional coding and preamble options, improvements to existing modulations to increase the integrity and accuracy of the ranging measurements, and additional element definitions to facilitate ranging information exchange. The amendment also enhances the media access control (MAC) to support the control for time-of-flight ranging procedures and exchange ranging-related information between the participating devices:

US:

IEEE 802.15.4a/z – has been optimised for micro-location and secure communication

- ETSI Standard EN 302 065
- IEEE 802.15.4a – impulse radio technology
- IEEE 802.15.4z for security extension

AUS:

- ETSI Standard EN 302 065

Europe:

- ETSI EN 302 065
- ETSI (https://www.etsi.org/technologies/ultra-wide-band)
- ETSI EN 302 065: Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD) using UWB technology
- ETSI EN 302 435: Electromagnetic compatibility and Radio spectrum Matters (ERM); Short Range Devices (SRD); Technical characteristics for SRD equipment using UWB technology ; Building Material Analysis and Classification equipment applications operating in the frequency band from 2.2 GHz to 8.5 GHz

1.1.4 Regulatory institutes

Australia

The Australian Communication and Medio Authority is responsible for regulating the UWB standards (Decawave, 2015).

- The specific regulations are targeting models within communications, short range vehicle radar, In-ground UWB sensors and Building material analysis devices.
- Generic UWB transmitters can operate between 3.4 – 4.8 and 6.0 – 8.5 GHz and must comply with **EN 302 065 or EN 302 500**.
- In-ground UWB transmitters are restricted to -62 dBm/MHz between 4.2 – 4.8 and 6.0 – 6.8 GHz.
- Building material analysis transmitters can operate in the 2.2 – 8.5 GHz range and must comply with **EN 302 435**.
- For generic UWB transmitters:
    - The transmitter must not be operated on board any aircraft or from any fixed outdoor location.
    - The transmitter must not be operated within a nominated distance of a specified Australian radio-astronomy site.
    - The transmitter must not be operated in the 8400–8500 MHz band within the nominated distance of a specified SRS earth station.
- For in-ground UWB transmitters:
    - The transmitter must comply with **Part 2 of ETSI Standard EN 302 065**.
    - The transmitter must not be operated within a nominated distance of a specified Australian radio-astronomy site.
- For building material analysis transmitters:
    - The transmitter must comply with ETSI Standard **EN 302 435**.
    - The transmitter must be operated in a position such that emissions are directed into building material.
    - The transmitter must not be operated within a nominated distance of a specified Australian radio-astronomy site
    - The transmitter must not be operated in the 8400–8500 MHz band within the nominated distance of a specified SRS earth station.

1.1.5 Key players/market leaders

UWB Chip Manufacturers

1. Decawave Ltd. (Now Qorvo)
    - Decawave focuses on developing semiconductor solutions, software, modules and reference designs that enable real-time, ultra-accurate, ultra-reliable localisation service. The UWB wireless technology enables an entirely new class of highly intelligent and secured products and applications.
    - At Decawave, the company also wanted UWB technology to become ubiquitous, and they added low-power and low-cost to the definition of our UWB chips (Decawave, n.d.).
2. NXP Semiconductors
    - The company is a global semiconductor company that provides a combined product portfolio of process technology power management and digital signal processing.
    - NXP's ultra-wideband technology enables secure ranging and precision sensing. The main functions involve determining a device's relative position with UWB localisation capability in a precise, secure, and efficient manner in real time.
    - The UWB function can be adapted towards secure hands-free access, indoor navigation, hands-free payment, credential sharing and item tracking (NXP, n.d.).
3. STMicroelectronics
    - STMicroelectronics uses the UWB technology for precise indoor tracking services by offering tailored solutions addressing specific use cases designed from the silicon right up to the applications.
    - To help unleash the potential of UWB technology in real-time positioning and location systems, designers can count on ST's strengthened STM32 microcontroller family and supporting development ecosystem (ST, n.d.).
4. Alereon, Inc
    - The company is a semiconductor company developing innovative Ultrawide band wireless chipsets in the hope of simplifying networking by removing cables.
    - The Alereon Ultra-Wideband chipsets consist of two chips: a combination MAC/Baseband and an RF transceiver. The solution also includes embedded software to implement a complete WiMedia UWB solution that supports multiple protocols (Alereon, 2021).
5. Cambridge Consultants
    - The company was one of the first to develop chipsets that aims to deliver overall location system performance, ensuring that all their clients understand the likely level of performance which can be achieved in the real world.
    - The system is able to provide accurate performance estimates, given a detailed understanding of the requirements and modelling of the hardware (Cambridge Consultants, n.d.).
6. Time Domain
    - The company was recently acquired by Humatics and is responsible for manufacturing circuit boards used for global positioning technology.
    - The company is the developer of the ultra-wideband PulsOn chipset which is a foundational technology that enabled a significant advancement and even new functionality in wireless communication, precision location and tracking, and high-definition portable reader (Humatics, n.d.).
7. Wireless2000
    - Wireless 2000 is an engineering development company that brings together highly qualified engineers and scientists with practical experience in RF, RFID, Digital Signal Processing (DSP),

wireless communications and Ultra-Wideband technology. It is also a world leader in medical applications of UWB technology.
    - The first product introduced is a wireless, non-contact Patient Assessment Monitor for bed occupancy (Wireless2000, n.d.).
8. CEVA RivieraWaves UWB
    - CEVA-RivieraWaves™ UWB is a low power ultra-wideband (UWB) MAC and PHY platform internet protocol (IP) based on 802.15.4 HRP, the FiRa Consortium and the Car Connectivity Consortium (CCC) requirements. It delivers secure, centimetre-level accuracy and robust location information through ToF ranging and Angle-of-Arrival (AoA) processing (CEVA, n.d.).

UWB Chip Integrators

1. Apple
    - Apple recently released devices line-up that had the Apple-designed U1 chip integrated with Ultra-Wideband technology for spatial awareness.
    - The U1 chip allows the iPhone to precisely locate other u1-equipped Apple devices, which is the equivalent of having GPS indoors.
    - In a practical example, with U1 and iOS 13, the user can point his/her iPhone toward someone else's, and AirDrop will prioritise that device so the user can share files faster (Locatify, n.d.).
2. Samsung Electronics Co., Ltd
    - Samsung has worked closely with Google to get UWB on Note 20 Ultra integrated with Nearby share protocol. Another UWB device will show encircled in a blue ring in the Nearby Share menu on Note 20 Ultra (Singh, 2021).
    - Samsung has revealed its plans to develop UWB connectivity on Galaxy Note 20 Ultra for Smart Things Find, which will use AR interface and help locate smart objects indoors, and also as a Digital key that will help you unlock doors, cars, etc (Gartenberg & cgartenberg, 2021).
3. Taiyo Yuden Co., Ltd
    - The Taiyo Yuden R&D Centre of America (www.trda-inc.com)—the U.S. R&D arm of Taiyo Yuden Co. Ltd.—has successfully developed the first ceramic chip antenna for Ultra-Wideband applications. Such miniaturisation was previously unattainable. In the past, this problem actively hindered the commercial progress of UWB. Taiyo Yuden is also releasing engineering samples of the UWB antenna to standardisation working groups in various locations, including Japan (Konish, 2003).
4. Zebra Technologies Corporation
    - Designed with over 25 years of expertise, Zebra's UWB products provide customers with a world-class platform enabling accurate asset and personnel visibility solutions.
    - The products are designed for all sorts of applications that require precise and high update rate real-time location of assets.
    - The technology is compatible with Wi-Fi (ZEBRA, n.d.).
5. Pulse ~Link
    - Pulse ~Link released a unique UWB implementation with an operating range up to 10 meters. All of CWave wireless solutions share a common feature where they all include Ethernet-over-coax technology and are delivered from a common chipset.
    - CWave is a short-range, secure, high-data rate UWB wireless networking technology suitable for a variety of applications (Pulselink, n.d.).
6. 5D Robotics, Inc
    - 5D Robotics, Inc is a world leader in development of localisation technology that provides extremely accurate position and navigation.

- In 2016, 5D Robotics announced the acquisition of Time Domain, which is the world leader in Ultra-Wideband technology products and services. The company provides small, low-power UWB ranging radio and radar sensors which measure distance with an accuracy of 2 centimetres (Globenewswire, 2016).

7. Ignion
    - Ignion has pioneered the use of geometry-based antenna design and development to deliver antenna technology that reduces antenna size, enables multi-band operation and improves antenna performance.
    - The company aim to provide high-performance, cost-effective antenna aligned with the Multiband Orthogonal frequency division multiplexing (OFDM) alliance (MBOA) recommendations for Ultra-Wideband devices, ideal for W-USB and W-USB enabled devices (Ignion, n.d.).
8. Nanotron Technologies Gmbh
    - Nanotron Technologies is a leading provider of electronic location awareness solutions. The solutions aim to deliver precise position data augmented by context information in real-time. In 2020, the company was acquired by Inpixon and was able to enhance Inpixon's offering and homogenise the positioning of people and assets both indoors and outdoors (Inpixon, n.d.).
9. Johanson Technology, Inc.
    - The company aims to add more functionality to handheld, worn, portable devices within the limited antenna performance. The company targets keyless remote entry (keyfob), portable payment systems, location services and many other applications. The mini chip antenna provides Ultra-Wideband function in order to focus on this issue (Johanson Technology, n.d.).
10. Pozyx
    - The company aims to bring the same power of UWB within the corporate smartphone and vehicle brands to the business and industrial world.
    - Pozyx develops and designs its products in-house including antennas and housing. The final Real-time Locating System (RTLS) solution, made up of Pozyx hardware and firmware, are combined with algorithms and analytics software to translate real time locations to smart data (Pozyx, n.d.).

1.1.6 Existing vendors/product – case studies

Commercial Products

1. Ubisense Dimension 4 UWB Real-Time Location System (Figure 6)
    - Centimetre-level accuracy in three dimensions that pinpoint the true 3D location, movement and identity of people and things.
    - The tag is able to measure both Time-Difference-of-Arrival and 2-axis Angle-of-Arrival of UWB signal in the same system, this providing up to three times more location information than comparable systems.
    - Accurate 3D tracking information is made possible when two sensors detect a tag.
    - Small, lightweight and cost-effective at a continuous 1Hz UWB tracking update rate (Ubisense, n.d.).

Figure 6. Ubisense Tags

2. The WISER Locator System (Figure 7)
    - The system utilises WISER's patented Redundant Radio Localisation and Tracking (RRLT) technology that allows for immediate asset visibility and tracking in real-world environment. The system can be used to automate inventory and eliminate manual scanning and searching.
    - The WISER's user-friendly Tag and Track software translates hardware data into centimetre-level coordinates. The system also provides GUI which overlays the coordinates on a site map, thus making actionable data accessible on a computer or mobile device.
    - IC compliant with IEEE 802.15.4-2011 (Wiser Systems, n.d.).

Figure 7. The WISER's Locator System

3. Eliko Industrial Real Time Locator System (Figure 8)
    - The system aims to tackle common industrial challenges such as unplanned downtime, lack of transparency, environmental impact and workplace safety.
    - The indoor tracking system for manually or automatically operated vehicles in warehouse which enables user to gain transparency over the logistic process.
    - The Eliko RTLS creates geofences around moving and static machines and gives warnings with visual and audio alerts. The system is able to detect when people come within a preconfigured range of the machine.
    - The system can also track pallets doth directly and indirectly.
    - Promised to improve the manufacturing operation OEE by around 3% (Eliko, n.d.).

Figure 8. Eliko UWB Locator Tags

4. The BlueCats UWB System (Figure 9)
    - The reader is able to measure the time of arrival and send it to the synchronisation distribution panel where the tag's precise location is calculated from the combined difference in time of arrival from multiple readers.
    - Note the reader does not transmit any signal but uses directional antennas to cover specific areas of customer's operation site (BlueCats, n.d.).

Figure 9. BlueCats UWB Reader

5. Sewio Indoor Tracking RTLS UWB Wi-Fi Kit (Figure 10)
    - The RTLS UWB kit combines hardware component, Decawave module and software to deliver real-time location data and accurate indoor positioning.
    - The kit is able to cover an area of 400 m^2 and provide a true 360 degrees omnirange UWB anchor.
    - The studio software also covers five Anchors and provide various features such as Open Application Programming Interface (API) for easy data access, Real-time movement visualisation in 2D and 3D, and location data analytics etc (Sewio, n.d.).

Figure 10. Sewio RTLS Kit

6. Infsoft Indoor Positioning UWB-Based System (Figure 11)
    - Infsoft offers solution based on UWB for real time location tracking, However, the system does not work with consumer standards such as Wi-Fi and Bluetooth Low Energy. However, it offers an accuracy at lower than 30cm.

- The object to be tracked is equipped with a small UWB tag which runs on battery power. It sends data such as ID and ToF to the Locator Nodes. The nodes have a fixed position in the infrastructure and can use the running time of light to calculate the distance of the asset (Infsoft, n.d.).

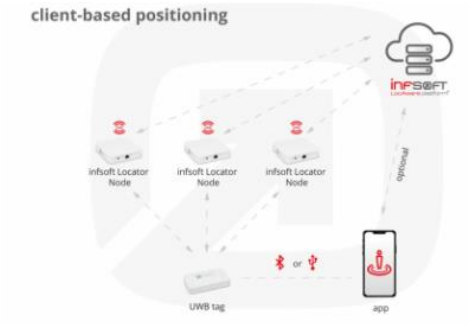

Figure 11. Infsoft Positioning System Infrastructure

7. Ubudu High-accuracy Asset Tracking Solution (Figure 12)
    - The company promotes an end-to-end RTLS that improves the operations' efficiency by up to 20%.
    - Ubudu's RTLS is based on electronic devices which enable to perform tracking of different assets. The products are all ready for industrial areas, equipped with a durable enclosure.
    - The whole system includes pinpointing the exact positions of all assets in real-time, geofencing certain areas depending on personnel groups, displaying recorded data through visualisation method and allowing real time management through providing real-time status data (Ubudu, n.d.).

8. Figure 12: Ubudu Tracking TagsChang Ying Precise Indoor Positioning System (Figure 13)
    - The Industrial 4.0-UWB IPS is a real-time location system that locates all equipment and objects within a factory. It is suitable for logistic and warehousing management, precise movement of equipment, access control etc.
    - The system promises a detecting method through TDOA/TOF with an accuracy of 10-30cm precision. The system is highly stable and has an operating range of 100m with a wireless transmission operating on RJ45/Wi-Fi based dual-way transmission required (Chang Ying, n.d.).

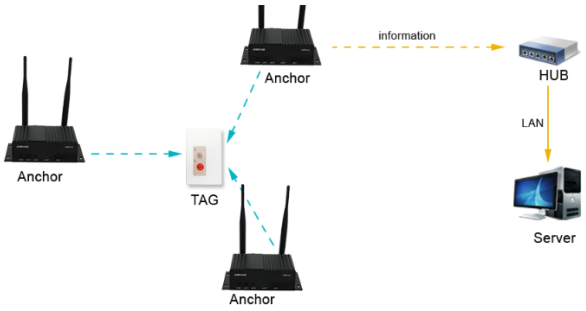

Figure 13 Chang Ying Indoor Positioning System Infrastructure

9. Estimote Location UWB Beacon (Figure 14)

- The Estimote Indoor Location system allows users to easily map the indoor spaces and locate the people within the map down to a few meters. The system is able to provide automapping function with 4 UWB Beacons. It is important to note that the indoor location function requires an app to proceed.
- The Indoor Location SDK allows the user to implement indoor location via their own personal device. The user is required to set up a location manually within the app. Then, the app will embed a built-in location view similar to that of Apple's Map View (Estimote, n.d.).

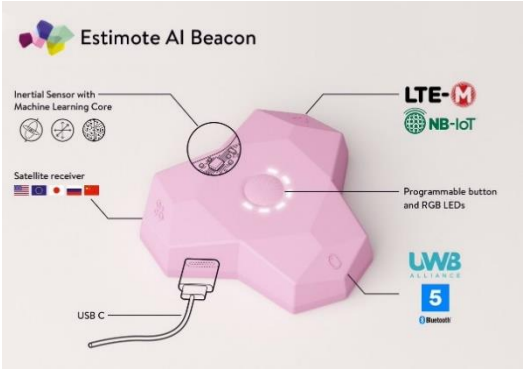

Figure 14: Estimote Beacon

10. Humatics Rail Navigation System (Figure 15)
    - The system aims to accelerate signal modernisation, improve service reliability, reduce maintenance, expedite completion of capital programs and enhance system safety with the help of UWB adaptation.
    - The navigation system UWB beacons are installed along the wayside of the track and continuously calculate the range between itself and the beacons on the trains. The system then combines the UWB ranges with IMU data to create real time location and speed of the train.
    - Piper Networks has received a CENELEC Safety Integrity Level 4 (SIL-4) Certification for its UWB train control system from independent safety assessor, TÜV SÜD. The certification is a milestone achievement for Piper and the transportation industry as it becomes the first ever UWB-based position and speed technology to achieve vitality. The system is now ready for integration with signalling and train control programs being implemented by transportation agencies and their engineering contractors in the US and worldwide (Humatics, n.d.).

Figure 15: Humatics Rail Application

11. RealTrac Proximity Detection System (Figure 16)
    - The system aims to prevent proximity to unsafe objects and provide instantaneous waning towards personnel about dangerous situations. The system consists of two main components which are the RealTrac Vehicle Tag which is installed on an object that is dangerous for approaching, and a RealTrac Tag worn by the staff.

- The specialised radio channel is programmed to measure the distance between the vehicle tag and the Realtrac Tag. In cases where the two get too close to each other, an alarm is generated (Sudonull, n.d.).

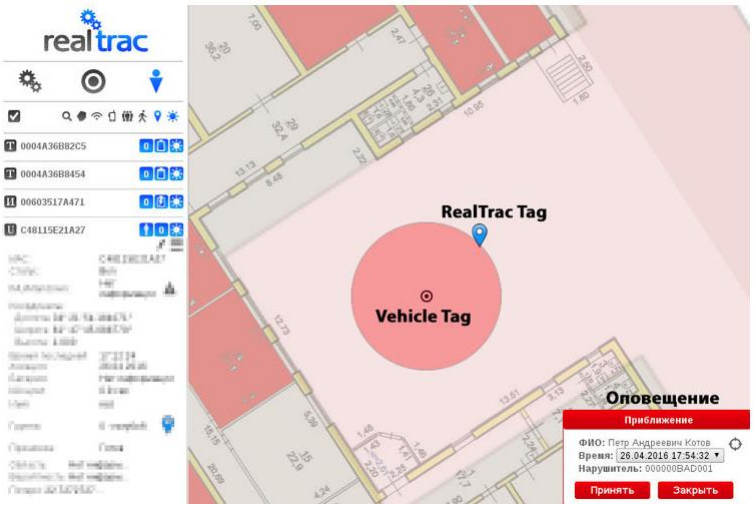

Figure 16: RealTrac Application

12. Continental and NXP Smartphone Car Keys (Figure 17)
    - The system aims to enable a broad range of new use cases which is handsfree smartphone car access. The function can be offer through unique UWB localisation capabilities. The technology can give spatial awareness to UWB-equipped cars and enable the car to know exactly where the users are.
    - The user can simply open and start the car while leaving their phones in their pockets or bags. It is important to note that the CoSmA chipset is integrated with Bluetooth Low Energy (BLE)/UWB technology (NXP, n.d.).

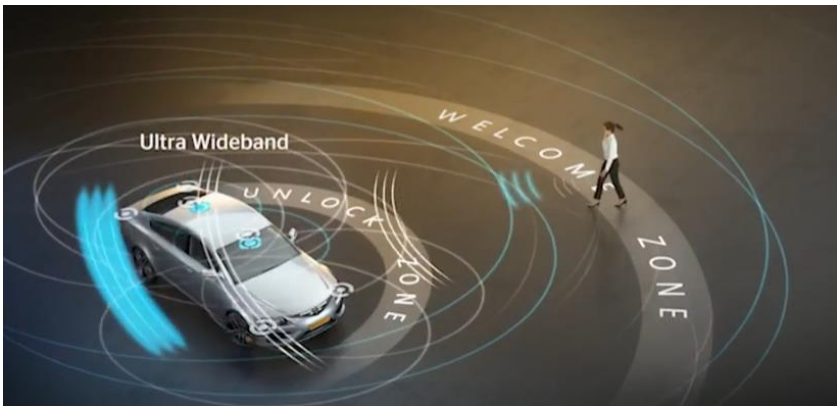

Figure 17: Continental and NXP UWB Application

13. Volkswagen and NXP Ultra-Wideband's Realtime safety system (Figure 18)
    - The company aims to use the unique capabilities of UWB, which is to accurately localise and fine ranging at maximum security levels.
    - The UWB chip is integrated into the car and is responsible for communicating with each other in addition with other mini transmitters such as car keys. The six chips continuously transmit signals back and forth and determine the exact position of the car owner. The system enables a real-time centimetre-precise, tamper-proof positioning control of the car at any time (Volkswagen, 2019).

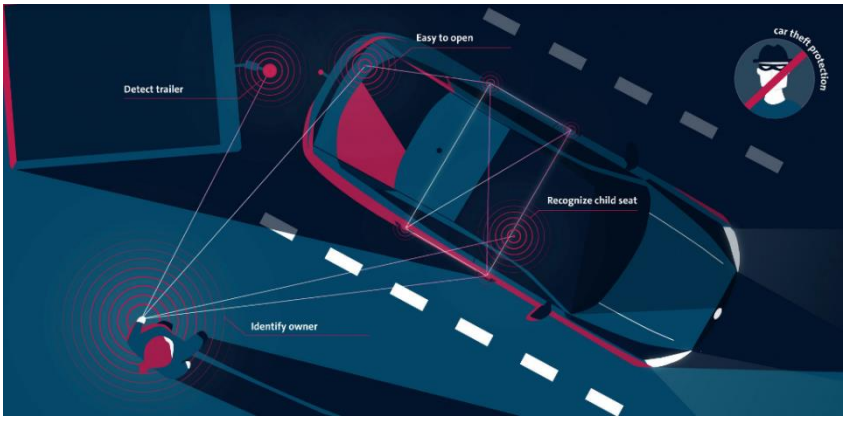

Figure 18: Volkswagen and NXP UWB Application

Mobile phone integration

1. Apple iPhone 11 onwards
    - The main goal of Apple to include UWB as a major feature for the upcoming devices is that it enables the highly-accurate location tracking, with devices using UWB potentially able to identify the distance relative to itself within a few inches.
    - Apple initially adopted the usage of UWB in late 2019 in the iPhone 11 range.
    - Recently in June 2020, Apple introduced a "Nearby Interactions" developer framework for the UWB equipped devices, enabling developers to create apps that take advantage of relative direction and distance data. For example, a ride-share app can allow the passengers to find each other easily (AppleInsider, n.d.).
2. Samsung Galaxy S21 onwards
    - The UWB function had recently been adopted in Samsung's Galaxy S21+ and S21 Ultra 5G. Samsung aims to use the UWB positioning ability to instantaneously track the device's movements in real-time. This will allow UWB-enabled devices to understand both motion and relative position.
    - Samsung has also integrated UWB into its SmartThings Find application. Through the use of augmented reality and intuitive directions, users can precisely locate other UWB-enabled devices.
    - Samsung also announced at its January 2021 Unpacked, the new Galaxy SmartTag+ will feature UWB which can be attached to almost all belongings.
    - Samsung is also teaming up with companies to turn UWB-enabled phones into a digital key. The UWB-enabled digital key will send a short pulse between the mobile device and the car. Then, it will make a super-precise distance calculation in real time, unlocking the door when the user is nearby. The function can also be used to directly guide the user to the car (Stone, 2021).

1.1.7 Future Roadmap

Standardisation

The FiRa Consortium is committed to define standards and certification programs to ensure full interoperability within the UWB ecosystem. More than 45 companies, among the market leaders in mobile, industrial, Internet of Things (IoT) and auto markets, have joined FiRa Consortium. The complete standardisation of this technology will allow the public market to trust and adopt it. As seen in Figure 19, within the near future, UWB will be implemented in all fields including smart home, retail, building infrastructure and transport.

Emerging UWB Application Areas

Personal Vehicle

While UWB has been widely used in localisation and mapping, it is only recently that generic automotive applications such as car-to-car and car-to-infrastructure communication have started to emerge. Applications such as keyless entry, tire pressure measurement are some of the functions that are being looked into by automotive companies (Celis, et al., 2011).

In a typical scenario, the in-car environment is very challenging for wireless applications due to metal shielding. UWB technology can bypass such issue and achieve reliable functionality for wireless applications. Through the adaptation of UWB, wireless connection of a sensor in the engine compartment to its electronic control unit can be made possible. Furthermore, tracking the position of a small portable low-power tag inside and in close proximity is also made possible (keyless entry). The technology can also provide anti-theft capabilities with passive localisation system. Through the detection of UWB signal, the car can determine the position and tracks the movement of an object in close proximity.

Personal Device

With the current market in mind, smart phones are playing an important role in the adaptation of UWB into the current society. The big companies such as Samsung and Apple are making the technology more accessible to the broad consumer market. With both of the companies announced full support for UWB in their latest flagship phone releases, it is inevitable that more consumers will have UWB-enabled personal devices (Dachs, 2020).

