Low-Latency MAC Protocols for Real-Time Wireless Control Systems

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1 Introduction

1.1 Motivation for Real-Time Wireless Control

Real time wireless control systems are being used in lots of automation places now. The delay in communication is really important in these systems because it has an effect on how the machines work. You see sensors send information to the controllers. Then the controllers send commands back to the actuators. If the information gets delayed for long, the control process for the wireless control systems may not work like it should. Wireless control systems need everything to happen quickly so they can work properly.

Industrial control networks are different from networks. They cannot just send information and Hope it gets there. Industrial control networks need to know when the information will arrive. This is because industrial control networks need timing. Some recent studies on networking for industrial control networks show that having a structured way of accessing the network helps in keeping the timing stable [9]. Because of this, researchers are working hard on designing protocols, for industrial control networks. These protocols are called MAC protocols. The goal of these MAC protocols is to reduce delay and make the network more consistent. Industrial control networks need these MAC protocols to work well.

People like to use wireless communication in a lot of situations. This is because it gets rid of a lot of wires and makes it easier to design systems. Wireless networks can also cause problems like interference and collisions. Sometimes they even have to resend information again. All these things can make delays happen at many times.

When we talk about industrial IoT scheduling we see that it is really important to keep delays the same. This is often more important, than trying to send a lot of data at once [13]. So when we make MAC protocols for real-time systems we need to focus on making sure things happen in an order. We cannot just try to send as much data as possible.

Industrial systems these days need to be flexible. Production lines are often changed. Wireless communication helps with this flexibility. At the same time it is hard to keep the timing of things happening in a predictable way when the traffic conditions are changing.

Research on industrial communication systems shows that the way we access the system and the control requirements have to work closely together to make sure we have flexibility and that things happen on time [15]. This is why designing a system that can send information quickly called a low-latency MAC is an important area of research, for industrial systems.

1.2 Role of the MAC Layer in Latency Control

The MAC layer is really important because it decides how different devices use the channel. So when a lot of devices try to send information at the same time they can interfere with each other. This is called a collision. When collisions happen it takes longer for devices to send and receive information. It also makes it hard to predict when things will happen.

In IoT networks this can be a big problem because it can affect how well the system is controlled. Some people did research on something called slot allocation in 6TiSCH systems. They found out that when devices take turns sending information in a structured way it reduces delays and makes timing more consistent [7]. This just shows that the MAC layer is very important for controlling latency.

Traditional contention-based protocols are good for communication but they do not promise that messages will be delivered on time.For systems that need to work with timing people usually use slot-based or scheduled access.

The WiFi-based time-sensitive networking studies show that better scheduling can really help, even when things are moving around [2].This shows how important it is to have a MAC design for wireless systems used in industries.

The MAC layer also affects how reliable something is. It has rules for sending things handling priority and making reservations and all these things can make a difference in how long things take. In networks where things have to go through many hops even small delays can add up. People who study how to make communication predictable in wireless systems say that when we make decisions about access we have to think about what kind of traffic it is and when it needs to be done [12]. So modern MAC protocols use scheduling that is structured and coordination that can adapt to keep everything stable.

1.3 Impact of Latency on Control Stability

Delay in communication affects the level of control in a system. Late sensored data causes the controller to make decisions based on old information. This may cause future issues such as loss of accuracy or even instability.

It is especially important in the case of wireless systems to have strict regulations regarding the appearance of data to ensure that the system remains stable [12].

Control performance of the communication system directly depends on communication delay. Constant timing is also necessary, of the communication system and sensor data.

One of the issues that predominantly occur here is jitter. Jitter implies that the delay with which packets arrive may vary every time. This is also very important. The updates must be made simultaneously to many control algorithms. When the time is not always the same whenever the system is used, then it might not perform as it should be. Individuals conducted research on timing services within wireless systems and discovered that when everything is synchronized correctly it aids in the minimization of the variation in delay [3]. MAC protocols that do not cause things to wait arbitrary times can be used to reduce jitter.

In systems with a high number of devices operating simultaneously, delays and timing errors can accumulate. Although the average delay may appear fine, odd timings may influence processes. According to some deterministic networking research, the ability to control delay or jitter variations can be more important than simply minimizing the mean delay. Therefore, the MAC protocols governing the communication between devices should ensure that messages are dispatched at a predictable time particularly in a real-time control system.

1.4 Research Scope and Objectives

This paper looks at low latency MAC protocols for wireless control systems that need to work in time. The paper is focused on deterministic scheduling controlling contention in an adaptive way and using hybrid methods to get access. Research on 6TiSCH management found that when things are coordinated in a structured way it helps to make delays more stable in industrial settings [4]. These mechanisms are important for wireless control systems to have communication that is predictable.

Apart from designing protocols this study also thinks about scalability and integration with wireless systems. Looking at research on scheduling over time-sensitive networks it seems that giving resources in a smart way makes communication more consistent [14]. This paper looks at what other people have written in journals to see how the design of the medium access control layer helps make communication reliable and fast.

Industrial systems must also integrate with emerging technologies such as 5G and time-sensitive networking. Survey research on convergence between these technologies shows that cross-domain coordination is becoming important [11]. Therefore, this study not only examines performance aspects but also looks at practical deployment considerations.

