Design for Internet of Things
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Lecture - 44
IEEE 802.15.4e – 02

Folks welcome back. We did look at few wireless technologies particularly we looked at the IEEE 802.15.4 basically the MAC and PHY which is defined by the IEEE and a stack which is built on top which is typically the ZigBee stack and applications can use the ZigBee API and then start you know using building applications using the this particular radio.

Now the design aspect actually comes by looking at why should I choose this particular radio as against another radio, right? And if you recall, we showed about the picture about the SOC.

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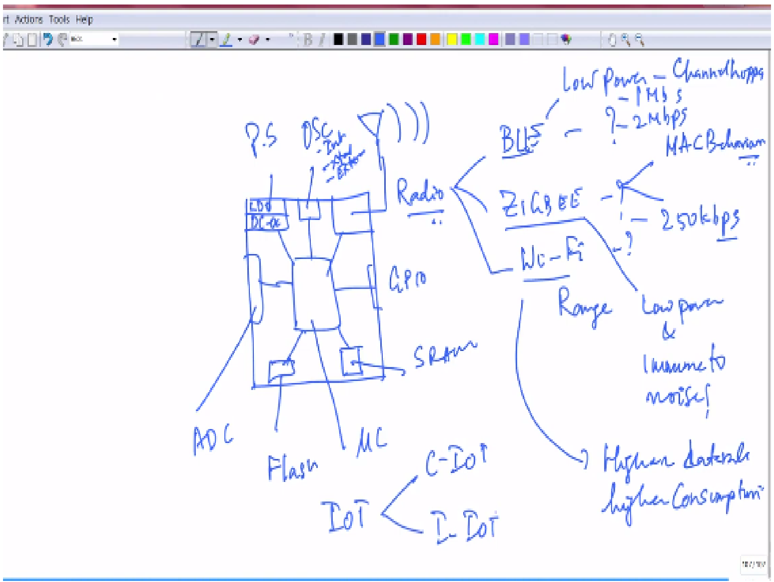

If you look at the SOC that we know very well now we have the microcontroller and then you have the radio. I will remove the remaining parts for the moment okay, I have not put that. You have ADC and you have GPIO, these are all the GPIO ports. We can quickly write them though and this is the SRAM. Then you have Flash. Then you have power supply. We can put here LDO.

You can put DC-DC. So I will call this the power supply block. Then you have the oscillator block. This can be either internal or it can be crystal or it can be completely external from the board, any one of them, so okay. So all of them are connected and so on. Now this radio here whatever gets integrated into an SOC typically are you can either have Bluetooth Low Energy radio or it can be ZigBee and sometimes it can also be Wi-Fi which is embedded inside the system.

Now question is when to use these, it has always occurred to you. Well, you can look up several pieces of literature to find out that. But at the same time I am interested in telling you within ZigBee itself there are several standards, okay. There are several versions of ZigBee what is called the MAC behavior. The MAC behaviors actually hold the key to using ZigBee in the most effective manner.

So the choice really is here, what type should I choose and this is just an example, right? One is broadly you can go between Bluetooth ZigBee and Wi-Fi because of its capability in terms of range, okay. And this has huge advantage of low power, extreme low power. This is also low power, low power and this is not so not low power and immune to noise, noise. This is very critical of ZigBee.

Well BLE is not all that agile to noise, but of course it is also providing you certain features like channel hopping and so on. And ZigBee by the way also has introduced channel hopping I will come to that very soon. And this offers you higher data rate though; 1 Mbps, 2 Mbps and so on, much greater than even 2 Mbps nowadays. But ZigBee says I will not give you anything greater than 250 kilobits per second.

Wi-Fi Of course gives you a much higher data rates, higher data rates and higher power consumption so on. Now there is a certain flavor for IoT where you have to understand the commercial IoT versus the industrial IoT, okay. Now that differentiation comes in the following way.

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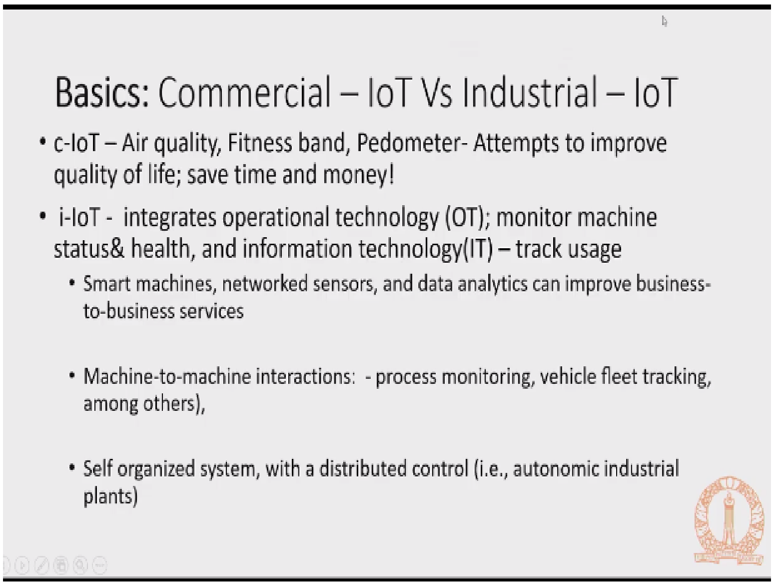

If you look at the commercial IoT, we look at stuff like air quality that you want to measure, the fitness band that you know very well, the pedometer applications, which essentially do step counting. All of them essentially are revolving around how to improve quality of life. How do you save time and how do you save money and so on. This is mostly human centered and something that will benefit humans.

Even if it is automated, it is mostly to benefit the humans. The industrial IoT is mostly to benefit manufacturing. As you can see here, this is about integration of OT, which is the operational technology basically monitor in a high level view, you can say it is monitoring the machine status and health when you talk about the OT, and the IT part, which is the information technology part essentially tracking the usage of these systems of this equipment and so on.

So essentially, it is industrial IoT is essentially bridging the two. It is combining both the OT and the IT part and providing you smart machines, network sensors, analytics and all that which are because of this merged behavior, merging integration of these two technologies, you make machines smarter by using network sensors.

You can collect lot of data, perform data analytics, so that it can improve the business-to-business service and so on, right? You can also do machine-to-machine interaction. Process monitoring for instance is a very good example. Vehicle tree, fleet tracking and so many other related applications are there.

Good thing about the industrial part is that they are self-organized systems with distributed control, essentially autonomic industrial plants form the networks which are used there are essentially self-organized systems with all this control built into the networking infrastructure right then and there. So the requirements for communication are completely different folks.

Here is where the design comes in. If you are looking for very low latency, throughput and all that, which may be required for the industrial environments, then you may have to look at IIoT technologies right, whatever is most suited for IIoT communication. If it is for air quality and let us say the pedometer kind of applications, which humans are involved, then it may be a different requirement in terms of quality of service.

The commercial IoT communications are typically machine-to-user. As I mentioned, it is user centric. Of course, there is client server interaction, but by and large it is out there where you are interested in battery life, low power, ease of installation, cost and all that. The industrial IoT is not like that. It is trying to look at timeliness which is very critical.

Reliability, because if you have a problem with the process plant and if there is an error in the process plant you want everything to be detected in high speed and ensure that you do not waste resources by moving on with the process the in the you know assembly chain or even the manufacturing chain. So these things have to be monitored in real time, okay.

So that essentially means that those sensors that are applied there have a different criteria in terms of reliability, in terms of quality of service and so on. And therefore, the communication network there also has to be very different. You must be able to go beyond just the, not just meeting the stringent deadlines, but you may also have to be robust to packet losses and you must be safe and resilient to any damages that might occur or any vandalism that might occur to these systems accidentally.

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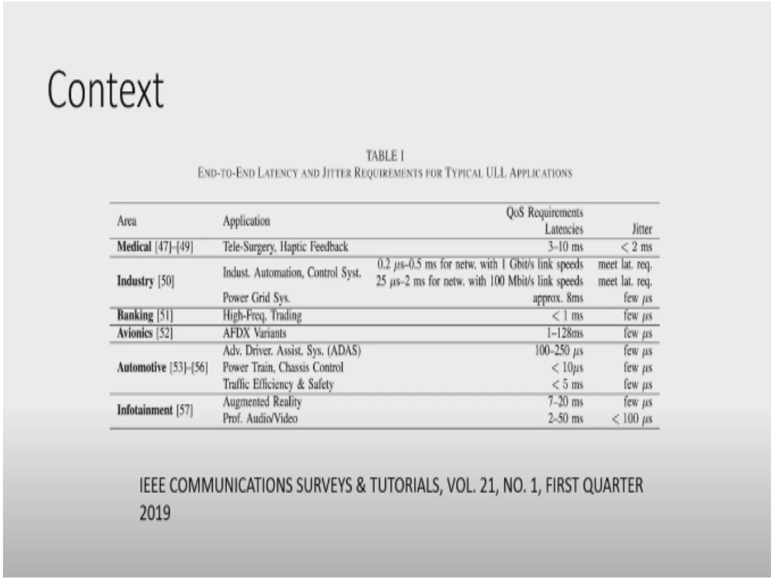

Context

TABLE I
END-TO-END LATENCY AND JITTER REQUIREMENTS FOR TYPICAL ULL APPLICATIONS

Area	Application	QoS Requirements Latencies	Jitter
Medical [47]–[49]	Tele-Surgery, Haptic Feedback	3–10 ms	< 2 ms
Industry [50]	Indust. Automation, Control Syst.	0.2 µs–0.5 ms for netw. with 1 Gbit/s link speeds	meet lat. req.
		25 µs–2 ms for netw. with 100 Mbit/s link speeds	meet lat. req.
	Power Grid Sys.	approx. 8ms	few µs
Banking [51]	High-Freq. Trading	< 1 ms	few µs
Avionics [52]	AFDX Variants	1–128ms	few µs
Automotive [53]–[56]	Adv. Driver. Assist. Sys. (ADAS)	100–250 µs	few µs
	Power Train, Chassis Control	< 10µs	few µs
	Traffic Efficiency & Safety	< 5 ms	few µs
Infotainment [57]	Augmented Reality	7–20 ms	few µs
	Prof. Audio/Video	2–50 ms	< 100 µs

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Which clearly indicates that the requirements for latency and jitter are completely different.

