Whitepaper

5G and Mobile Robotics

Scaling for the future of robotics.

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Introduction

Mobile robotic systems such as Unmanned Ground Vehicles, Unmanned Surface Vehicles, Unmanned Aerial Vehicles and Autonomous Underwater Vehicles are becoming increasingly prevalent today with a broad number of applications including defense, medical, logistics, manufacturing support and personal use. With the rise of Artificial Intelligence and Machine Learning, many of these systems can function in autonomous or semi-autonomous states.

For the sake of this paper, the focus will be on mobile robotic uses in the manufacturing space and how communications will need to evolve to account for the specific needs of this use case.

“Our products connect millions of devices around the world and enable our customers to widen their market and improve their business. HMS’ long expertise, large installed base, and wide market coverage, make us the undisputed market leader of our field. HMS stands for Hardware Meets Software™. HMS products, solutions and know-how enable industrial hardware to get connected to IoT software. As such, HMS enables the Industrial Internet of Things which is all about Connecting Devices™ “

Staffan Dahlström, CEO
HMS Networks
Mobile Robotic Market

To get some perspective on how critical this will become over time, it is beneficial to gain some perspective on how fast the market is growing. If the entire scope of applications are considered, some estimates size the market at $54.1B by 2024 ($18.7B 2018) which amounts to a 23.71% CAGR, but if the focus is narrowed to Autonomous Guided Vehicles (AGV) that are used in logistics and manufacturing support the market is expected to reach around $12B by 2025 with an estimated 15.8% CAGR as shown in Figure 1. This is based on a rough averaging of multiple sources as data is somewhat variable.

The key takeaway when looking at the market growth for these devices is that they are going to continue to be a significant and increasing part of our manufacturing and logistics environment.

As numerous human workers occupy these spaces, it will be critical to ensure that these systems can coexist safely. In this paper, we will address how these systems work in their current ecosystems, the challenges that are presented and how 5G communications technology could be used to address some of these challenges.

Figure 1
Understanding the Ecosystem

To understand how communications must evolve to meet the needs of mobile automation, it helps to understand the ecosystem within a warehouse or manufacturing plant they operate in. When one considers AGVs, they often do not simply consist of the base vehicle but are often integrated with other automated components for assembling or positioning material.

These systems also interact with other machinery in a warehouse or factory. Figure 2 provides a snapshot of the potential ecosystem that mobile robots work in. The AGV itself manages most of its internal controls from the AGV Controller that interacts with control systems for Steering, Drive, Power and Collision Avoidance.

These systems typically communicate over deterministic control networks based on technologies such as CAN or industrial Ethernet (ex. EtherCAT, EtherNet/IP, PROFINet, etc.) as the data exchanged is critical for coordinated control functions and safe operation. Within these self-contained systems, the devices are typically on copper-based networks so wireless communications is seldomly required.
AGVs are most often interconnected with some form of robotic system on the vehicle. A couple of example applications would be operating a lift system for transporting material on pallets or racks, or as a mobile loader placing material into or removing material from a machine cell. These robotic control tasks may not be integrated into the AGV controller but operated by a separate controller. This control system does however need to be interlocked with the AGV controller as their tasks are cooperative in nature and while they are separate control systems, they are often integrated on to the same copper-based network.

The navigation for the AGV is handled by some form of traffic management software which applies maps of the facility the AGV is operating in to do path optimization. This may be a stand-alone application or integrated into a Warehouse Execution System. Since these applications run outside of the local control network of the AGV typically on PCs or servers, it is not feasible for the AGV to interact over a physical medium so wireless technologies are used for these interfaces.

This is also true for the plant or warehouse machinery that the AGV and robotic system need to interact with during the performance of its tasks. These include but are not isolated to static systems such as manufacturing cells, automated storage and retrieval systems, robotic cells and automated conveyors. Wireless communications allow critical control and safety data to be exchanged.