2 Background and Conceptual Foundations

2.1 Architecture of Real-Time Wireless Control Systems

Sometimes a wireless control system is simply a mass a bunch of stuff sensors, controllers, actuators jammed into a wireless mesh. These sensors themselves are the ones that are providing the actual measurement about us and ping the data to the controllers. The controllers crunch numbers and make decisions and send the commands to the actuators on what to do. And they are required to do all that within a limited period.

Nowadays in factories and industries it is not a separate plumbing sheet that devices use to communicate with each other, but is an inseparable part of the control system itself. Control and communication The behavior of control and communication of wireless control are closely linked. The study done on fusing 5G with time-sensitive networking (TSN) indicates the extent to which it is imperative to synchronize the communication schedule with the requirements of the control loop [11].

The networks when we actually implement them tend to connect to wired elements in order to ensure that everything is on time. Imagine the 5G platform as an intermediary between devices and the time-sensitive networks that are highly sensitive. In that manner, there is the ability of the data to pass back and forth between various types of links in lockstep.

The 5G stack and wireless connections have the potential to work with older components in such a way that industrial controllers are able to communicate with both wired and wireless components without compromising the hard and fast data limits. Whereby when we consider wireless + TSN infrastructures we must, in actual sense, consider the way they blend. That is one of the reasons why automation stacks make the deadline. The integration of wireless and TSN is fundamentally the core of real-time, in the contemporary automation.

The entire system is a quilt of elements, and their interaction is summed up in Figure 1. By far, the most notable one is the delay in communication- it has the potential to disrupt the feedback loop of the system.

Radio conditions in the industrial deployments are regularly struck with gnarly conditions: interference, multi path fading, signal blockage-therefore you have retransmits and variable delay.

A set of papers by ultra-wide band real-time industrial connectivity was assembled [6]. In such studies, ultra-wide band is given to be in need of solid MAC-layer coordination, which is critical in short-range wireless fixes. It maintains performance at the trenches.

Latency in the network and performance of the control system are two inseparable sides of a coin. This means that we have to be holistic in designing the industrial deployments. That is what we refer to as cross-layer design awareness in ultra-wide band real-time industrial connectivity and the applications that are dependent upon it.

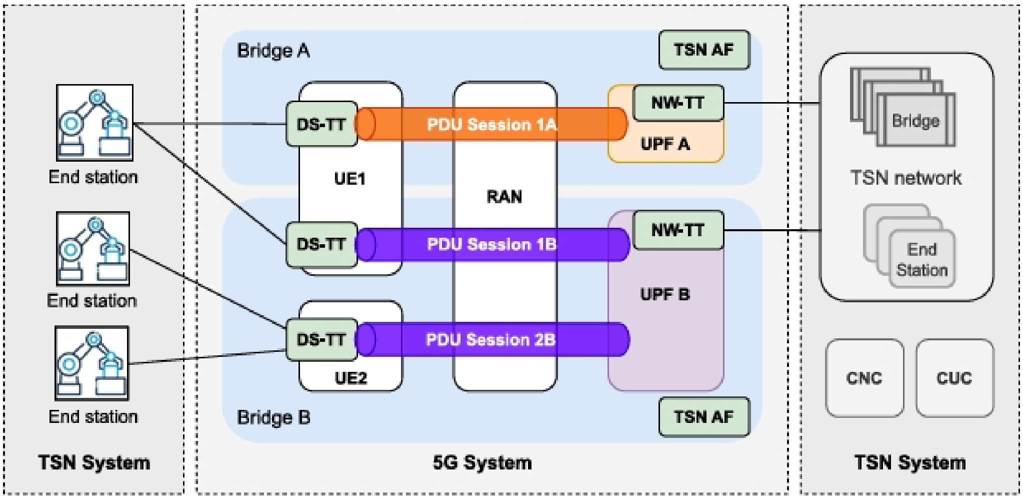

Figure 1: Architecture of a real-time wireless control system including sensors, controller, wireless network and actuators. Adapted based on concepts discussed in [11].

2.2 Latency Components in Wireless Networks

Delay in wireless control systems consists of a number of components among them: transmission time, processing time, queuing time, and time it takes to access the medium. Among them, medium access delay is the most difficult to predict since it is determined by the way all the nodes interact amongst themselves to gain an opportunity to transmit data.

In a number of studies investigating the implementation of reinforcement learning to schedule uplink traffic in latency sensitive networks it is demonstrated that smart scheduling decisions can minimize the variability of access delay [10]. The control of access to the medium by nodes is thus important in case we desire the communication to be predictable.

The perhop delay can slow the entire process even more in multi modular networks, or in distributed systems like industrial networks. Resource reservation schemes have been established by researchers to aid in timing in high performance systems such as automotive networks. As an example, resource reservation has been demonstrated to decrease deadline violations of time-sensitive vehicular networks [1]. This shows that we should be keen in establishing the rules of equation of communication in time critical systems of devices.

The time taken to connect to a network is based on how many devices are on the network and the policies used to decide what devices are allowed to transmit data. According to studies about autonomous allocation of slots in industrial IoT, structured scheduling minimizes the variability of delay with respect to contention-based access at the network level of access control and management [7]. One of the factors that should be considered is medium access delay.