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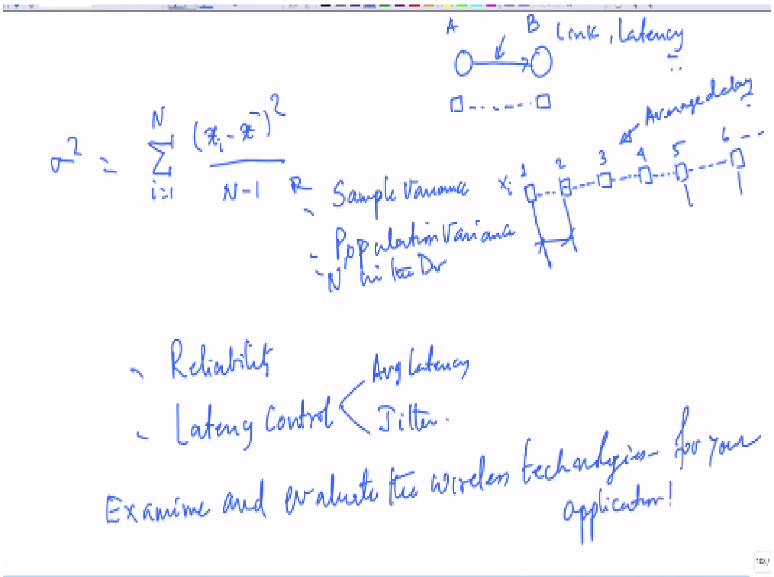

Supposing you have one packet This is packet 1, which requires a certain amount of latency between let us say, first let me put the abstraction. This is node A. This is node B let us say. And then there is a packet which starts from here and reaches here and then maybe there is a acknowledgment back from here, but for the moment let us just see one direction, okay.

Now A to B essentially has there is a link between the two, right? There is a link here and there is a link latency. And you need to measure this link latency. I will show you what exactly this jitter means when we talk about latency. See latency is let us say first packet comes here and exactly after some time, the second packet should come and exactly after that the third packet should come and so on.

It turns out that because of network, okay this is not even. So let me bring it maybe a bit closer so that it gives you a feeling that they are even. It is possible though that one packet might come here, okay. So you can see the spacing is not uniform. It is also possible that a packet can come here, which means again this spacing is not uniform, okay.

So essentially we are looking at what is the average, what is the average delay and how much is tolerated in terms of variance in the delay, okay. So essentially how do you calculate that? Take the average delay, which is let us say x bar okay and take every sample 1, 2, 3, 4, 5, 6 and so on you keep getting. You take the sample here, this is x i. So you take x i.

You would have a priorly calculated the delay, the average delay which is x bar. So you take the square of it. You divide by n - 1 and you sum it over all the samples. So essentially you can put a summation here, okay. This is your jitter calculation, okay. This is just for, just let me put it as this okay. In fact you should be using small x. So let me be precise and put a small x.

So basically you can be talking about sample variance. This is actually sample variance. You will also have population variance. And in population variance, you will be using N instead of, you will be using N here in the Dr in the denominator. N in the denominator but N – 1 in the case of sample variance.

Anyway, so just to tell you that the jitter here, you can see in this picture here is less than 2 milliseconds if you are talking about medical applications. Remember I was telling you about tactile CPS right in the first class. You can see the kind of jitter that is expected. And depending on what type of medical surgeries systems you are building with haptic and all that QoS requirements for that specific application can be as low as 10 to a maximum of 10 milliseconds.

So you can see average, these are all average numbers, what you see here is average. But if you go down a little bit to the automotive applications, you will see that things are in microseconds not even in milli. Jitter has to be almost in very close to microseconds and this is a very important requirement. Now do wireless technologies that we are discussing actually support this is the question.

That is the link to what I was trying to tell you. Now, so you need as we discussed here, we need reliability. We need reliability and we also need latency control, latency control right? I will simply say latency control, which essentially means average latency and also the jitter associated with the latency. Both should be under, well under control.

Otherwise you cannot really call it, you cannot use the technology for any industrial applications, okay. Now having, okay I will not go into this detail, but if you want to support anything like that folks, there is only one way you have to examine the, examine and evaluate the wireless technologies for your application; very important.

Now you must first of all be aware what is out there so that you can start evaluating them, right. So that is another important requirement for you.

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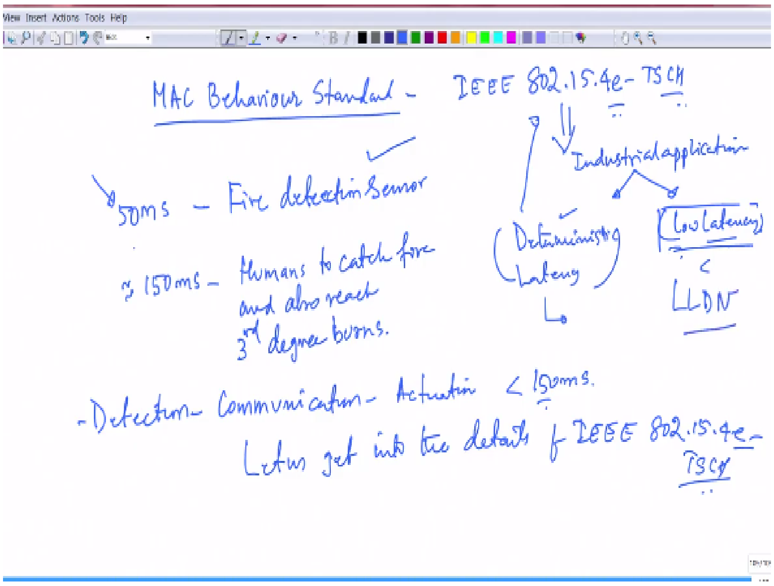

So to do that, I will introduce you to one more MAC behavior standard MAC behavior standard, okay. And that MAC behavior standard is the IEEE 802.15.4 which we know well e-TSCH. There is a reason why I am writing it this way. This is called time synchronized channel hopping; very well suited for industrial applications, okay. Now you have to be very careful when you talk about industrial applications.

You can be talking about deterministic latency or you can say low latency. Which one of them is 15.4e? Well it is deterministic. What does it mean? It means you will get latency all right, but it will always be something that is hard. You know it, a priori you know that latency. Then it is called deterministic latency. That means you can, you are able to determine the latency and you are very sure that the wireless technology will give you that.

Now that kind of latency may not be suitable in several situations, let me give you one instance. Take the case of fire. Take the case of fire in a room. God forbid, but there is fire. That fire detect, let us say you have, you deploy a technology which is deterministic. That means that sensor which is connected to this deterministic network will come, will be given opportunity to transmit every one second let us say.

Because that is fixed, it is deterministic. So what is the latency? Latency is under control. Latency may not be suitable for this application, but it is under control. Every one second for sure you will get access to that fire detection sensor. One second is like 1000 milliseconds, please note. It is in fact it is 1000 milliseconds. Let us say the, so you have one second. You can get the data from the fire detection sensor.

But you need only I think it is around 150 milliseconds for humans to catch fire and also reach third degree burns. Third degree burns can actually happen in 150 milliseconds. So if you say I have a deterministic wireless network which can do fire detection, this is not going to work at all folks, right? You need low latency. You need a MAC behavior.

You need a media access control behavior where the application gets low latency. That means lower than some number and in this case, it is lower than has to be much lower than 150 milliseconds. If you have to target 150 milliseconds latency, the whole system should perhaps from detection to transmission to the actuation, from detection to communication to actuation should be less than 150 milliseconds.

Now if your detection is good, but your communication comes every one second is no good, right? So that is what we are trying to say. So if you have to meet this hard deadline, you need a media access control, medium access control which will give you low latency. And that is what we are to, our target is indeed.

So let us see while we do not have time to really look at the low latency part, I can excite you on the deterministic latency part and essentially the 15.4e TSCH standard, which is a very important thing not suitable for fire detection if you are doing one second. But if you are doing fire detection every 50 milliseconds but still using 15.4e then it is okay, you do not have to worry about it.

So how you plan the 15.4e systems to meet application requirements which are the fire detection kind of systems is where the real design of the IoT node, the design of the radio choice and so on actually start playing an important role. So let us get into the details. Let us get into the details of IEEE 802.15.4e-TSCH, time synchronized channel hopping. Great.

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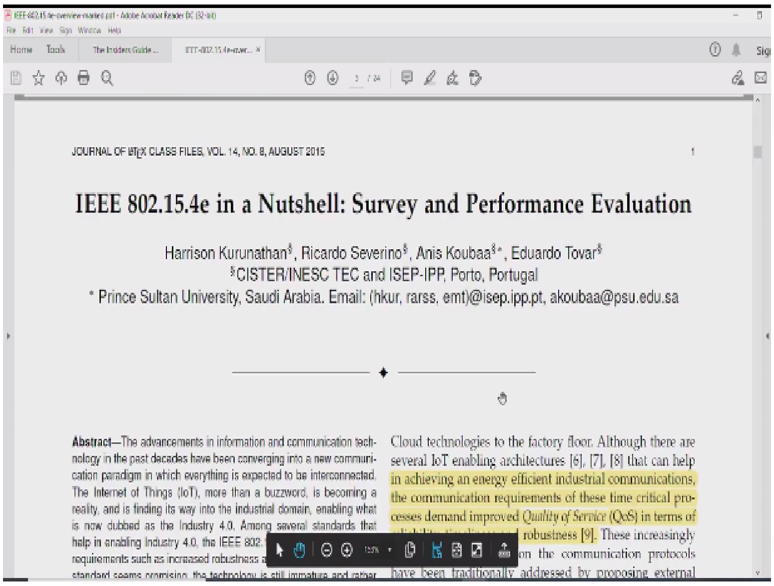

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IEEE 802.15.4e in a Nutshell: Survey and Performance Evaluation

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Abstract—The advancements in information and communication technology in the past decades have been converging into a new communication paradigm in which everything is expected to be interconnected. The Internet of Things (IoT), more than a buzzword, is becoming a reality, and is finding its way into the industrial domain, enabling what is now dubbed as the Industry 4.0. Among several standards that help in enabling Industry 4.0, the IEEE 802.

Cloud technologies to the factory floor. Although there are several IoT enabling architectures [6], [7], [8] that can help in achieving an energy efficient industrial communications, the communication requirements of these time critical processes demand improved *Quality of Service* (QoS) in terms of robustness [9]. These increasingly

So for that let me direct you to this nice paper which I was reading and this paper is about IEEE 802.15.4 in a Nutshell: Survey and Performance Evaluation. So I am sure by reading this paper you will be excited to understand what I was trying to get at when you want to choose a technology for your wireless technology for your application.