It is important to understand what type of data is typically exchanged in these systems and how important network reliability is for certain types of information. Slow-moving variables such as power levels or other environmental measurements can be more tolerant of network inconsistencies while control and safety data need to pass over extremely reliable networks with consistent time cycles. It is difficult for a manufacturing process to be productive if there are network errors when a mobile robot is trying to interact with a machine cell and neither system can effectively move forward in their task without the data exchanged.

In this paper, we will often refer back to safety data during the following topics. Formerly, safety circuitry had to be hard-wired and could not move over a network, but this has shifted and there now exist safety network protocols such as CIP Safety, PROFIsafe and FSoE (Functional Safety over EtherCAT) among others. In addition to running over copper-based networks, this data can move over wireless networks as well. The key with safety data is that the network and the data is reliable, not necessarily fast.

Most networks measure network reliability in terms of packet loss, but this is less important for safety data. The safety protocols can handle packet loss though the minimum safe reaction time may be impacted. Safety applications are far less tolerant of bit errors since this brings into question the integrity of the underlying data.

Safety protocols running over Ethernet typically have a residual bit error tolerance of less than 1 out of 100 bits. Unreliable network connectivity can lead to bursts of these bit errors sending the safety network into a fault state.
Wireless Networks for Mobile Robots-Today

The most commonly used technology for wireless connectivity to mobile robotic systems is based on the IEEE 802.11x set of standards commonly known as Wi-Fi™. These networks transmit at publicly available frequencies within either the 2.4 GHz or 5 GHz space and are sliced into channels usually 20 MHz or 40 MHz wide (adjacent channels bonded).

These channels are essentially the pipes that data can pass through and the width of these channels significantly impacts throughput in the system. Over time, the IEEE 802.11x specification has evolved to incorporate changes in areas such as radio modulation and antenna structure (MIMO) to improve overall system throughput and reliability. Updated standards such as 802.11n and 802.11ac can realize networks speeds of several hundred bits per second.

802.11x-based networks are based on the lower layer Ethernet protocols for its network structure with both its use of MAC addressing for unique device identifiers and IP protocols for logical network addressing. This gives a rough network capacity of 255 devices (including Access Point) on a single subnetwork.

One amendment under 802.11 that is heavily used in mobile automation applications is 802.11r, which is a provision for fast roaming between access points. 802.11 already has support for roaming but in normal operation this requires re-authentication when transitioning between access points which can result in reconnect times amounting to several seconds, which can be unacceptable in automation applications, particularly with control and safety data.

With 802.11r, the authentication key can be cached allowing transition times to be reduced to a few milliseconds (30-50ms typically). Figure 3 shows an example of 802.11r in action. With the higher throughput wireless standards (802.11n and 802.11ac) plus 802.11r fast roaming, 802.11 has gained greater acceptance inside the factory.

![Network Diagram](image)
802.11 Limitations and Considerations

Wireless is being effectively used today for some challenging applications but like any communications technology, there are limitations in performance that must be considered when implementing. For the sake of this paper, we will consider factors that impact scalability and reliability of 802.11-based networks.

There are a couple of factors that affect the scalability of 802.11-based networks. While the theoretical limitation of a single IP-based subnetwork segment is 255 devices, the practical limitation is significantly fewer devices. This is due partially to the fact that 802.11 channels at 2.4 or 5 GHz are typically 20 MHz or 40 MHz wide and that all devices on the network need to share that channel. As the number of devices increase, smaller slices of bandwidth are available for each device to pass data through which can impact performance of the overall system. Specifically, for safety data, this may mean that longer timeouts need to be used and that the minimum safe reaction time may be longer than desired for the application in question. In those cases, the network may need to be de-scaled to allow for enough bandwidth to the devices on the network.

Additionally, 802.11 is based on publicly available, unlicensed frequencies, which means that the channels may be shared by multiple networks, further reducing the amount of available bandwidth. This is difficult to avoid at 2.4 GHz frequencies as there exist only four (4) non-overlapping channels that can be used for networks and it should be expected that 2.4 GHz channels will be shared.