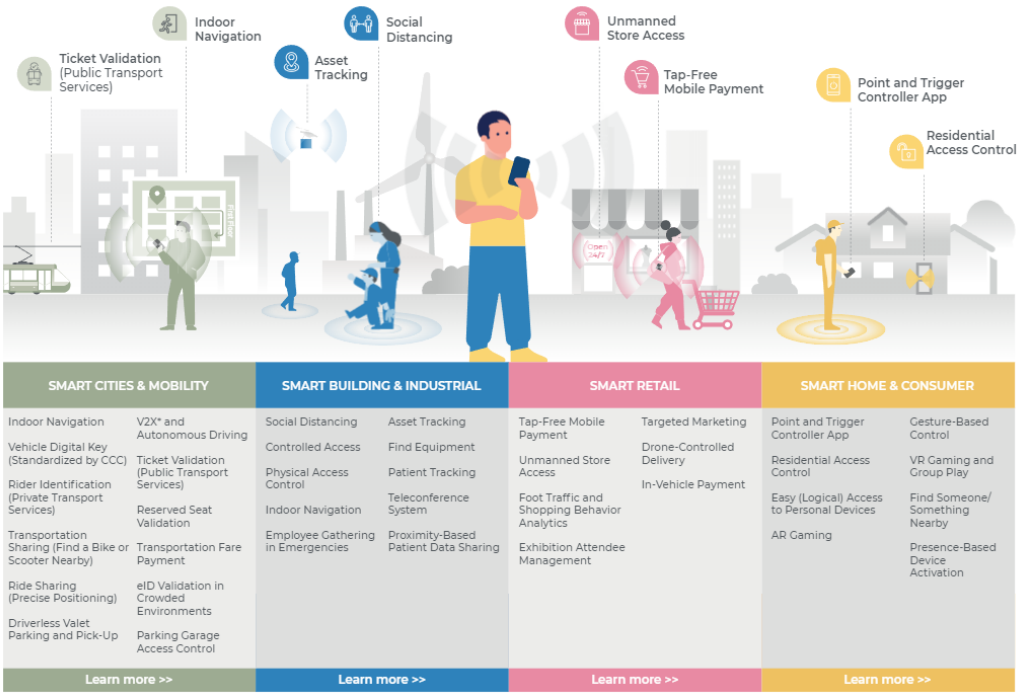

Figure 19: FiRa UWB Future (FiRa, 2020)

Table 4 Key challenges and strategic recommendations for the UWB ecosystem (FiRa, 2020)

Inhibitor	What Needs to be Overcome	How it is Being Achieved
Antenna Integration	The integration of antennas, an important part of an UWB system that affects its performance, presents a problem to the market. The size of the antenna is a challenge, particularly when integrating into smaller mobile devices and wearables.	Technology providers are undertaking large amounts of R&D to reduce the size of the antennas. This will allow UWB to continue to be integrated into more devices, included small-sized IoT products. For more basic ranging only devices, such as tags, antennas are more simple and low cost.
Awareness	Other location technologies are well established within devices, sensors, and companies. There is also a large amount of awareness around these technologies, with companies and consumers more likely to opt for something familiar. To provide UWB, these technologies need to be replaced or integrated. Low awareness leads to little development, so few compelling devices or use cases are provided, which does not promote further development or awareness.	UWB organisations have dedicated their efforts to promoting the technology and bringing together OEMs to ensure new solutions, standards, and certifications are developed, allowing for new use cases and devices. This has helped the technology to build significant momentum within multiple different markets, reducing the chicken-and-egg ecosystem problem that has plagued other technologies.
Cost	The cost of UWB components and infrastructure is often higher than alternative technologies, due to relative immaturity. The technology industry has previously backed technologies like Bluetooth LE and Wi-Fi, reducing the cost of components and infrastructure as development continues, though UWB is not yet at the same level.	As the UWB market is continuing to develop, and as chipsets begin to ship in higher volumes as the number of UWB-enabled high tier devices grows, the cost of the technology will continue to decline, also allowing it to make its way into middle and lower tier products. As more use cases emerge, the cost-per-use case will also decrease.
Evolving Competitive Landscape	While UWB provides unique advantages versus the competition, other technologies continue to evolve to better support location services. Wi-Fi, Bluetooth Angle of Arrival, and 5G Positioning are all evolving to offer better accuracy for RTLS and other location services. This may be adequate enough for many applications such as personal tracking tags, indoor navigation, and less stringent asset tracking.	UWB should position itself in environments where it has a clear advantage over the competition, enabling better accuracy, robustness, security, and creating new experiences that previous technologies are not capable of delivering. As the installed base scales, the value proposition will become more compelling.
COVID-19	As is the case with many technology markets, the UWB market has seen some impact from the COVID-19 pandemic. With many factories having had been shut down and companies reducing the number of on-site staff, there has been a reduction in the need for new connectivity deployments. Many companies have had other aspects to focus on, leaving UWB behind for the time being, leading to less demand within the market.	Despite COVID-19 reducing the initial demand, it has highlighted contact tracing use cases, designed to reduce the spread by alerting people when they have been near someone with COVID. Alongside this, as the world begins to see activities returning to normal, demand for UWB is increasing.
Regional Variations	As is often the case with communications and locations technologies, regional variations and restrictions add complications to the development and deployment of UWB. This increases chipset design complexity due to the different requirements in different regions.	UWB organisations are working hard to develop worldwide standards for the technology to ensure that regulations across different regions are similar and do not affect the market.

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1.2 5G

1.2.1 Introduction

5G is the fifth-generation technology standards for broadband cellular networks. The technology was first deployed in 2019. 5G networks, similar to their predecessors, are cellular networks where the service area is divided into small geographical areas.

5G wireless technology aims to deliver high multi-Gbps data speeds while maintaining a low latency. In a technical sense, 5G brings wider bandwidths through expanding the usage of spectrum resources, from sub-3 GHz used in 4G to 100 GHz and beyond. 5G can also operate in lower bands as well as mmWave, which defines the extreme capacity that 5G offers. 5G, similar to that of 4G Long Term Evolution (LTE), is Orthogonal frequency-division multiplexing based and operates based on the same mobile network principle. However, the 5G NR air interface enhances the multiplexing to deliver a higher degree of flexibility and scalability. The advantages of 5G allow it to impact every industry such as transportation, remote health care, agriculture and more. With forward compatibility design in mind, 5G aims to support three main types of connected services: enhanced mobile broadband, mission-critical communications and massive IoT.

The recently published version of 5G, also known as Release 16, included radio enhancements such as NR Industrial Internet of Things, NR Vehicle-to-Everything . The main function that focuses on accurate positioning is known as 5G Location and Positioning Services, which is released alongside TR 21.916. The function includes better accuracy, address mapping, velocity, vertical positioning and more. The localisation is calculated through using the time difference of arrival technique through mathematical deduction of the TDOA equations where the theoretical position of the user is determined.

As of March 2021, 157 mobile operators have launched commercial 5G services in 62 countries, according to GSMA Intelligence. The study forecasts 551m subscriptions by the end of 2021, and 1.8 billion by the end of 2025. Here are the recent steps done so far:

- North America 5G was available in some locations in 2019. It won't take off in most areas until 2020.
- In the US, more precisely, ATT announced nationwide coverage in the first half of 2020. Verizon 5G was the first carrier to roll out 5G.
- Deutsche Telekom started 5G in Berlin, Darmstadt, Munich, Bonn, and Cologne in Sept 2019.
- Telcos in France announced 5G offers by the very end of 2020 for real availability in 2021.
- In the UK, many cities have seen 5G in 2019 and more in 2020. EE, Vodafone, and O2 are actively deploying 5G since mid-2019.
- Indian Telcos are getting prepared for the 5G roll-out in 2021.
- China Unicom has set up 5G in a few locations in 2019. GSMA expects 460 million 5G connections in China by 2025.

5G is advancing our world and our societies. 5G opens cutting-edge ways of improving safety and sustainability. For example,

- Smarter electricity grids for greatly reduced carbon emissions, more connected vehicles sharing data to prevent road collisions
- Faster deployment of emergency services to accidents
- Connected sensors that can detect and warn of natural disasters early
- Drones becoming a key tool to accelerate and support emergency situation response
- Remote expertise with specialists smoothly consulting/diagnosing patients elsewhere

1.2.2 Technical features

4G VS 5G

As mentioned in the introduction, 5G is the new generation of cellular network that aims to replace the current 4G network. While 4G was built upon the data and application technology introduced by 3G, 5G builds upon it by adding ultra-fast speed and high reliability while maintaining low latency, which is lacking for the 4G network (iSelect, n.d.). In a theoretical perspective, 5G can reach data transition speed 20 times faster than that of 4G LTE. While 4G has a peak speed of around 1GB per second, 5G could go up to 20GB per second theoretically. Furthermore, 5G has the capacity to handle up to million devices per square kilometre, meaning the user will have guaranteed network and not be concerned with dropped connections. Initially, 4G was designed as the first generation of cellular network to focus on data over voice calls. It is able to offer data speed 10 times faster than that of 3G and support more intensive activity such as video streaming. 5G, as the newest generation of mobile cellular network, is able to offer super-fast data speeds, more network capacity and enable smart technology such as Indoor positioning and connected vehicles (Dannelly, 2020) (Dannelly, 2020).

The biggest differences between 4G and 5G are speed, latency, bandwidth and coverage (Johnson, 2020). This is accomplished through a mixture of improved technology, updated infrastructure, and utilising new wireless frequencies. In the near future, 5G will also be launched on higher frequencies of between 30 GHz and 300 GHz, which is known as the millimetre wave or 'mmWave'. Instead of 5G towers built on every street similar to that of 4G, there will be a combination of towers and small cells with a short signal range in populated areas for operation.

Table 5. 4G vs 5G

Generation	Theoretical Speed	Technology	Features
4G	100 - 300 Mbps	-WiMax -LTE	-Fast download Speed -Enabled HD Streaming
5G	10 - 30 Gbps	-Developing	-Ultrafast download speed -Improved reliability

New Radio (NR) Positioning Support (Release 16 and beyond)

The required enablers for precise positioning in 5G include mmWave frequency bands, which enables wideband signals, beamforming and precise angle estimation with multiple antennas. Moving on from the Global Navigation Satellite System (GNSS), the 5G NR positioning support will bring high accuracy positioning to indoor scenarios.

Architecture

The newly created location management function (LMF) is the backbone of 5G positioning support. The LMF is responsible for receiving measurements and assistance information from mobile device, otherwise known as user equipment (UE) and next generation radio access network (NG-RAN) via the access and mobility management function (AMF). The function uses the accumulated data to compute the exact location of the UE through the use of LTR positioning protocol via AMF.

In contrast and as an improvement beyond LTE, new reference signals, known as positioning reference signal (NR PRS) in the downlink and sounding reference signal (SRS) in the uplink, were added to the NR specifications. The NR PRS is the main reference signal supporting downlink-based positioning methods and is designed to provide the highest possible levels of accuracy and coverage. As each base station can transmit

information at the same time, the new solution is latency efficient. With regards to minimising potential interference, it is also possible for the user to mute the PRS signal from more than one base stations.
For the uplink direction, SRS is responsible for positioning in 3GPP Release 16. As the fundamental positioning algorithm involves measurements from multiple receiving base stations, the new signal much have enough range to reach the UW, but also neighbouring base stations involved in the localisation process. The SRS is also designed to cover the full bandwidth in order to cover all subcarriers (Satyam Dwivedi, 2020).

Methodology

Similar to the technologies mentioned before, different positioning methods may require different measurements such as time and angle. 3GPP has standardised power, angular and time measurement support for the PRS. As shown in the Figure 20below, different beam represents a difference resource. The 5G technology enabled the previously adopted observed time difference of arrival (OTDOA), uplink time difference of arrival (UL-TDOA) and positioning methods based on power measurements. The list also extended to include round trip time (RT) and angle-based positioning for a higher accuracy measurement.

The Roundtrip Time (RTT) based positioning eliminates the need of tight network timing synchronisation across nodes. It is also able to offer additional flexibility in network deployment and maintenance as such. Note, gNB is a radio node that allows 5G UE to connect with 5G core using 5G air interface. (RF Wireless World, n.d.) In simple terms, the UE initiates a request to localise itself, the gNB and UE then performs Rx-Tx time difference measurement for the signal of each cell. The measurement reports from the UE and gNBs are sent to the location server to determine the round-trip time of each cell and thus, derive the UE position (3G4G5G, n.d.). Note this is a bi-direction communication method.

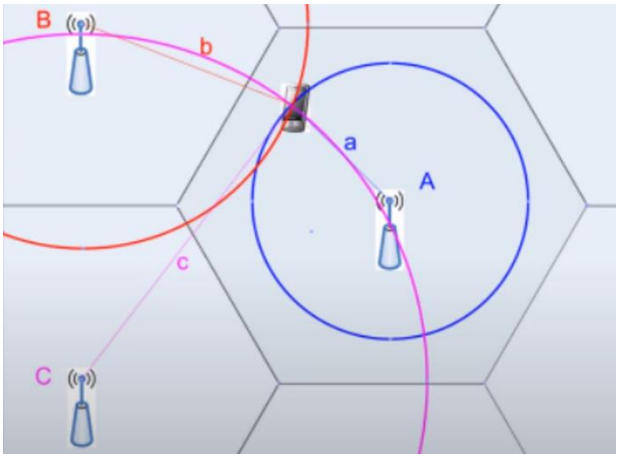

Figure 20: Multi-Cell Round Trip Time graph

Angle-Based Positioning

The Angle-based positioning method includes uplink angle-of-arrival (UL-AOA) and downlink angle-of-departure (DL-AoD). The gNB firstly measures the angle-of-arrival based on the beam where the UE is located in. The measurement reports are sent to the location server to determine the UE position. Similarly, for downlink angle of departure, the UE measures the downlink reference signal receive power per gNB. The measurement reports are then used to determine the angle of departure based on UE beam location for each radio mode. The location server would then use the angle of departures to estimate the precise UE location.

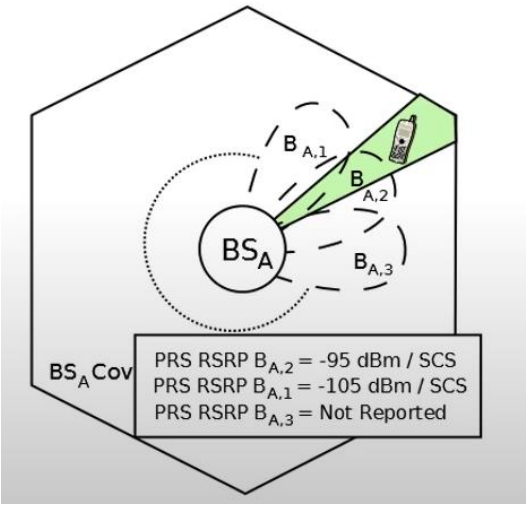

Figure 21: Angle-based positioning graph

5G V2X with NR Sidelink (Removes the requirement for a beacon)

In recent years, automotive, communications companies, academics, and the government in the world, are developing a novel vehicle communication technology. It is termed as the ***vehicle-to-everything (V2X)***, which can provide a real-time and highly reliable information data pipe to enable safe, efficient, and economical transportation services and provide the possibility to connect and autonomous driving.

V2X can create a vehicle's collective perception of the surrounding environment and help it making more informed decisions, based on exchanged local views and planned manoeuvres from nearby vehicles, instead of relying on local awareness built upon on-board sensors only (e.g., radar, LIDAR, cameras) like an autonomous vehicle would do (Molinaro & Campolo, n.d.).

- Vehicle-to-Vehicle (V2V): communicating directly with different moving vehicles;
- Vehicle-to-Infrastructure (V2I): communicating with infrastructures along the roadside;
- Vehicle-to-Network (V2N): communicating with IT networks and/or data centers

FRMCS Phase 2 Mobile Communication System for Railways

The latest version of 3GPP TR 22.889, Study on Future Railway Mobile Communication System; Stage 1 is from Release 17. The introduction to the document clarifies:

- The railway community is considering a successor communication system to GSM-R, as the forecasted obsolescence of the 2G-based GSM-R technology is envisaged around 2030, with first FRMCS trial implementations expected to start around 2020.
- The Future Railway Mobile Communication System (FRMCS) Functional Working Group (FWG) of the International Union of Railways have investigated and summarised their requirements for the next generation railway communication system in the Future Railway Mobile Communication User Requirements Specification (FRMCS URS). The present document is based on this input given by the UIC/ETSI TC-RT.

Study on FRMCS Evolution (FS_eFRMCS), available as SP-201038 clarifies:

- The UIC FRMCS programme was recently releasing stable version 5.0.0 of the User Requirement Specification, version 2.0.0 of the Functional Use Cases and a new specification item, version 1.0.0 of the Telecom On-Board System - Functional Requirements Specification, as a further step in the evolution of the FRMCS specifications. The UIC FRMCS Programme is developing all the technical conditions for the 5G FRMCS, with the main objective to make available a "FRMCS First Edition" ecosystem available for procurement by Q1 2025.
- The UIC FRMCS 3GPP Task Force has been identifying and analysing impact of this newly released set of FRMCS specifications on existing use cases and requirements collected in TR 22.889. The UIC FRMCS 3GPP Task Force analysis has concluded that refining existing use cases, defining new use

cases such as merging railway emergency communications and real-time translation of conversation, and deriving potential new requirements, will be necessary to align FRMCS and 3GPP specifications. The potential impact on normative work is estimated to be limited and much less compared to the study work.

- As approved in SA1#90-e (S1-202245), TR 22.889 has now been re-named to TR 22.989 from Rel-18 onwards (latest version is TR 22.989 v18.0.0) to make it visible to the Rail community to be able to follow the 3GPP normative work in line with their needs. It is of most importance for the Rail community that specifications from different organisations (i.e., UIC, 3GPP and ETSI) are all aligned.

Due to the expected 3GPP work overload in Release 18 (SA1 and downstream groups), it is proposed to reduce the scope of the present Rel-18 study to evolution of critical applications related use cases only already identified by UIC – what is really essential for the railways as part of the "FRMCS First Edition" and the migration phase from GSM-R to FRMCS.

1.2.3 Industry standards and protocols

Industry standards

In 3GPP documents, the term V2X collectively refers to communications among different entities (i) V2V for direct communication between vehicles in close proximity; (ii) V2I for communication between vehicles and a roadside unit (RSU) in radio range, which can be implemented either in an eNodeB or in a standalone device (e.g., a traffic light); (iii) Vehicle-to-Pedestrian (V2P) between vehicles and vulnerable road users (e.g., pedestrians, bikers); and (iv) Vehicle-to-Network (V2N) for communications with remote servers and cloud-based services reachable through the cellular infrastructure.

- **IEEE 802.11**: IEEE 802.11, in particular its amendment .11p (ITS-G5 in Europe), has been investigated since nearly two decades as the enabling radio access technology for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. Its main attractive feature was the capability of supporting distributed localised interactions among vehicles even in the absence of a roadside infrastructure. Several worldwide field trials have demonstrated the .11p feasibility of supporting cooperative awareness applications (e.g., emergency brake light, stationary vehicle warning) and truck platooning.
- **3GPP Rel-15 TR 21.915:** As the Release 15 work has matured and drawn close to completion, the group's focus is now shifting on to the first stage of Release 16, often referred to informally as '5G R15Phase 2'. By the end of the year, 83 studies relating to Release 16 plus a further thirteen relating to Rel-17 were in progress, covering topics as diverse as Multimedia Priority Service, Vehicle-to-everything (V2X) application layer services, 5G satellite access, Local Area Network support in 5G, wireless and wireline convergence for 5G, terminal positioning and location, communications in vertical domains and network automation and novel radio techniques. Further studies were launched or progressed on security, codecs and streaming services, LAN interworking, network slicing and the IoT.
- **3GPP Rel-16 TR 21.916:** Release 16 is a major release for the project, not least because it brings our IMT-2020 submission - for an initial full 3GPP 5G system - to its completion (see details below).In addition to that formal process, work has progressed on around 25 Release 16 studies, on a variety of topics: Multimedia Priority Service, Vehicle-to-everything (V2X) application layer services, 5G satellite access, Local Area Network support in 5G, wireless and wireline convergence for 5G, terminal positioning and location, communications in vertical domains and network automation and novel radio techniques. Further items being studied include security, codecs and streaming services, Local Area Network interworking, network slicing and the IoT.
  Technical Reports (the result of the study phase) have also been developed on broadening the applicability of 3GPP technology to non-terrestrial radio access (initially satellites, but airborne base

stations are also to be considered) and to maritime aspects (intra-ship, ship-to-shore and ship-to-ship). Work also progresses on new PMR functionality for LTE, enhancing the railway-oriented services originally developed using GSM radio technology that is now nearing end of life.

1.2.4 Regulatory institutes

3GPP

The 3rd Generation Partnership Project (3GPP) unites seven telecommunications standard development organisations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as "Organisational Partners" and provides their members with a stable environment to produce the Reports and Specifications that define 3GPP technologies. The project covers cellular telecommunications technologies, including radio access, core network and service capabilities, which provide a complete system description for mobile telecommunications. The 3GPP specifications also provide hooks for non-radio access to the core network, and for interworking with non-3GPP networks. Until present, 3GPP is defining standards for 5G through continuous releases, with the most updated one being Release 17. Some areas of generalisation include specific technical requirements and device communications.

FCC (USA)

The Federal Communications Commission is responsible for regulating interstate and international communications through cable, radio and so on, in all 60 states of USA including the District of Columbia and U.S. territories. The main goal of the FCC to expand the use of broadband services and facilities through promoting investment and innovation, supporting the nation's economy through ensuring the advancement of communications revolution, encouraging the highest and best use of spectrum, and provide leadership in strengthening the defense of the nation's communications infrastructure (FCC, n.d.).
With the continuous expansion of the 5G network, the FCC has developed a 5G Fast Plan which acts as a comprehensive strategy towards the adaptation of 5G in the market, updating infrastructure policy and modernising all related regulations. For example, in the spectrum area, the FCC had taken action to make additional spectrum available for 5G services such as auctioning high-band, millimetre-wave spectrum. The commission has also updated several infrastructure policies such as speeding up federal, state and local review of small cells (FCC, n.d.) (FCC, n.d.).

ACMA (Australia)

The Australian Communications and Media Authority is a government authority body which is responsible in the communications spectrum. The authority is independently operated with the goal to ensure Australia's media and communications legislation, related regulations, and numerous derived standards and codes of practice operate in an efficient and effective manner towards the public (Australian Communications and Media Authority, n.d.).

As the 5G technology is still at the rollout stage for Australia, ACMA is closely monitoring this latest generation of mobile technology. The main role of the ACMA is to make sure telcos, the companies responsible for installing transmitters, follow the rules set by the ACMA on how to install and the about of EME (electromagnetic energy) that can be emitted. It is also important to note that the rules and limitations are set by ARPANSA, which is the Australian Government's expert agency on health matters related to EME. Some of the factors that ACMA focuses on are displayed below (Australian Communications and Media Authority, n.d.):

- Checking the EME levels of mobile phone towers, broadcast towers and small cells, and ensure the levels are blow maximum public exposure levels set up within the ARPANSA's Radiation protection Standard
- Telcos provide accurate records once a site is in operation. (For inspections and audits purposes)

ARPANSA (Australia)

As mentioned above, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) is a regulatory agency under the national Commonwealth government of Australia which aims to protect the Australian citizens from ionising and non-ionising radiation. In a general sense, the agency regulates all entities that use or produce radiation with the goal in mind to protect the people and the environment from harmful effects of radiation released by technology, which in this case, would be from the EME released via 5G. (ARPANSA, n.d.) (ARPANSA, n.d.)

Regarding to the subject of 5G, the ARPANSA safety standard sets limits for exposure to RF EME. It is important to note that the numbers are set well below levels that may cause harm to people. With the assistance from international organisations such as World Health Organisation (WHO) and the International Commission on Non-Ionising Radiation (ICNIRP), AEPANSA is able to publish safety standards with established the safety towards any adverse health effects from the exposure of low RF EME towards populations or individuals. In the near future, ARPANSA has announced their continuous review and research on 5G to provide updated advice towards the Australians(ARPANSA, n.d.) (ARPANSA, n.d.).

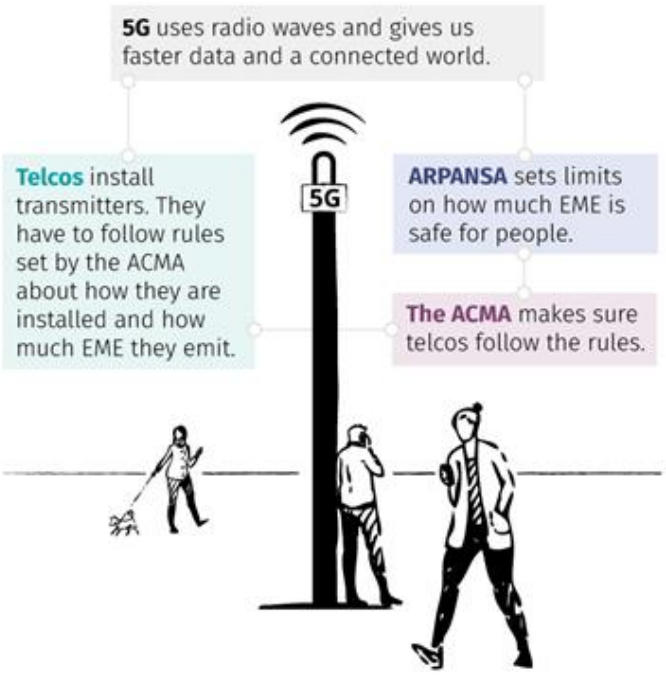

Figure 22: 5G Institutions

1.2.5 Key players / market leaders

GSMA

The GSMA is a global organisation unifying the mobile ecosystem to discover, develop and deliver innovation foundational to positive business environments and societal change. Our vision is to unlock the full power of connectivity so that people, industry, and society thrive. Representing mobile operators and organisations across the mobile ecosystem and adjacent industries, the GSMA delivers for its members across three broad pillars: Industry Services and Solutions, Connectivity for Good, and Outreach.

Samsung

- Samsung is one of the leading research leaders in 5G technology. In 2013, Samsung successfully developed the world's first adaptive array transceiver technology operating in millimetre-wave Ka bands for cellular communications. This invention went on to become the core of the 5G mobile

communication and allow for data transmission several hundred times faster than that of 4G network.

- In February 2017, Samsung and Charter Communications, Inc announced a collaboration on 5G and 4G LTE wireless networks lab and field trials. The 5G trial evaluated fixed use cases using Samsung's pre-commercial system and devices. The 4G trials were performed at 3.5 GHz (CBRS), utilising Samsung's combined 4G LTE small cell technology in an outdoor environment to evaluate mobile use cases.
- In February 2019, Samsung completed the development of mmWave Radio Frequency Integrated Circuits (RFICs) and Digital/Analog Front End (DAFE) ASICS. The new RF chipsets has reduced size, weight, and power consumption. Samsung has shipped over 36,000 5G base stations as of February 2019 (Samsung, n.d.).