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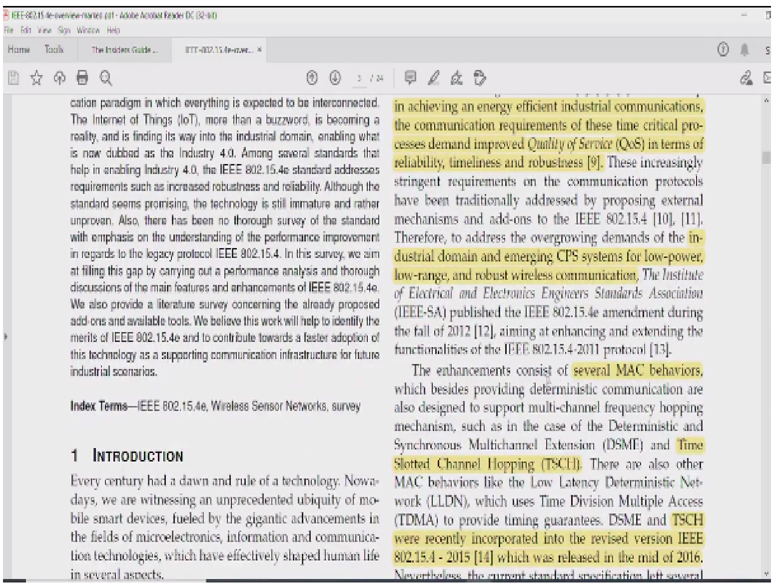

cation paradigm in which everything is expected to be interconnected. The Internet of Things (IoT), more than a buzzword, is becoming a reality, and is finding its way into the industrial domain, enabling what is now dubbed as the Industry 4.0. Among several standards that help in enabling Industry 4.0, the IEEE 802.15.4e standard addresses requirements such as increased robustness and reliability. Although the standard seems promising, the technology is still immature and rather unproven. Also, there has been no thorough survey of the standard with emphasis on the understanding of the performance improvement in regards to the legacy protocol IEEE 802.15.4. In this survey, we aim at filling this gap by carrying out a performance analysis and thorough discussions of the main features and enhancements of IEEE 802.15.4e. We also provide a literature survey concerning the already proposed add-ons and available tools. We believe this work will help to identify the merits of IEEE 802.15.4e and to contribute towards a faster adoption of this technology as a supporting communication infrastructure for future industrial scenarios.

Index Terms—IEEE 802.15.4e, Wireless Sensor Networks, survey

1 INTRODUCTION

Every century had a dawn and rule of a technology. Nowadays, we are witnessing an unprecedented ubiquity of mobile smart devices, fueled by the gigantic advancements in the fields of microelectronics, information and communication technologies, which have effectively shaped human life in several aspects.

in achieving an energy efficient industrial communications, the communication requirements of these time critical processes demand improved *Quality of Service* (QoS) in terms of reliability, timeliness and robustness [9]. These increasingly stringent requirements on the communication protocols have been traditionally addressed by proposing external mechanisms and add-ons to the IEEE 802.15.4 [10], [11]. Therefore, to address the overgrowing demands of the industrial domain and emerging CPS systems for low-power, low-range, and robust wireless communication, *The Institute of Electrical and Electronics Engineers Standards Association* (IEEE-SA) published the IEEE 802.15.4e amendment during the fall of 2012 [12], aiming at enhancing and extending the functionalities of the IEEE 802.15.4-2011 protocol [13].

The enhancements consist of several MAC behaviors, which besides providing deterministic communication are also designed to support multi-channel frequency hopping mechanism, such as in the case of the Deterministic and Synchronous Multichannel Extension (DSME) and Time Slotted Channel Hopping (TSCH). There are also other MAC behaviors like the Low Latency Deterministic Network (LLDN), which uses Time Division Multiple Access (TDMA) to provide timing guarantees. DSME and TSCH were recently incorporated into the revised version IEEE 802.15.4 - 2015 [14] which was released in the mid of 2016.

I mentioned to you about the MAC behavior and TSCH is one such MAC behavior. DSME is another MAC behavior. Low latency deterministic network is another behavior. Please note I had shown that here this is LLDN in a way. This is LLDN in a way, okay. And what we have shown here is TSCH. This is TSCH. Great. So all these things are there and DSME is another type of MAC behavior.

And TSCH both of them were incorporated as latest as 2015 and released in 2016. And essentially, several issues open for investigation including analysis of protocols under different settings, scheduling of flows in the time frequency domain, delay bound analysis and so many other related advantages with this system. Alright. So I will skip the 15.4 part of it because we had primer already.

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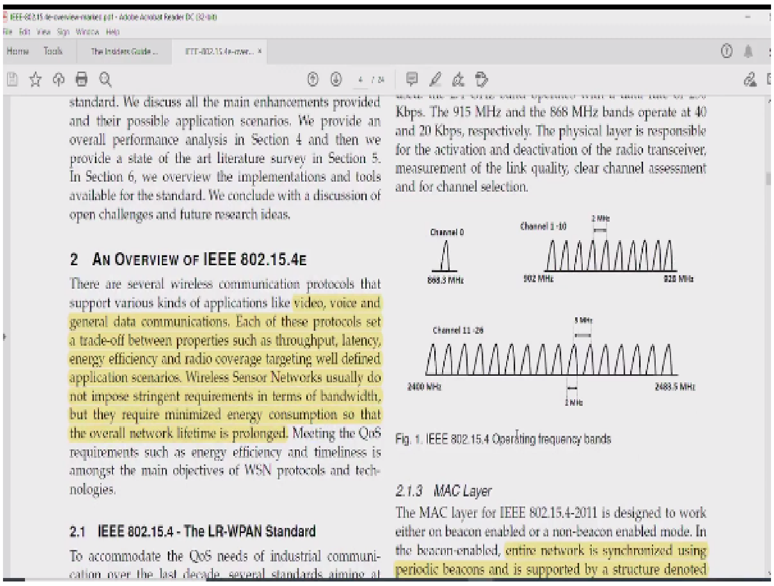
standard. We discuss all the main enhancements provided and their possible application scenarios. We provide an overall performance analysis in Section 4 and then we provide a state of the art literature survey in Section 5. In Section 6, we overview the implementations and tools available for the standard. We conclude with a discussion of open challenges and future research ideas.

2 AN OVERVIEW OF IEEE 802.15.4E

There are several wireless communication protocols that support various kinds of applications like video, voice and general data communications. Each of these protocols set a trade-off between properties such as throughput, latency, energy efficiency and radio coverage targeting well defined application scenarios. Wireless Sensor Networks usually do not impose stringent requirements in terms of bandwidth, but they require minimized energy consumption so that the overall network lifetime is prolonged. Meeting the QoS requirements such as energy efficiency and timeliness is amongst the main objectives of WSN protocols and technologies.

2.1 IEEE 802.15.4 - The LR-WPAN Standard

To accommodate the QoS needs of industrial communication over the last decade, several standards aiming at

Kbps. The 915 MHz and the 868 MHz bands operate at 40 and 20 Kbps, respectively. The physical layer is responsible for the activation and deactivation of the radio transceiver, measurement of the link quality, clear channel assessment and for channel selection.

Fig. 1. IEEE 802.15.4 Operating frequency bands

2.1.3 MAC Layer

The MAC layer for IEEE 802.15.4-2011 is designed to work either on beacon enabled or a non-beacon enabled mode. In the beacon-enabled, entire network is synchronized using periodic beacons and is supported by a structure denoted

This is 15.4 e for you. Wireless communication protocols when you talk about it, you have video voice and data and all this. Essentially you are trading you are trying to tradeoff between several properties such as throughput latency and energy efficiency with and radio coverage targeting well-defined application scenarios, right?

See, the wireless sensor networks usually do not impose any requirements of bandwidth, but they are they require long lifetime. I am sure you appreciate that sentence because in the sensors world we are always talking about 10 plus years of lifetime for these systems, okay. Now just an overview to start you up on this.

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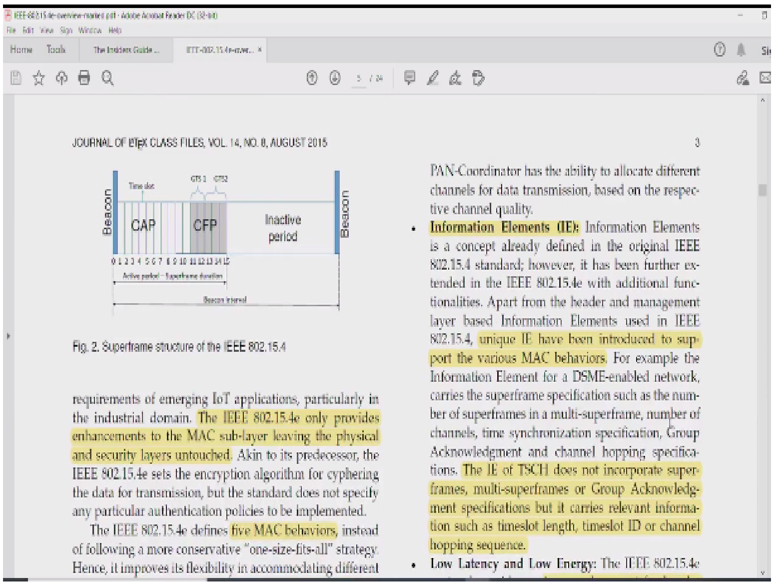

And when you go down, you realize that all these are something specific to the 15.4 particularly figure 2 is something very specific to the 15.4 system. The 15.4e for instance, it provides enhancements and the enhancements are quite significant. In any case, the generic enhancements are the following.

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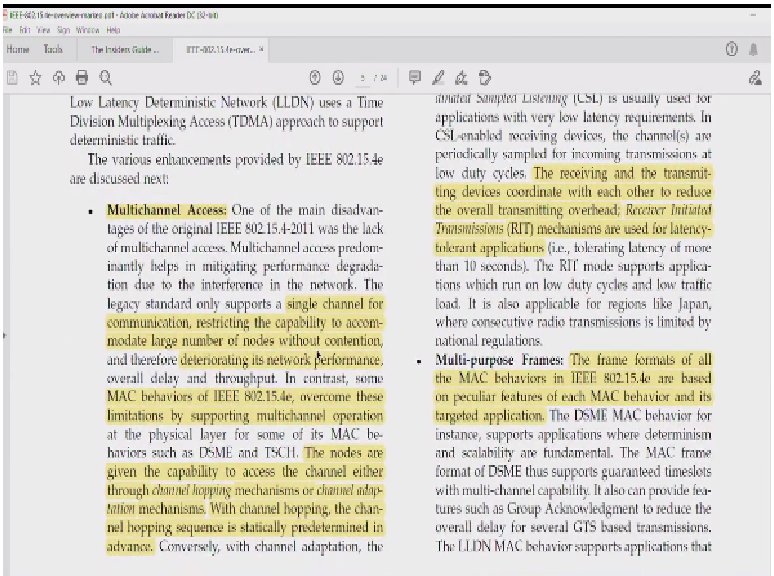

First one is multichannel access, okay. See the problem with the ZigBee system which we studied, there is one problem that you only have a single channel for your complete PAN system that you set up, okay. You have a PAN coordinator and all nodes identify the PAN coordinator and then they communicate to that PAN coordinator.