2.3 Fundamental MAC Design Principles

In case we are designing a protocol of wireless control systems which must work in real time then we must ensure that the access of wireless channel is predictable. Devices should be capable of transmitting and receiving information at specified times and we also need to ensure that the data is passed through successfully.

The recent studies in AI-assisted management of radio resources in next-generation wireless networks indicate that delay limits have to be satisfied, particularly in mission-critical communication [8]. By avoiding collisions in the network we can reduce the rate of such collisions deterministic access control will minimize this, and by so doing we can guarantee that devices will have a chance to send data.

In the case of industrial automation communications, energy efficiency and scalability will be important. The research on automation architecture in the industry indicates that it is essential to strike a balance between latency performance, complexity, and scalability of the system [15]. Consequently, the MAC protocol design should take into account minimizing the latency and reducing the synchronization overhead and be able to extend the network.

The modern MAC protocols incorporate protocol features like guard intervals and synchronization-correction approaches. It has been proposed that timing services in advanced wireless systems are relevant, and careful clock synchronization is necessary when using scheduled communication to achieve efficiency [3]. The MAC-layer design based on these principles is more reliable to be applied in industrial changing conditions.

2.4 Performance Evaluation Metrics

We have to consider timing consistency, not merely speed, when we consider MAC protocols to wireless control systems. Closed loop control is highly reliant on end-to-end delay and jitter. Studies on cloud-fog automation systems indicate that foreseeable communication indeed enhances coordination in the industrial setting [5].

Reliability and meeting deadlines are also an issue to consider. Studies on the deterministic federated learning in time-sensitive networks indicate that smart resource distribution can be used to reduce wasted deadlines [14]. Latency, jitter, reliability, and deadline measurements allow us to understand the performance of the MAC protocols better.

The main metrics used to evaluate low-latency MAC protocols are summarized in Table 1.

Table 1: Performance metrics used to evaluate low-latency MAC protocols in real-time wireless control systems, based on concepts discussed in [9].

Metric	Description	Relevance to Control Systems
End-to-End Delay	Time required for a data packet to travel from sensor to actuator	Determines responsiveness and stability of the control loop
Jitter	Variation in packet transmission delay across communication cycles	Affects timing predictability and synchronization accuracy
Packet Delivery Ratio	Percentage of successfully delivered packets within the communication interval	Indicates reliability of wireless transmission
Deadline Miss Ratio	Proportion of packets exceeding predefined timing constraints	Direct measure of control performance degradation

3 Core Concepts and Approaches

3.1 Deterministic Scheduling Mechanisms

The key to low-latency MAC protocol design in control systems based on real-time wireless control depends on the deterministic scheduling. In essence, it ensures that every device will be assigned a time slot at which it is allowed to send data. With pre-definition of these slots, it is known by all devices when it is their time hence we can predict channel usage.

An example of this is the recent project that suggested automated slot allocation scheme of 6TiSCH-based industrial internet of things networks [7]. The findings show that deterministic scheduling can greatly reduce delays and increase stability of the system. These schedules eliminate the simultaneous transmissions and reduce retransmissions to achieve more reliable real-time operation, which is important in the critical applications.

Effective communication is only possible through synchronization. In case of device clock drift, overlap of transfers and major delays are observed. The authors have analyzed the development of timing services on wireless systems and find that the efficient use of synchronization mechanisms is crucial to the steady performance of the networking system [3]. With all the clocks remaining closely linked, the network can run in a smooth fashion and it is particularly significant in the case of industrial applications. Synchronization therefore is the key to successful wireless systems.

Deterministic MAC designs typically use a mixture of fixed slot allocation and multi-channel diversity, which makes them more resilient.

Scheduling transmissions over many frequency channels enhances the mitigation of interference and reduces the retransmission.

Changing channel hopping together with structured slot allocation in sensor networks has been established to enhance reliability and latency stability measurements, such as those in the paper of van Leemput et al. (2024) (180034). Such systems are useful especially in high-density, electromagnetically noisy systems.

Slot-based deterministic communication is structured into repeated structures known as slotframes. A slot frame consists of fixed-length transmission windows, which are basically a chance to transmit data. These slot frames allow collision-free orderly operation since all slots are of equal length. The slots are in practice a certain time, guaranteed transmission chance.

Autonomous slot allocation schemes are of great value in the IoT environments. They show that strategically using slot frames can be a huge factor in enhancing delay stability and scalability [7]. This access control plays a critical role in ensuring that there is a consistent performance in distributed systems.

Recent advances into Wi-Fi 8 suggest that it is increasingly being supported in mission-critical scenarios with the need of reliable connections via wireless connection. According to a study by Singh, (2025), the Wi-Fi 8 would be able to support the high connectivity needs in such a situation.

Between the scheduled transmissions, guard intervals are added to allow compensating synchronization errors and propagation delays.

Guard intervals also allow eliminating overlapping transmissions by offering a temporal buffer, which minimizes the mutual interference.

Guard intervals are known to reduce the bandwidth usage, but increase the reliability of transmission timing even in systems with clock skew or interference.