Huawei

- Huawei had invested a lot of money into research on 5G wireless network and patenting key technologies. The company aims to divide the technical standards for the next-generation wireless communication technology.
- Differ from any other companies, Huawei aims to involve AI in 5G as an integral element. The company also aims to release an array of Huawei commercial equipment including wireless access networks, core networks and devices.
- In February 2019, Huawei partnered with China Mobile's Shanghai unit and launched the 5G Digital Indoor System in the city's Hongqiao Railway Station. The system allows all passengers to have access towards 5G network.
- In May 2020, Huawei announced that the company had built over 200,000 5G base stations in its home countries and also planned to have a total of 800,000 to be placed in 340 different cities at the end of the year (HUAWEI, n.d.).

LG

- LG, operating as a Korean company, has been researching 5G for some time and built up its reputation by publishing various 5G related reports. Similar to that of the companies mentioned above, LG deployed both the 5G network and products that utilises the 5G network.
- In October 2019, the company announced the successful development of a communication module for automotive based on a 5G Qualcomm chip. It is the first company to develop a communication module that can be applied to a vehicle. The module offers exciting new functions such as sharing real-time traffic information, precise location measurement, V2X communication, and transmission of larger amounts of data.
- In December 2020, LG worked in conjunction with Hanyang University's automotive electronic control lab, and ControlWorks to demonstrate the world's first 5G-based self-parking in an online conference. This event marked the first time 5G-based autonomous driving and parking has been demonstrated on roads in an uncontrolled environment (Pai, 2021).

Ericsson

- Ericsson has been continuously working on all continents to make 5G a global standard for the next generation of wireless technology. The company's 5G radio prototypes are the first products which allowed operators to conduct live field trials in their own networks, thus leading to a better understanding towards potential of 5G.
- In February 2018, the company conducted a 5G trial with Korea Telecom with Intel by connecting a car to live 5G network in the centre of Seoul. In the dense urban environment, 4K video was streamed to and from the car.
- In October 2018, Telstra Australia announced Ericsson as its key 5G partner under agreement with the aim to deliver the next generation of mobile technology in Australia (Ericsson, n.d.).

- The company announced the achievement of 4.3Gps - the fastest 5G speed to date in February 2020 within Ericsson's lab in Kista, Stockholm. The landmark was achieved during interoperability testing using commercial solutions.
- Until May 2020, Ericsson had secured 91 commercial 5G agreements with unique communication service providers. The company believes standardisation of 5G is the cornerstone for digitisation of industries and broadband. As per Bird & Bird analysis, Ericsson is currently leading with most standard patents with a share of 15.8% of all 5G standard patents.

Qualcomm

- Unlike other companies that were previously mentioned, Qualcomm is known as a leading 5G chip maker and focuses more on building products (Qualcomm, n.d.).
- After 3GPP released the 5G standards in 2016, Qualcomm began working on the next wave of 5G NR technologies that would pave the way to the subsequent 5G NR standard releases.
- In February 2019, Qualcomm announced the second-generation Qualcomm Connected Car Reference Design in order to facilitate the next generation connected vehicles. The design features a highly advanced suite of connectivity technologies, precise positioning technology and integrated processing.
- Until 2020, Qualcomm had collaborated with 18 telecoms and 20 manufacturers to publish 5G-enabled products beyond mobile phones.

Nokia

- Nokia is working continuously in developing, researching and partnering with other companies to further enhance the state of 5G communication. The main project of Nokia involves implementing the Future X network architecture for 5G to deliver robust network coverage while reducing cost (Nokia, n.d.).
- Nokia had been offering several services which were designed to help operators with the major undertaking of moving to 5G in the 5G World 2018. The services include Nokia 5G Digital Design, which uses AI to simulate 5G use cases.
- In Mobile World Congress 2019, Nikia has introduced a new FastMile 5G Gateway which allows the user who wishes to upgrade their LTE network to capture new Fixed Wireless Access revenue and therefore, accelerate the 5G rollouts.
- In February 2020, Nokia announced that they are the first vendor to launch new end-to-end slicing network functionality for 4G and 5G New Radio. The function will support connectivity from 4G and 5G devices over sliced networks to applications running in private and public clouds.

ZTE Corporation

- While ZTE is mainly known as the leader in the 4G LTE department, the company has also maintained its position in the 5G research and tests. It is important to note that ZTE was the first company to propose its Pre5G concept and series solution to battle out the various bottlenecks introduced by 4G (ZTE, n.d.).
- In June 2016, at the Mobile World Congress, ZTE officially released the Pre5GL Building the Bridge to 5G whitepaper. The company is the first vendor to propose Pre5G technology as mentioned before.
- ZTE Corporation announced its participation in the second phase of China's 5G test as well as breakthroughs in a number of technical solution verifications. The project's research and development (R&D) can be divided into three phases: key technology verification, technical solution verification, and system verification.
- In August 2019, ZTE was awarded the Best 5G Solution Award which recognises the company's effort to introduce 5G in the early stages and commitment in establishing cooperation in developing 5G technologies with different operators in Indonesia.
- Until February 2020, ZTE has secured a total of 46 5G commercial contracts around the world covering China, Europe and Asia - Pacific.

NEC Corporation

- NEC Corporation is a Japan company that plans to collaboratively create new business models and services that connect information from different industries and companies by utilising advanced information and communications technologies with 5G acting as the backbone (NEC, n.d.).
- In 2017, along with other telecom companies, NEC Corporation made a statement that the completion of the first 5G NR standard has set the stage for the global mobile industry to start full-scale development of 5G NR.
- NEC also announced the provision of a facial recognition demo system which utilises Multi-access Edge Computing, a network architecture concept for next-generation communications.
- The company had been continuously supplying radio units (RU) for 5G base station equipment to the Japanese operators.

Verizon

- Verizon is a US telecom company that positioned itself at the forefront of 5G technology as they provide modern infrastructure all over the country (Verizon, n.d.).
- In February 2018, the company was able to complete a call on 5G NR network while working in collaboration with Nokia and Qualcomm. Similarly, in April 2018, the company was able to complete its first pre-commercial video call using Samsung 5G tablets.
- Verizon states the company has many plans for 5G technology, with the biggest goal in mind to be the first ever company to provide 5G service in the US.
- In partnership with Motorola, Samsung Electronics America, and Qualcomm Technologies completed the world's first 5G data transmission on a smartphone on a commercial 3GPP 5G New Radio (NR) network.
- In January 2020, Verizon partnered with HERE Technology to develop a connected service that utilises Verizon's 5G network infrastructure. The project aims to finalise two proofs of concept which are targeting collision avoidance for pedestrian safety, and Visual Positioning Service for better location identification and navigation.

Orange

- Orange is a French mobile network operator that claims to be a genuine multi-service network designed to adapt to a whole host of smart devices. The company is engaged in a 5G co-construction from transportation to manufacturing (Orange, n.d.).
- Orange has been chosen by UTAC CERAM, world leader in testing and certifying vehicles as its 5G connectivity partner.
- In late 2018, the company partnered with Nokia and Katherin for designing an antenna for managing 4G/5G connectivity. Orange also announced its aim to launch 5G technology in 17 major European cities during 2019.
- Orange and NTT also signed a strategic research and development framework agreement in 2019 with the main goal to share research on internet of things, smart cities, cloud services, etc.

AT&T

- AT&T claimed to be the first company to provide 5G services in the US (AT&T, n.d.).
- One of AT&T's in-house projects built at the lab is the Advanced 5G NR Testbed System, which is a first-of-its-kind 5G testbed system.
- In February 2019, AT&T launched the 5G Innovation program which helps create and develop new customer experiences with the power of 5G. The company aims to utilise the program to jumpstart work with app developers and network vendors to bring 5G ideas to life.
- In April 2020, AT&T announced that it delivered speed gains across 51 markets in early 2020.

Cisco Systems

- Cisco Systems is a US networking hardware company that supports 5G automation, infrastructure and services. The company plans to connect more than 30 billion devices to 5G in the next three years (Cisco, n.d.).

- Cisco recently introduced a 5G security architecture which utilises AI with deep learning to create a network. This approach had lowered the time to detection on optimal network efficiencies from 100 days to just four hours.
- In February 2020, Cisco announced advancements to its IoT portfolio which enable service provider partners to offer optimised management of cellular IoT environments and new 5G use cases.

1.2.6 Existing vendors / product – case studies

Overground trains

- Virgin Trains has been testing out 5G-powered Wi-Fi on its trains. The company believes it is the first railway company to trial the new tech. The trial happened on services between London Euston and Birmingham New Street, and between London Euston and Manchester Piccadilly (Brittain, 2021).
- However, Virgin Trains hasn't yet said if and when it plans to offer 5G-powered Wi-Fi on board its trains.
- The Vodafone 5G network was used to provide the 5G service - the red network has installed 5G in key transport locations including Birmingham New Street station.
- Virgin says the speeds seen were up to ten times faster than current on-board Wi-Fi.

Keolis trials 5G-connected, remotely monitored autonomous electric minibus

- On 28 October 2021, Keolis and its partners – Ericsson, Telia, Urban ICT Arena, Intel and T-engineering – tested a 5G-connected, remotely monitored autonomous electric minibus at Kista Science Centre in Stockholm. The bus is supported by an internal artificial intelligence (AI) system that detects passengers' wellbeing and behaviour (Intelligent Transport, 2021).
- This demonstration explores how real-time data from inside the autonomous vehicle can be transmitted to the centralised supervision (traffic) tower and how, in return, the vehicle responds to its commands with the support of an AI system and extremely high 5G network data speeds. The data, collected by cameras, includes counting passengers and tracking items left behind on the bus. These lost items are signalled to passengers using outboard microphones. The system also detects 'abnormal' passenger behaviour and informs the supervision tower if someone is not feeling well. The operator in the supervision tower can then take immediate action by calling a doctor or an ambulance.

West Midlands pioneers UK's first 5G connected tram

- Tram 35 from West Midlands Metro in England became the first fully-realised 5G enabled tram – part of a trial undertaken by West Midlands Metro (WMM), West Midlands 5G (WM5G), and GoMedia (Intelligent Transport, 2021).
- Transport Accessibility looks to solve the problem of a lack of real-time information for those who need more help when travelling on the UK public transport network.
- The focus of the trial is to increase the number of independent journeys the visually impaired can make whilst travelling across the public transport network. Developed in collaboration with the Royal National Institute of the Blind (RNIB), it will provide timely and accurate information to passengers who need additional assistance while in a station or on the transport network.
- With the UK's first 5G-connected tram, 5G's increased bandwidth allows for high-definition CCTV footage captured on the tram to be securely and remotely transferred to the Regional Traffic Control Centre while in operation. The on-board connectivity would also allow passengers to enjoy live travel updates (WM5G, n.d.).
- Mobile device which has live passenger information service and when the passengers walk to the platform, the device will tell the passengers what platform they are on, what tram is going to arrive at what platform. It aims to help a particular group of passengers who need extra assistance.

- John Worsfold, Innovation and Technology Implementation Manager at RNIB, added: “Technology has and continues to open up the world for people with sight loss, and this opportunity has the potential to increase access to relevant information whilst travelling for blind and partially sighted people.
- “We’re delighted to be supporting this initiative in raising the bar of independently accessing information whilst making journeys, and the benefits this will bring for people with sight loss in the West Midlands.”

The Kerbside Parking Availability Trial

- The West Midlands is the first region in the UK to trial the concept of 5G-enabled identification of live kerbside parking availability. With the support of a parking technology provider, a series of trials took place in Sparkhill. The demonstration saw a live HD street scan being captured from a vehicle travelling an agreed section of roadway. The footage was transmitted and processed via 5G networks to confirm parking availability in real-time to the app. By unlocking real-time availability parking data to drivers journey times, the flow of traffic and emissions levels can be improved. This aims to reduce congestion, improve air quality within urban environments, and make it more accessible for visitors to access our city centres and local highstreets (Mehmet, 2020).

Keolis launches 5G electric CAV trial in Stockholm

- The trial explores how 5G-connected vehicles, which are monitored by a control tower remotely, can facilitate the safe introduction of self-driving electric buses in more complex and demanding urban areas.
- Keolis, in partnership with Urban ICT Arena, Telia, Ericsson Intel and T-engineering, has launched a new autonomous self-driving, electric minibus trial in Stockholm, Sweden, using 5G technology to remotely control and supervise the vehicle.
- The trial aims to explore the safe introduction of self-driving autonomous electric vehicles in complex urban areas with a view to optimising route planning and traffic. The trial is being conducted in Royal Djurgården, one of Sweden’s most popular tourist destinations, from 24 September to 8 October 2020. The autonomous minibus will drive along a 1.6km route, serving the National Museum of Science and Technology, the Maritime Museum, the Nordic Museum and Vasa Museum.
- Keolis has been trialling public-facing autonomous vehicles since launching a pilot in Lyon, France in 2016. Since then, it has operated autonomous vehicles in Australia, Belgium, Canada, the USA and the UK, carrying 200,000 passengers and covering over 100,000km.
- The pilot project at Djurgården explores how a system with 5G-connected vehicles, which are monitored by a control tower remotely, can facilitate the safe introduction of self-driving electric buses in more complex and demanding urban areas. Benefits of such a system include improved route planning and traffic flows, reduced operational costs and pollution and a more reliable, accessible form of public transport for passengers.
- The unique technical features of the 5G network, including extremely high data speeds combined with low latency, mean that the connected buses can respond in real time to commands from the centralised control tower. This is a prerequisite for the safe remote control of vehicles and an important step in moving the driver from the bus into the control tower.
- Telia is providing 5G connectivity in collaboration with Ericsson. Intel is delivering processing power to both the IT system in the vehicles and the control tower, as well as the mobile network. The vehicle, which is equipped with self-driving technology, is provided by the Swedish technology firm T-engineering. It features seven seats and will drive at a maximum speed of 18km/h. Services will feature a safety driver in the vehicle at all times (Intelligent Transport, 2020).

City of Ingolstadt enters 5G technology partnership with Audi and Telekom

- One possible 5G application is connected traffic signals at road junctions that exchange anonymised movement data with cars and other road users via the 5G network. This will enable drivers or cars themselves to react more quickly to unforeseen movements. Mobile 5G devices of pedestrians and

cyclists can also be integrated into real-time communication between infrastructure and cars, so that all road users can be connected as comprehensively as possible.

- New technologies such as 5G can also reduce the time spent searching for parking spaces, which is a significant proportion of increased traffic volumes in cities. Free parking spaces will be communicated to drivers in real time so that they can navigate directly to them (Intelligent Transport, 2019).

China pilots first 5G smart bus route in Guangzhou

- Guangzhou, capital of South China's Guangdong Province, has launched the country's first pilot BRT route that fully adopts a 5G intelligent coordination system. The Guangzhou Municipal Transportation Bureau on Monday said this can effectively streamline the city's public transportation scheduling and save the route's transport capacity by up to 10 percent.
- The new 5G application enables video monitoring of the inside and outside environment of the moving vehicle, as well as the buses' and drivers' performance, and issue early warnings if a dangerous situation occurs, ensuring the safety of the trip in real-time, the statement said.
- Information on the B27 bus route is also transmitted to city public transportation guiding app "Xingxuntong," allowing passengers to learn the location of the closest bus and how crowded it is.
- "The app displays different emojis which read 'not so crowded' or 'seat vacancy available' and so on," a Guangzhou resident surnamed Huang, who is a frequent passenger on the B27 route, told the Global Times. She also found it quite useful knowing if there were seats on the coming buses to make her trip more comfortable (Huaxia, 2020).

QCraft launches China-first 5G ride-hailing Robobus on open streets

- China’s autonomous driving solutions developer QCraft has recently started the normal operation of three bus routes using its 5G autonomous Robobus that are open to the public in the CBD area of Wuxi City.
- As an emerging public transportation model, manual ride-hailing buses have been tested in several Chinese cities and received positive feedback. The company was permitted to operate the said buses on three microcirculation routes totaling 15 kilometers. The routes cover multiple complex urban scenarios such as office areas, residential areas, schools, and shopping centers, connecting bus and subway hubs. Users can call for the bus by typing in their destinations via a mobile application (Gabriella, 2021).

China's Shenzhen pilots 5G communication of subway trains

- China's southern tech hub Shenzhen on Monday piloted the use of the 5G wireless network to transmit a huge volume of data from the subway train to the station. "In times of emergency, the 5G train-station communication will work with facial recognition and intelligent behavior analysis to locate dangerous people and behaviors in the train," said Ren Bo, a manager with Shenzhen Metro's communication center."In the future, the technology will also help realise functions such as alerts for lost luggage and searching for missing passengers," Ren said (Xinhua, 2021).
- Using technology developed by the Chinese tech giant Huawei, the network enables real-time transmission of data from the trains to the stations and rail yards so that information about passenger flows and the condition of the trains, tunnels, and electric wires can be better monitored (China Plus, 2019).
- For example, thanks to the ultra-high capacity of the 5G network, the large amount video produced by the high-definition surveillance cameras throughout the trains can be transmitted to control centres where it can be used to provide information about emergencies.

1.2.7 Future Roadmap

With the current advancement of 5G network and ever-expanding functions of 5G based on Release, many countries have started to plan for real-time action on 5G, deciding on how to deploy private 5G alongside their current 4G options in order to build networks that can quickly respond to the need of the mass. The current 5G communities, with many R&D, standardisation, academia, etc. around the globe, are aiming to fulfill the demands with a broad set of new technologies and capabilities being developed. (IEEE, n.d.) (IEEE, n.d.)

Release 17 and Standardisation

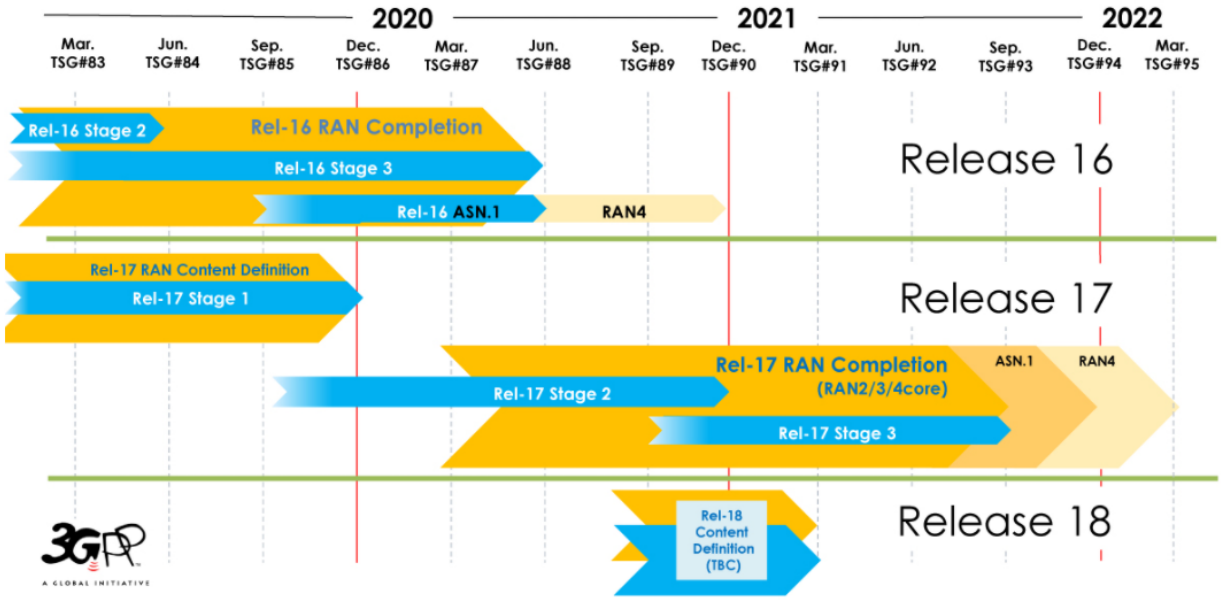

Figure 23: 5G Release Schedule

Since the 3GPP standardised Release 16 was completed in July 2020, the impact of 5G has taken a giant leap towards Industrial Internet of Things industry such as transport. Release 17, currently being standardised, builds on many preliminary aspects offered by the previous build such as reliability enhancement, multi-user MIMO, power savings and private networks. The headline features of Release 17 include ultra-reliable low latency communications (URLLC) for Industrial IoT, NR sidelink, integrated access and backhaul, network slicing for NR and many more.

However, it is important to note that due to the effect of the pandemic limiting in-person meetings of 3Gpp, the progress towards RAN1 physical layer specifications release have been delayed, a positive progress have been recorded by December 2021. The next update will be followed by the Stage 3 freeze by March 2022 and the ASN.1 freeze, and the performance specifications completion by September 2022 (Keenan, 2021) (Keenan, 2021).

The standardisation methodology offered by3GPP will ensure that the key functionality of 5G is delivered to expectations, while also ensuring that the present issues such as compatibility, configurability, and energy efficiency can be easily mitigated.

Emerging Technologies

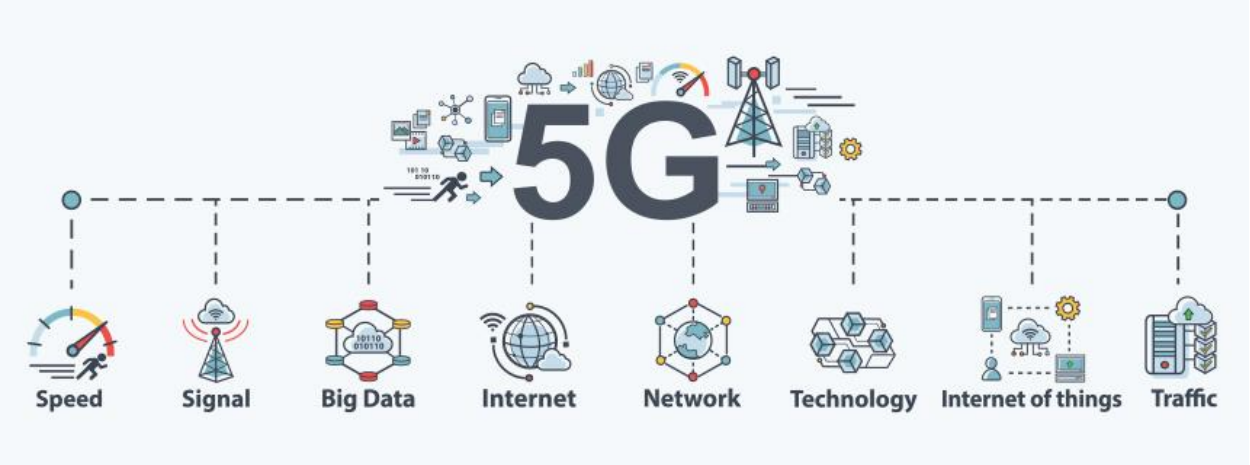

Figure 24 Emerging Technologies

With the advancement of new technologies, there are variety areas of technology that are becoming mainstream and will enable the next generation of applications with the help of 5G. New functions are guaranteed to arrive with the new releases and there are constantly some new applications that can be applied to these technologies (IEEE, n.d.).

- Robotics and drones: The adaptation of 5G towards robotics will heavily focus on drones and unmanned aerial vehicles (UAVs). UAVs will have the capability to deliver products and perform surveillance. The current ecosystem is exploring options to enable complex flight operations with the help of 4G. 5G enhancement will furtherly enable UAV deployments.
- Virtual / Augmented Reality: With the high bandwidth and minimised latency offered by 5G, a new set of end-user devices enabled with virtual realities are becoming more popular with real-world simulations.
- Artificial Intelligence (AI): With the capabilities of 5G to communicate large amount of data, advances in deep learning have led to complex algorithms being applied in everyday applications. AI plays a major role in autonomous vehicles, robotics and automation etc. In the near future, AI will also allow for self-optimising networks (SON) which requires 5G networks to respond to common traffic issues such as congestions.

Challenges

A challenge that will surely impose the advancement of 5G is the necessary capital investments. While 5G is created as the replacement of 4G, it cannot be powered using 4G-LTE mechanics and will require a complete overhaul of the existing base stations into smaller towers, and replacement of the networks of fibre optic cables that connects them (Poliakine, 2021).

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1.3 Biometrics

1.3.1 Introduction

Biometric - Facial recognition

Facial recognition is a technology that compares a human face feature to a photo or a video from the system to verify a person's identity. Different situations can lead facial recognition has different accuracies. When clear, static images (like passport photo) is used to match people face, the accuracy is very high that can be up to 99.97%. On the other side, the error rate can up to 9.3% when photos are captured in public. Facial recognition system is used widely nowadays, however, it can raise privacy issues. It is necessary to develop policies to protect people's privacy from facial recognition (Symanovich,2021).

Facial recognition technology has improved rapidly over the past several years. In ideal conditions, facial recognition systems have extremely high accuracy. As of December 2020, the best face identification algorithm has an error rate of just 0.1 percent. This degree of accuracy requires consistency in the images' lighting and positioning and ensuring that the facial features of the subjects are clearly visible and not obscured (Patrick Grother, 2019).

Biometric – Fingerprint

The fingerprint recognition is the oldest and the most well–known biometric authentication approach. It is digitised, automated version of the ancient ink-and-paper system used for identification by law enforcement agencies. It is based on the recognition of individual's fingerprint, by analysing its characteristics. Fingerprints are distinguishable and immovable for every individual and their basic properties never change with time. Even the fingerprints of identical twins are distinct. Also, the fingerprints on both the fingers of the same individual are different. A fingerprint is made up of ridges and furrows. The patterns of ridges, furrows and the minutiae points on the finger are used to determine the uniqueness of a fingerprint. The loops, whorls and arches are the three basis categories of ridge patterns. The pattern comparison of ridges, furrows and minutiae points are involved in the fingerprint biometrics. The two fundamental principles immutability (ridge patterns never change during the life time) and uniqueness (distinct ridge patterns on different fingers of the same individual) are used in identification of individual's fingerprint (T.Sabhanayagam, 2018).