Which means out of the 16 channels which are supported, only one channel you will be using all the time. That is a very restrictive thing. So therefore, you must find a way to sort of exploit the remaining channels as well, right? And 15.4e does exactly this. Exactly this. It does channel hopping and it does channel adaptation mechanisms so that it can battle interference.

It can battle fading on the wireless channel and provide you very good connectivity. So you can see already it is moving in the direction of being reliable, okay.

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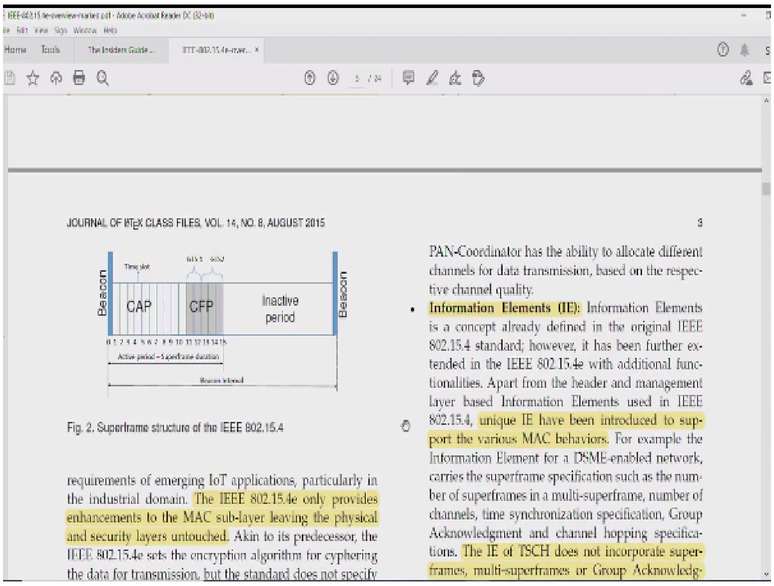
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Fig. 2. Superframe structure of the IEEE 802.15.4

requirements of emerging IoT applications, particularly in the industrial domain. The IEEE 802.15.4e only provides enhancements to the MAC sub-layer leaving the physical and security layers untouched. Akin to its predecessor, the IEEE 802.15.4e sets the encryption algorithm for cyphering the data for transmission, but the standard does not specify

PAN-Coordinator has the ability to allocate different channels for data transmission, based on the respective channel quality.

- **Information Elements (IE):** Information Elements is a concept already defined in the original IEEE 802.15.4 standard; however, it has been further extended in the IEEE 802.15.4e with additional functionalities. Apart from the header and management layer based Information Elements used in IEEE 802.15.4, unique IE have been introduced to support the various MAC behaviors. For example the Information Element for a DSME-enabled network, carries the superframe specification such as the number of superframes in a multi-superframe, number of channels, time synchronization specification, Group Acknowledgment and channel hopping specifications. The IE of TSCH does not incorporate superframes, multi-superframes or Group Acknowledg-

Then there is this concept of information elements, which was already there in the 15.4 but not well spoken of, okay. Now the IE is actually part of the MAC frame and this has been introduced to support the various MAC behaviors. The frame will look identical, but the MAC behavior will be different. So you have an information element which says this is 15.4. This is 15.4e TSCH. This is 15.4e LLDN.

This is 15.4 e DSME and so on. So all these things have to be differentiated and therefore, that information element essentially takes care of that. Now low latency and low energy are important hallmarks which are suitable for, you need that for the industrial control systems. The 15.4 e allows devices to operate at a low duty cycle though. And the synchronization is a very important thing in this system.

That is how you get determinism in the whole thing. So you can think of the whole MAC as deterministic MAC because there is synchronization.

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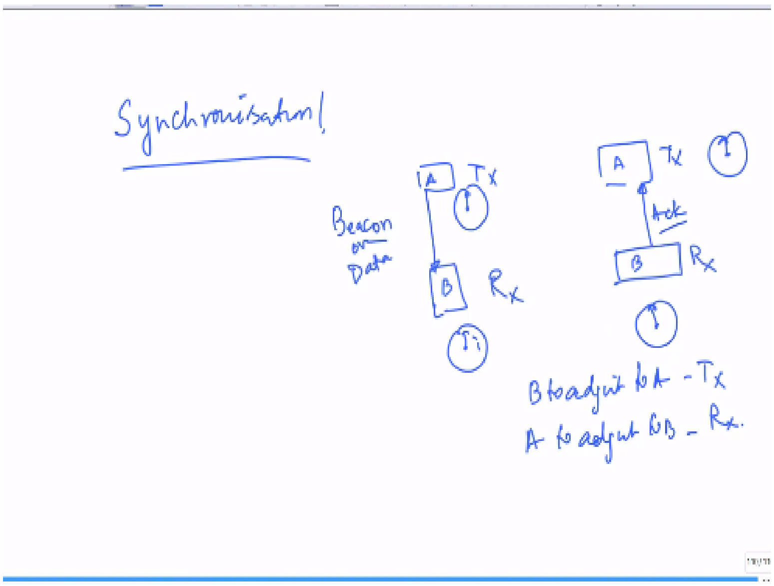

Synchronization is the key here and you can either do, you have a transmitter, you have a receiver. You either transmit. Whenever there is a Beacon, whenever there is a Beacon transmission the receiver can adjust its clock okay, exactly aligning to the transmitter's clock. Either you can do it with Beacon or you can also do it the other way, right. You can have, you have one clock here.

This guy will also have his own independent clock. Now the ACK packet which goes in this direction, unlike this which can be either Beacon or data packet. Here you are getting only ACK, okay. This is the same node A to B and this is A, B. But this time it is B to A which is a small ACK packet. Now A can adjust to B's clock. Either you adjust B to A's clock, B to adjust to A or A to adjust to B.

B adjust to A is transmit driven and A adjusting to B is receiver driven, both are possible. And all these mechanisms are built into the system here.

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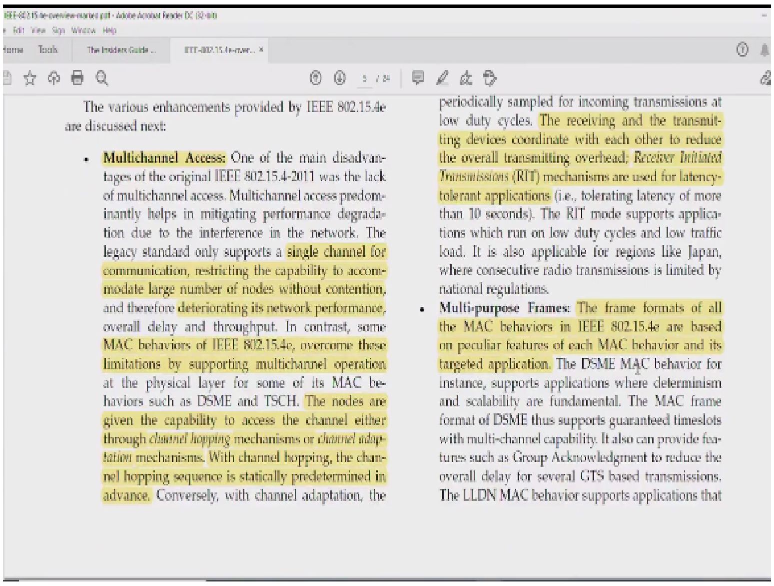
The various enhancements provided by IEEE 802.15.4e are discussed next:

- **Multichannel Access:** One of the main disadvantages of the original IEEE 802.15.4-2011 was the lack of multichannel access. Multichannel access predominantly helps in mitigating performance degradation due to the interference in the network. The legacy standard only supports a single channel for communication, restricting the capability to accommodate large number of nodes without contention, and therefore deteriorating its network performance, overall delay and throughput. In contrast, some MAC behaviors of IEEE 802.15.4e, overcome these limitations by supporting multichannel operation at the physical layer for some of its MAC behaviors such as DSME and TSCH. The nodes are given the capability to access the channel either through *channel hopping* mechanisms or *channel adaptation* mechanisms. With channel hopping, the channel hopping sequence is statically predetermined in advance. Conversely, with channel adaptation, the

periodically sampled for incoming transmissions at low duty cycles. The receiving and the transmitting devices coordinate with each other to reduce the overall transmitting overhead; *Receiver Initiated Transmissions* (RIT) mechanisms are used for latency-tolerant applications (i.e., tolerating latency of more than 10 seconds). The RIT mode supports applications which run on low duty cycles and low traffic load. It is also applicable for regions like Japan, where consecutive radio transmissions is limited by national regulations.

- **Multi-purpose Frames:** The frame formats of all the MAC behaviors in IEEE 802.15.4e are based on peculiar features of each MAC behavior and its targeted application. The DSME MAC behavior for instance, supports applications where determinism and scalability are fundamental. The MAC frame format of DSME thus supports guaranteed timeslots with multi-channel capability. It also can provide features such as Group Acknowledgment to reduce the overall delay for several GTS based transmissions. The LLDN MAC behavior supports applications that

Then there is the third one, which is multi-purpose frames. Basically the advantage here is the frame formats of all MAC behaviors are based on the peculiar features of this MAC behavior and its targeted applications. So it is another important feature. You are not just configuring one type of frame, but you will be able to embed different MAC behaviors into that frame itself.

Essentially, the IE is doing that right? So it is giving you that feature. And essentially, that is what is mentioned here.

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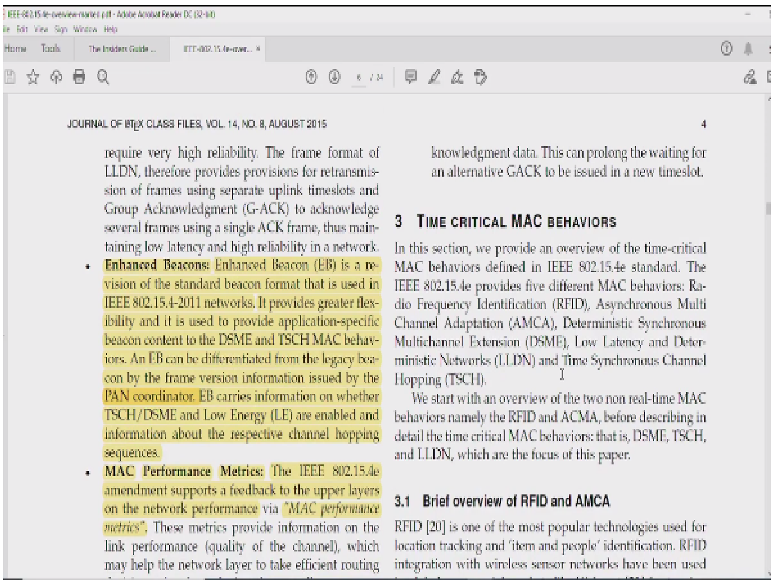
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require very high reliability. The frame format of LLDN, therefore provides provisions for retransmission of frames using separate uplink timeslots and Group Acknowledgment (G-ACK) to acknowledge several frames using a single ACK frame, thus maintaining low latency and high reliability in a network.

