Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Applicability of NG-SUN to time-sensitive industrial applications

Date Submitted: May 12, 2024

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Re: TG4ad Next Generation SUN PHYs

Abstract: This contribution describes a potential application for Next Generation SUN PHYs.

Purpose: Discussion

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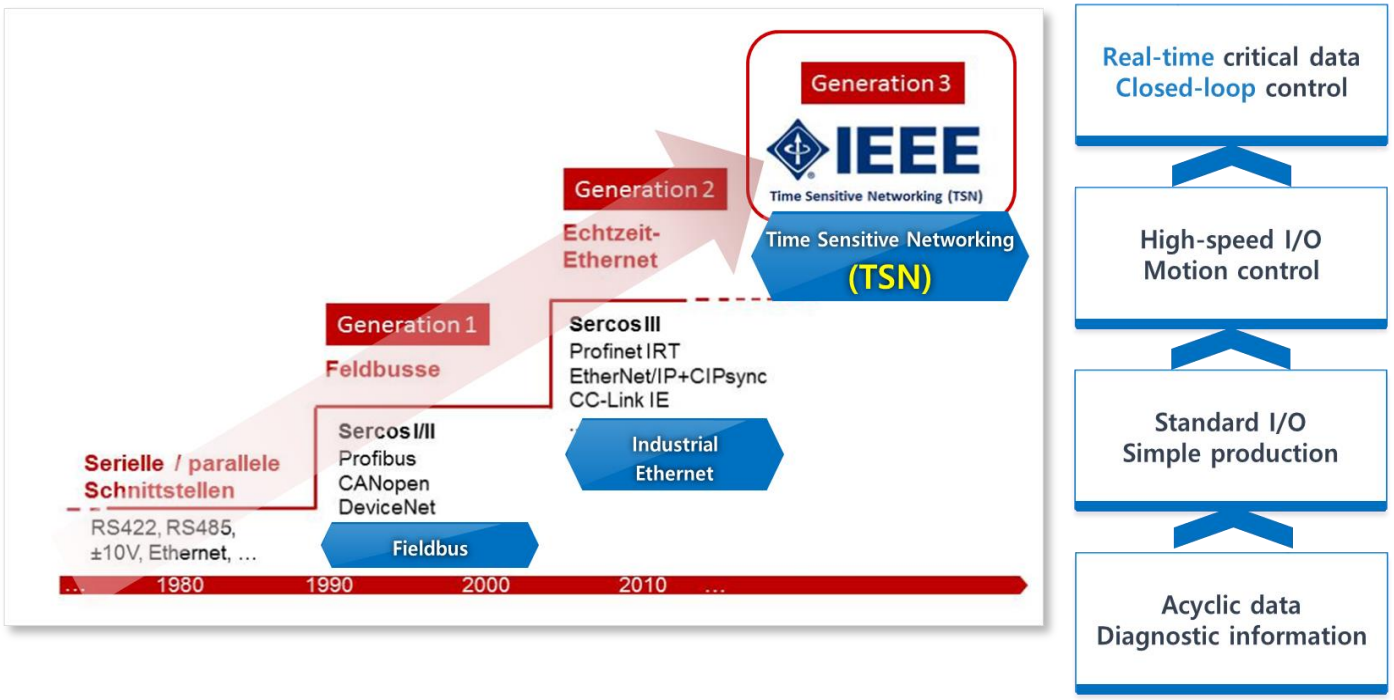
Industrial Applications

- Industrial communications area with increasing requirements
  - Condition Monitoring (CM)
    - State monitoring by monitoring a large number of different sensors
    - Synchronization for consistent time base for all signals form the sensors is more important than the real-time aspect.
    - ZigBee, Bluetooth
  - Process Automation (PA)
    - Continuous production processes for large quantities of a certain product
    - For quality assurance, high data rates must be allowed to recode and/or transmit very large amounts of data
    - WirelessHART, WSAN
  - Factory Automation (FA)
    - Discrete manufacturing processes for machining, assembling, testing, packing, etc
    - Closed loop feedback systems for each distinct steps are automated and controlled by a variable number of sensors and actuators
    - **Very short and fast movements** have to be controlled in a limited spatial extent
    - **No standardized wireless technologies yet**

※ *Source: Steven Dietrich et al., "Performance Indicators and Use Case Analysis for Wireless Networks in Factory Automation", IEEE ETFA 2017*