Biometric - Voice recognition

Today, the voice recognition biometrics is most significant research area. Voice biometrics also known as speaker recognition biometrics. Human voice features are distinct for every individual as well as for twins also and voice could be replicated perfectly. For every individual, unique voice patterns are produced by the combination of physical and behavioural factors. The vocal tract, lips, nasal cavity and shape and size of mouth are the physical characteristics and the pronunciation, emphasis, speed of speech, accents are the behavioural characteristics.

The various factors such as ambient noise, variation of speaker as well as in the tone of the same speaker, sensitiveness of phonetic input systems, distance and regular variations are used to analyse the performance of speech recognition system. The voice recognition systems are used in healthcare, government offices, banking, entertainment applications, PIN smart cards, access control, customer authentication and other security purposes (T.Sabhanayagam, 2018).

Biometric - Vein recognition

The vein recognition system is one of the recent biometric technologies. The main focus of the vein recognition systems is the veins in the user's hands. The vein recognition systems attract the researchers since it has variety of functions which other biometrics technologies do not have. The level of security is high. The

veins are blood vessels that carry blood to the heart. These vein patterns are unique for every individual. The vein patterns are unique for the twins and even each individual's left and right hand is distinct. The accuracy of the vein recognition systems is very impressive. The veins are highly stable, robust and developed before birth. The hand Vein patterns are still in the developing stage of research. The vein biometric system suffers from some disadvantages like invasive, not affordable to all and it is still being tested and reliability is yet to be proved (T.Sabhanayagam, 2018).

1.3.2 Technical features

Biometric factors are defined by seven characteristics: universality, uniqueness, permanence, collectability, performance, acceptability, and circumvention.

Table 6. Technical features of biometric

Technical features	Explanation	Example
Universality	Universality stipulates that we should be able to find our chosen biometric characteristic in the majority of people we expect to enrol in the system.	For instance, although we might be able to use a scar as an identifier, we cannot guarantee that everyone will have a scar. Even if we choose a very common characteristic, such as a fingerprint, we should take into account that some people may not have an index finger on their right hand and be prepared to compensate for this.
Uniqueness	Uniqueness is a measure of how unique a particular characteristic is among individuals.	For example, if we choose to use height or weight as a biometric identifier, we would stand a very good chance of finding several people in any given group who are of the same height or weight. We can select characteristics with a higher degree of uniqueness, such as DNA, or iris patterns, but there is always a possibility of duplication, whether intentional or otherwise.
Permanence	Permanence tests show how well a particular characteristic resists change over time and with advancing age.	If we choose a factor that can easily vary, such as height, weight, or hand geometry, we will eventually find ourselves in the position of not being able to authenticate a legitimate user. We can instead use factors such as fingerprints that, although they can be altered, are unlikely to be altered without deliberate action.
Collectability	Collectability measures how easy it is to acquire a characteristic with which we can later authenticate a user.	Most commonly used biometrics, such as fingerprints, are relatively easy to acquire. If we choose a characteristic that is more difficult to acquire, such as a footprint, the user will need to remove his shoe and sock in order to enrol (and to authenticate again later), which is considerably more troublesome than taking a fingerprint. These can change over time. Today there are efforts to be able to collect iris scans from a distance so the users can be identified while they walk toward the device and they never even have to stop.
Performance	Performance is a set of metrics that judge how well a given system functions. Such factors include speed, accuracy, and error rate. Performance metrics include False Match Rate (FMR), False Non-Match Rate (FNMR), Equal Error Rate (EER), False Acceptance Rate (FAR), False Rejection Rate (FRR), True Acceptance Rate, Weighted Error Rate, Template Capacity and Matching Speed.	for example: typically, biometric systems are used to allow access to restricted areas only to authorised persons. Suppose there are two people X and Y, Y has access to the system while X has no permission. A false acceptance is obtained when X is recognised as Y (or any other person with permission) at the time of the verification by granting him permission to access reserved areas even if he or she is not entitled to it (THAKKAR, 2021).
Acceptability	Acceptability is a measure of how acceptable the characteristic is to the users of the system.	In general, systems that are slow, difficult to use, or awkward to use are less likely to be acceptable to the user. Systems that require users to remove their clothes, touch devices that have been repeatedly used by others, or provide tissue or bodily fluids will likely not enjoy a high degree of acceptability. Circumvention describes the ease with which a system can be tricked by a falsified biometric identifier. The classic example of a circumvention attack against the fingerprint as a biometric identifier is found in the "gummy finger." Some of the newer generations of biometric systems have features specifically designed

		to defeat such attacks by measuring skin temperature, pulse, pupillary response, and a number of other items.
Circumvention	Circumvention describes the ease with which a system can be tricked by a falsified biometric identifier.	*The classic example of a circumvention attack against the fingerprint as a biometric identifier is found in the "gummy finger." In this type of attack, a fingerprint is lifted from a surface, potentially in a covert fashion, and is used to create a mould with which the attacker can cast a positive image of the fingerprint in gelatine. Some of the newer generations of biometric systems have features specifically designed to defeat such attacks by measuring skin temperature, pulse, pupillary response, and a number of other items (Andress, 2014).*

1.3.3 Industry standards and protocols

ISO/IEC 19794-5 (Information technology — Biometric data interchange formats — Part 5： Face image data)

This defines specifically a standard scheme for codifying data describing human faces within a CBEFF-compliant data structure, for use in facial recognition systems

FIDO industry standard for accuracy.

This includes False Reject Rates (FRR) of less than 5:100, and False Accept Rates (FAR) of less than 1:10,000. Definitions are as follows:

- FRR (%) = (Number of genuine transactions for which decision is reject or FTA happens for all attempts) / (Number of genuine transactions conducted) * 100
- FAR (%) = (Number of zero-effort imposter transactions for which decision is Accept) / (Number of zero-effort imposter transactions conducted) * 100

ISO/IEC 29109—5 (Information technology — Conformance testing methodology for biometric data interchange formats defined in ISO/IEC 19794 — Part 5： Face image data)

- Specifies elements of conformance testing methodology, test assertions, and test procedures as applicable to two-dimensional face images defined in the ISO/IEC 19794-5:2005 biometric data interchange format standard for face image data.

ISO/IEC TR 29794—5: 2010 (Information technology – Biometric sample quality-part 5: Face image data)

- Specifies terms and definitions that are useful in the specification, use and testing of face image quality metrics;
- Defines the purpose, intent, and interpretation of face image quality scores.

ISO/IEC 24779—5 (Information technology-cross-jurisdictional and societal aspects of implementation of biometric technologies-pictograms, icons and symbols for use with biometric system-part 5: Face applications)

- Although the pictograms, icons and symbols are presented individually, the pictograms, icons and symbols are intended to be combined to fully illustrate the facial image capture interaction.
- This set of pictograms, icons and symbols is designed to be used to identify the type of biometric sensor; (IEEE., 2020).

ISO/IEC 39794—5 (Information technology —Extensible biometric data interchange formats — Part 5： Face image data)

- Generic extensible data interchange formats for the representation of face image data
- Application specific requirements, recommendations, and best practices in data acquisition (IEEE., 2019).

ISO/IEC WD 24358 (Face—aware capture subsystem specifications)

- The document will establish requirements and recommendations for face- aware systems, which:
    - Captures images automatically and semiautomatically.
    - Captures (output) images that target application specific quality related requirements
    - Supports the capture of images suitable for human examination adds requirements on real-time capture feedback on image quality

ISO/AWI 37183 (smart community infrastructures-Guidance on smart transportation using face recognition)
IEEE Std2790—2020 (Biometric Liveness Detection)

- This document establishes features and definitions of liveness detection. In addition, this document specifies the liveness detection process, implementation model and metric.

IEEE P2884 (Performance Evaluation of Biometric Information: Facial Recognition)
This standard defines requirements and testing methods for a facial recognition testing system for end-user devices such as mobile phones. It specifies system and security requirements, algorithm testing, testing methods, and criteria level. Key metrics for quantised performance evaluation indexes including false accept rate (FAR), false reject rate (FRR), attack presentation false acceptance (APFAR), and Bona Fide Presentation False Rejection Rate (BFPFRR) are defined (Kim, 2020).

1.3.4 Regulatory institutes

Australian Privacy Principles (APPs)
In Australia, the Australian Privacy Principles (APPs) govern rights and obligations surrounding the collection, use and sharing of personal information. APPs states that “An organisation or agency may only scan your biometric information as a way to identify you or as part of an automated biometric verification system, if the law authorises or requires them to collect it or it’s necessary to prevent a serious threat to the life, health or safety of any individual.” “Under the Privacy Act 1988 (Privacy Act) your biometric information is sensitive information. This means that if the Privacy Act covers the organisation or agency collecting it then they must first ask for your consent, with some exceptions, and also make sure it has a high level of privacy protection. The Privacy Act covers Australian Government agencies and any organisation with an annual turnover of more than $3 million, and some other organisations” (Government, 2021).

The European Commission's (EC) proposed Artificial Intelligence (AI) regulation.
The use of biometric identification techniques is currently governed by the EU General Data Protection Regulation (“GDPR”) and, in the UK, also the Data Protection Act 2018 (“DPA”). The EU General Data Protection Regulation document includes the following key issues related to facial recognition: data protection officer, right of access and personal data. “GDPR defines biometric data as personal data resulting from specific technical processing relating to the physical, physiological or behavioural characteristics of a natural person, which allows or confirms the unique identification of that natural person, such as facial images or fingerprint data”. GDPR states that “use of facial recognition technology requires legal grounds in accordance with GDPR, such as explicit consent, legal obligation or public interest” (Oy, 2021).

Privacy Act 1988.

Under the Privacy Act 1988 (Privacy Act) your biometric information is sensitive information. This means that if the Privacy Act covers the organisation or agency collecting it then they must first ask for your consent, with some exceptions, and also make sure it has a high level of privacy protection. An organisation or agency may only scan your biometric information as a way to identify you or as part of an automated biometric verification system, if the law authorises or requires them to collect it or it's necessary to prevent a serious threat to the life, health or safety of any individual (Government, 2021).

EDPB published 3/2019 Guidelines on processing of personal data through video device (2019):

- The original data needs to be stored separately
- Biometric data, especially isolated fragments of data need to be encrypted and the encryption method needs to be described in encryption and key management policies
- Prohibit external access to biometric data
- Delete the original data in time (Jelinek, 2020).

The Biometric Information Privacy Act pass

It guards against the unlawful collection and storing of biometric information. It states:

- Obtain consent from individuals if the company intends to collect or disclose their personal biometric identifiers.
- Destroy biometric identifiers in a timely manner.
- Securely store biometric identifiers (assembly, 2008).

***Biometrics and the Information Privacy Principles (IPPs*)** states that

- The collection of biometric information should only be done if it is necessary to fulfil an organisation's function.
- Biometric information should only be used or disclosed for the primary purpose for which it was collected (Commissioner, 2019).

Commercial Facial Recognition Privacy Act of 2019

This prohibits entities from collecting, processing, storing, or controlling facial recognition data unless such`entities

- provide documentation that explains the capabilities and limitations of facial-recognition technology
- obtain explicit affirmative consent from end users to use such technology (Sen. Blunt, 2019).

Ethical Use of Facial Recognition Act

It prohibits any officer, employee or contractor of a federal agency from engaging in specified activities. Specifically,

- Prohibits any such individual from setting up a camera to be used in connection with facial recognition technology,
- No federal funds may be used by a state or local government to invest in facial recognition software, purchase facial recognition technology services, or acquire images for use in facial recognition technology systems (Merkley (Sponsor), 2020).

1.3.5 Key players/market leaders

Facial recognition

- **IDEMIA** is a multinational technology company headquartered in Courbevoie, France.
  It provides identity-related security services and sells facial recognition and other biometric identification products and software to private companies and governments. The facial recognition technologies proposed by IDEMIA allow for smooth passage through the airport or stadium entrances and are also used to spot people banned from the stadium, identify fugitives in crowds or check the identity of people entering reserved areas. IDEMIA's Facial Recognition Ranked #1 in NIST's Latest FRVT Test (Wikipedia, 2021).
- **Apple** Inc. is an American multinational technology company that specialises in consumer electronics, computer software and online services. It is the largest information technology company by revenue (totalling $365.8 billion in 2021) and, as of January 2021, it is the world's most valuable company, the fourth-largest PC vendor by unit sales and fourth-largest smartphone manufacturer. It is one of the Big Five American information technology companies, alongside Amazon, Alphabet (Google), Meta (Facebook), and Microsoft (Tillman, 2021).
- **Google** LLC is an American multinational technology company that specialises in Internet-related services and products, which include online advertising technologies, a search engine, cloud computing, software, and hardware.
- **Microsoft**. It has a new evaluation conducted by the National Institute of Standards and Technology, or NIST, verified the progress we've made in developing facial recognition technology that now ranks in the top tier across the IT sector. The algorithms Microsoft submitted to that evaluation were consistently ranked as the most accurate or nearly the most accurate of 127 algorithms tested (Smith, 2018).
- **Amazon**. It is an American multinational technology company which focuses on e-commerce, cloud computing, digital streaming, and artificial intelligence. The company has been referred to as "one of the most influential economic and cultural forces in the world", as well as the world's most valuable brand. Amazon Rekognition is a software that be used for facial recognition. It has been sold and used by a number of United States government agencies, including U.S. Immigration and Customs Enforcement and Orlando, Florida police, as well as private entities (Wikipedia, 2021).
- **Fujitsu**. Fujitsu laboratories, Ltd collaborates with the Carnegie Mellon University School of Computer Science and Fujitsu Laboratories of American Inc to develops the facial recognition technology with "normalisation process" to adjust the face for better resemblance of the frontal image. "With this technology, images of the face taken at various angles, sizes, and positions are rotated, enlarged or reduced, and otherwise adjusted so that the image more closely resembled the frontal image of the face" (Fujitsu Laboratories Limited, 2019).
- **Thales Group**. Thales Group is a French multinational company, it mainly serves five key sectors: aerospace, space, ground transportation, digital and security and defence and security. Thales has already developed the facial recognition system to improve passenger travel experience in 2019 (Group, 2021) (Group, 2020).
- **NEC** Corporation. NEC corporation is the world's leading provider of Facial recognition solutions, and presently develops systems for governments, security organisations and commercial sector operators in 120 countries. Powered by NEC's Digital ID solution, Delta Airlines launched the USA's first fully biometric airport terminal in Atlanta (NEC, 2021). NEC has implemented over 1,000 systems with its fingerprint and face recognition technologies in more than 70 countries and regions in the world. Besides police forces and national government systems, NEC's products and solutions are widely deployed for needs such as corporate building entry/exit management, PC login management, and applications in the entertainment industry.

- **TrueFace**. It was founded in 2014, the California-based company provides services with speed and transparency. Trueface is certified by NIST and with its first submission, it ranked in the top ten in the world for genuine match speed of face templates. The company's partners are industry leaders in retail, Fintech, security and hospitality.
- **Face ++** is a face detection platform that offers computer vision technologies and enables users' applications to read and understand the world better. It allows businesses to easily add deep learning-based image analysis recognition technologies into their applications, with simple and powerful APIs and SDKs. In 2019, the platform raised a whopping amount of US$750 million in a funding round to develop facial recognition.
- **Verifyoo** is an ID verification solution platform that provides secure, password-less access to online users worldwide. Verifyoo is based on non-intrusive biometrics that is hard to forge and can be revoked, unlike fingerprints, facial recognition and other physiological biometrics. It significantly reduces account hijacking by using next-generation 3-factor authentication, utilising the user's device, memory and biometric characteristics.

Fingerprint

According to Competitive Assessment report, ABI Research investigate fingerprint technology and lists the top vendors (in alphabetic order) are Apple, Egis Technology, Fingerprint Cards (FPC), Goodix, IDEX, NEXT Biometrics, Qualcomm, Silead and Synaptics (ABI-research, 2018). As follows:

- Apple. Apple's Touch ID is an embedded fingerprint sensor that will scan, read and recognise fingerprints. It allows user to unlock screen by the fingerprints, authorise Apple Pay payments, authorise App Store purchases, or sign into apps instantly. Touch ID reads fingerprints in 360-degrees of orientation, analyses the subepidermal layers of the skin and categorises each fingerprint into arch, loop or whorl categories. Touch ID is secure, because it stores "mathematical representation" of fingerprints instead of images of fingerprints. The user's fingerprint can't be accessed by the OS on your device or by any applications running on it. It's never stored on Apple servers, it's never backed up to iCloud or anywhere else, and it can't be used to match against other fingerprint databases.
- Egis Technology. It is Lens Type Fingerprint Sensor Technology. When a finger touches the screen, the optical technology under the screen will illuminate the image of the fingerprint's concave and convex patterns (peaks and valleys) for software identification, and use algorithms to learn and memorise fingerprint images.
    - Suitable for full screen mobile phone screen
    - Applicable to online financial payment applications
    - Suitable for middle and high-end mobile phone
    - Egis's products can effortlessly scrutinise a fingerprint to authenticate and verify the identity of the user with the absolute highest degree of confidence. In the current market, this fingerprint touch sensor module has one of the fastest enrolment and authentication processes available. It can even read various fingerprint conditions, such as wet or dry fingerprint (Egis, 2020).
- Fingerprint Card. Fingerprint Cards is a Swedish biometrics company that develops and produces biometric systems. Fingerprint Cards was founded in 1997 by Lennart Carlson. Fingerprint produces the world's No1 capacitive fingerprint touch sensor. Fingerprints offers a complete range of fingerprint biometric technologies that can be used separately or in combination - including sensors, biometric processors, and modules. The competitive advantages offered by Fingerprints are:
    - unique image quality
    - extreme robustness
    - low power consumption (Fingerprints, 2021).

- Goodix. Goodix is the only provider with a full range of fingerprint solutions including IN-DISPLAY FINGERPRINT SENSOR™, Live Finger Detection™, IFS™, covered (glass, ceramic, sapphire) fingerprint sensors, and fingerprint sensor with hard coating (Goodix, 2021).
    - In-Display fingerprint sensor
    - Live finger detection
    - It is the world's first IFS (Invisible fingerprint sensor)
    - Support glass, ceramics, and sapphire covers.

- Qualcomm is an American multinational corporation headquartered in San Diego, California, and incorporated in Delaware. It creates semiconductors, software, and services related to wireless technology. It owns patents critical to the 5G, 4G, CDMA2000, TD-SCDMA and WCDMA mobile communications standards. Qualcomm Technologies' first generation of Qualcomm 3D Sonic Sensors were featured in many flagship smartphones including the Samsung Galaxy S10, Note10, S20, and Note20 series. Flagship smartphones use Qualcomm 3D Sonic Sensors to deliver in-display fingerprint scanning that is fast and reliable — it can identify prints even when your fingers are wet. Qualcomm 3D Sonic Sensor is also ultra-thin, measuring a scant .2mm (Qualcomm, 2021).
- FlexEnable. FlexEnable Ltd is a technology provider that develops flexible organic electronics technologies and OTFT materials. The company launched in 2015 which has developed the world's first 500 dpi flexible fingerprint sensor on plastic. The 0.3mm thick optical sensor allows for small and large area fingerprint scanning, and can also image veins. The ability to capture both the fingerprints and the veins makes this solution unique as it provides two modes of authentication and a mode for liveness detection. The sensor is also suitable for FBI certification. Flexible sensor arrays based on organic electronics are ultra-thin, light and robust. They can be made into different form factors allowing for their integration into devices with various designs. As they are made of plastic, they bring cost advantages to large area manufacturing due to the low temperature process being used and high yield (FlexEnable, 2021).
- NEC Corporation. NEC's fingerprint and palmprint recognition technologies have the longest history among our biometric technologies. The technologies have earned a high reputation as having the world's highest level of performance. With the characteristics of lifelong invariance and uniqueness, the system is used as a rigorous personal identification technology, contributing globally to safety and security (Corporation, 2021).
- Technavio has announced the top six leading vendors in their recent global fingerprint module market report until 2020. The vendors are BioEnable, Crossmatch, Fingerprint Cards (It has been introduced above), Fulcrum Biometrics, HID Global and Suprema. This research report also lists four other prominent vendors that are expected to impact the market during the forecast period (businesswire, 2016).
- BioEnable. BioEnable is headquartered in Pune, India. It works in the fields of advanced electronic identification, automation, and tracking products and services. The company provides technologies for fingerprint recognition, facial recognition, iris recognition, vein recognition, and smart cards. It develops fingerprint recognition-based products and provides biometrics software services. Fingerprint recognition modules are stand-alone devices attached to an optical sensor, mainly used for authentication process of individuals. Some of the products the company offers are FDA01M, Fingerprint Sensor Modules-FIM Series, and FIM10-LV. The company provides software for various applications such as access control, ATM, point-of-sale, network security, workstation security, and bank and financial transactions (businesswire, 2016).
- Crossmatch. Crossmatch provides hardware and software for biometric identity management. It serves various sectors such as BFSI, retail, government, law enforcement, and defence. It is headquartered in Palm Beach Gardens, Florida, US, and has offices worldwide. The key product of this company is TCESC4K TouchChip Swipe Module which is cost-effective and can be used for embedding

fingerprint biometrics to enhance the security of organisations. The module can be used in laptops, door locks, garage door openers, and safes. The processor of the module can store the fingerprint templates of 100 users (businesswire, 2016).

- Fulcrum Biometrics. The company is headquartered in San Antonio, Texas, US. It develops, deploys, and manages biometric identification systems and other biometric devices. The company's products include mobile biometric devices, fingerprint scanners, eye/iris cameras, palm/vein scanners, and live scan devices. It offers solutions such as mobile apps, live scan systems, access control units, PC/network login, time and attendance management, and member management. The key product of this company is Futronic FS51 OEM Module, which attached to an advanced optical system that can capture a high-quality image in 0.1 second. It makes the recognition of fingers that are wet and scarred without any problem. So, the module can be used in any harsh environment (businesswire, 2016).
- HID Global. HID Global is headquartered in Irvine, California, US. The company offers security identity solutions including biometrics, ID badge printing, and visitor management. Its solutions protect against fraud and data breaches by providing strong authentication and network security and identity access management. The company ensures the safety of data by providing digital certificates in the BFSI sector (businesswire, 2016).
- Suprema. Suprema specialises in biometrics technology. Suprema's portfolio of products includes biometric access control systems, time and attendance devices, fingerprint/live scanners, and embedded fingerprint modules. The key product of this company is SFM5000 Series which is certified by FIPS201 that supports authentication of an individual. Also, the module helps in the liveness detection of an individual (businesswire, 2016).

Voice recognition

- **ID R&D** is a biometric technology company on a mission to deliver a new generation of "zero-effort" identity verification and authentication. Their biometrics research focuses on Voice Biometrics using Artificial Intelligence, including
    - Deep Neural Networks and Convolutional Neural Networks
    - New inventions such as our patented p-vector algorithms and optimised x-vector algorithms for feature extraction
    - Anti-spoofing to protect voice and face biometrics from fraud attacks
    - Acoustic Event Detection using Deep Neural Networks and signal processing analysis of sounds to detect and alert on non-speech events of interest
    - ID Voice Verified combines ID R&D's core voice verification biometric engine, IDVoice, with a voice liveness detection, IDLive Voice, to create a high-performance solution for strong authentication, fraud prevention, and anti-spoofing verification (Verified, 2021).

- **Voice Match** was introduced in 2017 with the launch of the Pixel 2 smartphone and as a feature for Google Home smart speakers.
    - It enables the company's Assistant to automatically recognise who's speaking and offer personalised information from that person's Google account.
    - Originally, speakers would say the "Hey Google" wake word command several times and the system would create a voice model profile for each user from those recordings.
    - After you teach the Google Assistant to recognise your voice, a unique voice model is created. This voice model is created on Google's servers and then stored only on the devices where you've turned on Voice Match.

- When someone speaks to your device, your device sends the voice model to Google to process the query and determine if it's you by comparing it against the voice model. Google deletes the voice model and comparison data immediately after processing (KINSELLA, 2020).

- **NEC** technology extracts characteristics inherent in speakers from their voices to identify them. Each person's vocal organs such as his or her mouth, throat, and nose are like musical instruments. Because of differences in their shapes and movements among individuals, unique characteristics arise (Corporation, 2021).

Vein recognition

The palm vein scanner market is dominated by a few globally established players such as Fujitsu Ltd. (Japan), Hitachi, Ltd. (Japan), NEC Corporation (Japan), M2SYS Technology (US), and BioSec Group Ltd. (Hungary). These companies have adopted both organic and inorganic growth strategies such as product launches and developments, partnerships, contracts, agreements, and collaborations to strengthen their position in the market (MarketsAndMarkets, 2020).

1.Fujitsu.

PalmSecure provides a high level of accuracy, is easy to implement and uses - a non-intrusive and contactless reader. This ensures virtually no physiological user restrictions while proving to be extremely hygienic as no contact to the skin is required. As veins are internal and have a wealth of differentiating features, attempts to forge an identity are extremely difficult, thereby enabling a high level of security (Fujitsu, 2021).