- **Enhanced Beacons:** Enhanced Beacon (EB) is a revision of the standard beacon format that is used in IEEE 802.15.4-2011 networks. It provides greater flexibility and it is used to provide application-specific beacon content to the DSME and TSCH MAC behaviors. An EB can be differentiated from the legacy beacon by the frame version information issued by the PAN coordinator. EB carries information on whether TSCH/DSME and Low Energy (LE) are enabled and information about the respective channel hopping sequences.
- **MAC Performance Metrics:** The IEEE 802.15.4e amendment supports a feedback to the upper layers on the network performance via *"MAC performance metrics"*. These metrics provide information on the link performance (quality of the channel), which may help the network layer to take efficient routing

knowledgment data. This can prolong the waiting for an alternative GACK to be issued in a new timeslot.

3 TIME CRITICAL MAC BEHAVIORS

In this section, we provide an overview of the time-critical MAC behaviors defined in IEEE 802.15.4e standard. The IEEE 802.15.4e provides five different MAC behaviors: Radio Frequency Identification (RFID), Asynchronous Multi Channel Adaptation (AMCA), Deterministic Synchronous Multichannel Extension (DSME), Low Latency and Deterministic Networks (LLDN) and Time Synchronous Channel Hopping (TSCH).

We start with an overview of the two non real-time MAC behaviors namely the RFID and ACMA, before describing in detail the time critical MAC behaviors: that is, DSME, TSCH, and LLDN, which are the focus of this paper.

3.1 Brief overview of RFID and AMCA

RFID [20] is one of the most popular technologies used for location tracking and 'item and people' identification. RFID integration with wireless sensor networks have been used

Of course, the IE contains which MAC behavior is there. So it is easy for receivers to know what is the way the transmitter is actually thinking. Apart from that the

Enhanced Beacon is an important thing. We had Beacons in the 15.4 world. Here we have Enhanced Beacon. And this EB carries information about whether it is time synchronized channel hopping and low energy are enabled.

And information about the respective channel hopping sequences. All that is held in the EB part of the Beacon. So it is just not the old Beacon we knew in the 15.4 but it is indeed the Enhanced Beacon format. Also there is MAC performance metrics which are supported by just the feedback.

You can basically infer the number of transmitted frames that require one or more retries for acknowledgement, the number of transmitted frames that did not result in an acknowledgement during a term called MAC's frame retries and so on. So lot of stuff, a lot of interesting enhancements have been done to the basic MAC. So one can read this article and get into the details.

But I think what is important for you to skip all this section and go directly into the section related to time synchronized channel hopping.

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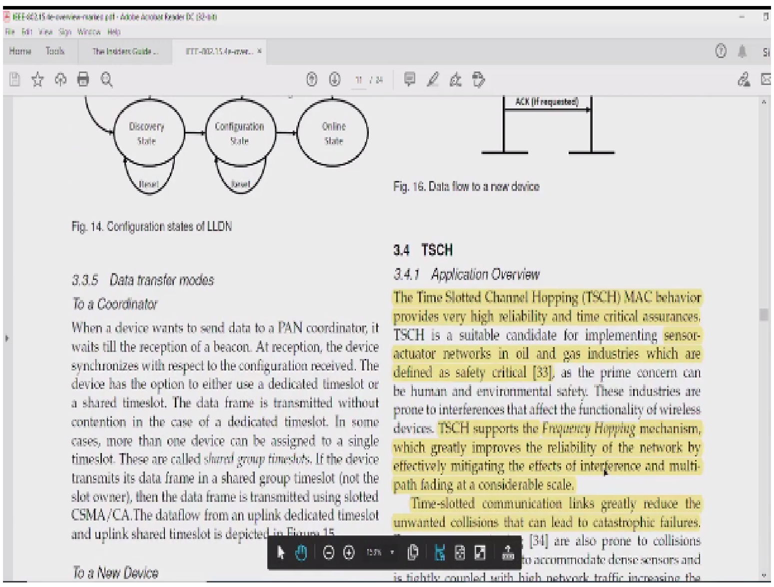

Fig. 14. Configuration states of LLDN

3.3.5 Data transfer modes

To a Coordinator

When a device wants to send data to a PAN coordinator, it waits till the reception of a beacon. At reception, the device synchronizes with respect to the configuration received. The device has the option to either use a dedicated timeslot or a shared timeslot. The data frame is transmitted without contention in the case of a dedicated timeslot. In some cases, more than one device can be assigned to a single timeslot. These are called *shared group timeslots*. If the device transmits its data frame in a shared group timeslot (not the slot owner), then the data frame is transmitted using slotted CSMA/CA. The dataflow from an uplink dedicated timeslot and uplink shared timeslot is depicted in Figure 15.

To a New Device

Fig. 16. Data flow to a new device

3.4 TSCH

3.4.1 Application Overview

The Time Slotted Channel Hopping (TSCH) MAC behavior provides very high reliability and time critical assurances. TSCH is a suitable candidate for implementing sensor-actuator networks in oil and gas industries which are defined as safety critical [33], as the prime concern can be human and environmental safety. These industries are prone to interferences that affect the functionality of wireless devices. TSCH supports the *Frequency Hopping* mechanism, which greatly improves the reliability of the network by effectively mitigating the effects of interference and multi-path fading at a considerable scale.

Time-slotted communication links greatly reduce the unwanted collisions that can lead to catastrophic failures. ... [34] are also prone to collisions ... to accommodate dense sensors and is tightly coupled with high network traffic increasing the

Now it will actually tell you the 15.4e TSCH where can it be applied, okay? We will get into the details of that, understand that in a little more detail. Let us just look up the TSCH MAC which I mentioned is a MAC behavior.

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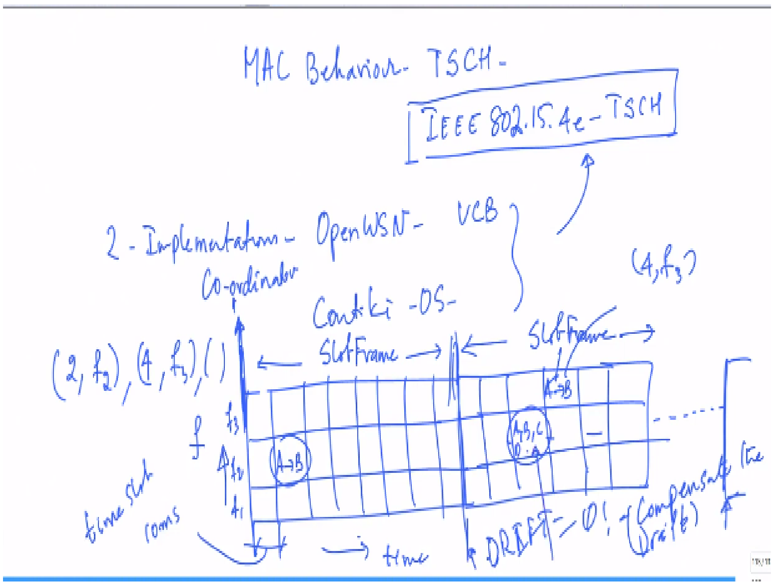

The MAC behavior of interest to us for several industrial applications is the time synchronized channel hopping MAC which is nothing but 802, so let us put it technically correct IEEE 802.15.4e-TSCH. You must not forget this because you can have dash DSME. You can have LLDN so on, right? So we are only worried about the TSCH implementation. Now as I mentioned to you the main implementation of this MAC, TSCH MAC is not a straightforward thing.

However, there are two implementations available to you, two implementations available, okay two implementations are there. One is under OpenWSN. This is again from Berkeley, UC Berkeley. UC Berkeley has this. And the other one is on Contiki, Contiki OS. And both of them have the support for this 15.4e. But before we get into the detail of that I think what is important is to know a little more about the protocol itself, okay.

So let me show you what exactly TSCH does in its and how it is able to how the beauty of this TSCH protocol and its ability to you know provide you some reliable communication, high reliability, okay. So let me point you to this paper here.

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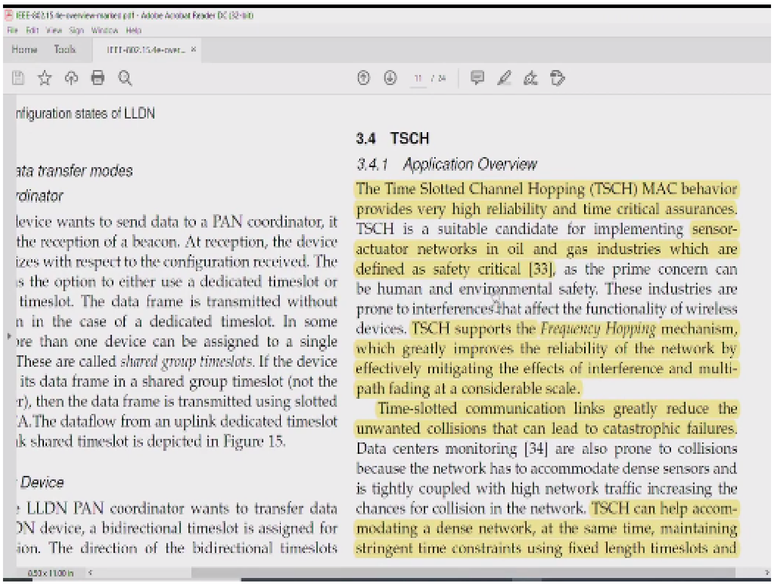
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levice wants to send data to a PAN coordinator, it the reception of a beacon. At reception, the device izes with respect to the configuration received. The s the option to either use a dedicated timeslot or timeslot. The data frame is transmitted without n in the case of a dedicated timeslot. In some ore than one device can be assigned to a single These are called *shared group timeslots*. If the device its data frame in a shared group timeslot (not the r), then the data frame is transmitted using slotted A. The dataflow from an uplink dedicated timeslot k shared timeslot is depicted in Figure 15.