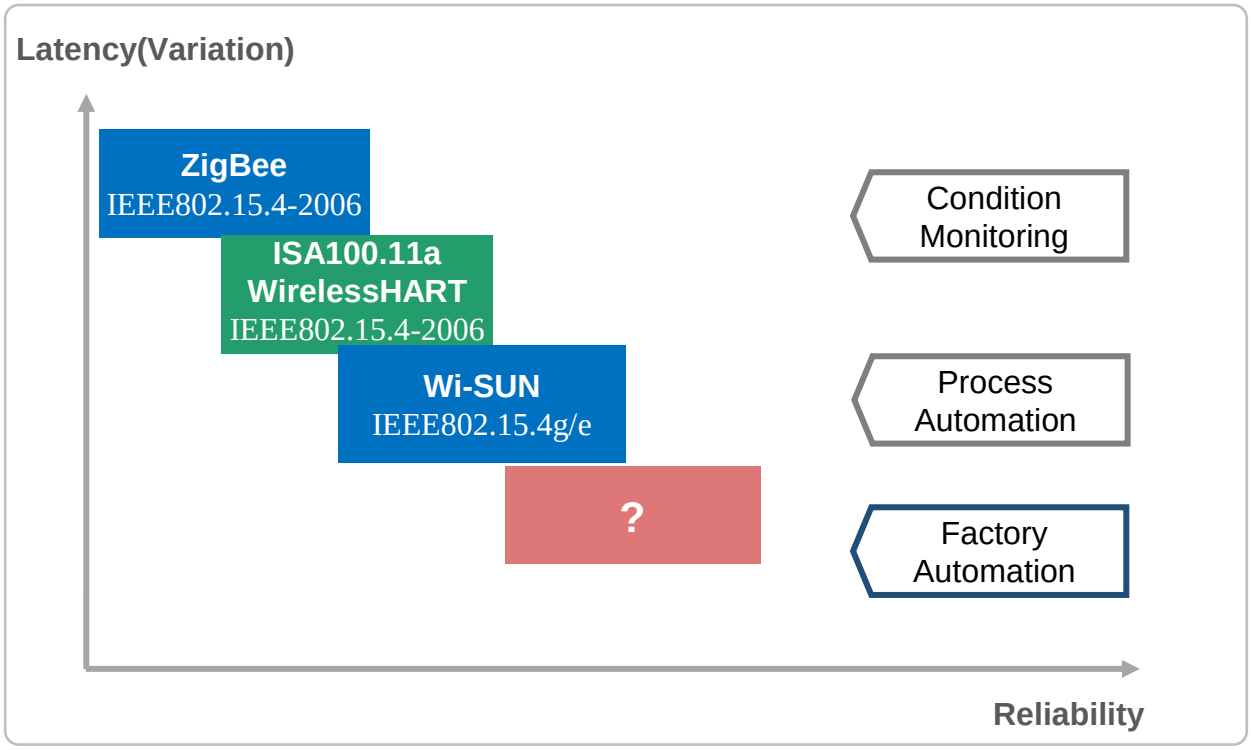
Standardization on Industrial Network(I)

- Evolution of wired industrial network
  - Isochronous real-time for closed-loop control is an essential requirements for industrial network

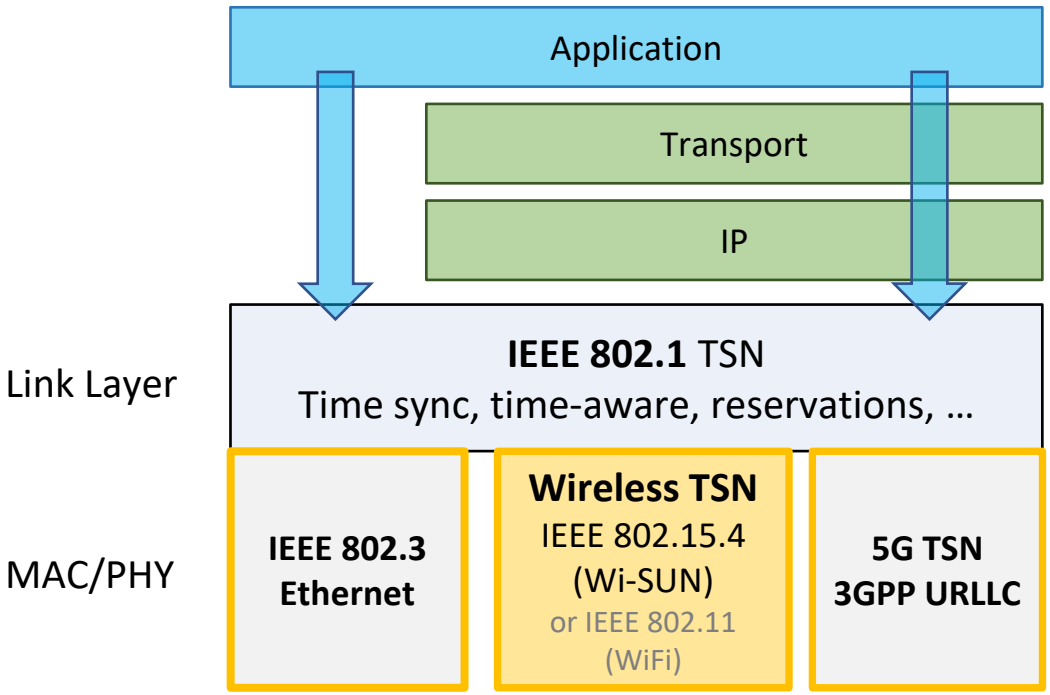


Standardization on Industrial Network(II)