Heterogeneous network studies show that with proper set up guard intervals, it is possible to cope with delays in a network where various communication systems coexist with each other [9]. Therefore, the choice of the slot time and guard time is of paramount importance to the low-latency MAC systems; the wrong tuning of the system may cause a deterioration in its performance.

As an example, we can consider scheduling in 6TiSCH networks which is based on slot frame-based scheduling. The allocation of devices to transmit within repeating cycles is indicated in the Figure 2 This approach can avoid interference, and it helps to provide a collision-free network communication.

Using this scheduling, devices in 6TiSCH networks do not interfere with each other during transmission, allowing communication without collisions.

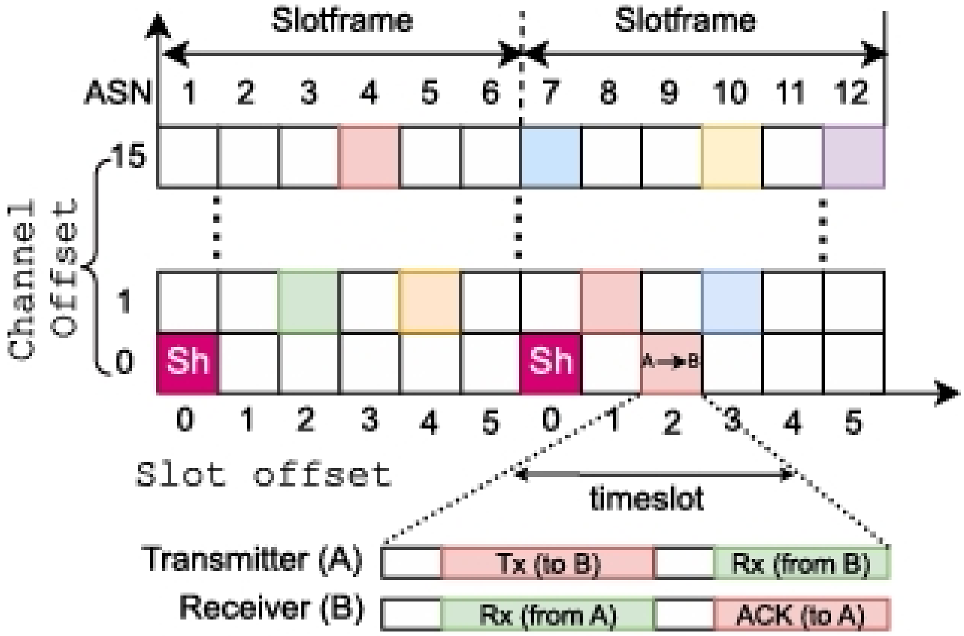

Figure 2: Example of slot scheduling in a 6TiSCH network using slotframe-based scheduling concepts discussed in [7].

3.2 Contention Optimization Strategies

Deterministic protocols are fairly good at avoiding delays. On the other hand, contention-based mechanisms are more suitable when addressing dynamic situations. The thing with the ones which are contention based is that they can make things slow unless you use them properly.

I learned that a reinforcement learning-based schedule of uplink transmissions can in fact reduce delays when reliability and speed are of primary concern [10]. In simple terms, the methods modify the transmission configurations in order to reduce latency.

Adaptive contention-window tuning allows nodes to cope with changing loads of traffic fairly smoothly generally they can change gears with the load and maintain delays constant. It is particularly useful with contention based systems since it allows nodes to respond to traffic bursts in a more controlled manner.

Combined resource reservation models are in fact magnificent in maintaining contention under control. They accomplish that by establishing a clear sequence of the devices to strike the channel and it is most beneficial in time-sensitive traffic. According to experiments conducted on deterministic wireless multi-domain networking [9], delays decrease and reliability peaks when you are good at planning the access of devices. Using adaptive techniques in combination with this organized access, you can adjust the competition of the devices on the network, improving its performance without complicating the addition of new devices.

3.3 Hybrid and Adaptive Access Models

Hybrid MAC styles are very convenient since they combine two methods of time slot management. They employ a standard routine to certain things and a loose style to others. Things that must happen every time in such systems are assigned their special time slots. The remaining time is then spent on things which must be done when a particular thing happens.

People have discovered that it is a good idea to implement energy-conscious adaptive scheduling strategies in the wireless sensor networks [13]. This implies that the system is capable of adapting to current events. As an example, when something should occur immediately, the system may provide space. VanLeemput presents a study that demonstrates this approach to be effective.

The advantage of this balance is that we know when something will occur and this is very crucial in certain systems. Meanwhile it also ensures that we are optimally utilizing our resources. Location The key to all hybrid MAC approaches is to find this balance and ensure the system works in general.

Adaptive resource management is actually very useful in the networking environment. It assists in scalability and wireless architecture integration. Other studies of time-sensitive scheduling networks reveal that resource scheduling in a flexible manner is beneficial in the attempt to ensure the consistency of communication among systems that are distributed out [14]. One such method of providing support to various types of traffic in real-time wireless control networks is the use of hybrid and adaptive MAC models. The reason behind this is that these models are able to support mixed traffic patterns and meet the differing requirements of the wireless control networks. The two models useful to networking environment and real time wireless control networks are adaptive resource management and hybrid MAC models.