Device

LLDN PAN coordinator wants to transfer data DN device, a bidirectional timeslot is assigned for ion. The direction of the bidirectional timeslots

3.4 TSCH

3.4.1 Application Overview

The Time Slotted Channel Hopping (TSCH) MAC behavior provides very high reliability and time critical assurances. TSCH is a suitable candidate for implementing sensor-actuator networks in oil and gas industries which are defined as safety critical [33], as the prime concern can be human and environmental safety. These industries are prone to interferences that affect the functionality of wireless devices. TSCH supports the *Frequency Hopping* mechanism, which greatly improves the reliability of the network by effectively mitigating the effects of interference and multi-path fading at a considerable scale.

Time-slotted communication links greatly reduce the unwanted collisions that can lead to catastrophic failures. Data centers monitoring [34] are also prone to collisions because the network has to accommodate dense sensors and is tightly coupled with high network traffic increasing the chances for collision in the network. TSCH can help accommodating a dense network, at the same time, maintaining stringent time constraints using fixed length timeslots and

This one says that the TSCH protocol is MAC behavior it mentions and it provides reliability and critical assurances and it says that it can be applied for networks such as oil and gas industries and so on wherever critical, safety critical applications are of prime importance and it is frequency hopping and that supports mechanism which greatly improves the reliability of the system, right?

And okay, when you do frequency hopping, you are not transmitting on just one frequency as I mentioned earlier, it is able to hop across frequency and there is a schedule for hopping. Time slotted communication links greatly reduce the unwanted collisions that can lead to catastrophic failures. What this simply means is if you take a large frame, this is a large frame, I recall having mentioned this to you already.

But quickly I will write it for you. This is the f the frequency and this is the time and this is one time slot right, this is one time slot. And it can go on like this. You can have typically 10 millisecond time slots into any number of time slots you can have. And then it repeats again from here. It again repeats from here, okay this is a repeat. And so it can go on like this.

If A is communicating to B here, it is possible in the next time slot it may be transmitting from here to here, it is possible. That depends on how it hops, right. And that is a shared understanding between A and B. So this is essentially a slot frame.

This is called a slot frame. And this is called a time slot, this is a 10 millisecond time slot. You have to be just little bit careful on this name.

The slot frame can be of any size, I restricted the size here. So the slot frame begins all over again here, okay. And how it hopped from here, this frequency this is f 1. This is f 2. This is f 3 let us say. How it hopped from here? So it is f 2. Here it was in if you take it like this, it is time slot 2, f 2 right? It is 2, 2. This is 1 and this is 2. So 2, f 2. That means it has gone to this. It has now jumped to 1, 2, 3, 4; 4, 3.

That means f 1, f 2, f 3 it is 3. So something like that. So the sequence is 4, f 3 I will call it. It can be like this. So this is how it is hopping 4, f 3 and so on. How to hop is a formula which you can easily understand, but anyway this is the main concept behind the fact that it is hopping. So A and B have to hop together. Only then they can continue to communicate and battle the interference problem.

Here this picture also tells you that there is no collision because time slot is perfectly reserved for a communication between A and B and this can be for different lengths. Typically it is 10 millisecond. But what is important is to ensure that there is no drift, this time slot begins exactly here. So you have to ensure that drift is equal to practically equal to zero right, which is not possible with given the kind of components that we are talking of, crystal oscillators and so on.

It is not going to work for you that it will not drift. But that is a challenge. You must have a way to compensate the drift. First you should evaluate the drift and then compensate the drift and ensure that systems in fact come exactly the same time for communication. So that is essentially what you should do. Otherwise industrial networks where deterministic latencies are required will not work.

So TSCH can accommodate very dense network because you can keep increasing the size of the slot frame as I mentioned. And fixed length time slots also can be changed, right. So if the slot frame changes, everything will change. So that is a good thing.

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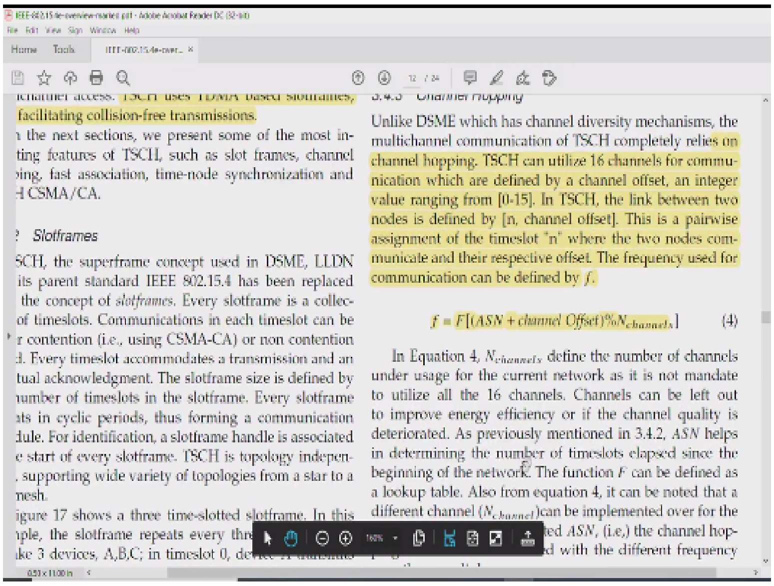

facilitating collision-free transmissions.

the next sections, we present some of the most in- ting features of TSCH, such as slot frames, channel ping, fast association, time-node synchronization and CSMA/CA.

Slotframes

SCH, the superframe concept used in DSME, LLDN its parent standard IEEE 802.15.4 has been replaced the concept of *slotframes*. Every slotframe is a collec- of timeslots. Communications in each timeslot can be r contention (i.e., using CSMA-CA) or non contention d. Every timeslot accommodates a transmission and an tual acknowledgment. The slotframe size is defined by number of timeslots in the slotframe. Every slotframe ats in cyclic periods, thus forming a communication dule. For identification, a slotframe handle is associated e start of every slotframe. TSCH is topology indepen- , supporting wide variety of topologies from a star to a mesh.

igure 17 shows a three time-slotted slotframe. In this nple, the slotframe repeats every thr

ke 3 devices, A,B,C; in timeslot 0, de

Unlike DSME which has channel diversity mechanisms, the multichannel communication of TSCH completely relies on channel hopping. TSCH can utilize 16 channels for communication which are defined by a channel offset, an integer value ranging from [0-15]. In TSCH, the link between two nodes is defined by [n, channel offset]. This is a pairwise assignment of the timeslot "n" where the two nodes communicate and their respective offset. The frequency used for communication can be defined by f.

$$f = F[(ASN + channel\ Offset)\%N_{channels}] \quad (4)$$

In Equation 4, $N_{channels}$ define the number of channels under usage for the current network as it is not mandate to utilize all the 16 channels. Channels can be left out to improve energy efficiency or if the channel quality is deteriorated. As previously mentioned in 3.4.2, ASN helps in determining the number of timeslots elapsed since the beginning of the network. The function F can be defined as a lookup table. Also from equation 4, it can be noted that a different channel ($N_{channel}$)can be implemented over for the

ted ASN, (i.e,) the channel hop-

d with the different frequency

Now come to channel hopping. Now channel hopping is simple expression here. You can see that the frequency of interest is essentially a function of ASN. This is called the absolute slot number. Now what is absolute slot number? ASN simply means when the system was switched on, the coordinator sent out the first slot frame at this point.

Now if there are many frames that have evolved okay many frames that have evolved, it will tell you when the initial time was started. So the absolute slot number is giving you an indication of when the first slot frame started and the time at which the first time slot started. And you anywhere know the current time, then you exactly know how many time slots have passed back, right. You know the current time slot. You know the current time.

And from the current time and from the very first time the first time slot started which is the absolute slot number you can actually use that with added to the channel offset and take a modulo of the number of channels. Typically modulo of 16 is taken. I think they choose 16 channels and you do a modulo of that and you get your corresponding frequency that you want to settle down to, okay.

So essentially you can see that n, channel offset is what is mentioned here. And I have also put down almost the same thing. An integer value ranging from 0 to 15 the channel hopping, so TSCH can utilize 16 channels for communication, which are defined by a channel offset, an integer value which is ranging from 0 to 15, right? This is a number essentially.

Channel offset is a number between 0 to 15. The TSCH, in TSCH the link between two nodes is defined by n, channel offset; n, this is essentially this n this is a pairwise assignment of timeslot n, where the two nodes communicate and their respective offsets. So essentially this when I say A to B or in this slot frame and A to B in the other slot frame and so on, that essentially is the n, channel offset.

This is a pairwise. A and B form a pair. And this is a pairwise assignment of the time slot n where the two nodes communicate and their respective offset. The frequency used for communication can be defined by this expression in which f should it go is defined by this expression, right? So kindly note that this is how the whole system computes.

And you can see in this channel 4, equation 4, n channels is defined as the number of channels and typically it is 16. And some channels can be left out for energy efficiency and all that. So ASN essentially helps in determining the number of time slots that have elapsed since the beginning of the network. That is pretty straightforward.

Because the ASN actually contains the start of when the time, first slot frame started. And you know the current time as I mentioned. A difference of the two will tell you exactly that**.** It tells you the number of time slots that have elapsed since the beginning of the network. The function f can be defined as a lookup table basically and you can put it up there.

Also from equation 4, it can be noted that a different channel that is n channel can be implemented over for the same offset for an incremented ASN. The channel hopping mechanism can be utilized with the different frequency over the same link. In other words, you can restrict, you can put n channels as any number that you like. But the whole network should know, that is the key point.

You may want to use only 4, you may want to use all 16 and so on. So that part should be made extremely clear. So unless you work on this, you may not get a full grip.

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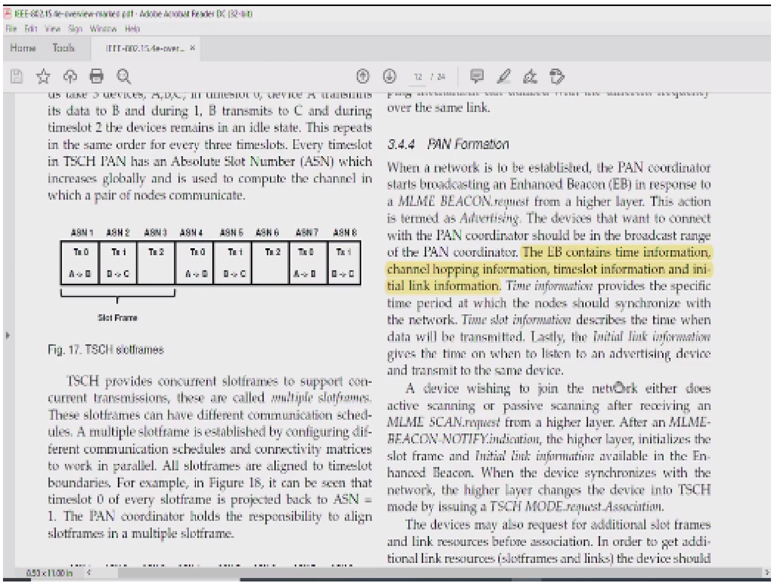
its data to B and during 1, B transmits to C and during timeslot 2 the devices remains in an idle state. This repeats in the same order for every three timeslots. Every timeslot in TSCH PAN has an Absolute Slot Number (ASN) which increases globally and is used to compute the channel in which a pair of nodes communicate.