- Wireless industrial network for providing isochronous real-time service
  - Not yet standardized
  - Why not consider NG-SUN?



Media Specific MAC/PHY Support for TSN



Source : Mikhail Galeev et al., Next-Generation Wi-Fi Networks for TimeCritical Applications, Intel, 2019.
Industrial Ethernet Book Issue 117 / 8, Wireless TSN use cases and standards challenges

Requirements for Industrial Applications

❖ Wireless User Requirements for the Factory Workcell ※

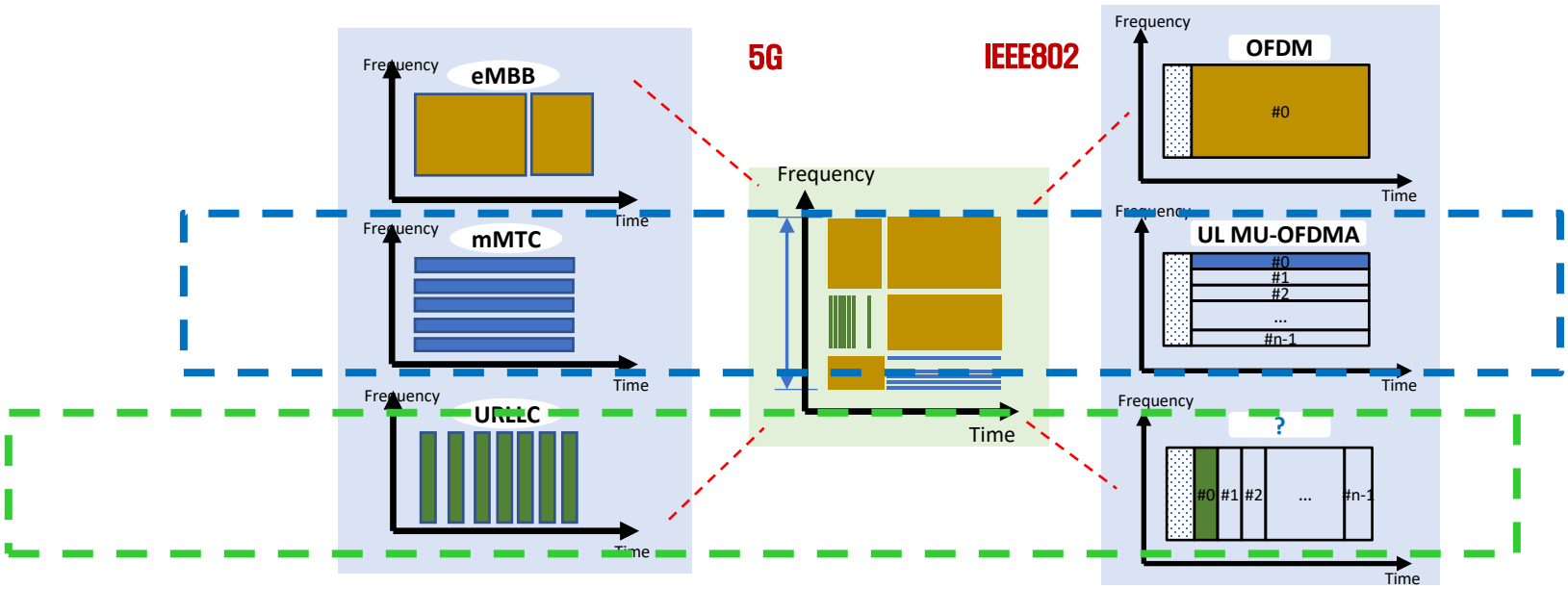
		Class 0	Class 1	Class 2
# of links	Typical	8	10	10
	Maximum	24	30	30
Update Rate (Hz)	Typical	125	125	25
	Maximum	1000	2000	125

- **Class 0: Safety**
  - highly critical, for example, safety integrated systems.
  - applications : typically used to prevent damage to equipment or personnel
- **Class 1: Closed Loop Regulatory Control**
  - multiple single-input single-output control loops, designed to regulate local variables such as flow, speed, etc.
  - Applications : robot end-effectors, arc-welders, laser cutters and precise position-based arm control etc
- **Class 2: Closed Loop Supervisory Control**
  - applications : Discrete manufacturing, tasks are completed sequentially