3.4 Time-Sensitive Networking Features in Wireless MAC

Time sensitive networking principles were first made for wired Ethernet to be very predictable. Now these principles are also being used to design MAC protocols. This means that things like scheduling that considers time and controlling the flow of traffic are being used to make sure that wireless systems in industries have low latency. People are studying how 5G and Time Sensitive Networking technologies can work together. They want to see how wireless parts can work like bridges to make sure that behavior is predictable when it is not wired [11]. This makes it possible for different types of communication systems to work together in a synchronized way. Time sensitive networking principles are very important, for this.

One of the key mechanisms derived from TSN is the use of scheduled transmission windows that isolate critical control traffic from background data. By allocating dedicated time intervals for high-priority streams, MAC protocols can prevent interference from lower-priority transmissions. Studies on deterministic communication in advanced wireless frameworks indicate that structured scheduling combined with resource reservation significantly improves delay predictability [12]. Integrating TSN-inspired mechanisms into wireless MAC layers therefore strengthens the reliability of real-time control systems.

4 Comparative Discussion

4.1 Determinism versus Flexibility

Deterministic MAC protocols simply determine the moments where each node can transmit information. They establish time schedules such that each device is well aware of the time it has permission to use the channel. Then the network will always remain organized, and it is easy to predict when something will occur, to make the time between transmissions predictable. Even a small timing variation can disrupt the behavior of machines in control systems, and thus deterministic MAC is exceptionally helpful as it allows us to predict behavior. they are very good at reducing variation between packets, which is essential to industrial control. Recent studies on future systems reveal that scheduling the time of shipments is actually beneficial to such arrangements when timing is an issue such as in the case of [12].

It is never the same with the industrial networks. The trend of traffic changes according to what is being produced or the number of devices on the line. Thus a strict schedule on network management is not necessarily the best- it can restrict the network to be able to adapt to change of conditions.

Recently, the people have been experimenting with solutions, particularly in 5G and time-sensitive networking. In these designs, priority traffic is served by scheduled access and the lower-importance data is served by more relaxed methods. What is aimed at is ensuring that the system continues running smoothly despite the occurrence of traffic hiccup. Both TSN and industrial networks have to deal with these changes.

In checking performance, a gradual scheduling plan commonly provides us with an understanding of the worst-case delay. Other mechanisms which allow devices to compete over the channel can be okay when there is low traffic but with increasing number of devices; delays increase and prediction becomes unreliable.

Those who investigated resource sharing in time-sensitive systems found out that scheduling the timing of data transfer is important in making sure tasks are completed on time even when the network is busy.

When we are dealing with MAC protocols and real time control, however, we must not just think of the average delays, we must be able to know how each protocol contributes to the real time performance. It is crucial to assess worst-case delay to ensure the stability of operation in the industrial setting.

4.2 Latency Stability and Reliability Trade-offs

Latency stability is really important in real-time wireless control systems. It is more important than the average delay. When we use scheduling it helps reduce the variation in delay. This happens because it minimizes collisions and retransmissions.

For example Cloud-fog automation frameworks show us how structured communication can improve coordination across industrial components [5].

When the communication timing is stable it directly improves the accuracy of the control loop and the precision of the actuator in wireless control systems. This is because stable communication timing is crucial, for wireless control systems.

When we talk about communication we have to think about the speed at which things happen. Some ways of doing things can make sure that things happen at the speed on average but sometimes they can get really slow when a lot of things are happening at the same time. People who study how to make mobile communication work for factories and things like that say that we need to make sure that our systems are reliable which means they work all the time and that we also need to control how long things take to happen.

We can use a different methods to make our systems more reliable like sending the same information multiple times making sure important things get done first and saving resources just for the things that need them. These methods can help make sure that our information gets where it needs to go. They can also make our system more complicated and use more resources. So we need to find a balance between making sure things happen quickly and smoothly that they work all the time and that we do not waste resources.

To get good communication with almost no delays we often need to add some extra help and send information through many paths. We have found that setting aside resources just for very important traffic can really help meet deadlines [?]. However if we set aside many resources it can limit the amount of bandwidth available for things that are not as important. So when we design the medium access control or MAC for short we need to make sure it is good at keeping the communication reliable while also using the spectrum in a smart way for all the different types of traffic in an industrial setting.

4.3 Scalability and Deployment Considerations

The problem of scalability occurs significantly when you have a large number of devices in industries. In the absence of such devices, the simplest method of assigning each one a time slot is likely to be reasonably successful: a pure scheduler. However with a large fleet of ships, such a simple plan can turn into a nightmare to maintain organized.

Studies of 6TiSCH network management demonstrate that grouping the devices and organizing them into a structured framework can indeed enhance scalability without scaling performance down (see [4]). The management strategies which cut across multiple devices are more likely to have a more reliable system in large industrial implementations. As a student, I feel that these approaches would offer a nice compromise between structure and freedom.

Hybrid scheduling strategies come in particularly conveniently when you have mixed types of traffic all swarming around together. An example is recent research on networks that combine a large number of different components which indicate that resource allocation across the components can enhance reliability without rendering the system too inflexible (see [9]). Practically, we need to think in practice about the number of devices which are connected to a network when we are actually rolling them out, the time that it takes to bring everything into a coordinated state and the importance of maintaining firm control over the network.