ASN 1	ASN 2	ASN 3	ASN 4	ASN 5	ASN 6	ASN 7	ASN 8
Ts 0 A -> B	Ts 1 B -> C	Ts 2	Ts 0 A -> B	Ts 1 B -> C	Ts 2	Ts 0 A -> B	Ts 1 B -> C

Slot Frame

Fig. 17. TSCH slotframes

TSCH provides concurrent slotframes to support concurrent transmissions, these are called *multiple slotframes*. These slotframes can have different communication schedules. A multiple slotframe is established by configuring different communication schedules and connectivity matrices to work in parallel. All slotframes are aligned to timeslot boundaries. For example, in Figure 18, it can be seen that timeslot 0 of every slotframe is projected back to ASN = 1. The PAN coordinator holds the responsibility to align slotframes in a multiple slotframe.

over the same link.

3.4.4 PAN Formation

When a network is to be established, the PAN coordinator starts broadcasting an Enhanced Beacon (EB) in response to a *MLME BEACON.request* from a higher layer. This action is termed as *Advertising*. The devices that want to connect with the PAN coordinator should be in the broadcast range of the PAN coordinator. The EB contains time information, channel hopping information, timeslot information and initial link information. *Time information* provides the specific time period at which the nodes should synchronize with the network. *Time slot information* describes the time when data will be transmitted. Lastly, the *Initial link information* gives the time on when to listen to an advertising device and transmit to the same device.

A device wishing to join the network either does active scanning or passive scanning after receiving an *MLME SCAN.request* from a higher layer. After an *MLME-BEACON-NOTIFY.indication*, the higher layer, initializes the slot frame and *Initial link information* available in the Enhanced Beacon. When the device synchronizes with the network, the higher layer changes the device into TSCH mode by issuing a *TSCH MODE.request.Association*.

The devices may also request for additional slot frames and link resources before association. In order to get additional link resources (slotframes and links) the device should

I just wanted to tell you that PAN, the Personal Area Network formation begins by what is known as an Enhanced Beacon which is entered by the PAN coordinator. The PAN coordinator is the guy who actually switches on the time when the first slot frame also started from there. And the Enhanced Beacon contains very useful information, channel hopping information, time slot information, and initial link information all of that is held there.

Now what is time information provides a specific time period at which node should synchronize with the network, okay. And time slot information describes the time when the data will be transmitted. Lastly, the initial link information gives the time on when the when to listen to an advertising device and transmit to the same device.

So all of this information is held in the basic Enhanced Beacon part which is issued by the PAN coordinator, okay. And this EB keeps getting rebroadcasted as the network starts getting bigger and bigger. The parents essentially will be you know transmitting the EB.

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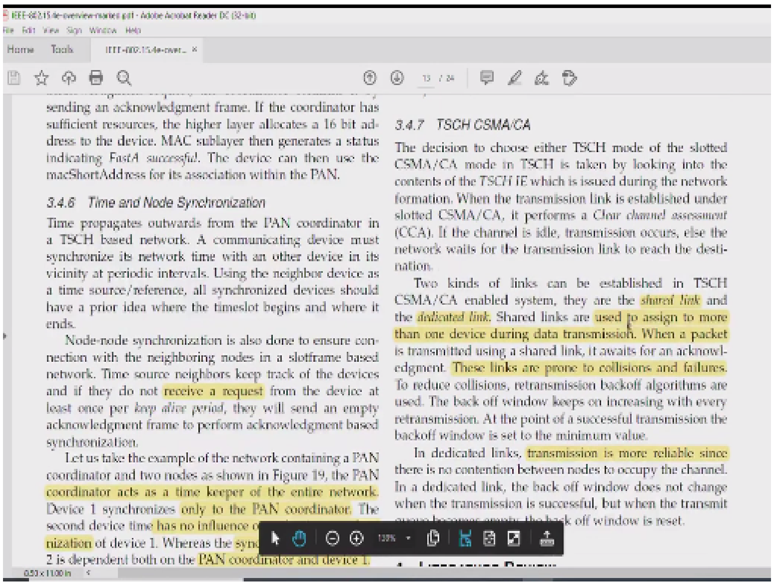

sending an acknowledgment frame. If the coordinator has sufficient resources, the higher layer allocates a 16 bit address to the device. MAC sublayer then generates a status indicating *FastA successful*. The device can then use the macShortAddress for its association within the PAN.

3.4.6 Time and Node Synchronization

Time propagates outwards from the PAN coordinator in a TSCH based network. A communicating device must synchronize its network time with an other device in its vicinity at periodic intervals. Using the neighbor device as a time source/reference, all synchronized devices should have a prior idea where the timeslot begins and where it ends.

Node-node synchronization is also done to ensure connection with the neighboring nodes in a slotframe based network. Time source neighbors keep track of the devices and if they do not receive a request from the device at least once per *keep alive period*, they will send an empty acknowledgment frame to perform acknowledgment based synchronization.

Let us take the example of the network containing a PAN coordinator and two nodes as shown in Figure 19, the PAN coordinator acts as a time keeper of the entire network. Device 1 synchronizes only to the PAN coordinator. The second device time has no influence o[illegible] nization of device 1. Whereas the sync[illegible] 2 is dependent both on the PAN coordinator and device 1.

3.4.7 TSCH CSMA/CA

The decision to choose either TSCH mode of the slotted CSMA/CA mode in TSCH is taken by looking into the contents of the *TSCH IE* which is issued during the network formation. When the transmission link is established under slotted CSMA/CA, it performs a *Clear channel assessment* (CCA). If the channel is idle, transmission occurs, else the network waits for the transmission link to reach the destination.

Two kinds of links can be established in TSCH CSMA/CA enabled system, they are the *shared link* and the *dedicated link*. Shared links are used to assign to more than one device during data transmission. When a packet is transmitted using a shared link, it awaits for an acknowledgment. These links are prone to collisions and failures. To reduce collisions, retransmission backoff algorithms are used. The back off window keeps on increasing with every retransmission. At the point of a successful transmission the backoff window is set to the minimum value.

In dedicated links, transmission is more reliable since there is no contention between nodes to occupy the channel. In a dedicated link, the back off window does not change when the transmission is successful, but when the transmit [illegible]k off window is reset.

Here you also have to note that links are of two types. I mentioned all this already, there is a shared link and a dedicated link. Essentially, this is a dedicated link. It is also possible that A, B, C, D whatever may also want to content and use this link in which case it becomes a shared link. And these shared links obviously are prone to lot of errors, because of the collisions that seem to happen there.

So I mentioned to you about this is about what TSCH is all about. I want to point you to the OpenWSN part of the work that has happened on the web. So if you wish to work on you know 15.4e here is a basic implementation.

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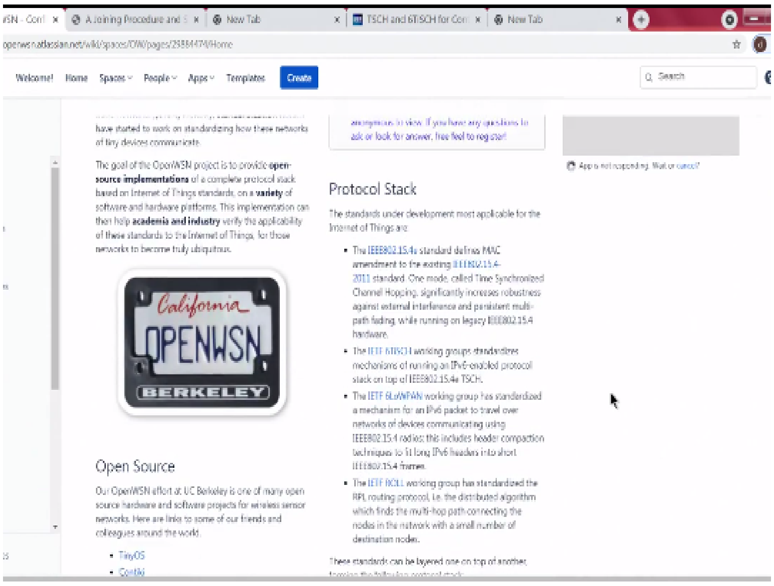

As mentioned here 15.4e standard defines the MAC and all that it writes. It says time synchronize channel hopping is there. And then this has been implemented. There is something called an IETF TSCH, 6TSCH working group, which is talking about how to have IPv6, running over time synchronized channel hopping.

And then there is the working group called 6LoWPAN, essentially for an IPv6 packet, how to travel over networks of devices, communicating over 15.4 radios that is mentioned in 6LoWPAN and so on. And then there is a routing protocol called RPL, okay, routing over lossy links. There is this protocol called RPL routing protocol.

That is essentially a distributed algorithm which finds the multi hop path connecting the nodes in the network with a small number of destination nodes. So do look up OpenWSN to get more information. But do not stop there.

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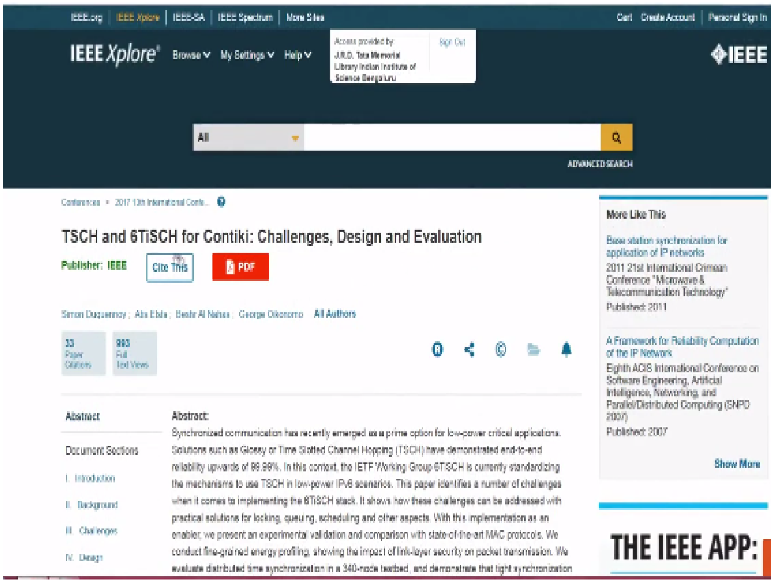

There is also the Contiki implementation of the 6TSCH. And I see that there is an IEEE paper it is called TSCH and 6TSCH for Contiki challenges, design and evaluation. Please see if you can download this paper and read it. In this paper the apart from the basic background literature that is described, the challenges are mentioned here.