※ *NIST Advanced Manufacturing Series 300-8 Revision 1*
Wireless User Requirements for the Factory Workcell

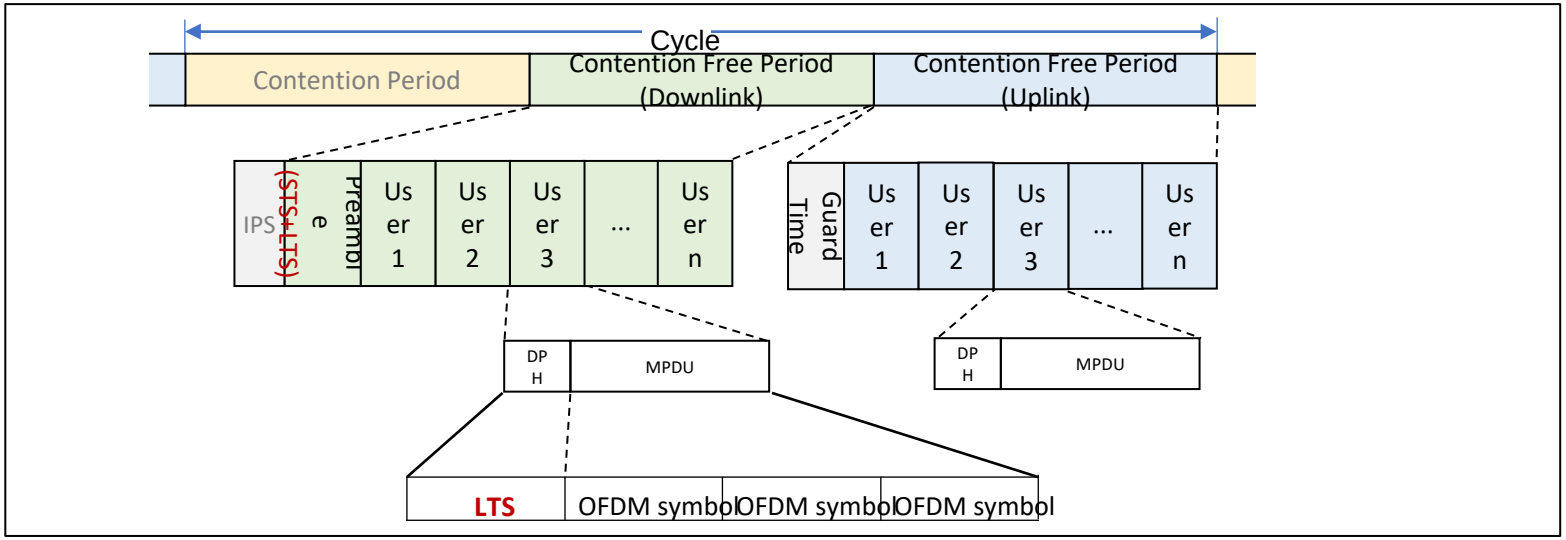
Motivation of Ultra Low Latency SUN

	5G	IEEE802
Capacity Enhancement - AR/VR, …	eMBB	OFDM
Massive IoT - Low cost, Low energy, …	mMTC	UL MU-OFDMA Wi-SUN
Critical IoT - High reliable, Low latency, …	URLLC	? (NG-SUN)



Basic Idea of Ultra Low Latency SUN

- Deterministic Latency(Wi-SUN, 802.15.4e) using Contention Free Period
  - Short length, High Update Rate for supporting wireless TSN
  - Downlink : LTF in Preamble is used for Downlink symbol timing estimation
  - Uplink : LTF is used for Uplink preamble



$$T_{Cycle} > T_{pre} + 480 \times N_{DownLinkUserCount} + T_{GI} + 480 \times N_{UpLinkUserCount}\ [\mu s]$$