Higher throughput channels in the 5 GHz spectrum are more readily available with fewer overlapping frequencies and are being increasingly used for critical applications. This will come under strain over time as more networks are configured in the 5 GHz space. Reliability can also be a challenge when using 802.11-based networks. The biggest factor that impacts network reliability is signal interference, particularly at 2.4 GHz frequencies.

As previously mentioned, these frequencies are available publicly and while 2.4 GHz is most closely associated with 802.11 networks, this frequency is used by other devices and communications technologies including cordless handsets, microwave ovens, Bluetooth and Zigbee among others. In addition to accounting for the density of networks in the spectrum, the noise generated by these other devices can have significant impact on the quality of communications.
Figure 4 below features an example from a spectrum analyzer of a manufacturing facility featuring both significant congestion on the 2.4 GHz assigned channels and significant noise from other signal generators in the spectrum, including other 802.11 networks on nearby frequencies. The sum of these secondary signals is referred to as the noise floor and the difference between this noise floor and the overall signal strength is referred to as the Signal-to-Noise Ratio (SNR). When the SNR is too low, packets loss and bit errors can occur leading to fault states or loss of critical data. This particularly important when looking at safety data, which as previously mentioned is sensitive to bit errors and is a critical part of the mobile robotics system.

In addition to congestion, the presence of physical objects can impact the reliability of wireless communications. In a perfect environment, wireless transceivers connect with each other over open air, but this is not practical in a manufacturing environment, as there will be machinery and building structures to contend with. Absorption or reflection of wireless signals by structures can significantly reduce the effective range of these networks and create holes where signals may be lost completely. Materials such as solid metals and concrete provide the biggest challenges for wireless signals. Loss of signal can lead to bit errors and timeouts, which can negatively impact safety communications.

The practice of roaming between access points, which is to be expected in most manufacturing facilities, can also have negative impacts on critical communications. 802.11r mitigates this significantly, but if there are any issues during re-authentication that extends the hand-off significantly past the normal 30-50 ms timeframe, this can create packet loss and bit errors that can significantly impact control data and safety data.
Addressing Challenges with 5G Cellular

It is important to state that 5G cellular technology is still emerging and current implementations are limited, however there is much that is built into this network that will address many of the challenges currently posed by other wireless networks. Additionally, much has been written about the core capabilities of eMBB (Enhanced Mobile Broadband), uRLLC (Ultra-Reliable Low Latency Communications) and mMTC (Massive Machine-Type Communications) and will have limited mention.

The first challenge to focus on is the complications posed by running critical communications for mobile robots in unlicensed frequencies. With 5G, you have a mixture of licensed and unlicensed bands (5 GHz spectrum). Figure 5 shows the range of frequencies that will be part of the 5G spectrum. One slice of spectrum to make note of in North America is the 3.5 (3.55-3.7) GHz band known as CBRS (Citizens Broadband Radio Service) which has traditionally been reserved for naval radar communications.

This has been released to be used for semi-private networks. Instead of having to request a license for spectrum from a government entity or purchase a private network from a public provider, manufacturers can request a band from a Spectrum Allocation Server that then assigns the band based on terrain and RF density calculations. The benefit to the manufacturer is that as long as they are using lower power radios they can have wireless spectrum that is specifically allocated to their facility without interference from other networks. This in combination with the high speed (<20 GBPS) and low latency (<1ms) characteristics of 5G make this feasible for transmitting the critical control and safety data associated with mobile robots.

Another challenge that 5G technology helps address is the impact of physical structures on reliable wireless communications. While any wireless signal is impacted by structures, 5G can use reflected signals in a beneficial way. 5G supports the use of a high-density antenna construct known as massive MIMO (Multi-Input Multi-Output) and beamforming to optimize connection pathways.