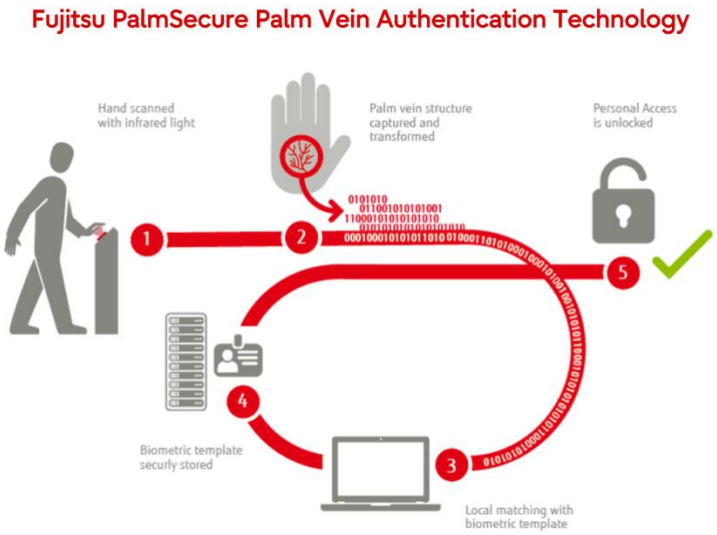

Figure 25 Fujitsu Palm Secure Plan Vein Authentication Technology

2.Hitachi in Oceania

Hitachi's VeinID Biometric Authentication technology is one of the most advanced biometric identification technologies. Hitachi's Finger Vein attesting technology identifies finger vein patterns that exist inside the human body, eliminating tampering while increasing reliability and security and, as everyone's finger vein pattern is individual, it provides an ideal identification method without being intrusive. Near-infrared light is transmitted through the finger and partially absorbed by haemoglobin in the blood, enabling an image of the finger vein pattern to be captured by a sophisticated CMOS-based camera. The captured image is then stored as an encrypted template which is used for matching with future scans. The key features include:

- Finger vein indenticiation offers a fast, convenient and non-invasive method of authentication, while maintaining individual privacy.
- The veins are inside the body, invisible to the eye and not easily accessible. Therefore, finger vein patterns are extremely difficult to acquire, forge and manipulate.
- The use of light transmission to gather biometric data means that the condition of the skin surface generally does not affect accurate processing. It is also contactless hence more hygienic for end users.
- Finger vein patterns are unique even with identical twins and remain constant throughout the adult years.
- Since only a small amount of data is required, one-to-one authentication can be done in less than 1 second.
- Finger vein authentication eliminates potential loss or theft of key cards, password cracking and impersonation (Oceania, 2021).

3.NEC Corporation
This technology identifies users by detecting veins on fingertips and analysing the image features of the veins. As the technology uses vein information inside the user's finger, theft or falsification of information is difficult. NEC's finger vein recognition technology combines finger veins and fingerprints information to authenticate both biometrics simultaneously for PC logins and other applications. Besides achieving more secure identification of the user, the technology also contributes to security measures for government agencies and private enterprises because it is difficult to falsify. NEC's finger vein recognition technology is used in its Hybrid Finger Authentication products (Corporation, 2021).

4.M2SYS Technology. M2SYS Technology is a global biometric identification management company that provides biometric identity management software and hardware along with enterprise software applications to several vertical markets including; public safety, workforce management, point of sale, healthcare, education, child care, transportation security, banking and membership management. They offer Software Development Kits to software vendors that wish to add biometric identification to their applications and solutions directly to end users (Wikipedia, 2021). M2-FINGERVEIN Works by passing near-infrared light through the finger which is partially absorbed by the haemoglobin in the veins allowing an image to be recorded on a CCD camera. Finger vein authentication is extremely robust, demonstrating a unique ability to easily cope with sweaty, dry, or aged fingers (Technology, 2021).

5.BioSec. BioSec is solely specialised in palm vein recognition-based solutions and does not develop on other technologies, thus ensuring the highest level of knowledge. BioSec is primarily specialised in biometric mass authentication plus also non-biometric mass authentication, logical- and physical access control solutions, integration of palm vein recognition into 3rd party solutions, ensuring highly secure, simple to use and convenient solutions in every field of life. BioSec's palm vein recognition-based solutions are perfectly suitable for mass authentication, which is underlined by several references (BioSec, 2021).

1.3.6 Existing vendors/product - case studies

Case studies
1. GUIYANG, July 1 (Xinhua) -- Subway and Bus Rapid Transit (BRT) systems now support payment by face scanning in Guiyang, capital of southwest China's Guizhou Province. To access the service, citizens need to download and register on a mobile application. After ID verification and facial recognition on self-registration terminals, citizens can take subway or BRTs simply by having their faces scanned. According to the city's government, this service is an important trial in the integrated development of the internet, artificial intelligence, transportation, city management, and market transactions (huaxia, 2020).

2. Tokyo, March 25, 2021 - NEC Corporation (NEC; TSE: 6701) today announced the operator of Narita International Airport (NRT), Narita International Airport Corporation (NAA), and the operator of Tokyo International Airport (Haneda Airport, HND), Tokyo International Air Terminal Corporation (TIAT), will commence trial for "Face Express," a new boarding procedure for international departure flights using facial recognition technology, in April 2021, utilising a facial recognition system that belongs to NEC's portfolio of advanced biometric authentication technologies, "Bio-IDiom" (*1), and features the world's most accurate precision (NEC, 2021).

3. Tokyo, December 1, 2020 - NEC Corporation (NEC; TSE: 6701) announced today that Lufthansa Airlines and Swiss International Airlines (SWISS), Lufthansa Group airline members of Star Alliance, launched the “Star Alliance Biometrics" identity verification platform utilising NEC's facial recognition technologies at Frankfurt Airport and Munich Airport. Passengers using this service can pass through security access and boarding gates without contact by registering face images and passport information with mobile apps from each company in advance. This platform features NEC's facial recognition engine, which has been evaluated as the world's most accurate (*2), in order to ensure high-precision certification, even when individuals are wearing masks. With the worldwide spread of COVID-19, NEC aims to contribute to safer and more secure air travel by helping to control the spread of illness by enabling non-contact, mask-worn check in airport boarding procedures (NEC, 2020).

4. IDEMIA equips Avinor Oslo Airport with a new border control solution featuring the latest facial recognition technology. Avinor Oslo Airport is the first in Europe to use IDEMIA’s advanced biometric ABC solution that features walk-through facial recognition technology. This eliminates queues and improves the overall airport experience for both passengers and border agents (IDEMIA, 2021).

5. NEC helps Delta Air Lines to launch first biometric terminal in the U.S. Facial recognition technology is used to

- Check in at the self-service kiosks in the lobby
- Drop checked baggage at the counters in the lobby
- Serve as identification at the TSA checkpoint
- Board a flight at any gate on concourse F
- Go through CBP processing for international travellers arriving into the U.S (writer, 2018) (NEC, 2012).

6. Moscow Metro has started tests of Face Pay – a service where passengers will be able to pay for transport using facial recognition technology. Three Russian-made facial recognition systems from VisionLabs, Ntechlab and Tevian will be used in the initial rollout (Carey, 2021).

7. **T-Money** trials face biometrics for contactless payments to public transportation. The facial recognition payment system, the report explains, can be used by downloading the T-Money mobile application, capturing the user’s biometric selfie using the phone’s camera, and then linking it to the payment appropriate method (Macdonald, 2021).

8. In January 2019, China's Jinhua City tried to pay for the bus fare with face recognition. The bus cloud card requires the user to submit personal identification information and photos for identity authentication, and bind the bank card for balance refilling.

9. A new “fast-track passport control service” that uses face and iris-recognition technologies has been launched at Dubai airports. The biometric system has been deployed at 122 smart gates at arrival and departure terminals which allows the passengers to complete passport control procedures (Future-travel-experience, 2021).

10. In 2018, National Australia Bank and Microsoft have collaborated to design an ATM with a face scan. The cloud-based application is developed using Azure Cognitive Services, it allows the customer to use facial recognition and a pin to withdraw (Barbaschow, 2018).

11. Russia’s X5 group, the country’s leading food retailer, cooperates with the Visa payment system and Russia’s state giant Sberbank launches facial recognition payment system. This service is being used in 150 supermarkets. When the customers want to pay, they just need to look at the camera to pay (AFP (The-Moscow-Times), 2021).

12. In 2016, the Thales, cooperates with the Mastercard to develop a facial recognition system, which allows the cardholder takes a selfie on their smartphone to securely authenticate their identity. So, the customer can use their face to buy things if they forget their card password (The-Thales-Group, 2021).

13. In 2019 Brit Awards used facial recognition technology to enhance its event security, deploying it to screen guests at multiple entrances in London. The system linked to mobile apps, which enabled trained staff members to make secondary face-to-face identity verification checks (The-Thales-Group, 2021).

14. **"Hand Pay Service" is introduced by Korean credit card company Lotte Card Co., Ltd.** A payment system using palm vein authentication called "Hand Pay Service" has been introduced by the major Korean credit card company Lotte Card Co., Ltd. Making full use of the palm vein authentication technology proudly provided by Fujitsu, Lotte Card started the first bio-pay service in Korea on May 2016, which allows Lotte Card customers to make lump-sum credit card payments even when they are not carrying their cards, by just using biometrics and phone numbers to authenticate who they are. The encrypted data are divided and stored in the Bio-Information Distributed Data Management Center of the Korea Financial Telecommunications & Clearing Institute (KFTC) and the system environment of Lotte Card, to strengthen security even further. Moreover, it was Fujitsu Korea that established the system that works with the Biometric Information Distributed Data Management Center of the KFTC to which the Lotte Card "Hand Pay Service" is linked.

15. **AEON Credit Service and Fujitsu begin a trail of using Fujitsu's palm vein biometric authentication technology.** AEON Credit Service and Fujitsu will begin a field trial of a cardless payment system using Fujitsu's palm vein biometric authentication technology. Starting in September 2018, the trial will take place in selected Ministop convenience stores. Customers use this service by registering in advance, then adding their palm vein pattern to their AEON card information. When paying at a register, customers can pay with their registered AEON card by inputting their date of birth and then scanning the palm of their hand over the reader. Customers can use their AEON card with greater convenience, without the bother of taking the card out of their wallet or purse. AEON Credit Service and Fujitsu will be conducting a field trial for AEON Group employees at a number of Ministop locations beginning in September 2018. Based on the results of the field trial, the companies plan to roll out the technology for use in store locations for the various AEON Group companies.16.

16. **Korea Airport Corporation adopted vein authentication for boarding check.** In South Korea, the Korea Airports Corporation (KAC) has deployed palm vein authentication system at all 14 domestic airports under its jurisdiction, to ameliorate congestion by identifying boarding passengers with biometric authentication. Users can register in advance at registration devices installed in airports, linking their palm vein pattern with their citizen ID number, name and phone number. Then, after scanning a barcode on their ticket, users can confirm their identity by holding out their hand at the newly installed identity confirmation gates before security checkpoints. Users will not have to constantly carry their citizen ID cards, and the system will slash waiting times and enable smoother processing at airports. This system began operation on 28 December 2018, and it has been used over 1 million times, with 160,000 individuals who have already registered their palm vein patterns (Shinzaki, 2019).

Existing vendors/product

1. **Alipay** is a technology that introduced by Alibaba Group affiliate, Ant Financial Services Group in China. To authorise payment, the user just needs to simply look at the kiosk and a 3D camera, then their identities will be confirmed.

2. PopID is the first biometric payment system based on facial recognition which is being developed in California. The user needs to register an account and the set-up process is very easy: Sign up with a selfie. The user needs to upload their selfie to the account, and the picture will be translated into a secure digital key and stored in the PopID cloud.

When they want to pay, they can look into the camera of a PopID tablet, and is verified by the system. If the verification process is done, the payment will go through successfully. If the customer wants to tip, they can hold out a peace sign to the screen. The entire process only takes 5 seconds to be finished (ArganoUV, 2021).

3. Face Match is a feature on **Google's** new **Nest Hub Max** that uses a front-facing camera and always-on facial recognition software to help it identify which household member is currently using it. Unlike other devices, it is the first device with always-on face detection which means it doesn't need any trigger to activate facial recognition. If you want to turn off Face Match. There are three ways to turn off Face Match. Google points out that facial data are stored and processed on the Nest Hub Max itself, and the data is used to improve product experience occasionally, but all the facial data will be deleted after the process finishes.

4. FaceAPI is an embed facial recognition into your apps that developed by Microsoft. The features include face detection that perceives facial features and attributes- such as a face mask, glasses, or facial hair in an image, and identification of a person by a match to your private repository or via photo ID. It can detect, identify, and analyse faces in images and videos.

5. DeepFace is a deep learning facial recognition system created by a research group at Facebook. It identifies human faces in digital images. The program employs a nine-layer neural network and was trained on four million images uploaded by Facebook users. The Facebook Research team has stated that the DeepFace method reaches an accuracy of 97.35% ± 0.25% on Labelled Faces in the Wild (LFW) data set where human beings have 97.53%.

6. FindFace technology. The neural network is trained to identify unique facial features so that it can then find similar faces in the database. NtechLab's face detection algorithm works with global facial databases, allowing for a split-second search.

7. VisionLabs Face Recognition Plug-in. The key features are

- real-time face detection and face recognition
- Face recognition events and alerts in XProtect interface

VisionLabs Face Recognition plug-in adds face recognition functionality to Milestone XProtect. It is designed to work in conjunction with VisionLabs LUNA PLATFORM facial recognition system (VisionLabs, 2021).

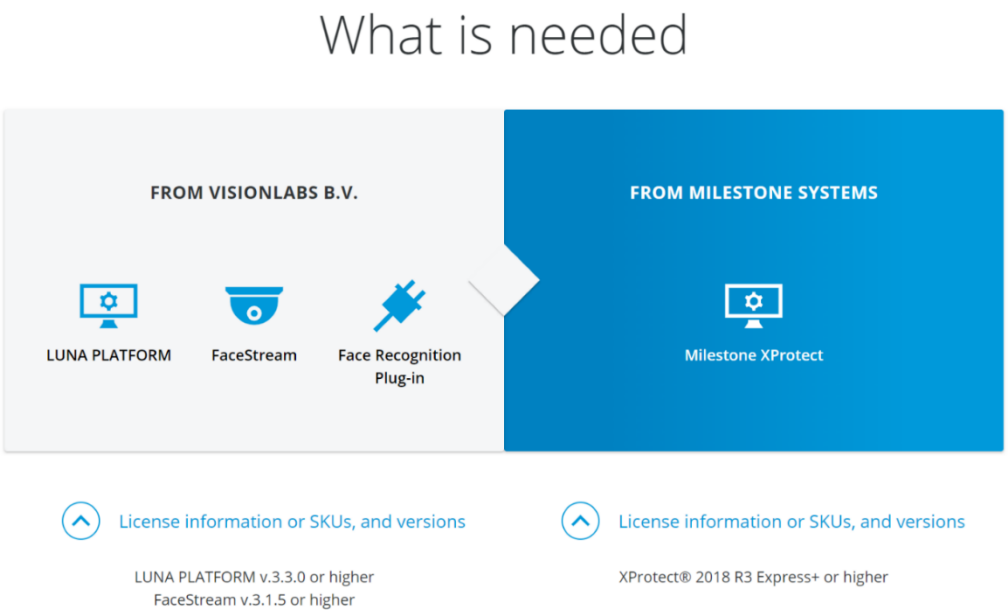

Figure 26 LUNA platform

8. SingPass is one of the world's most advanced national digital identity technology in Singapore. Facial recognition is a feature of SingPass, it enables users to log in to their accounts securely without the need to remember passwords. It can be used at public kiosks, on home computers, tablets and mobile phones (Low, 2020).

1.3.7 Future Roadmap

Biometric authentication and verification are integral to the modern technology landscape.

1. High security and assurance – Biometric identification provides the answers to "something a person has and is" and helps verify identity.
Biometrics provide increased levels of assurance to providers that a person is real by verifying a tangible, real-world trait as both something the user has and something the user is. Most user's passwords and PINs and personal identifying information have likely been compromised with a data breach, meaning, billions of accounts can be accessed by fraudsters who retain the answers to traditional authentication methods. Introducing biometric authentication into the process adds in a road-block for fraudsters that only a real, authorised user can circumnavigate - though a fraudster may know a person uses their dog's name and some lucky numbers for most of their online accounts, they can't use their fingerprint to unlock an account if they can't provide it on the spot. Additionally, biometrics can only be provided by living, breathing people - at this point in time, a robot would have a hard-time passing an iris scan.

2. User Experience – Convenient and fast
While the internal process for biometric authentication is technical, from a user's point of view it's incredibly easy and quick. Placing a finger on a scanner and unlocking an account in seconds is faster than typing out a long password that has multiple special characters. In addition, forgetting a password is a common mistake of most users. The chances of you forgetting your own biometrics? Never!

3. Non-transferrable – Everyone has access to a unique set of biometrics
Biometric authentication requires its input is present upon authorisation. You can't transfer or share a physical biometric digitally – the only way to utilise most biometric authentication systems is with a physical application.

4. Spoof-proof – Biometrics are hard to fake or steal
Biometrics like face patterns, fingerprints, iris scanning, and others are hard to replicate with current technology. There's a one in 64 billion chance that your fingerprint will match up exactly with someone else's. Said a different way, you have a better chance winning the lottery than having the same fingerprint as a hacker trying to get into your account that's secured by biometrics (Mitek, 2021).

How many people are using biometric authentication now?

- By 2024, Mercator forecasts that 66% of smartphone owners will use biometrics for authentication.
- Currently, Mercator estimates that 41% of smartphone owners are using biometrics.
- Just one year ago, in 2019 only 27% of consumers used biometrics to authenticate.
- Although fingerprint readers remain the top option for authentication, an increasing percentage of users are reporting facial and voice recognition.
- Voice recognition increased to 20% of biometric authentication in the last year – up from 11% in 2019.
- Facial recognition jumped to nearly 30% of biometric authentication, up from 11% in 2019.
- Phone brands play a big role in dictating authentication methods, with Android and iPhone owners clearly emerging as more likely to use voice and facial recognition
- Mercator market research indicates biometric use is increasing even as consumers adopt a greater variety of methods choosing among fingerprint, facial recognition, and voice recognition. Biometrics are important because they utilise new mobile security hardware and software to revamp

authentication, lower the risk of fraud, address the mandates of the European Union's revised Payment Services Directive (PSD2), and induce changes in consumer behaviour (Payments Journal, 2020).

Moreover, Spiceworks, a professional network for the information technology industry that is headquartered in Austion, Texas, found that 62 percent of organisations currently use biometric authentication technology, and an additional 24 percent plan to utilise it within the next two years.

The result shows that 46% of the enterprises they surveyed in 2018 were already using biometric authentication on smartphones (with an additional 5% planning to implement it in the next two years) (Poza, 2021).

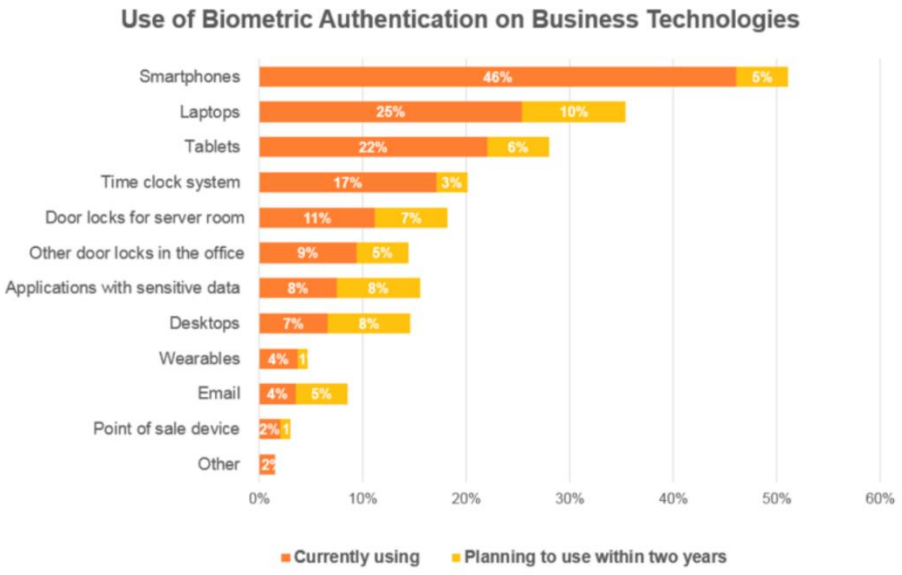

Figure 27 Spiceworks survey in 2018

How many people want to use biometric to verify identity or to make payments – survey by Visa

According to the results from a recent survey commissioned by Visa, consumers are ready to leave the password behind. Among 1,000 Americans surveyed, the findings revealed:

1. More than 65 percent of consumers are already familiar with biometrics.
2. 86 percent of consumers are interested in using biometrics to verify identity or to make payments.
3. 70 percent of consumers believe that biometrics are easier, and 46 percent think they are more secure than using passwords or PINs (Visa, 2021).

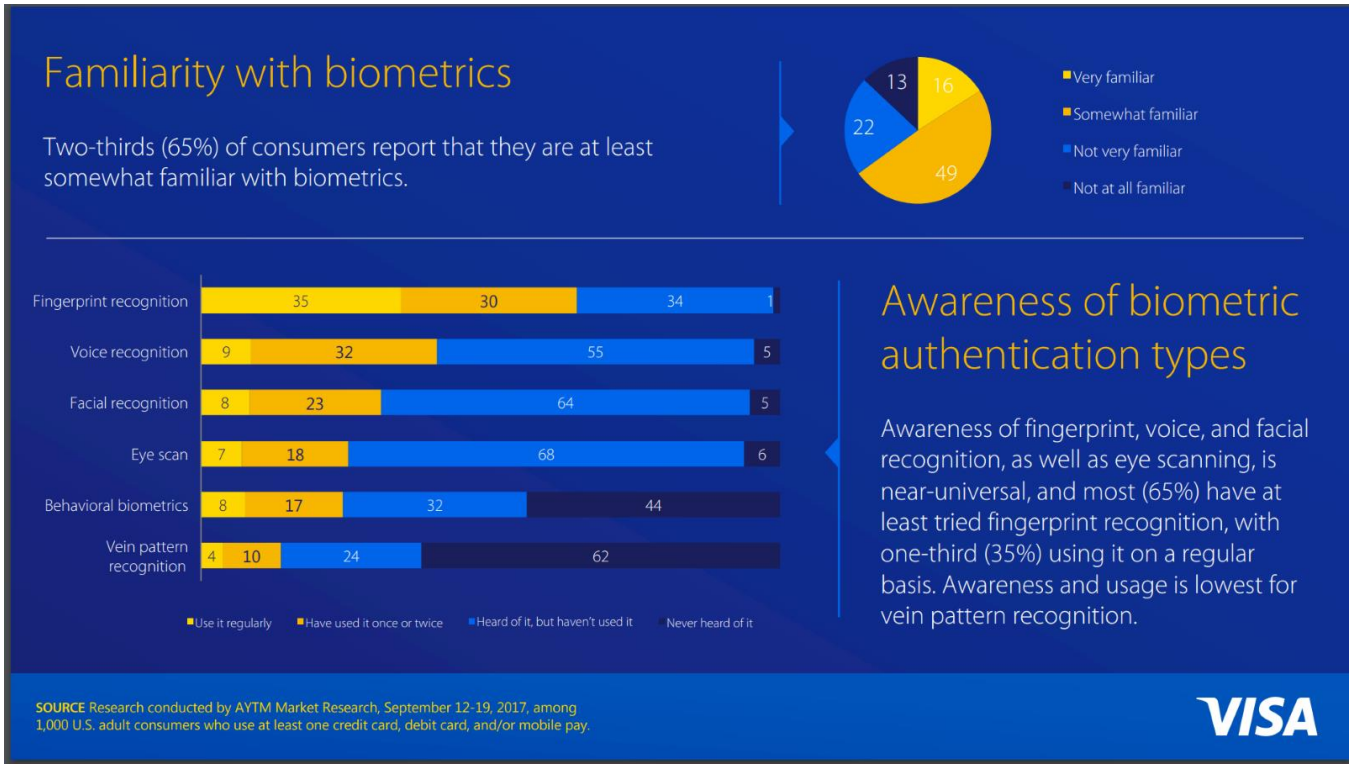

Figure 28 Familiarity with biometrics

From the survey we can see that 35% of consumers are very familiar with fingerprint recognition, 30% of them are somewhat familiar with it. The result shows that two-thirds (65%) of consumers report that they are at least somewhat familiar with biometrics.

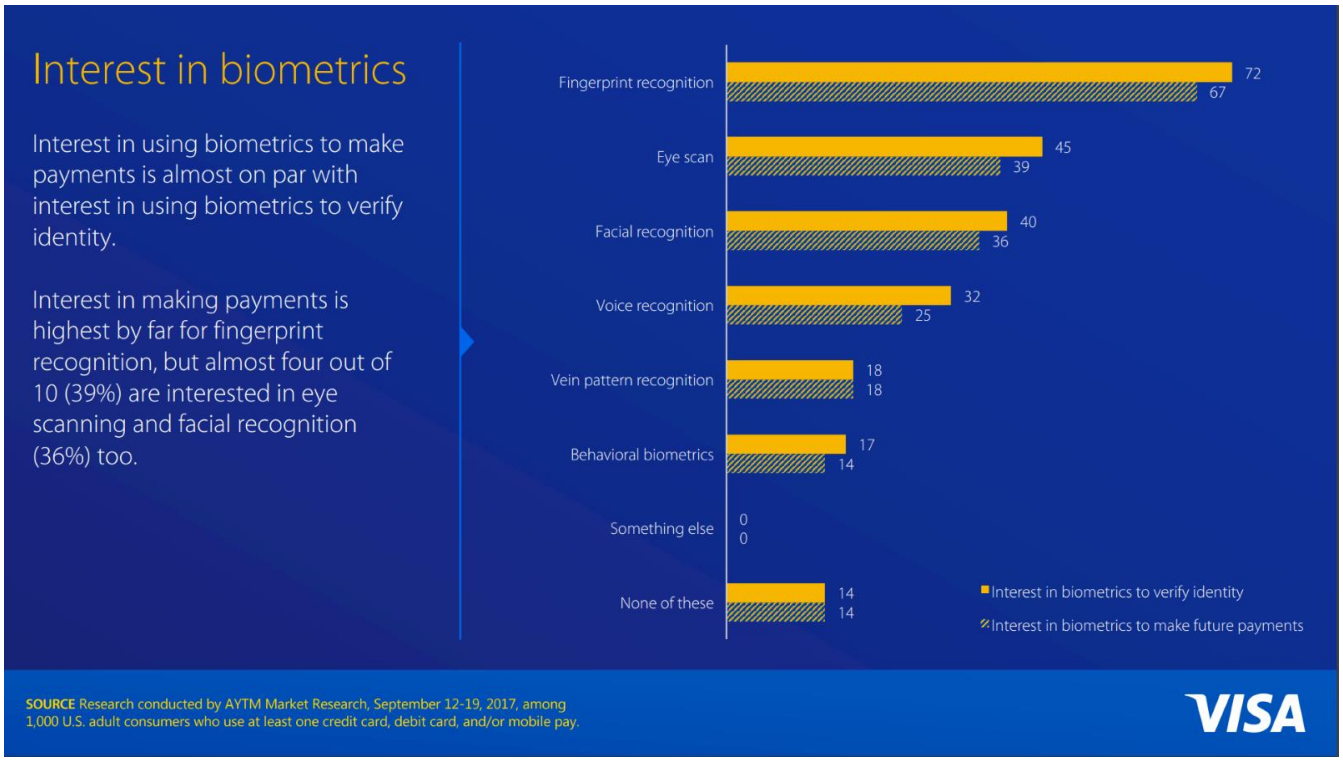

Figure 29. Interest in biometrics

As we can see interest in making payments in highest by far for fingerprint recognition, which is up to 72%, but almost four out of ten (39%) are interested in eye scanning and facial recognition (36%) too.