Ex) $N_{DownLinkUserCount} = N_{UpLinkUserCount} = 20$

$$T_{Cycle} > T_{pre} + T_{GI} + 19.2\ [ms]$$

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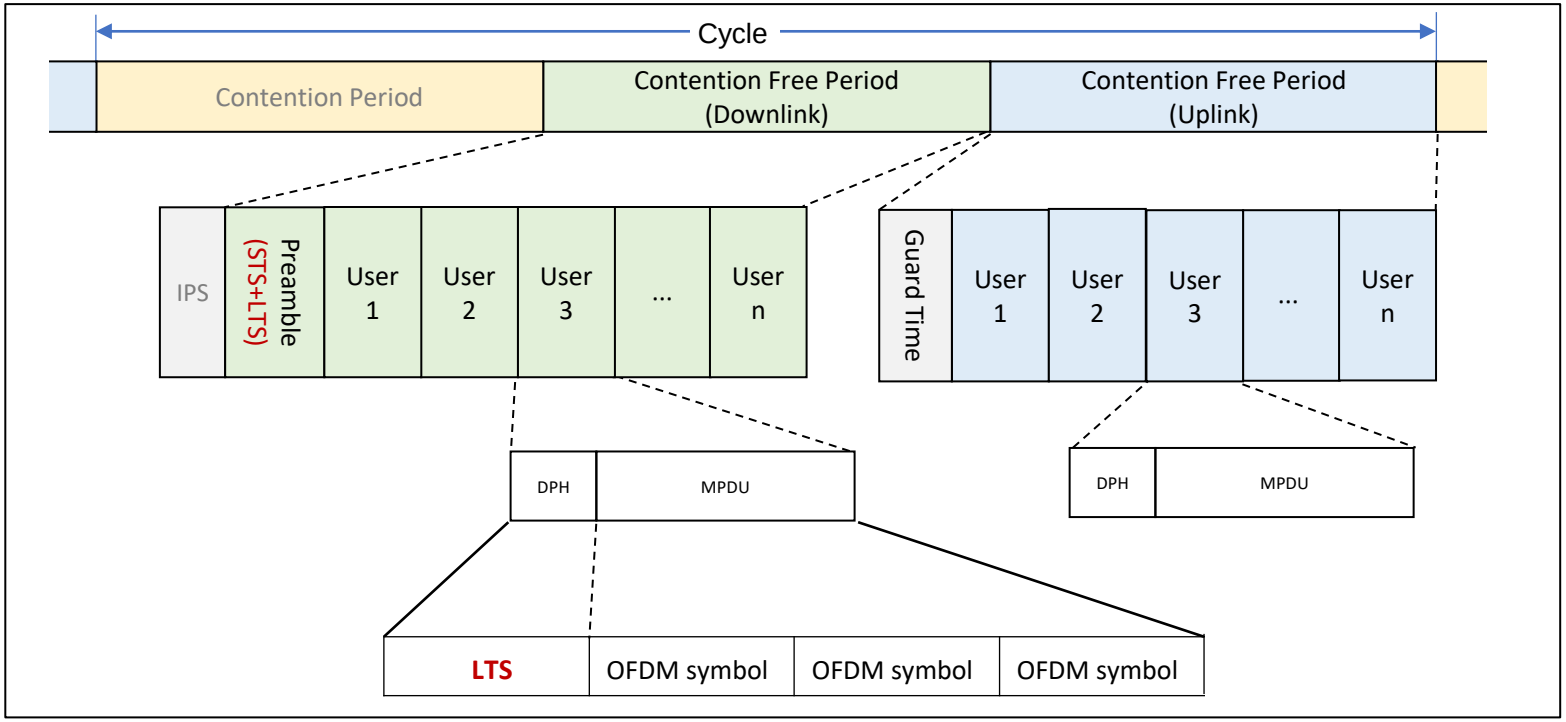
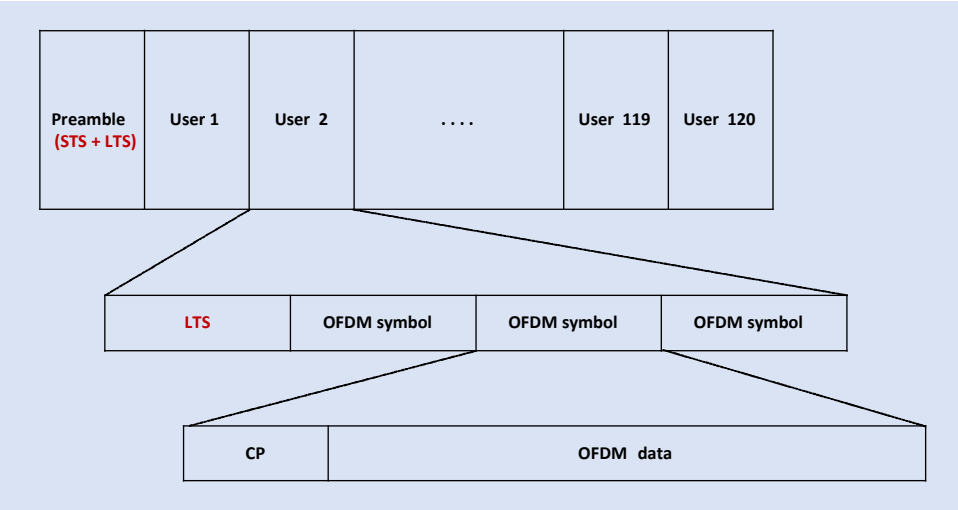