Transmitters can broadcast signals in multiple directions while the receiver sees multiple copies of the same signal which is then either destructively averaged if out of phase or constructively summed if in phase. This increases the reliability of these connections with the added benefit of increasing throughput as well. With more reliable connectivity, critical communications for control and safety can be maintained. Figure 6 shows a simplified view of a multi-path system of Base Stations (BS) and end devices (ex. AGV) in a manufacturing environment.

<table>
<thead>
<tr>
<th></th>
<th>&lt; 1 GHz</th>
<th>1-3 GHz</th>
<th>3-5 GHz</th>
<th>5-8 GHz</th>
<th>24-28 GHz</th>
<th>37-40 GHz</th>
<th>64-71 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>600 MHz</td>
<td>1900 MHz</td>
<td>3100 – 3550 MHz</td>
<td>5180 – 5350 MHz</td>
<td>5470 – 5835 MHz</td>
<td>5925 – 7125 MHz</td>
<td>27.50 – 28.35 GHz</td>
</tr>
<tr>
<td>EU</td>
<td>694 – 790 MHz</td>
<td>3400 – 3800 MHz</td>
<td>5150 – 5350 MHz</td>
<td>5470 – 5876 MHz</td>
<td>24.25 – 27.50 GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>3300 – 3600 MHz</td>
<td>4400 – 4500 MHz</td>
<td>4800 – 4900 MHz</td>
<td>5170 – 5330 MHz</td>
<td>5735 – 5835 MHz</td>
<td>24.25 – 27.50 GHz</td>
<td>37.00 – 43.50 GHz</td>
</tr>
<tr>
<td>Japan</td>
<td>3600 – 4200 MHz</td>
<td>4400 – 4900 MHz</td>
<td>5180 – 5330 MHz</td>
<td>5490 – 5710 MHz</td>
<td>27.50 – 28.25 GHz</td>
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<tr>
<td>Korea</td>
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<td>26.50 – 29.50 GHz</td>
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<td>Australia</td>
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<td>5490 – 5835 MHz</td>
<td>24.25 – 27.50 GHz</td>
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The final challenge we will address is handover times associated with roaming. While 802.11-based networks supporting 802.11r minimize handover times to a few milliseconds, this can still impact critical communications. 5G technology addresses this by allowing devices to make connection to other base stations before separating from a previous base station as shown in Figure 7. This allows for seamless communications on the 5G network and eliminates the possible issue of timeouts and bit errors during handovers.

The final question is whether this can be scaled to meet a growing market for mobile robotics. While it is not expected that mobile robotics will be deployed to this scale, with support for mMTC (Massive Machine Type Communications) service on 5G, network density can achieve up to $10^6$ devices/km².
Afterword

Wireless technologies are gaining acceptance in manufacturing as the need to increase capacity within a limited physical footprint drives the need for mobile robotic systems that can be flexibly deployed. With existing wireless technology still presenting some technical hurdles, maximizing productivity of these systems can be challenging. 5G communications addresses many of these challenges and looks to have significant long-term impact on communications in manufacturing.

There are a lot of considerations when it comes to addressing connectivity on mobile equipment but fortunately solutions exist to ensure that critical data will be available when needed.

Automated Guided Vehicles (AGVs) are increasingly being used in manufacturing and warehouse operations for deployment of raw and finished goods. They employ complex systems for motion, safety, power management and traffic management often using multiple communications technologies. One of the biggest challenges is ensuring that these systems are interconnected so data can move seamlessly between different control tasks. Join HMS Networks for this 30-minute webinar to learn how we can help you overcome these challenges.

As Solution Manager for HMS Networks, Jason Block helps HMS customers and distributors enable IIoT by solving challenging applications for network interconnectivity and remote management using our Anybus, IXXAT, and eWON product lines. With over 20 years of experience, he brings value to customers as an analytical, consultative sales professional.

Jason Block
Solution Manager
HMS Networks
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