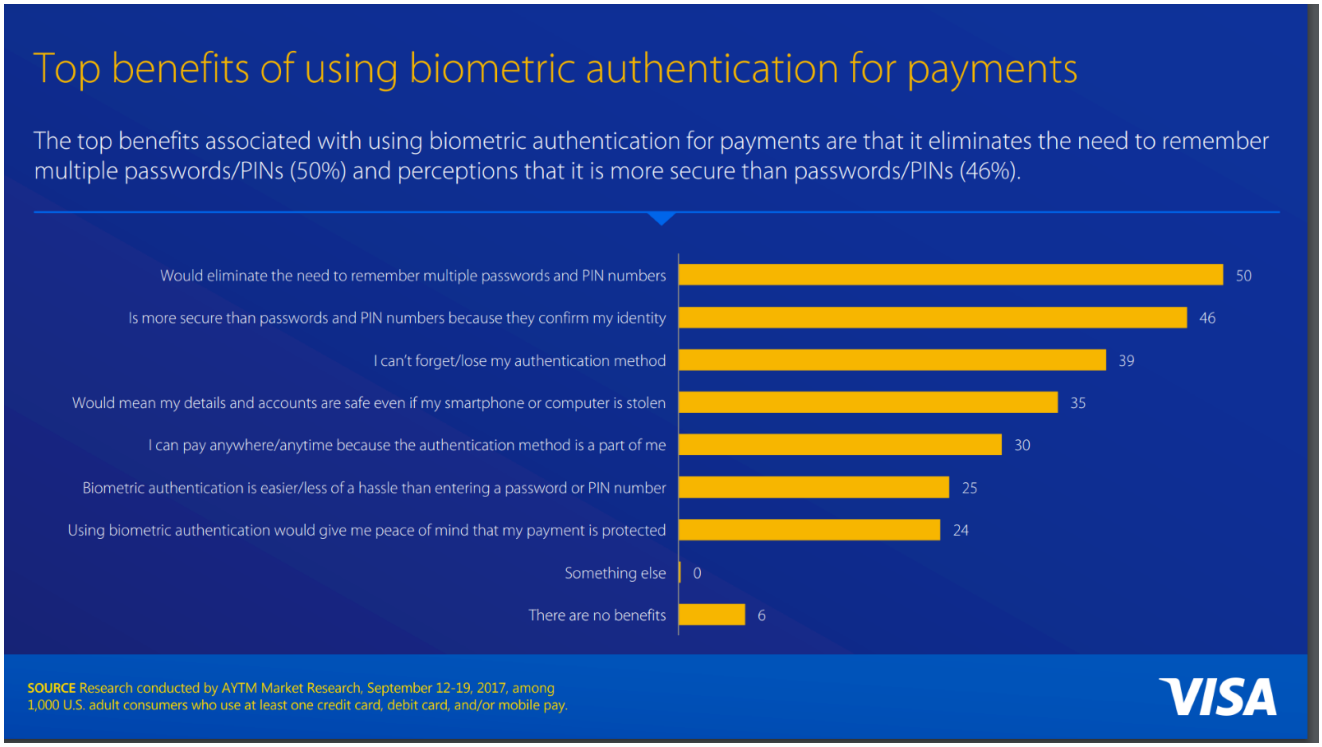

Figure 30 Top benefits of using biometric authentication for payments

39% of consumers states that they can't forget/lose their authentication method, 30% of them think they can pay anywhere/anytime because the authentication method is part of them (Visa, 2021).

Conclusion

Biometric technology has gained wide acceptance over recent years as a legitimate identification method. Various traits of biometrics such as finger, face, iris, palm, voice, ear, etc., have been deployed in a variety of applications, including access control, surveillance, forensic sector, immigration, behaviour analysis, etc(Sunil Kumar Singla, 2021).

Facial recognition is becoming increasingly prevalent, even though using facial recognition technology is controversial in many places, it is more reliable than expected. Many authorities are using facial recognition for identity verification, for example, CBP (Customs and Border Protection) currently uses the technology for identity verification at 172 airports around the world, including at exit in 32 U.S. airports. To date, more than 77 million travellers have participated in the biometric facial comparison process at air, land and seaports of entry. CBP has promised to use facial recognition on 97% of international passengers by 2023. The statistic is shown in Figure 31 (Runaway-suitcase, 2021) In addition, according to data from the most recent evaluation of NIST (National Institute of Standards and Technology)'s FRVT (Face Recognition Vendor Test) report, under ideal experiment environment, for the top 20 algorithms, accuracy of the highest performing demographic versus the lowest varies only between 99.7% and 99.8% (Jake Parker, 2021). In reality, facial recognition technology at airports works in conjunction with law enforcement and government databases to recognize the passenger. In the United States, the U.S. CBP maintains the database. The matching is instantaneous and is 99% accurate. It only takes 2 seconds to analyse a face in the system (Runaway-suitcase, 2021). Facial recognition surveillance in China located a BBC reporter wandering across a city of 3.5 million people in a mere seven minutes (techsciresearch, 2019).

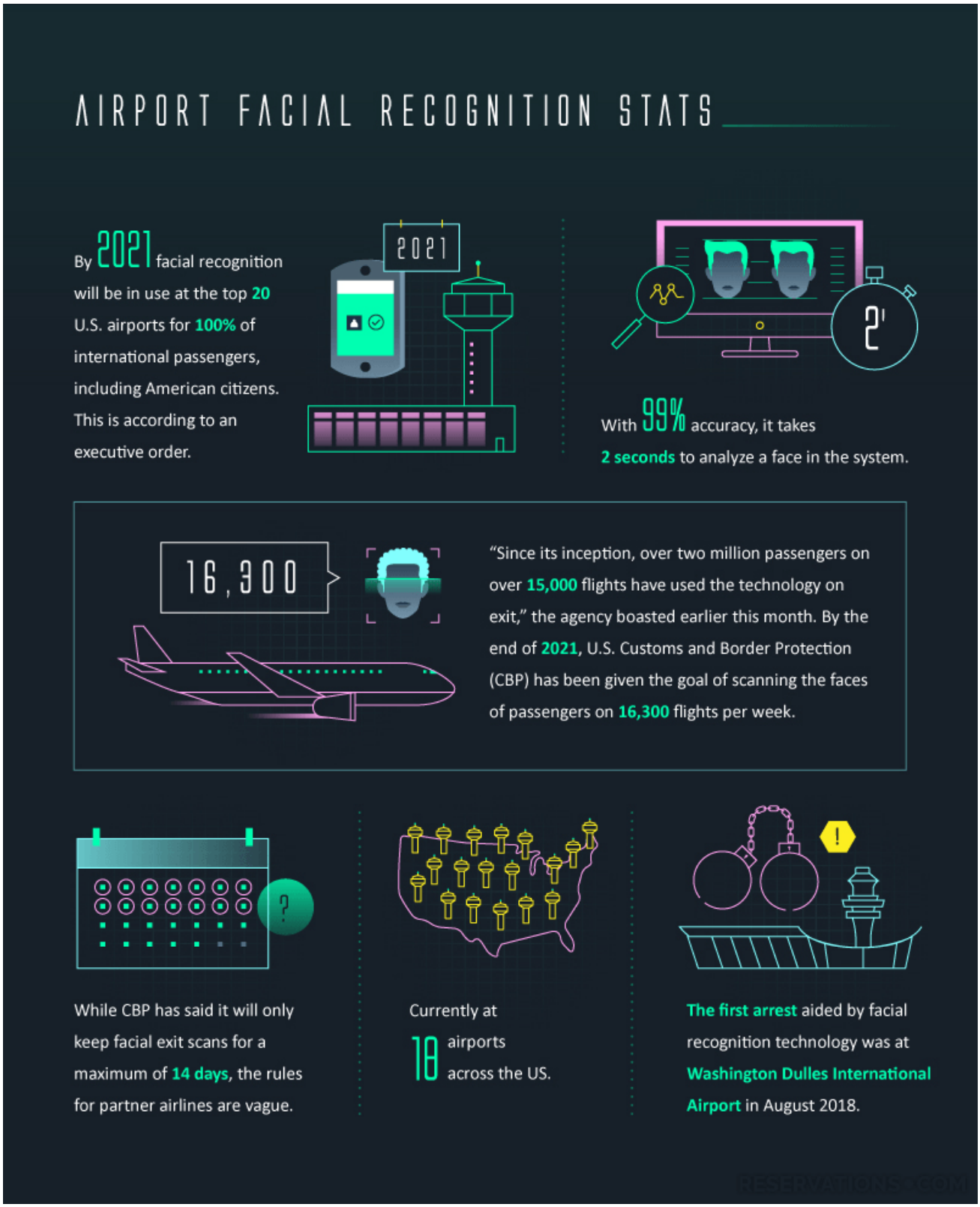

Figure 31. Facial Recognition Technology Stats

Figure 32. Delta Air Lines shows new biometrics scanning technology at Terminal F in Harsfield-Jackson International Airport in Atlanta

For transport, perhaps the finger-vein and palm-vein can be considered as they are developing with a focus on being touchless, fast and accurate. They are highly accurate as the acquisition of the biometric is done beneath the skin, hence not easy to forge either. Given the penetration of the use of Biometrics in everyday life, we can foresee 2 future scenarios': One Optimistic that remediates the concerns of governments and society for very careful application and strict governance which creates trust and widespread acceptance. There is however also a scenario wherein something goes horribly wrong with the data and privacy data are abused causing real pain and grief. If the latter scenario occurs, the use of Biometrics in public transport will be among the first to be scrutinised.

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1.4 SLAM

1.4.1. Introduction

SLAM (Simultaneous Localisation and Mapping) is a method, used for instance by autonomous vehicles, that builds a map and localises a vehicle in that map at the same time. Broadly speaking, there are two types of technology components used to achieve SLAM. The first type is sensor signal processing, including the front-end processing, which is largely dependent on the sensors used. The second type is pose-graph optimisation, including the back-end processing, which is sensor-agnostic (Matlab, 2021).

It is the process of mapping an area whilst keeping track of the location of the device within that area what makes mobile mapping possible. This allows map construction of large areas in much shorter spaces of time as areas can be measured using mobile robots, drones or vehicles. SLAM systems simplify data collection and can be used in outdoor or indoor environments (GeoSlam, 2021). SLAM is central to a range of indoor, outdoor, in-air and underwater applications for both manned and autonomous vehicles.

SLAM has recently entered the phone device; using a SLAM mobile map app, you can walk through a location, creating a digital mapping as you go, saving a lot of time by eliminating the need for lengthy setups. I The app also warns for obstacles that are approaching. SLAM enables you to scan complex and enclosed locations manually or by attaching a scanner to a trolley, drone, or pole (news, 2021).

1.4.2 Technical features

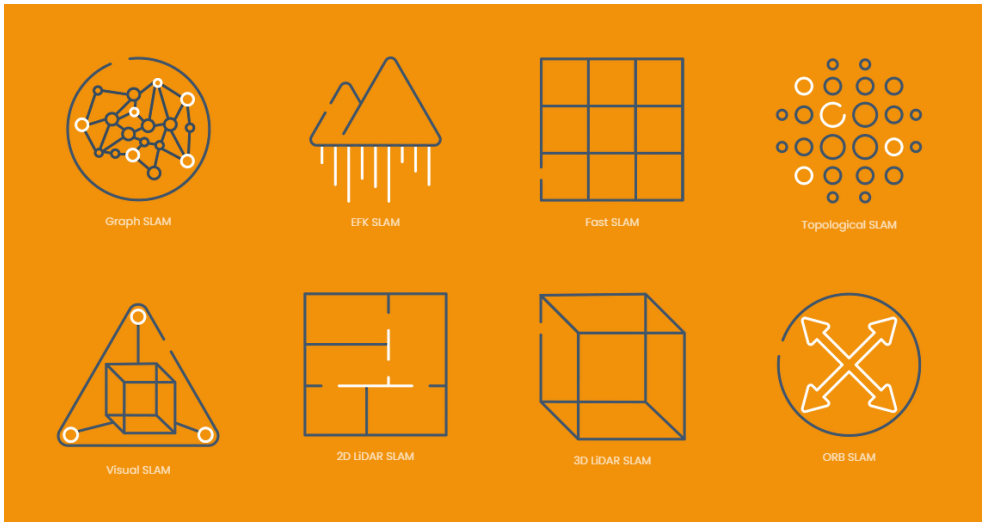

Figure 33 SLAM Models

Self-Localisation

SLAM functions in a similar fashion to that of a person trying to find his / her way in an unknown location. The person needs to determine his / her own location in relation to the landmark. As the person observes the environment more and more, the person will be able to recognise and build a mental image regarding this previously unknown location. For the SLAM algorithm, the most important step is to determine the current location before understanding what the surrounding environment is. The robot usually relies on odometry to estimate its own position (Maxwell, 2013).

Odometry is used to measure the change in position of the robot over time based on the data recorded from the motion sensor. The change in position data is then used to estimate the robot's position relative to a starting position. Note that the data is recorded using rotary encoders on its wheels. The data will then undergo instrument calibration and processing for the data to become valuable for localisation purposes (Robo-Rats Locomotion, 2001). Train operations frequently use odometry devices to locate their trains. With the help of stationary sensors placed in precise locations, the **absolute position** of a train can be found.

Visual SLAM

One of the most common methods used for mapping is known as visual SLAM. It calculates the position and orientation of a device with respect to its surroundings while mapping the surrounding environment at the same time through visual input of a camera. It is not surprising that the major cost of the SLAM technologies lies in the type of cameras that are being used. With the help of the feature-based function, SLAM can track points of interest through successive camera frames to triangulate the 3D position of the cameras relative to the location and build the map (GeoSLAM, 2022).

Visual SLAM is often employed with a single camera as the only sensor. This is known as monocular SLAM. However, as the camera does not provide any additional information such as depth, this method is proven to be challenging without the assistance of another device and may lead to reprojection error (Association For Advancing Automation, 2018). This problem can be solved through employment of AR markers, checkerboards which help defines the location of the robot, or fusing the camera information with another sensor such as the inertial measurement units (IMUs). The IMUs are often used to measure the velocity and orientation of the adapted robot. Through the map initialisation process, tracking process, local mapping and algorithm loop closure, an accurate SLAM result can be produced (Pao, 2018).

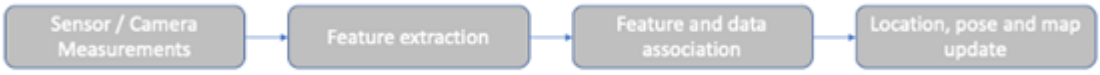

Figure 34 Feature-based Visual SLAM process (Kudan, 2020)

LiDAR SLAM

Another main approach towards SLAM is light detection and ranging (Lidar), which primarily uses a laser sensor for distance detection. One of the major challenges with Visual SLAM is inconsistency and lack of precision. The Lasers in Lidar SLAM are significantly more precise and are therefore often used in high velocity devices for an accurate measurement.

The data produced by the LiDAR sensor can be 2D (x,y) or 3D (x,y,z) point cloud data. The point cloud data generated by LiDAR is able to provide high-precision distance measurements and is able to generate an accurate map with SLAM. It is important to note that registration algorithms such as iterative closest point (ICP) and normal distributions transform (NDT) algorithms are used for cloud matching purposes. The movement of the robot is then estimated through matching the point clouds (MathWorks, n.d.).

While LiDAR SLAM has proven to be more precise, the point clouds recorded by the laser sensor are not as finely detailed as image in terms of density. If the robot is placed in a location with few obstacles, the system will have difficulties aligning the point clouds and thus fail to self-localise. Furthermore, point cloud matching requires high processing power. Therefore, other measurement units are often used to tackle these challenges such as wheel odometry and IMU data.

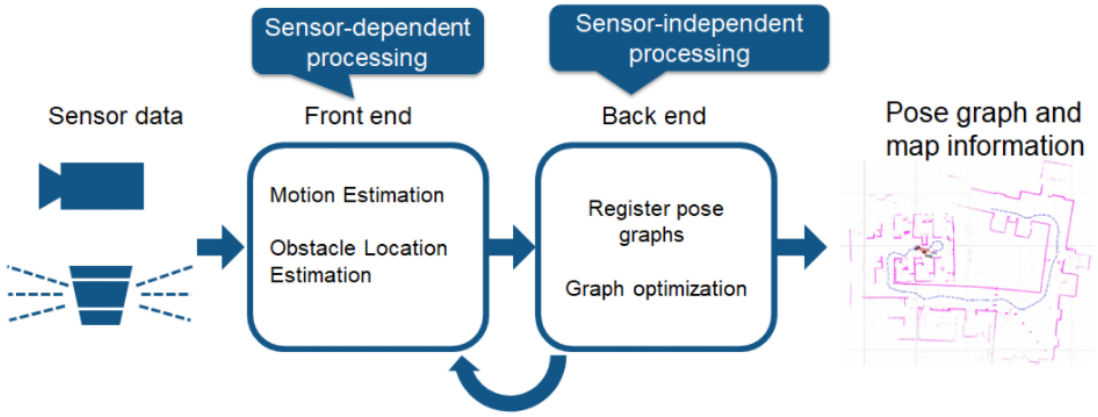

Figure 35 General SLAM Processing Flow (MathWorks, n.d.)

Signal-based SLAM

A previous study also mentioned the adaptation of SLAM with mixed Wi-Fi, Bluetooth, LTE and magnetic signals. The localisation function relies on measuring a collection of RF signals such as the Received Signal Strength (RSS) from Wi-Fi, in conjunction with spatial maps of signal fingerprints. The authors also looked to rely on the Reference Signal Received Power (RSRP) provided by 4G LTE telephony small cells to build a multi-modal signal map for localisation purposes. Within the study, all data that can be acquired via smart phone and crowd-source the data collection from several experimenters walking freely through a building, collecting time-stamped Wi-Fi and Bluetooth RSS, 4G LTE RSRP, magnetic field magnitude, GPS reference points when outdoors, Near-Field Communication (NFC) readings at specific landmarks and pedestrian dead reckoning based on inertial data (Mirowski, et al., 2013).

While the motion of the observed pedestrians is unknown, the experiment aimed to use crowd-sourced RF data to map out the trajectory of the user within the building. The system is split into two fundamental blocks which are the pedestrian dead reckoning with position fixes and SLAM algorithm adapted for RF signal data. With the help of their modified algorithm known as SignalSLAM, the system can self-localise based on absolute location and pairwise constraints that incorporate multi-modal similarity. With the help of inertial measurement units as well as the abundant RF signals generated within the building, the unknown pedestrian dead reckoning estimates can be found. Furthermore, this experiment also accounted for phone pose, thus avoiding any common restriction imposed.

1.4.3 Fundamental Specifications and Algorithm

Tracking Camera (Visual SLAM) – T265 Sample

In order to proceed with the mapping process, the algorithm would require input that represents the surrounding environment in the form of point clouds. The primary job of the camera is to track set points through successive camera frames in order to triangulate their 3D position, while simultaneously using this information to approximate camera pose (Association for Advancing Automation, 2018). For example, the Intel RealSense Tracking Camera T265 gas a complete embedded SLAM solution that uses Visual Inertial Odometry to track its own orientation and location (Anders Grunnet-Jepsen, n.d.). The embedded processor would run the entire SLAM algorithm and analyse the stereo images while fusing all sensor information together into 6 Degree-of-Freedom tracking, as seen in the following figure. The whole visual SLAM process goes as following:

- Calibration and Initialisation: The device needs to be moved around sufficiently to estimate its internal parameters.
- Mounting considerations: The camera itself needs to be mounted in the case in rigid format.

- Coordinate system: The position calculated by T265 camera is provided in relative to the centre of the two cameras.
- Time Stamp: The camera reports the time for all sensors for the use of time synchronisation mechanism between the host computer and the camera.
- Visual Output: The output of the camera can be observed via the Intel RealSense Viewer application which produces a visual pose output through graphical interface.

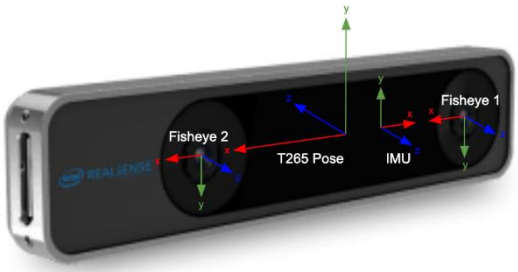

Figure 36 The Intel RealSense Tracking Camera T265

IMU (Inertial measurement unit) Sensor – Bosch BMI055 Sample

The introduction of the tracking camera T265 previously introduced also includes a IMU sensor. An IMU sensor is responsible for measuring both directional movement and rotation of the body. It also measures the specific force, angular rate and orientation of the body through the combine effort of accelerometers, gyroscopes and magnetometers.

In the case of Bosch BMI055 IMU sensor, it comprised of triaxial 12bit linear acceleration and triaxial 16bit angular velocity gyro sensor (Intel Realsense, 2019). In the case of SLAM, working in conjunction with the tracking camera, the sensor provides raw IMU data towards the Intel Movidius Myriad 2 Vision Processing Unit. The data is also complemented by video from two fisheye monochrome sensors. Through the raw IMU data and VPU processed data, the tracking camera is then able to produce a reliable and persistent calculations of the body movement to the host PC.

LiDAR (Light detection and ranging) Sensor – L515 Sample

The LiDAR sensor is able to directly obtain 3D structural information in the environment. However, it is important to note that it generally has a higher cost and lower resolution. In the case of LiDAR SLAM, the sensor uses environmental features extracted from the point cloud to match and obtain pose changes for navigation. It is a recursive algorithm where the navigation error would gradually diverge corresponding to moving distance. This function is especially useful in indoor environment (Chang, et al., 2020). For example, the Intel Realsense LiDAR Camera introduced a solid-state LiDAR depth technology specially made for indoor applications. A major challenge experienced by LiDAR sensor is the edge fidelity in 3D scanning process. The intel camera is able to scan fast moving objects up to 9 meters with no motion-blur. It also combines with a FHD RGB camera and IMU sensor for a robust approach towards scanning solutions (Intel Realsense, n.d.).

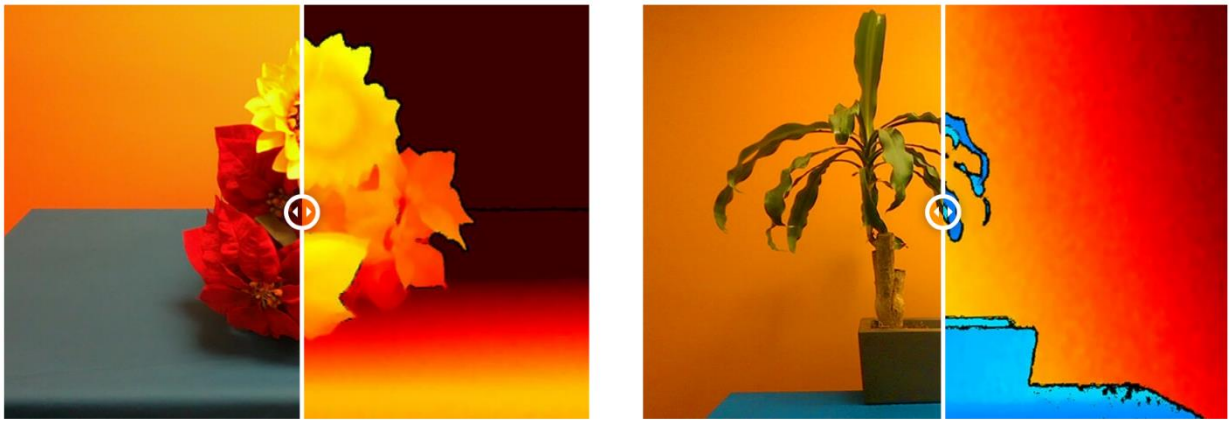

Figure 37 Camera L515 Graphical Output

Algorithms to solve SLAM problem

Simultaneous localisation and mapping (SLAM) is the computational problem of constructing or updating a map of an unknown environment while simultaneously keeping track of an agent's location within it. While this initially appears to be a chicken-and-egg problem there are several algorithms known for solving it, at least approximately, in tractable time for certain environments. Popular approximate solution methods include the *particle filter*, extended *Kalman filter*, *covariance intersection*, and *GraphSLAM* (Wikipedia, 2022).

Particle Filter

Particle filter is a method where a set of particles is used to represent robot's belief, $bel\ (xk)$ instead of using parametric values (i.e., mean, μ and variance, $\sigma 2$) to describe $bel\ (xk)$ distribution such as in Kalman Filter and Extended Kalman Filter. Set of particles in circles represent the belief of a robot pose, xk. In particle filter, each particle contains a hypothesis of robot pose that assume its position is correct. Then, by using this assumption, every particle will maintain its own map (Norhidayah Mohamad Yatim, 2015).

Kalman Filter

Several algorithms are used in tackling this problem and the most highlighted algorithms are based on the Extended Kalman Filter (EKF). The EKF SLAM method mainly consists of two steps which are the *prediction step* and the *correction step*. In the prediction step, both the estimated mean and the estimated covariance are calculated. The estimated mean is calculated which is a function of the robot motion model, either a velocity model or an odometry model. The calculated estimated mean result is the estimated robot state and the estimated location of the estimated landmarks, an acceptable estimation of the robot location at all points and a near accurate map of the environment (Lofty, 2016).