4.4 Implementation Complexity and Resource Overhead

The deterministic and hybrid MAC protocols are good because they help with delays.. When we try to use them in real life it gets complicated. We need to make sure everyone is on the page and that is hard to do. This is because we have to plan out when each device can send information. We also have to keep an eye on the network all the time.

People who study how to manage 6TiSCH deployments have found that we need to be careful about how we coordinate everything [4]. We have to make sure that the devices are working together smoothly without using up much bandwidth or computer power.

Hybrid and adaptive scheduling models need computer power because they change how things are set up on the fly. Models that use intelligence to decide how to use resources show that making smart scheduling decisions can reduce delays but they also need more processing power [8]. So when we look at MAC protocols we have to think about more than just how stable the delaysre. We also have to think about whether they're feasible to implement if they can be scaled up and what they cost in terms of energy.

We are looking at the MAC design approaches and comparing them in Table 2. This table shows us the differences in how long things take how they work with a lot of people and how hard they are to set up.

Table 2: Comparative analysis of low-latency MAC approaches for real-time wireless control systems synthesized from recent networking studies [12, 7].

Aspect	Deterministic MAC	Hybrid MAC	AI-Assisted MAC
Delay Guarantee	Strict bounded latency with predefined slots	Moderate bounds with adaptive reallocation	Adaptive latency optimization with learning-based control
Jitter Performance	Very low due to fixed scheduling	Controlled, variable under load	Reduced on average but may fluctuate during learning phase
Scalability	Moderate, depends on coordination overhead	High adaptability to dynamic traffic	High scalability with intelligent resource adjustment
Implementation Complexity	Medium, requires synchronization and slot management	Medium to high depending on configuration logic	High due to computational and training requirements
Industrial Suitability	Ideal for strict real-time control loops	Suitable for mixed critical and non-critical traffic	Promising for adaptive industrial environments

5 Practical Insights and Use Cases

5.1 Industrial Automation Systems

Industrial automation is a tough area for special protocols that help machines talk to each other quickly. In factories many machines need to communicate all the time to make sure everything is working correctly and safely. This means that sensors, controllers and actuators need to keep talking to each other.

Some special scheduling methods used in internet networks have shown that they can really help make sure that messages are delivered on time [7]. This is important because it means that the machines can work together smoothly.

Industrial automation, like this uses something called medium access. This ensures that important commands are delivered quickly and on time which reduces the chance that something will go wrong and the production line will stop. Industrial automation needs this to work properly.

Network management is really important for industrial setups. Studies on management frameworks for 6TiSCH networks show that grouping devices and using a coordinator can make performance more consistent in environments where timing is crucial [4]. When you combine scheduling that always follows a set pattern with management strategies it helps systems grow and still keeps delays under control. These real world examples prove that the design of the MAC layer has an impact on how reliable industrial control systems are. The 6TiSCH networks and their management are critical, to this reliability.

In advanced factories where machines do most of the work things need to happen very fast. We are talking about things happening in milliseconds or even faster. If there is any delay in communication it can cause problems with the way the machines work together.

The people who make these factories work are looking at ways to make sure everything happens at the time. They are using systems that can connect wireless devices to other devices that need to work together perfectly [11]. This helps make sure that all the machines are working together smoothly even if they are connected in ways.

Some factories have already tried this. It works well. They use a system where each machine has a time slot to do its job and there is a central computer that makes sure everything runs smoothly. This makes the whole factory more reliable, which is important because everything needs to happen at the time.

So it is clear that we need to make sure the machines can talk to each other in a way that's fast and reliable especially in the factories of the future. We need to make sure that the machines can work together perfectly and that is why MAC-level determinism is so important, in factories.

5.2 Robotics and Autonomous Systems

Robotic systems need to talk to each other. They have parts that sense things and parts that control things. If there is a delay in this talk it can cause problems. The robot might not move right or follow the right path. It might even have trouble avoiding things in its way.

There are methods that help robots talk to each other faster. These methods are based on something called reinforcement learning. They work well even when things are changing quickly. One of these methods is called uplink scheduling. It helps reduce delays when robots are talking to each other [10]. This is really important, for robots that are moving around and working together.

Hybrid communication models are really helpful for robots to work together in time. They do this by combining a way of allocating time slots with flexible scheduling phases. Some studies have looked at how wireless networking works in areas and they found that controlling access to the network helps devices that are in different places work together better. For example a study, by Rico-Menendez shows this [9]. These methods make it possible for multiple robots to work together reliably which is important because they need to be able to send and receive both updates and updates that happen because something specific occurred. Hybrid communication models make this possible by allowing both types of updates to coexist.

5.3 Smart Grids and Critical Infrastructure

In smart grids, communication plays an important role in monitoring, fault detection, and control of distributed energy resources. This is particularly relevant to wireless-based installations, in which the delivery of messages in a timely fashion is vital to the overall stability of the system as a whole [12].

The message transmission layer to which messages are sent out should be very reliable and ensure timeliness of key grid-control messages. Such timeliness is critical in ensuring a balanced power distribution, which is the foundation of smart grid working.

The coordinated management of resources is also highly beneficial to industrial automation networks that use mobile communication technologies. Zeydan and colleagues have expounded on this idea at length [15].