Feasibility Experiments(1)

- Configuring a test system to verify the applicability of wireless TSN in industrial applications
  - 120 Links / 500Hz, 5 Links / 8KHz
  - Operating Frequency : 5GHz, 6GHz

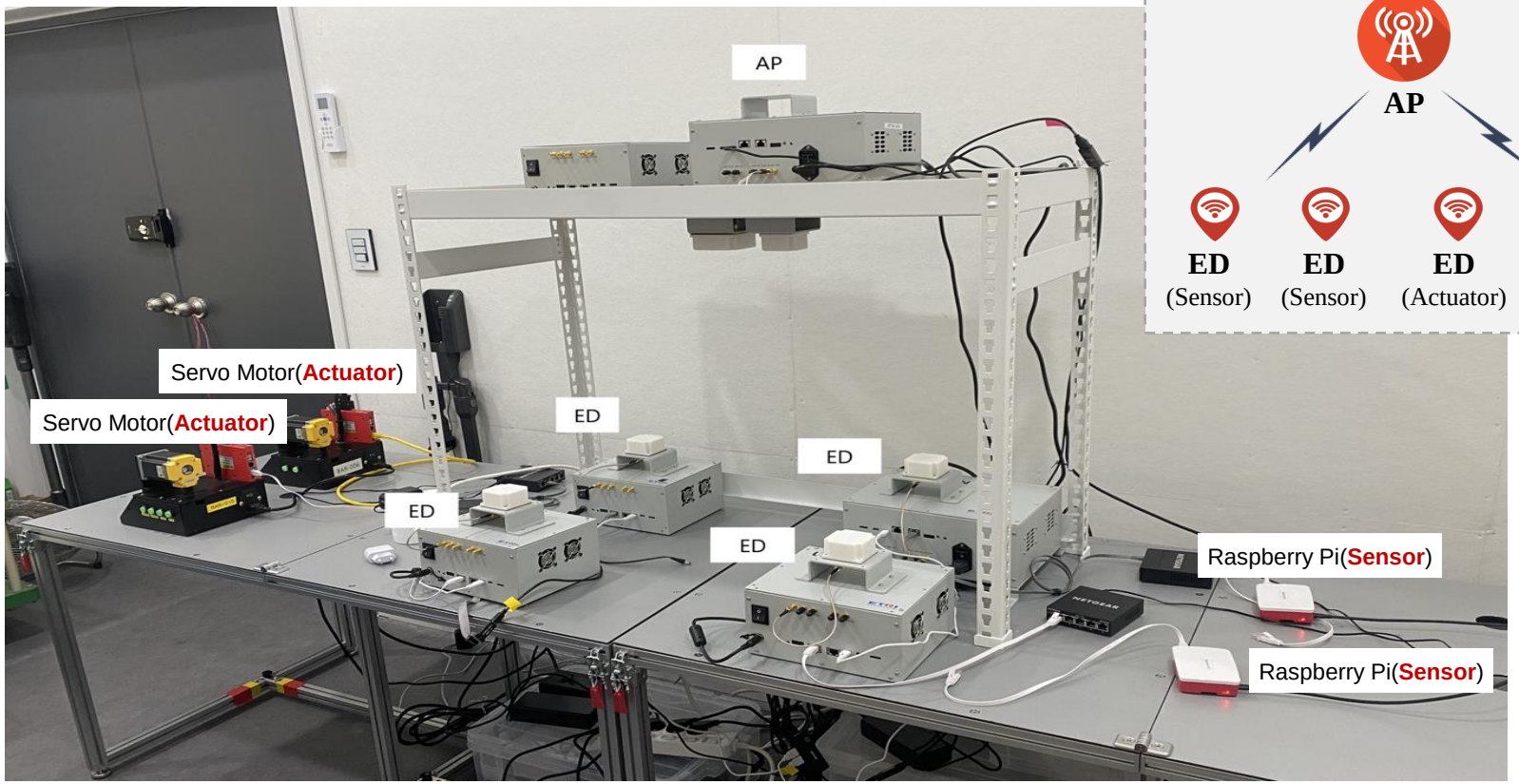
OFDM Parameters	
Signal Bandwidth	20 MHz
Number FFT Size	64
Subcarrier spacing	312.5KHz
The number of active subcarrier	52 for data
OFDM symbol duration	3.2 μs
Guard interval (Cyclic Prefix)	0.8 μs
Total OFDM symbol duration	4.0 μs
Modulation	QPSK



	Sensitivity	Bits/User	Code Rate	
QPSK	-72	312bits	1	Uncoded
QPSK	-79	150bits	0.5	Convolution code
QPSK	-83.47	175bits	0.68	EG-LDPC
QPSK	-77.97	175bits	0.68	EG-LDPC, TDL channel