1.4.4 Key players/market leaders

1. Apple

- Apple is an American owned multinational technology company which specialises in computer software and consumer electronics. It is the world's most valuable company with a total revenue of $365.8 billion in 2021.
- Apple currently dominates the simultaneous localisation and mapping market.
- In 2016. Apple indicated their desire to take advantage of AR poisoning in applications, with an iPhone-based version used for "Augmented reality maps" which would overlay a digital map and data on real-world camera view.

- Furthermore in 2017, a related filing suggested that AR device can be used to identify objects nearby for a user.
- A newly released Apple Glass that utilises the power of SLAM to capture data on a scene and share it for a better augmented reality experience (Owen, 2020).

2. Google LLC

- Google is an American owned multinational technology company that specialises mostly in internet-related services and products.
- In 2016, Google open-sourced its SLAm library called 'Cartographe', which they had been using internally for some time regarding indoor mapping and autonomous vehicles. The library can function in both 2D and 3D format environment by combining input data such as LIDAR, IMU and camera in order to simultaneously compute the position of the device and create a map of the device's surrounding. The reason for open-sourcing the library is to allow more people to get involved and increase the capabilities of the library (Kumar, 2016).

3. Intel Corporation

- Intel is an American owned multinational corporation and technology company. It is the world's largest semiconductor chip manufacturer by revenue, while being one of the largest United States corporations by total revenue for nearly a decade.
- In 2020, SLAMcore teams up with Intel RealSense technology to create the world's first "out-of-the-box" SLAM algorithms. It is a combination of cutting-edge hardware and software which delivers a powerful spatial AI solution for mass adoption in autonomous robots. SLAMCore works with Intel Real Sense stereo depth cameras to map out the surroundings for the robots.
- In 2021, the SLAM core team furtherly added 2.5 D mapping capabilities to its latest software release. With the help of 2.5D maps, robots can know where objects are and can safely plot routes through real-world environments (Crowe, 2021) (SLAMcore, 2020).

4. Amazon Robotics

- Amazon Robotics is a Massachusetts-based company which specialises in manufacturing robotics fulfillment systems. Previously known as Kiva Systems, Amazon acquired this company in 2012 for $775 million. As of 2019, there are more than 200,000 robots working in the company's warehouses.
- In 2021, Amazon introduced a robot known as Astro, which is a household robot with home monitoring capabilities. Astro's computer vision utilises SLAM function to give a robust perception in dynamic environments and avoid any obstacles. The obstacle sensor allows the system to build a detailed map of its immediate surroundings. The data is then constructed as point clouds and allows the robot to path plan and interact with its environment, and even perform complex tasks such as exploring home.
- Several research papers have also been published in 2021 from Amazon Robotics regarding 'Robust rank deficient SLM' and 'Overlap displacement error: Are your SLAM poses map-consistent?" (Wikipedia, 2021) (Jong Jin Park, 2021) (Samer B. Nashed, 2011) (Christian Mostegel, 2021).

5. ClearPath Robotics

- ClearPath Robotics is headquartered in Waterloo Region, Canada and the original goal was to streamline field robotics research for universities and private corporations. The company had since explained and worked in manufacturing self-driving vehicles in an industrial environment.
- In 2016, ClearPath worked with Mining Systems Laboratory (MSL) to create an Unmanned Ground Vehicle (UGV) to perform geotechnical mapping of rock masses, thus allowing the team to predict rock falls and rock bursts in and around mines. The function is done through 2-dimensional maps that chart the dominant directions of elements in the rock face (UNIVERSITY, 2021).

6. Microsoft Inc.

- Microsoft is an American owned multinational technology corporation that specialises in computer software and related services. It is one of the largest software makers by revenue as of 2016.

- In 2008, Microsoft (Andrew Davison) had begun a generalised SLAM methodology of sequential probabilistic mapping, which allows robots to navigate in the unknown environment. However, the limited processing resources of practical computers were shown to be a huge problem for this technology.
- A Microsoft Research Blog published in 2020 shows development that enables interaction between mixed reality and robots through cloud-based localisation. The newly released Microsoft HoloLens and mixed reality allowed the device to visualise the data over their environment and recognise their place within such a place. This is done through Azure Spatial Anchors.
- Recently in 2021, Microsoft Azure indoor mapping and IoT technology is used to help Microsoft employees to find their way around the company's campuses. This is done through the combination effort of Microsoft Azure Digital Twins and Azure maps to generate real-time visualisation of physical spaces (Davison, 2008) (Jeffrey Delmerico, 2020) (Alereon, 2021).

7.Kudan Inc.

- Kudan is a deep technology company, based in Japan, that specialises in developing commercial artificial perception algorithms based in SLAM since 2011. The main goal of the company's products is to enable solutions for its partners in automotive and mapping services.
- Kudan had partnered with OUSTER to create the Kudan Lidar SLAM. The product promises a wide range of high performance lidar sensors in order to provide 3D vision towards the robots and smart infrastructures.
- Recently in 2022, Kudan had demonstrated the use of 3D-lidar SLAM device to create a share point cloud without extra information from external IMU or GNSS receiver (Inc., 2021) (Cozzens, 2022).

8.MAXST Developers

- MAXST is a South Korea based company that specialises in helping millions of developers and organisations to build virtually enhanced physical reality with Augmented Reality.
- In 2019, MAXST demonstrated AR Cloud for City-scale through the use of Visual SLAM.
- In 2020, MAXST opened an affordable Sensor Fusion SLAM solution which integrates the use of cameras with IMU sensors. This technology is known as 'Sensor Fusion SLAM', which aims to provide an effective and powerful result. The MAXSR Sensor Fusion SLAM had shown superior performance to other open-source resources.
- In Match 2021, this technology was made available via IOS for the consumers (MAXST, 2019) (press, 2020) (MAXST, 2020).

9.Aethon Inc.

- Aethon is a company responsible for providing autonomous mobile robots in the healthcare and hospitality field. Their headquarters is based in Pittsburgh which is located in Pennsylvania.
- In the Healthcare industry, the company's product aims to improve patient care, employee satisfaction, safety, productivity and more. The autonomous robots act as a 24/7 worker moving materials and clinical supplies.
- In the hospitality industry, robots are designed to provide a guest experience based on safety and efficiency. This can be done through automating delivery of food and room supplies and responding to guest requests (aetho, 2022) (Aethon, 2022).

10.Hi-tech Robotic System Ltd

- Hi-tech Robotic Systems Ltd is a company based in Pune, India, which is backed by state-of-the-art infrastructural base with well-equipped technology and ultra-modern machines. The company was founded in 2004 with the aim to revolutionise On-Road Logistics with its vision-based autonomous vehicles.
- The company has a strong focus on revolutionary road logistics' vision analytics solutions through autonomous and driver assist systems (ADAS).
- In 2018, the company tied with Daimler India Commercial Vehicles for their uses of artificial intelligence and computer vision technologies to build an intelligent model of monitoring

driver behaviour in order to ensure the driver is in well condition. Secondly, tan active collision mitigation camera system was also introduced which offers safety features such as lane departure warning and forward collision warning (Rajgor, 2021) (Anon., 2022).

1.4.5 Existing vendors/product - case studies

1. Mobile indoor navigation using Google ARCore

ARCore is Google's platform for building augmented reality experiences. Using different APIs, ARCore enables your phone to sense its environment, understand the world and interact with information. Some of the APIs are available across Android and iOS to enable shared AR experiences.

ARCore uses three key capabilities to integrate virtual content with the real world as seen through your phone's camera:

- Motion tracking allows the phone to understand and track its position relative to the world.
- Environmental understanding allows the phone to detect the size and location of all types of surfaces: horizontal, vertical and angled surfaces like the ground, a coffee table or walls.
- Light estimation allows the phone to estimate the environment's current lighting conditions (ARCore, 2021).

2. Apple ARKit

Augmented reality (AR) describes user experiences that add 2D or 3D elements to the live view from a device's camera in a way that makes those elements appear to inhabit the real world. ARKit combines device motion tracking, camera scene capture, advanced scene processing, and display conveniences to simplify the task of building an AR experience. You can create many kinds of AR experiences with these technologies using the front or rear camera of an iOS device (Apple, 2021).

The features include:

- Depth API
    - The advanced scene understanding capabilities built into the LiDAR Scanner allow this API to use per-pixel depth information about the surrounding environment.
- Instant AR
    - The LiDAR Scanner enables incredibly quick plane detection, allowing for the instant placement of AR objects in the real world without scanning.
- Motion Capture
    - Capture the motion of a person in real time with a single camera.
    - Simultaneous front and back camera
    - You can simultaneously use face and world tracking on the front and back cameras, opening up new possibilities.
- Scene Geometry
    - Create a topological map of your space with labels identifying floors, walls, ceilings, windows, doors, and seats. This deep understanding of the real world unlocks object occlusion and real-world physics for virtual objects, and also gives you more information to power your AR workflows (Apple, 2021).

3. Amazon Astro

Astro is a new and different kind of robot, one that's designed to help customers with a range of tasks like home monitoring and keeping in touch with family. It brings together new advancements in artificial intelligence, computer vision, sensor technology, and voice and edge computing in a package that's designed to be helpful and convenient. Here are just a few of the ways Astro can be used around the house:

- Check-in on your home: When you're away, Astro helps provide the peace of mind that comes with knowing your home is safe. Astro can move autonomously around your home, navigate to check in on specific areas, show you a live view of rooms through the Astro app.
- Helps you look out for loved ones: Astro will be able to help customers who are remotely caring for elderly relatives and loved ones.
- Provides peace of mind with Ring: Astro also works with Ring, adding to the peace of mind in keeping your home safe (Amazon, 2021).

4. ClearPath Robotics Autonomy Research Kit (ARK)

The Autonomy Research Kit (ARK) is an all-in-one autonomy kit that enables robust point-to-point autonomous navigation of mobile robots. The features include:

- ROBUST & RELIABLE AUTONOMY. ARK software provides reliable point-to-point autonomous navigation in changing indoor environments with dynamic path planning, simultaneous mapping and localisation (SLAM) and obstacle avoidance.
- QUICK & EASY INTEGRATION. ARK integrates seamlessly with Clearpath research robots, including the Husky UGV and Ridgeback mobile manipulation platform. The ARK processor is designed to work with your ROS development environment and comes with a well-documented developer API, allowing you to get started quickly with existing research and widely available open-source ROS libraries.
- EFFORTLESS MAPPING & NAVIGATION. ARK provides an intuitive, web-based interface, called ARK Mapper, for manually controlling the robot and creating 2D maps of indoor environments. Once a map of the environment has been generated and saved to the robot, simply click a point on the map and the robot will navigate to that point autonomously, detecting and avoiding obstacles along the way (Clearpath, 2011).

1.4.6 Future Roadmap

Mobile devices will be a major emphasis of SLAM. Nonetheless, the technology is not limited to mobile devices; it will apply to various other devices. SLAM is likely to play a key role in various business and consumer applications, including navigation, advertising, and gaming (news, 2021). With cheaper hardware requirements and constantly improving algorithms, Visual SLAM is gaining more popularity and attention. The lower computing requirement and the fact that the camera used for Visual SLAM can be used for other perception activities makes it a tempting choice in making autonomous robots with slow to medium speeds. Vision sensors can exact more and viable information both in colour and per pixel about location than any other sensor. Vision sensors are favoured because people and animals seem to be navigating effectively in complicated locations using vision as a primary sensor. Various researchers have focussed on Visual Simultaneous Localisation and Mapping (VSLAM) with exceptional results. Visual sensors have been the main research direction for SLAM solutions because they are inexpensive, capable of collecting a large amount of information, and offer a large measurement range (Nirmal, 2022).

Common Challenges with SLAM

- **Localisation errors accumulate, causing substantial deviation from actual values**. SLAM estimates sequential movement, which includes some margin of error. This error accumulates over time, potentially causing substantial deviation from actual values. It can also cause map data to collapse or distort, making subsequent searches difficult.
- **Localisation fails and the position on the map is lost**. Image and point-cloud mapping do not consider the characteristics of a robot's movement. In some cases, this approach can generate discontinuous position estimates. For example, a calculation result showing that a robot moving at 1 m/s suddenly jumped forward by 10 metres. This kind of localisation failure can be prevented either by using a

recovery algorithm or by fusing the motion model with multiple sensors to make calculations based on the sensor data.

- **High computational cost for image processing, point cloud processing, and optimisation**. Computing cost is a problem when implementing SLAM on vehicle hardware. Computation is usually performed on compact and low-energy embedded microprocessors that have limited processing power. To achieve accurate localisation, it is essential to execute image processing and point cloud matching at high frequency. In addition, optimisation calculations such as loop closure are high computation processes. The challenge is how to execute such computationally expensive processing on embedded microcomputers (Matlab, 2021).

SLAM gives the device the ability to not only just determine the environment but also interact or relate with it in real-time. This makes it a crucial system for various technologies like autonomous vehicles, robotics and Augmented Reality. SLAM is a complex system with a variety of methods present and developing. Many tech giants like Apple, Google, Facebook and Amazon have been working on SLAM for Commercial, Household and Manufacturing benefits. Lastly, SLAM has large capabilities and demands and a huge growing market which did face disturbances due to the COVID-19 pandemic. However, even with those disturbances and technical complexity issues, development on SLAM is very active in recent years and issues are being constantly solved. The technology is evolving and reducing in complexity and even in this pandemic period the development and market keep increasing, soon we will have improved SLAM techniques which will advance robotics, autonomous vehicles and Augmented Reality as well into the next era of the technological age (Singhal, 2020).

1.4.7 Applied to frictionless ticketing case

Example: Applied Infrastructure

In a theoretical scenario, the traveller will have a personal electronic device that includes an IMU sensor and a tracking camera for the purpose of SLAM algorithm data processing. The device will continuously track the movement of the user within their pocket while also observing the surrounding environment via a LiDAR sensor. Via the X, Y and Z coordinate point clouds, a rough map of the surroundings can be visualised, including self-localisation. Based on some points of interest such as electronic gates or elevators, the accuracy of the map can be further increased via absolute points of reference. As the traveller moves toward the gate, the distance between the traveller and the gate can be calculated and thus, allow the passenger to go through the gate without any further physical actions. By introducing visual fiducial markers into the scene, it is possible to detect obstacles with copter-mounted cameras and fusing these detections with laser-based self-localisation in a graph optimisation. In an indoor scenario with sparsely distributed fiducial markers, more accurate maps can be built with both the laser scanner and video cameras.

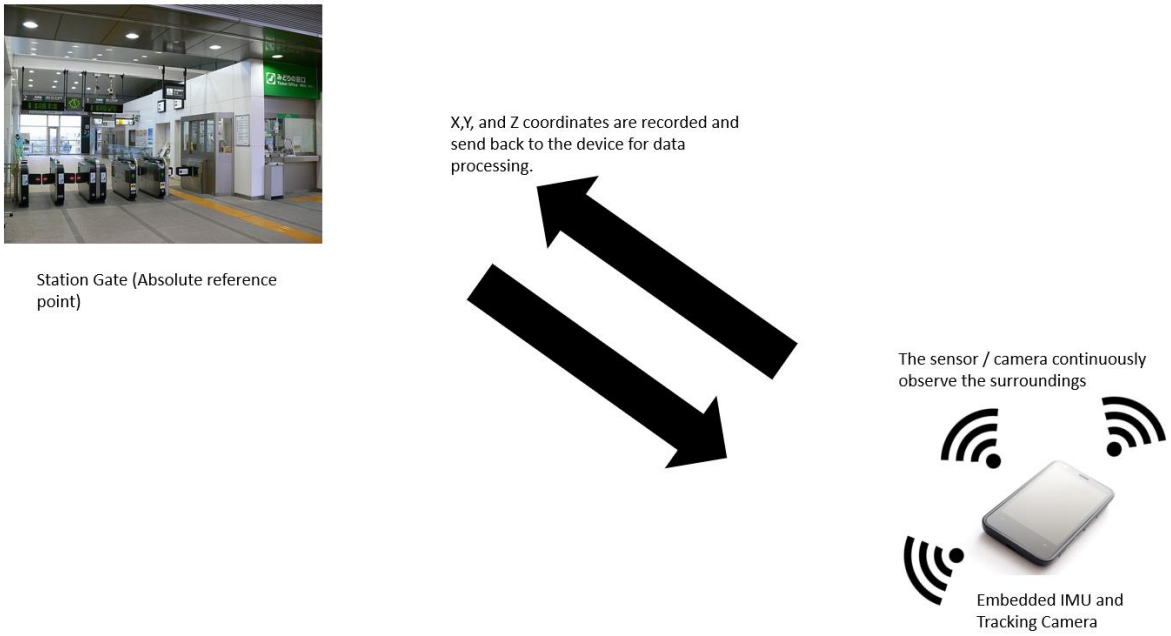

Figure 38 IMU Sensor and Tracking Camera

LiDAR typically being faster and more accurate, but also more costly. Visual SLAM is a more cost-effective approach that can utilise significantly less expensive equipment (a camera as opposed to lasers) and has the potential to leverage a 3D map, but it is not quite as precise and is slower than LiDAR. Visual SLAM also has the advantage of seeing more of the scene than LiDAR, as it has more dimensions viewable with its sensor (Pao, 2019).

SLAM is gradually playing a more significant role in our life. In GPS-denied environments such as indoors, underground, or underwater, a mobile agent must rely solely on its on-board sensors to construct a representation of the environment in order to localise itself. This is the scenario in which SLAM is needed. Even in situations where GPS can provide coarse localisation, SLAM can be used to provide a fine-grained estimate of the vehicle location (Latif, 2019).

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2: Global web review transport agencies

2.1 Country – USA

Region / State	Road Agency	NPC App Introduced Time	Frictionless ticketing / Observation
New York City	Metropolitan Transportation Authority(MTA, n.d.)	In 2017, it was announced MetroCard would be phased out and replaced by OMNY which is a contactless fare payment system. The payment would be done via Apple Pay, Google Wallet, debit/credit cards with near-field communication enabled or radio-frequency identification card(Barron, 2017).	None. Note: 5G adaptation and ultra-wideband is currently being developed for MaaS purposes. 5G Adaptation Ultra wide Band (Previous Proven)
	Port Authority Trans-Hudson (PATH)	In June 2019, PATH announced it was in talks with MTA to implement OMNY fare payment system on PATH. Under the announced plan, OMNY would be available to PATH riders by 2022, with both SmartLink and MetroCard being phased out by 2023(Wikipedia, n.d.).	None.
Los Angeles	Los Angeles County Metropolitan Transportation Authority(Metro, n.d.)	In January 2021, the company announced its Cubic Transportation Systems (CTS) business division and the Los Angeles County Metropolitan Transportation Authority (Metro) launched the regional TAP application for Android phones, delivering a safe, contactless way to pay transit fare on Metro and 25 additional TAP transit agencies in L.A. County(CUBIC, n.d.).	None.
	Metrolink (Metro-link, n.d.)	In July 2019, the new system will mean customers can simply touch-in at the start of a journey and touch-out at the end using a contactless bank card or another contactless-enabled payment device, such as a phone or watch. The system will then automatically work out the total daily fare for a customer's journeys, with the price being capped to ensure they are paying no more than the relevant adult daily one-day travelcard price(Intelligent Transport, 2019).	None.
Chicago	Chicago Transit Authority	In 2015, the Chicago-area agencies, including Metra, CTA, and Pace launched the Ventra app. In a later phase, customers will be able to download a virtual Ventra Card onto their near-field-communication-compatible mobile devices, allowing them to access their Ventra transit accounts to pay for rides on CTA trains and CTA and Pace buses directly. Towards the end of October 2020, the CTA announced that Ventra would be available within an Apple Pay wallet, allowing a customer's card to be scanned on an iPhone or Apple Watch device, though with the caveat that the customer's plastic Ventra card would no longer be able to be used. In June 2021, this functionality was extended to Google Pay on Android devices(Wikipedia, n.d.).	None. Note: Attempt use of Microsoft Azure for traveller density management(ITS International, 2021).
	Metra (METX)	Metra also offers mobile ticketing within their app. The payment is used in conjunction with the Ventra payment system. The payment options will include any credit or debit cards, Apple Pay or Google pay (Metra, n.d.). The roll out date is similar to that of CTA.	Test rail crossing monitoring systems that will allow Metra to track equipment performance and better enable proactive maintenance. As part of this program, Metra will test Siemens Smart Gate technology at five

			crossings in Mokena on the Rock Island Line(Mass Transit, 2021).
	Pace (Regional Transportation Authority)	Pay your exact fare into the fare box. If you have purchased a reloadable Ventra Card or are using a personal contactless bankcard, simply tap your card on the reader and board the bus. Ventra Cards can be loaded with value using the Ventra App (NFC and RFID). The roll out date is similar to that of CTA.	None.
Houston	Metropolitan Transit Authority of Harris County	In 2019, with the idea to revamp the fare system, the company started trialling payment through smartphone apps/wallets and contactless credit cards (NFC) (Begley, 2019).	None.
Phoenix	Valley Metro	In 2020, through an integration with Unwire, Vix Pulse will support a new innovative mobile application providing advanced trip planning capabilities and allowing riders to pay fares, check balances and top-up account value from their smartphone. The system will be complemented with a robust retail network where cash dependent customers can load their accounts at more than 1,000 convenient locations, alongside a call centre to provide customer support. Passengers will have the flexibility to pay via smartphones and contactless cards (NFC and RFID)(Mass Transit, 2020).	The Valley Metro: Plan and Trackapp is currently available, and passengers can plan trips with step-by-step navigation, track transit in real time, estimate travel times and receive service alerts, according to the release. Passengers will also be able to pay their fares through the app beginning in 2022(KTAR NEWS, 2021).
Philadelphia	Southern Pennsylvania Transportation Authority	The SEPTA key card is a smart card that introduced as a replacement for tokens. The card is based on Mastercard Contactless card issued by MetaBank, which is most likely NFC. The card was first deployed in February 2017 as a new hardware necessary for the system. A Mastercard Paypass chip is embedded in the card allowing it to be read wirelessly. Riders simply wave their card near a red fare validator pad(HATCH, n.d.).	None.
Austin	Capital Metropolitan Transportation Authority	Currently, fares can be paid with a physical pass card (magnetic stripe card and RFID), QR code or digital ticket on cell phones (Mobile wallet with CapMetro App) or NFC chip-enabled tickets. However, in the case of MetroRail, all services require the travels to present a valid pass or ticketing. This is known as a proof-of-payment system (September 2019)(Clark, 2019).	None. Note: Current development in 5G and Ultra-wideband as part of the roadmap.
San Antonio	Via Metropolitan Transit	In mid-2019, VIA introduced their contactless fare payment card, goCard. The VIA goCard is a new electronic reloadable fare card. With the goCard customers can add value and passes to their card instead of carrying cash. It is a great addition to VIA's innovative goMobile ticketing app(VIA, n.d.).	None. Note: New bus arrival strategy -> Riders can get real-time bus arrival information delivered to their cell phones, computers or other mobile devices by texting their 5-digit bus stop number to 52020(Via, n.d.).
Atlanta	Metropolitan Atlanta Rapid Transit Authority (MARTA)	Started to roll out 'Breeze mobile' which will complement and operate alongside the existing card-based system. It allows customers the option of using their mobile devices to pay fares on all MARTA services.	None.