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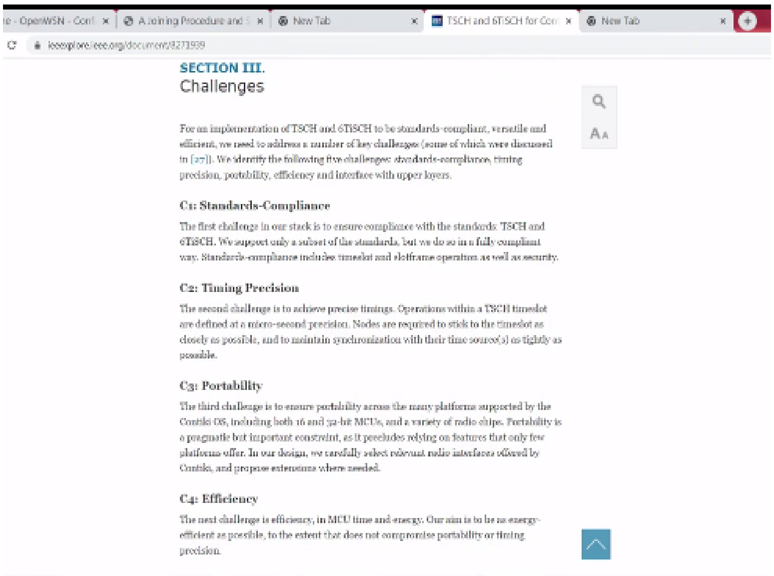

And I would like to read out the challenges if you are planning to implement these, this 6TSCH for any of the industrial networks. First standard is, first challenge is it should be standards compliance, right to ensure that TSCH and 6TSCH all of them, they should inter work quite easily. And only then you can actually say that across vendors it becomes fully compliant and people will be able to use them in a very effective manner.

Till date there is not any much, there are not many implementations of these, the 15.4e TSCH. So if you want to start, you may still be one of the beginners who would be implementing it from scratch. Now everything hinges on the fact that the timing information is an important thing because you are saying no collisions because of tightly synchronized systems.

Therefore, timing precision is an absolute critical thing, right? So timing precision is a challenge. And they have to maintain quite a bit of challenge there.

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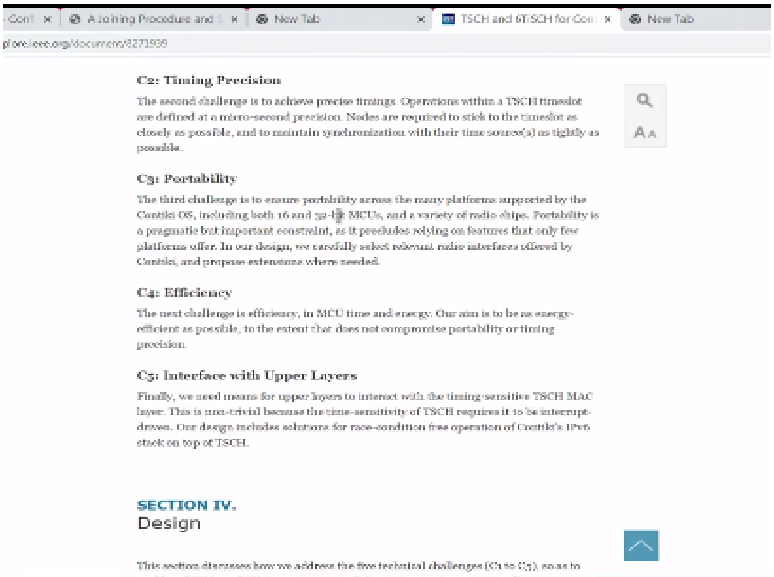

Portability, that means, if you write that code, it should be supported over, you know any 16 bit, 32 bit microcontrollers, and so on. So that is an important thing. Efficiency is also important because energy efficiency, time efficiency is important. And then of course, interface with upper layers, this is an important requirement. Otherwise, you cannot write applications which are, you know easy to get ported.

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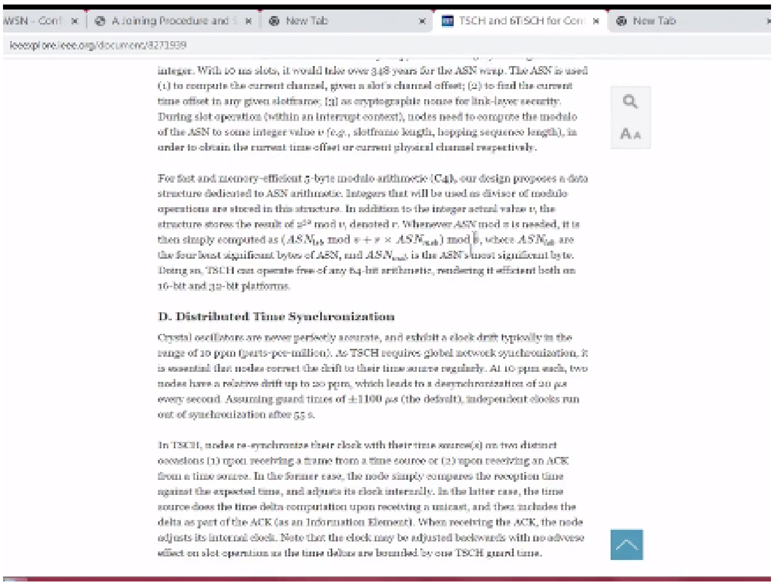
integer. With 10 ms slots, it would take over 348 years for the ASN wrap. The ASN is used (1) to compute the current channel, given a slot's channel offset; (2) to find the current time offset in any given slotframe; (3) as cryptographic nonce for link-layer security. During slot operation (within an interrupt context), nodes need to compute the modulo of the ASN to some integer value v (*e.g.*, slotframe length, hopping sequence length), in order to obtain the current time offset or current physical channel respectively.

For fast and memory-efficient 5-byte modulo arithmetic (C4), our design proposes a data structure dedicated to ASN arithmetic. Integers that will be used as divisor of modulo operations are stored in this structure. In addition to the integer actual value v, the structure stores the result of 2^{32} mod v, denoted r. Whenever ASN mod v is needed, it is then simply computed as $(ASN_{ls4} \bmod v + r \times ASN_{ms1}) \bmod v$, where ASN_{ls4} are the four least significant bytes of ASN, and ASN_{ms1} is the ASN's most significant byte. Doing so, TSCH can operate free of any 64-bit arithmetic, rendering it efficient both on 16-bit and 32-bit platforms.

D. Distributed Time Synchronization

Crystal oscillators are never perfectly accurate, and exhibit a clock drift typically in the range of 10 ppm (parts-per-million). As TSCH requires global network synchronization, it is essential that nodes correct the drift to their time source regularly. At 10 ppm each, two nodes have a relative drift up to 20 ppm, which leads to a desynchronization of 20 μs every second. Assuming guard times of ± 1100 μs (the default), independent clocks run out of synchronization after 55 s.

In TSCH, nodes re-synchronize their clock with their time source(s) on two distinct occasions (1) upon receiving a frame from a time source or (2) upon receiving an ACK from a time source. In the former case, the node simply compares the reception time against the expected time, and adjusts its clock internally. In the latter case, the time source does the time delta computation upon receiving a unicast, and then includes the delta as part of the ACK (as an Information Element). When receiving the ACK, the node adjusts its internal clock. Note that the clock may be adjusted backwards with no adverse effect on slot operation as the time deltas are bounded by one TSCH guard time.

Now related to time synchronization, I want to point you to this little sentence here, which is written pretty well. And perhaps, will give you an idea of how tight the synchronization should be. He writes here in this paper, this paper is as I said, as this title is 6TSCH, TSCH and 6TSCH for Contiki design challenges. So let me go down and then look at the challenge related to the time synchronization.

See folks, if you put a crystal oscillator, it is okay, it is very good, it is better than the internal RC oscillator, we discussed this last time. But clock drift can still be an issue. If you take a crystal which is 10 ppm range tolerance on the crystal oscillator, synchronization is become can become an issue as you can see in this example, if you take 10 ppm, two nodes have a relative drift up to 20 ppm, right?

They need not be matching exactly the same way. One of them may be drifting exactly at the time when the other one has stopped, you know has finished. So it can have a maximum of 20 ppm, which can actually lead to desynchronization. There will be a drift. If you say take 20 ppm, you have a 20 microsecond drift every second, okay.

And if you assume guard times of about 1100 microseconds, which is essentially the default, the independent clocks run out of synchronization after 55 seconds. So almost every minute, you are out of synchronization even if you put a 10 ppm crystal, okay.

So here note that individual drift is 10 ppm, the relative drift between two nodes is 20 ppm. This is an important thing.

And it is written here clearly that it is a relative drift. So it is not going to work folks. So you need to have extremely tight synchronization between them. Either you do act based synchronization or you do receiver based synchronization or you do transmit based synchronization. Moment you receive something from the transmitter, you synchronize with the transmitter.

Or the transmitter synchronizes after it receives an ACK from the receiver. So it is either ACK based or it can also be transmission based. You have to make these decisions before you start using them very effectively, okay. And that is essentially what is written in this paragraph. This time source thus the delta, time delta computation upon receiving a unicast and then includes the delta as part of the ACK.

So whenever you are passing the ACK packets and so on, do look at the ways by which you want to resynchronize the clocks, okay. So do read up this paragraph, which is interesting. So you can simply compare the reception time against the expected time and adjust the clock. And in the last case, what you should do is you the time source does the time delta computation upon receiving a unicast and then includes the delta as part of the ACK.

And that ACK is essentially another IE as it is called, and it is sent as part of the information element ACK. Now when receiving the ACK, what does the node do, the transmitter do? It adjust its internal clock, and that clock may be adjusted towards backwards with no adverse effect on slot operation as their time deltas are bounded by one TSCH guard time. So that is a good way to do.

You can build on the adaptive synchronization and do lot of interesting things. That is another challenge and so on. And you can see that the implementation is quite exhaustive. Read this paper to tell you more about the requirements for the five challenges that were described above here and how the system implementation tries to solve this problem. That is all I have for now folks, thank you very much.

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