Various types of traffic are regularly processed by critical infrastructure networks, and the control messages must be strictly scheduled, and the bandwidth assigned to monitor data flexibly.

The macro-deployments worldwide record that properly engineered MAC protocols contribute to reliability of the system and mitigates the risk of system breakdown during time-sensitive infrastructure activities, including industrial automation.

5.4 Automotive and Vehicular Time-Sensitive Networks

Wireless communication that is completely predictable is becoming more important in cars and other vehicles. This is because they need to be able to send and receive information in time to stay safe. Things like systems that help drivers and cars that can talk to each other need to be able to get information quickly and reliably so they can make good decisions.

When cars are moving around and things are changing special methods can help make sure that important information gets through on time. For example setting aside times for certain messages can really reduce delays [1]. This is really important when different parts of the system need to work and send information back and forth at the same time. Wireless communication that is completely predictable is crucial for things, like this to work properly. Advanced driver assistance systems and cooperative vehicular networks rely on this kind of communication to work safely and effectively.

The integration of wireless time-sensitive networking with vehicular systems also introduces mobility-related challenges. Maintaining deterministic performance while nodes frequently join or leave the network requires adaptive scheduling and synchronization management. Research on mobility support in wireless TSN environments highlights the importance of seamless handover mechanisms that preserve timing guarantees [2]. As industrial automation expands into autonomous transportation systems, low-latency MAC protocols will play a crucial role in ensuring operational safety and reliability.

6 Challenges and Open Issues

6.1 Synchronization and Timing Precision

Time synchronization is really important for computer networks. These networks need all the computers to have the time so they can talk to each other without interfering. This is especially true for networks that use a schedule to send information. If all the computers do not have the time they might send information at the same time and cause problems.

Researchers are looking at how to make sure all the computers have the time in big wireless networks. They think it is very hard to get all the computers to agree on the time even if it is just a tiny fraction of a second off [3]. There are a reasons why this is hard. Sometimes computers get a little slower or faster over time which can throw off their clock. It also takes some time for information to travel between computers, which can cause problems. Different computers might have small differences in how they work, which can also cause timing problems. Time synchronization is crucial, for MAC protocols and achieving precise time synchronization is essential for these networks to function correctly.

We also need to think about how integration with communication systems that are very reliable can affect how things work together. Some research on communication, in new wireless systems shows that we need better timing to keep very low latency going [12]. If we want to make sure everything is synchronized without using much extra resources that is still something we do not know how to do well in wireless control systems that need to work in real time.

6.2 Scalability and Network Density

Scalability is a problem when industrial wireless networks get really big and complicated. When we assign time slots in an order it works well for networks that are not too large. When we have a lot of devices in a small area it becomes hard to coordinate everything.

In 6TiSCH networks letting devices assign their time slots can actually help the network grow without getting too slow. This is shown in the work by Kalita [7]. However when we have a lot of devices we need to make sure they can all communicate without delays. This requires good coordination strategies, for the industrial wireless networks. Industrial wireless networks need strategies to manage all the devices.

Network management is really important for scalability. Some studies on managing time-sensitive networks using clustering show that working together in a structured way makes the system more robust. For example research like the one done by Graf shows this [4]. With these new ideas it is still hard to keep delays predictable when the network is changing and there are more devices. Network management frameworks like these are still a challenge for researchers to figure out. Network management is the key, to making this work.

6.3 Energy Efficiency and Coexistence

Wireless sensor networks have a problem with energy consumption. This is especially true for networks that run on batteries or get energy from their surroundings. The usual way of scheduling things often needs to be checking all the time and keeping an eye on the channels, which can use a lot of power. Some new ways of scheduling have been made for sensor networks that take into account how much energy is being used. These new ways show that we can use energy and still get the information we need on time by balancing when devices can send information and how much power they use [13]. Making protocols, for wireless sensor networks that work well and use energy is still a very hard problem to solve. Wireless sensor networks need to be designed in a way that they can send information quickly and use energy at the same time.

Living with wireless technologies makes it even harder for things to communicate in real time. In factories and other industrial places they often use different wireless systems that work on the same frequencies, which increases the chance of them interfering with each other. When we design systems for communication we need to make sure they can handle interference and work well together. This is really important, for making sure everything works reliably as we can see in the work of Zeydan and others [15]. Making sure that wireless communication works in a way even when there are a lot of other signals around is something that still needs to be figured out.

6.4 Security and Resilience in Deterministic Wireless Control

Security is a deal when we are designing low-latency MAC protocols. We have to think about this because real-time wireless control systems are used in important industries. If someone gets into the system without permission or interferes with it on purpose it can be very dangerous.

To keep these systems safe, there is a need to add some features like encryption and authentication at the MAC layer. This can make the system slower and it takes longer to send information.

Some people have done research on how to make sure communication happens in a way. They found out that we have to be very careful when we add security features so that we do not make the system too slow [12]. It is hard to make sure the system is both: secure and fast at the time. We have to balance security with speed. Security considerations like these are very important, in low-latency MAC protocol design.