		Mobile payment validators have been installed on all buses and at all stations, and a new Breeze Mobile app will allow customers to manage passes and payment methods. Projection for the near future: Account based system instead of card based and contactless payments such as open payments.	
	Atlanta Streetcar	Breeze Cards and Tickets are accepted as a valid fare media (After September 2020)(Pendered, 2020).	None.
Baltimore	Maryland Transit Administration	In 2018, WMATA announced that contactless mobile payments would be coming to Metro, this time through a closed system that emulates the physical smart card and works with current fare collection equipment. The reduced scope of the project lowered costs dramatically, while constraining users to loading a balance on a SmarTrip account instead of paying directly from a credit/debit card. The card is brought into close proximity with a circular target on the top or side of each faregate rather than inserted into a slot. Mobile payments through Apple Pay were added in 2020, with Google Pay support following in 2021(Wikipedia, n.d.).	The approval of the $63.6-million project by the Maryland Board of Public Works enables MDOT MTA to begin implementing a next-generation fare system that will enhance both operational efficiency and the rider experience (October 2021). Components of the new fare system will be phased in beginning in 2023 and the system is anticipated to be fully operational by 2025 (Mass Transit, 2021).
Great Boston	Massachusetts Bay Transportation Authority (MBTA)	The MBTA has various fare structures for its various types of service. The CharlieCard electronic farecard is accepted on the subway and bus systems, but not on commuter rail, ferry, or paratransit services. Passengers pay for subway and bus rides at faregates in station entrances or fareboxes in the front of vehicles; MBTA employees manually check tickets on the commuter rail and ferries. The CharlieCard is a contactless smart card that adopts NFC technology (After early 2017).	In 2022, the original CharlieCard system will be replaced during the "Automated Fare Collection 2.0" project, a system similar to the London Oyster Card. The new system will allow payments with contactless cards and smartphones, as well as new CharlieCards(Wikipedia, n.d.).
Erie and Niagara Counties	Niagara Frontier Transportation Authority	NFTA currently adopts mobile ticketing which allows the rider to pay through smart phone application. The application allows the user to buy rail passes on their phone. Since April 2019, fares are available in the token transit mobile ticketing app (NFTA-Metro, n.d.).	None.
New Jersey	New Jersey Transit (NJ Transit)	You can buy all tickets for any mode of transit on the NJ TRANSIT App, at a Ticket Vending Machine, or at a staffed Ticket Office. TVMs are easy to use. Simply follow the on-screen instructions. TVMs accept cash, debit cards and credit cards. The NJ TRANSIT App is built for your iOS or Android device, with streamlined navigation, easy access to your tickets, passes, and favourites with Touch ID and Face ID support (Display) (August 2021) With the new Map My Ride feature, NJ TRANSIT has added additional capabilities to its mobile app that allows customers to track locations of their buses and trains. With a simple tap on their mobile device, customers can see and map the location of the next bus or train along with the arrival time to their location(NJTransit, n.d.).	None. Note: IoT Micro positioning Revolution with Ultrawideband (UWB)(NJTransit, 2021).
North Carolina	Charlotte Area Transit System	The Charlotte Area Transit System has a new app that will allow passengers to track buses and pay for rides.	None. Note: Ultra-wideband technology is currently being investigated for UWB-

		Using the CATS-Pass app, users can see real-time locations and arrival times for buses across the CATS system. (First introduced in July 2017) However, NFC is not involved (Charlotte Area Transit System, n.d.).	based position and speed technology (Progressive Railroading, 2021).
Cuyahoga County, OHIO	RTA Rapid Transit	In addition to purchasing trip tickets online, the company also offers GoPass card and smartphone application to travellers. Vix enabled Dallas Area Rapid Transit (DART) to modernize its fare payment options with a state-of-the-art, account-based, open payment fare collection system (First mentioned in November 2016). Allows NFC-enabled smartphones, third-party or agency-issued transit cards and cEMV contactless bank cards(VIX, n.d.).	None.
Colorado	Regional Transportation District	Partnered up with Masabi to offer Software-as-a-Service ticketing and payments to public transport in January 2019. Masabi first launched mobile ticketing services for RTD in the fall of 2017 with the popular RTD Mobile Tickets app and this new functionality will further enhance the rider experience, enabling more seamless and convenient journeys. Technology concepts include mobile ticketing through online payment and QR code upon request for validation (Gooch, 2019).	None.
Los Angeles County, California	Los Angeles County Metro Rail	The company has implemented an electronic fare collection system through stored value smartcard known as Transit Access Pass. (TAP card) Recently TAP allows the user to use own personal smartphone as contactless fare payments. However, this requires NFC enabled devices to do so. Riders can either add the card directly through Apple Wallet and load Stored Value or download the TAP mobile app for account management, regional trip planning and access to all passes (September 2020).	None.
Greater Miami	Miami-Dade Transit	The Easy Card system is a series of linked contactless smartcard systems. It allows for electronic payment and is used by scanning them at card readers along the transport station. (RFID) In addition to the Easy Card system, Miami-Dade Transit implemented a system called Easy Pay, which you can download via App Store or Google Play, which allows payment of transit fares, and soon college easy ticket, using a smartphone. Once a fare has been purchased and activated, a QR barcode is generated containing the fare that can be scanned at selected turnstiles or shown to bus drivers. Later on in August 2019, Visa, Mastercard or Amex contactless cards can be accepted. (NFC)(Wikipedia, n.d.)	None.
Minneapolis – Saint Paul Metropolitan Area	Metro	Use cash or a credit card to buy a ticket from the ticket machine on the station platform, validate your Go-To Card or pass at the card reader on the platform or use the Metro Transit mobile app (Recently updated in July 2021).	None.
City of New Orleans and Orleans Parish, Louisiana	New Orleans Regional Transit Authority	The GoMobile app allows the user to track buses, purchase any fare type including senior fares, purchase tickets for buses and plan the trip. Use the wallet button to purchase the ticket before boarding. A QR code will appear once you activate the ticket (July 2018) (Non-NFC)(RTA, n.d.).	None.

Washinton	Port Authority of Allegheny County	The Port Authority of Allegheny County said it's looking to recruit up to 400 participants to try its new touchless mobile ticketing pilot program before it launches to a wider public audience. (2020) By using a free app on a rider's smartphone that is connected to their debit or credit card, the pilot program will allow riders to walk onto and ride a Port Authority bus after scanning their phone on a dashboard display, a process that takes almost the same amount of time as tapping a ConnectCard (Public release in August 2021)(Mass Transit, 2021).	None. Note: Investigation is currently on for ultra-wideband as a proposed solution for crowdsourcing (Traut & Steinfeld, 2019).
Portland Metropolitan Area, Oregon	Trimet, Portland Streetcar	Recently introduced Hop Fastpass as a contactless payment system. The user can buy and reload a Hop card at different retailers including supermarket. The card uses a close-loop transaction and simply requires the user to tap on and tap off (April 2018). Mobile wallet payment has also been recently adapted. This allows the traveller to pay their fare instantly with credit or debit card in Apple Pay, Google Pay or Samsung Pay (NFC)(Altstadt, 2018).	None.
Sacramento, California	Sacramento Regional Transit District	Littlepay's transit payments platform plugs-and-plays with a range of ticketing technology and financial institutions to deliver an end-to-end contactless ticketing solution. Riders using SacRT's Green Line light rail trains can now simply tap their contactless credit, debit, prepaid card or digital wallet on readers as they board (June 2021).	None.
Greater St. Louis	Metroblink	Passengers may also load fares onto a Gateway Card, a multi-use smart card that can be obtained at Metro's downtown retail store (RFID). Metro Transit also offers first- and last-mile connections to Metro with its Transit+ feature. For certain trips, Transit will suggest taking an Uber or Lyft part of the way, and connecting with MetroBus or MetroLink service. This first-of-its kind feature allows you to plan, book, and pay for a ride-sharing trip, while getting real-time updates on your connection — all in one app (MaaS focused) (March 2019)(Hibbard, 2019).	None.
Wasatch Front, Utah	Utah Transit Authority	Open the app on your mobile phone to plan a trip and purchase tickets. Add a credit or debit card for purchases. You can buy your tickets prior to riding and activate them when you are ready to ride. Unused tickets will expire after 90 days. Once you activate your ticket a countdown clock will show how much time you have before your ticket expires. When the screen is tapped, it will flip to an animated QR Code (September 2017) (None of NFC)(UTA, n.d.). The company has rejected Apple Pay, Google Pay or contactless credit cards starting on 4/8/2018.	None. Note: WSP is also helping UTA develop and pilot a Mobility as a Service (MaaS) program for new and existing transit riders, a micro transit pilot program to improve transit access, and an autonomous vehicle demonstration project in partnership with the Utah Department of Transportation (WSP, n.d.).
San Diego County, California	San Diego Metropolitan Transit System	PRONTO cards serve as a contactless payment option for the travellers. The cards are available at retail outlets. The PRONTO system replaces the Compass Card and Cloud system entirely. The system also includes smart phone application where the user can purchase the ticket via the app and show the QR code when going on board (First introduced in August 2021)(Mass Transit, 2021).	None.

2.2 Country – Europe

Region / State	Road Agency	NPC App Introduced Time	Frictionless ticketing / Observation
Austria	Austrian Federal Railways	(December 2018) Municipal transport stops are endowed with special machines where you can buy a ticket with the help of a bank card. However, contactless payments are still unavailable.	None. Note: 5GRail participants will validate specifications for FRMCS by developing and testing prototypes of trackside infrastructure and onboard applications in Germany and France by the middle of 2023. The UIC is aiming to deliver an FRMCS first edition based on 5G (3GPP Release 17) in 2025, which will be available for national pilots(IRJ, n.d.).
	Wiener Lokalbahnen	The Easymobil app is introduced in February 2020. With just a few clicks you can buy tickets for the Badner Bahn and the entire Eastern Region (VOR) on your mobile phone and always have your ticket with you. In addition to the ticket purchase, the app shows routing options and current departure and fault information.	None.
	Wiener Linien	Online ticket shop Can be purchased in vending machine and punched in a validating machine. Buy ticket on the WienMobil app or the Wiener Linen ticket app (QR Code) (March 2021)	None.
Brest, France	Brest Tramway	(September 2020) Users of the Bibus public transport network in the Brest Métropole area of France can now use their contactless payment cards to buy tickets on buses, trams and cable cars, transfer from one mode of transport to another at no additional cost, and pay for as many as six passengers with a single card. (NFC) This solution is compatible with all banks and contactless payment cards affiliated to MASTERCARD and VISA(Tom Philips, 2020).	None.
Germany	Bonn Stadtbahn	(November 2020) First contactless public transport ticketing system in Germany starts in Bonn. Passengers will now hold their contactless credit card in front of a validation device both when boarding and alighting in order to pay for their journey. The payment process is just as easy to handle once the card data is stored on a smartphone (NFC)(Scheidt&Bachmann, 2020).	None.
	VWG Oldenburg	(February 2021) Passengers simply tap or wave their bank card or mobile device over the card reader on the new pc-based ticketing machines to pay their fare. They do not need to enter a PIN and payment is received as quickly as it does when purchasing items in any retail setting. With their hybrid card readers these new units support EMV credit and debit card payments as well as all types of existing e-ticketing. The hardware migration is a particularly important step with regards to this year's upcoming switch to up-to-date 4G and 5G mobile radio standards in Germany (NFC + EMV)(Karlsruhe, 2021).	None.
	The Rhein-Main-Verkehrsverbund GmbH (RMV) and Rhein-Main Verkehrsverbund	GPS assisted mobile ticketing. (FAIRTIQ) As soon as the system suspects that a public transport journey has ended, it starts a countdown and sends a push notification to the user's smartphone. The user can simply let the app check them out automatically. Alternatively, the user can check out manually or stop the countdown if they	<-

	Servicegesellschaft GmbH	want to continue their journey (May 2021)(Fairtio, 2021).	
	Stadtwerke Osnabrück	By 2022 the number of e-buses is expected to rise to around 60. By then, Stadtwerke Osnabrück will be operating one of the largest fleets of e-buses in Germany. A Bluetooth and low-energy transmitter (SiMobility beacon) in the buses is used to record the customer's exact route data and compare it with the GPS position data of their smartphone. The beacon works independently without connection to a data network and sends encrypted, dynamic broadcast signals to the VOS-pilot app. The third aspect, outside of GPS position determination and beacon technology, is the motion technology within smartphones. With this, it is possible to detect whether the customer is sitting on the bus or, for example, walking beside the bus. In the medium term, this system will significantly reduce the standing times of buses with Check-in/Be-out, as payment on boarding is no longer required. At the same time, we will improve access to public transport and reduce existing inhibitions. The attractiveness of bus travel will be significantly increased. In the long term, however, we could even envisage a Be-in/Be-out system in which check-in and check-out are fully automated via smartphone recognition, but we are still at the very beginning of the technical development for this (May 2020) (Blome, et al., 2020).	<-
	Azienda Tranporti Bergamo and Tramvie Elettriche Bergamasche	(August 2021) Conduet Transportation announced the successful implementation and rollout of contactless payment system that allows tickets to be purchased directly onboard buses and funicular railways. Conduent validators allow riders to access the services using major contactless credit and debit cards, including Visa, Mastercard, Maestro, American Express, and NFC-enabled devices. These devices include smartphones and smart watches with digital wallets, such as Google Pay, Apple Pay and Samsung Pay(Conduent Business Services, LLC, 2021).	None.
Italy	ATAC Rome	(September 2019) Passengers using the subway and local trains in the Italian capital city of Rome can now use their contactless bank card to pay for the journeys they make each day — and can also opt to use their card as a replacement for their monthly travel pass. The service supports MasterCard, Visa, American Express, Maestro and Vpay contactless cards as well as Apple Pay, Google Pay and Samsung Pay. It is live at all A, B/B1 and C line underground stations and on Rome-Lido, Rome-Viterbo and Termini-Centocelle rail services(Clark, 2019).	None. Note: In the future, public transportation will be handled at the table, anticipating routes, schedules, priority traffic lights, and so on. Within an intelligent system, in fact, the possibility of having a flow of continuous data and a system to keep all the elements in a continuous dialogue allows you to multiply the overall efficiency of the integrated system(SportsGaming.win, 2020).
	Gruppo Torinese TRasporti (GTT), Turin	(July 2020) Travellers using the subway and selected bus services in the Italian city of Turin can now pay for their rides by tapping on and off public transportation using a Visa or Mastercard contactless card or their NFC phone. The service is currently available across the subway network and on the 18, 55, 56 and 68 urban bus lines. It will also be available on the 50 new electric buses and 30 new trams that the city is introducing next year(Clark, 2020).	None

Russia	Mosgortrans Urban Carrier, Moscow	(September 2019) From September, pay travel fare by bank card or smartphone on all routes of Mosgortrans urban carrier, including some 800 bus, tram, trolleybus and electric bus routes. To pay for a trip, touch the advanced validator with your bank card or mobile device. Their screens are to have payment system icons to buy a ticket. Passengers may pay fares using cards with PayPass and PayWave, and smartphones with contactless payment.	(5G) The new generation network will allow the transport operator to launch new operational technologies as well as passenger services, for example 5G terminals, robotic assistants, and also to apply AR technologies. Among advantages that 5G might bring, the authority cites higher data rates, lower latency and high-quality connection.
	Moscow metro	Passengers travelling on Moscow Metro can now buy and top up a Troika transit card directly from within their mobile banking app. The service is available to customers of Russia's Sberbank and enables them to use its mobile app's 'payments' section to purchase a new Troika card or replenish an existing one by entering their Troika card number. (February 2020)	Moscow Metro announced in January this year that it is to roll out Troika contactless ticketing across the Russian capital's entire public transportation network by the end of 2021 (Moscow Transport, 2021).
United Kingdom (UK)	Transport for London	Close to all contactless Visa, Maestro, MasterCard and American Express debit and credit cards issued in the UK, and also most international cards supporting contactless payment, are accepted for travel on London Underground, London Overground, Docklands Light Railway, most National Rail, London Tramlink and Bus services. Mobile payments - such as Apple Pay, Google Pay and Samsung Pay - are accepted in the same way as contactless payment cards (First mentioned in September 2014)(Transport for London, n.d.).	None
	Eurostar	Currently require online payment as well as any eVouchers. Eurostar Trains app allows the user to book tickets, quick access to mobile tickets and access live train times and travel alerts. (First introduced in 2017) After purchasing the ticket, the barcode will be presented as the traveller goes on board the train.	(By March 2021) Biometric system to reduce need for passports. Allowing them to prove their identity by walking through a camera-lined corridor instead of presenting passports and boarding documents. Mr Bud emphasised that the system would be opt-in, and that iProov simply verified the faces of travellers with images submitted earlier, rather than attempting to recognise personal identities from a mass database(FT, n.d.).
	First Group	UK bus operator First Group has partnered with ITSO Transit Hub Ltd to deliver ITSO-compatible mobile ticketing to First Bus passengers through Google Pay. The mobile ticketing technology enables passengers to securely purchase, fulfil and use their First Bus ticket on their Android mobile phone. Integrated with mobile ticketing provider Corethree, the solution delivers First Bus tickets within seconds from the operator's app directly into the passenger's Google Pay digital wallet. The virtual ticket is then instantly recognised by validator machines, supplied by Ticketer (November 2019) (Intelligent Transport, 2019).	

2.3 Country – China

Region / State	Road Agency	NPC App Introduced Time	Frictionless ticketing / Observation
Hong Kong	Hongkong Metro: http://www.mtr.com.hk/en/customer/main/index.html	**Scan and go**: With the QR code, you can get through the gates with just a scan of your mobile. **Easy payment:** Pay for your rides by AlipayHK EasyGo or MTR Mobile QR Code Ticket. The fares will be deducted directly from your mobile wallet. You can review the history of your QR code travel and payment on MTR Mobile if you pay by MTR Mobile (MTR, 2021).	None in Metro.
Taiwan	Taipei Metro: https://english.metro.taipei/Default.aspx	Taiwan doesn't have NFC technology for Metro, but they do launch this technology in airport. (Taoyuan Metro company will launch contactless payment via bank cards on 16 January 2020 to serve passengers travelling to and from the capital city of Taipei and Taoyuan International Airport.) (Paul, 2019).	None in Metro.
Beijing	Beijing subway: https://map_en.bjsubway.com/	Beijing Metro fully supports scanning code from September 20, 2017. Users can directly use the NFC function in the mobile to pass the gate machine (Zhou, 2017).	Beijing, China introduces biometric facial recognition tech which cooperates with Alibaba Group on train and railway station in Beijing Railway station. There are 30 self-service ticket checking machines with facial recognition technology in January, 2020 (Pascu, 2020). Hats, scarves, and smog masks off so the facial recognition system could get a clear picture of their face. Passengers also had to put their national identity card in the machine (CHAN, 2019).
Shenzhen	Shenzhen Metro: https://www.szmc.net/szmc_en	Shenzhen Metro Ticket QR Code: Passengers can register an account through a smart phone at WeChat Transit QR Code Mini Program, the official Shenzhen Metro App, MTR (SZ) live+ Mini Program or Shenzhen Metro E-Travel Mini Program and activate the account's ticket function. After successful opening of the account, Passengers can scan the generated Transit QR Code to pass through the gate for riding (SZMC, 2021).	A local subway operator in Shenzen is testing facial recognition subway access, powered by a 5G network, as spotted by the South China Morning Post. People entering the station can scan their faces on the screen where they would normally have tapped their phones or subway cards. Their fare then gets automatically deducted from their linked accounts. They will need to have registered their facial data beforehand and linked a payment method to their subway account. Shenzhen Metro did not elaborate when it will roll out the facial payment service (Identity-week, 2019).
Guizhou	None in English version	None	GUIYANG, July 1 (Xinhua) -- Subway and Bus Rapid Transit (BRT) systems now support payment by face scanning in Guiyang, capital of southwest China's Guizhou Province. To access the service, citizens need to download and register on a mobile application. After ID verification and facial recognition on self-registration terminals, citizens can take subway or BRTs simply by having their faces scanned. According to the city's government, this service is an important trial in the integrated development of the internet, artificial intelligence, transportation, city management, and market transactions *(Lab, 2021) (huaxia, 2020).*
Shanghai	Shanghai Metro http://service.shmetro.com/en/	Near-field communication (NFC) technology, which is already undergoing trials on Beijing's subway lines, may also be welcomed by Shanghai metro. Once the card readers needed for Alipay are upgraded, they will hold the technology to be able to accept various modes of payment (Press, 2018) (Nolan, 2018).	Shanghai subway to use Alibaba voice and facial recognition systems in AI push. The operator of the Shanghai Metro, Shanghai Shentong Metro Group along with the developer group plan that "far-field" voice recognition technology will be installed in ticket machines in all stations. To verify the identity of passengers they will set facial

			recognition systems at the entrance of stations. The initial plan to implement this system is to have passengers input their destination to the AI enabled ticket machine, then it will suggest the best route for that destination. It's important to mention that there are more than four thousand trains serving the Shanghai Metro network, which has 367 stations altogether (Perez, 2017) (Kubilius, 2017).
Hangzhou	China discovery: https://www.chinadiscovery.com/zhejiang/hangzhou/hangzhou-metro.html	NFC is not used in Hangzhou at the moment, but they use QR code to enter the gate. (The passengers need to install a mobile payment app and they will get a QR code on their phone, which they can use to enter the electric gate) (SHICONG, 2018).	None
Guangzhou	Guangzhou Metro: https://cs.gzmtr.com/ckfwEnglish/	Guangzhou allows passengers to use Metro pay function. Put the phone onto the reader on turnstile to go through the turnstile (KOP-SEE, 2019).	Instead of using tickets or swiping their smartphones, passengers can smile at a screen to unlock the electric gates in about half a second after completing a real-name registration on Guangzhou Metro's official mini-program on WeChat, China's popular social media platform (Clark, 2019).
Nanning	none	none	Nanning metro promoted a dynamic facial recognition system at stations on all its lines for residents to pay for tickets through facial recognition. Dynamic facial recognition, also known as fully non-inductive facial recognition, refers to technology that enables automatic facial recognition as long the person's face appears within the camera's view. Users can complete the identity recognition while walking. After registering on the official mobile app of Nanning Rail Transit, passengers can bind their Alipay or WeChat Pay account on the app to make password-free payment and pass the subway gate by dynamic facial recognition (MXJ, 2020).
Chengdu	None	None. The Chengdu subway doesn't accept Apple Pay and several other payment apps that use NFC -- a more secure alternative to the QR code (Chiu, 2019).	Passengers in Chengdu, capital city of Southwest China's Sichuan Province, can pay by scanning their faces at the turnstile at subway stations from September 1. In addition, the new technology allows passengers to use facial recognition devices while wearing masks in accordance with pandemic related health rules. Passengers need to apply for real-name registration on the application when opening scanning service, in order to protect the security of their financial accounts In response to users' doubt on the privacy security, Chengdu Metro said that the application will not store and collect personal information of passengers, in strict abidance with national laws and data privacy standards. In order to guarantee the security of private data, China has passed its Personal Information Protection Law on August 20, which is set to be implemented on November 1, requiring suspension or termination of services for apps that illegally process personal data (Times, 2021).

2.4 Country – Japan

Region / State	Road Agency	NPC App Introduced Time	Frictionless ticketing / Observation
Osaka	Osaka Metro: https://www.osakametro.co.jp/en/ No information about frictionless ticketing.	None	Some news say the Osaka Metro began testing facial recognition gates on the city's subway in December 2019. Only one person can be detected at one time and faces need to be registered in advance (Phillips, 2020) (Pascu, 2020).
Tokyo	Tokyo Metro: https://www.tokyometro.jp/en/	Suica is a contactless card that is most often used on Japanese public transport; you charge it with money at a ticket machine, then tap the gates at any train station or the readers inside buses and taxis. It's based on Felica technology, an early form of NFC developed by Sony (Byford, 2016) (Apple, 2021).	None
Sapporo	Sapporo station: https://www.sapporostation.com/sapporo-subway-namboku-tozai-and-toho-lines/	None	None https://www.city.sapporo.jp/st/english/fareandticket.html
Yokohama	City of Yokohama: https://www.city.yokohama.lg.jp/lang/residents/en/bus-subway/default20200310.html	Suica apple pay (Apple-Pay-Japan, 2017)	None
Nagoya	City of Nagoya: https://www.kotsu.city.nagoya.jp/en/pc/MANACA/TRP0001352.htm	None	None

2.5 Country – South Korea

Region / State	Road Agency	NPC App Introduced Time	Frictionless ticketing / Observation
Seoul	Seoul Metro: http://www.seoulmetro.co.kr/en/page.do?menuIdx=644	Mobile KOREA TOUR CARD is the mobile app version of the KOREA TOUR CARD. (Including the public transit service of Tmoney) With the NFC function of your mobile phone, users can use it to pay for public transportation (subway, bus, taxi, etc.) (KOREA-TOUR-CARD, 2021). Since December in 2015, Samsung pay worked in subways and on buses (HO-JEONG, 2015).	In 2021, the introduction of payment based on facial biometrics also began in the Seoul metro. To get access to the service, passengers need to upload a selfie to the service's mobile application and link a bank card to their account. The face recognition equipment installed in the turnstile area is able to identify users even if they are wearing medical masks (recfaces, 2021) (Phillips, 2021).
Gyeonggi-do	None	None	Korean buses with Bluetooth fare payment. Passengers travelling on three inter-regional bus routes in South Korea's Gyeonggi-do province can now test a 'tag-less' fare payment system that enables them to pay for their tickets without needing to tap an onboard contactless reader with their transit card or smartphone. The system uses Bluetooth technology to enable onboard fare readers located close to the bus doors to detect a Bluetooth signal from a passenger's smartphone when they board and alight from the vehicle. To use the service, passengers first install a 'tag-less pay' app on their smartphone and register a pre- or post-paid transit card that is charged automatically for their fare payments. "In addition, if a passenger presses the app's mobile drop-off bell button before getting off the bus, an alarm is displayed to the bus driver that there are passengers getting off, eliminating the need to manually press the alight bell or to get up and move." (Phillips, 2021) .
Busan	Busan Metro: https://www.busan.go.kr/eng/index	Support T-money feature (Flying-chalks, 2021)	None
Incheon	Incheon metropolitan city: https://www.incheon.go.kr/en/EN030202	Support T-money feature (Lui Gough, 2019)	None
Daegu	Daegu metro: https://www.dtro.or.kr/open_content_new/eng/	Support T-money feature (Wikipedia, 2021)	

2.6 Country – Indonesia

Region / State	Road Agency	NFC APP INTRODUCED TIME	frictionless ticketing/observation
East Jakarta	None	None. They use card-based ticket (ExploreSunda, 2021).	None
Surabaya	None	None	None
Bekasi	None	None	None

2.7 Country – Thailand

Region / State	Road Agency	NFC APP INTRODUCED TIME	frictionless ticketing/observation
Bangkok	None	Mobile ticketing based on NFC technology is gaining prominence and several cities use this technology. These include Bangkok, Beijing, Hong Kong, Jakarta, Manila, Shanghai, Singapore and Tokyo (Global-Mass-Transit-Report, 2016).	None
Ayutthaya	None	None	None
Chiang Mai	https://traintochiangmai.info/buy-train-tickets-to-chiang-mai/	None (They only accept printed tickets for travel on trains) (TRAIN-TO-CHIANG-MAI, 2021).	None

2.8 Country – Philippines

State	Road Agency	NFC APP INTRODUCED TIME	frictionless ticketing/observation
Manila	Philippines metro: http://mrt3.com/index.php/menu-fare-tickets City of Manila: https://manila.gov.ph/?s=transport	None	None

2.9 Country – Singapore

Region	Road Agency	NFC APP INTRODUCED TIME	frictionless ticketing/observation
Singapore	https://www.visitsingapore.com/en_au/travel-guide-tips/getting-around/	Singapore has adopted the Near Field Communication (NFC) technology where you are able to use your smartphones to make payments when taking the public transport. It is launched in 2016 (Tan, 2021).	None

2.10 Country – Vietnam

State	Road Agency	NFC APP INTRODUCED TIME	frictionless ticketing/observation
Ho Chi Minh City	None	It allows bus passengers to pay for their ride by swiping their near-field communication	None

		(NFC) cards on the bus to pay money from their UniPass account (Tre, 2021).	
Hanoi	None	None	None

2.11 Country – Malaysia

State	Road Agency	NFC APP INTRODUCED TIME	frictionless ticketing/observation
Kuala Lumpur	None	The CEO said it also plans to offer the service with other telecommunication companies as well after six months. The company has been piloting NFC smartphone apps with mobile operator Maxis and bank CIMB to allow customers to use their mobile devices as a Touch 'n Go card (Qing, 2017).	None
Penang	None	None	None
Georgetown	None	None	None

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