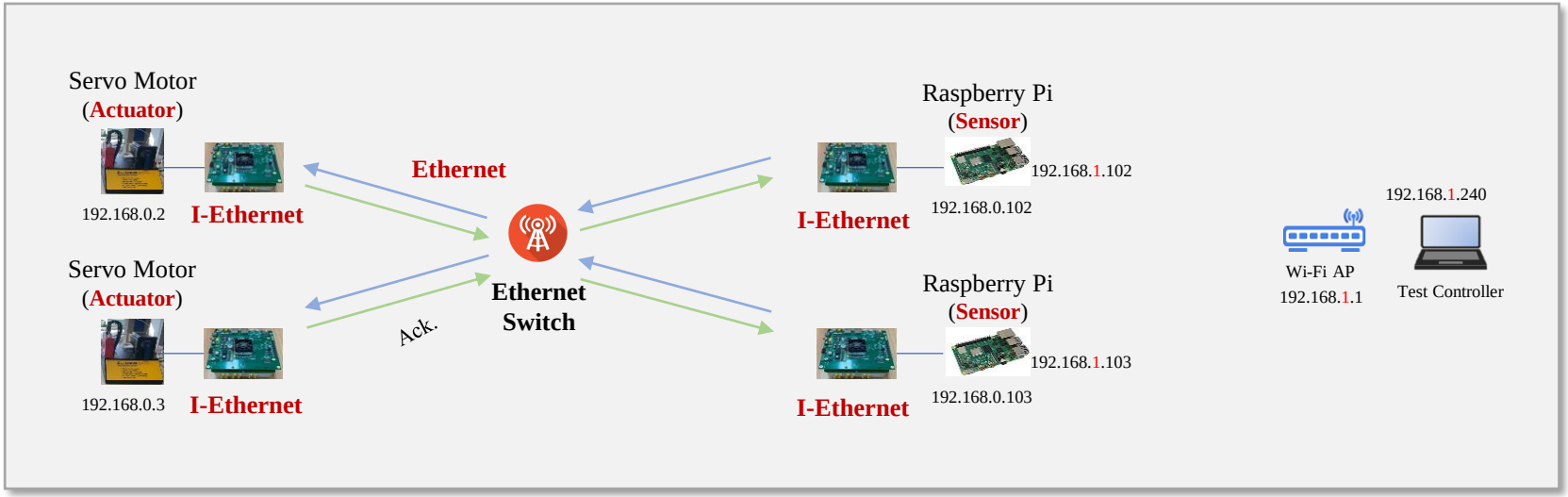
Feasibility Experiments(2)

- Periodic motor position control system for industrial applications
  - 1 AP + 4 Links (2 Sensors + 2 Actuators)
  - Update Rate : 33.3 Hz (Cycle Time : 30ms)



Scenario of Experiments(1)

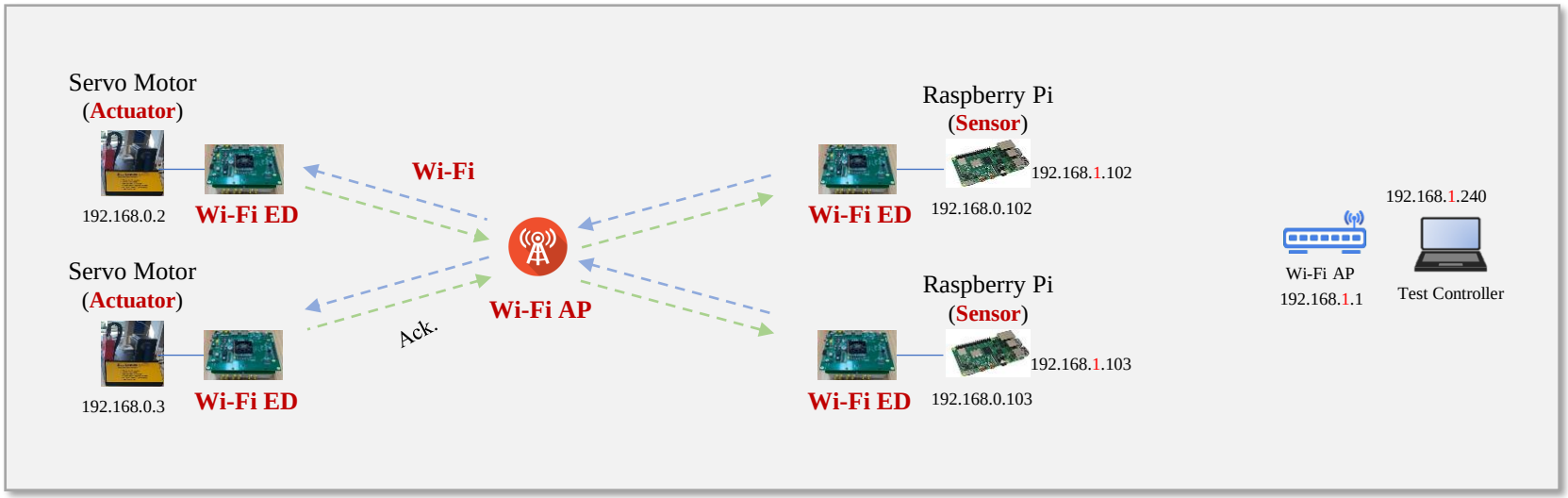
❖ Case 1) Wired motor control system : I-Ethernet