Resilience against interference and network faults is equally important in industrial settings. Wireless networks deployed in production facilities may experience signal obstruction, multipath fading, or intentional jamming. Structured scheduling combined with adaptive channel allocation improves reliability under adverse conditions [7]. However, maintaining deterministic guarantees during fault recovery or topology changes requires sophisticated coordination mechanisms. Future MAC designs must incorporate fault-tolerant scheduling strategies to sustain stable real-time control performance.

7 Future Directions

7.1 Integration with 6G and Advanced Wireless Systems

The move to 6G and better wireless systems is going to have an impact on how low-latency MAC protocols change over time. New ways of communicating that are very reliable and have controlled delays are being developed for services that need them [12]. If we combine these communication methods with MAC scheduling and future cellular systems, industrial control systems will be able to use big wireless networks and still keep strict timing rules. This is important for mission-critical services. The 6G technology and advanced wireless systems will make it possible for industrial control systems to work well with large-scale coverage.

Research on 5G technologies and time-sensitive networking shows that we can get deterministic performance in wireless environments if we reserve resources and schedule things carefully [11]. So future wireless control systems will probably use programmable radio access networks and structured allocation strategies to make sure delays are predictable. This means 5G technologies will work well with time-sensitive networking to give us better results.

As we get closer to having 6G wireless networks we need to make sure that our connections are really precise and that we can control how radios work. This is important because future networks will have to deal with strict rules about how long it takes for things to happen [12]. Some researchers propose deterministic communication paradigms that divide resources carefully and schedule transmissions so that they happen at the right time. If we can make our MAC protocols do this then we can use wireless networks for things like factories and still make sure that everything happens in real time. So over the next ten years we will probably see some big changes in how we design MAC protocols for deterministic networks. The way that cellular networks and industrial communication systems work will likely become more similar and this will change how we think about designing MAC protocols that can guarantee real-time performance.

7.2 Artificial Intelligence in MAC Scheduling

People are looking into ways that artificial intelligence can help make MAC-layer scheduling work. They are using intelligence to help decide how to share radio resources in next-generation wireless networks [8]. This shows that artificial intelligence can make decisions that change based on the situation, which can help reduce latency when the traffic on the network is changing a lot. Artificial intelligence can help MAC protocols adjust the settings for sending data while still meeting the required timing. This is done by using intelligence to find the best settings so the MAC-layer scheduling can work well.

Reinforcement learning-based scheduling methods show that intelligent adaptation can really work well in situations where communication needs to be very reliable and not slow [10]. These methods let systems get ready for congestion and changes in traffic before they happen. But when we use intelligence in real-time control we have to be careful about how much work the computer has to do and how long it takes to make decisions so we do not disturb the tight timing that is needed for reinforcement learning-based scheduling methods to work properly in ultra-reliable low-latency communication scenarios.

7.3 Cross-Layer and Deterministic Network Integration

Future research directions also include working closely between control algorithms and communication protocols. Deterministic networking approaches across multiple domains show how important it is to carefully plan how resources are used so that things can be done on time [9]. If we can include scheduling policies that consider control requirements into MAC protocols then we can make the system more stable when it is running.

The integration of MAC protocols with distributed industrial automation architectures is another important area. Cloud-fog automation frameworks show how communication across hierarchical layers can improve responsiveness and reliability [5]. Wireless MAC protocols and distributed industrial automation architectures can work together effectively in these frameworks because coordinated communication helps the system respond faster and more reliably.

Continued research in cross-layer design and deterministic resource coordination will help develop wireless control systems that are scalable, robust, and capable of operating in real time. So wireless MAC protocols and distributed industrial automation architectures will be important for real-time wireless control deployments.

7.4 Deterministic MAC in Integrated Sensing and Communication

Future wireless systems will probably combine communication and sensing together as one system. This means that the same radio signals will be used for both data exchange and environmental awareness. In factories and robotic systems this can help maintain situational awareness while preserving real-time control performance. Emerging deterministic communication frameworks emphasize that bounded latency must be maintained even when sensing data shares transmission resources [12].

The coexistence of sensing and control traffic introduces new scheduling challenges at the MAC layer. Resource allocation must ensure that sensing updates do not interfere with time-critical control packets. AI-assisted resource management approaches indicate that adaptive scheduling can dynamically prioritize latency-sensitive traffic while accommodating additional sensing flows [8]. Developing MAC protocols capable of supporting both deterministic communication and integrated sensing will be a key research direction in future industrial wireless networks.

8 Conclusion

Real-time wireless control systems need a way to communicate that is predictable and does not take too long. We discussed some protocols that can help with this. These protocols are designed for places like factories and other systems that rely on computers and machines. They have to work on time every time. Some scheduling mechanisms can make sure that things happen exactly when they are supposed to, which is very important for applications that cannot be late. Research in this area shows that when we carefully plan how resources are used it makes systems in factories and other places work reliably and consistently [9]. Real-time wireless control systems like these are very important for industries.

Comparative analysis further indicates that adaptive and hybrid MAC approaches can improve scalability while preserving acceptable delay bounds under varying traffic conditions. Emerging developments in deterministic communication for next-generation wireless systems suggest that integrating advanced timing coordination and programmable resource allocation will shape the future of industrial wireless control [12]. As industrial automation continues to transition toward fully wireless operation, advancing scalable and energy-efficient MAC protocol design will remain essential for achieving ultra-reliable low-latency performance.

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