If you continuously send control signals to both motors at 30ms intervals and stop the motor after a certain period of time, you can see that both motors stop at the same position

Scenario of Experiments(2)

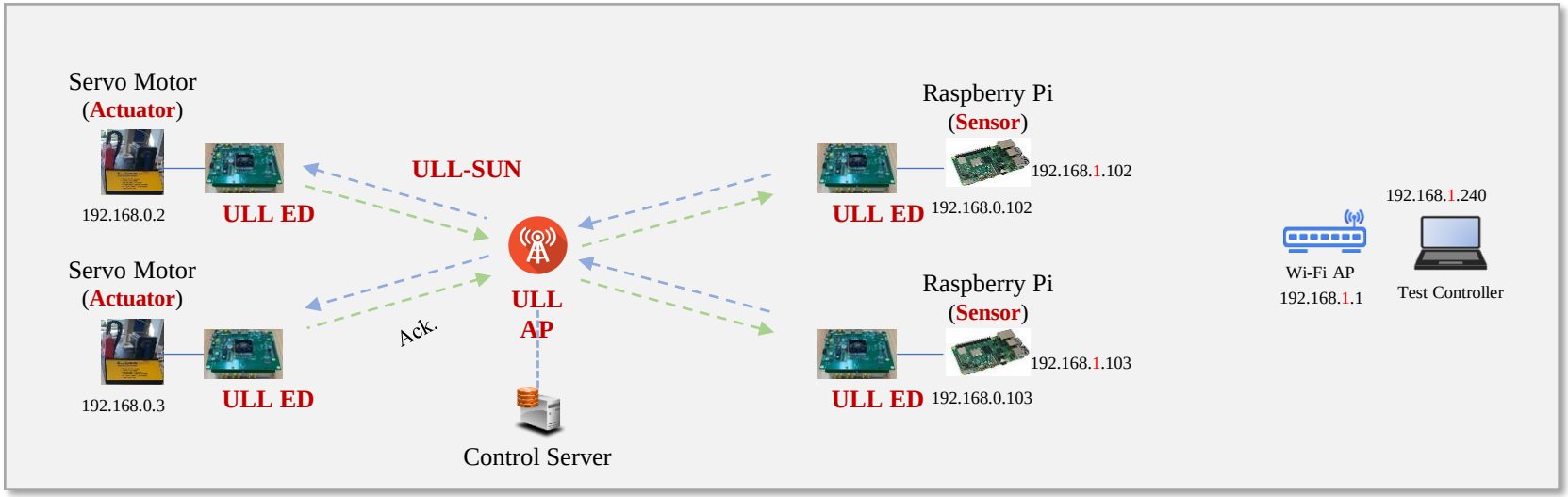
❖ Case 2) Wireless motor control system : Wi-Fi



If you continuously send control signals to both motors at 30ms intervals and stop the motor after a certain period of time, you can see that both motors stop at different positions.

Scenario of Experiments(3)

❖ Case3) Wireless motor control system : ULL-SUN *** ULL-SUN : Ultra Low Latency SUN**



If you continuously send control signals to both motors at 30ms intervals and stop the motor after a certain period of time, you can see that both motors stop at the same position

Comparison of Experiments

Case 1) Ethernet

Case 2) Wi-Fi

Case 3) ULL SUN

Experiment Results

❖ Verified the applicability of wireless TSN in industrial applications

- Maximum Update Rate : 8000 Hz
- Maximum # of links : 120
- Satisfy requirement of Isochronous Real Time for wireless TSN

Bandwidth	Active tones	# of links	Update Rate (Hz)
20MHz	52	5	8000
	52	120	500

* Wireless User Requirements for the Factory Workcell

		Class 0	Class 1	Class 2
# of links	Typical	8	10	10
	Maximum	24	30	30
Update Rate (Hz)	Typical	125	125	25
	Maximum	1000	2000	125

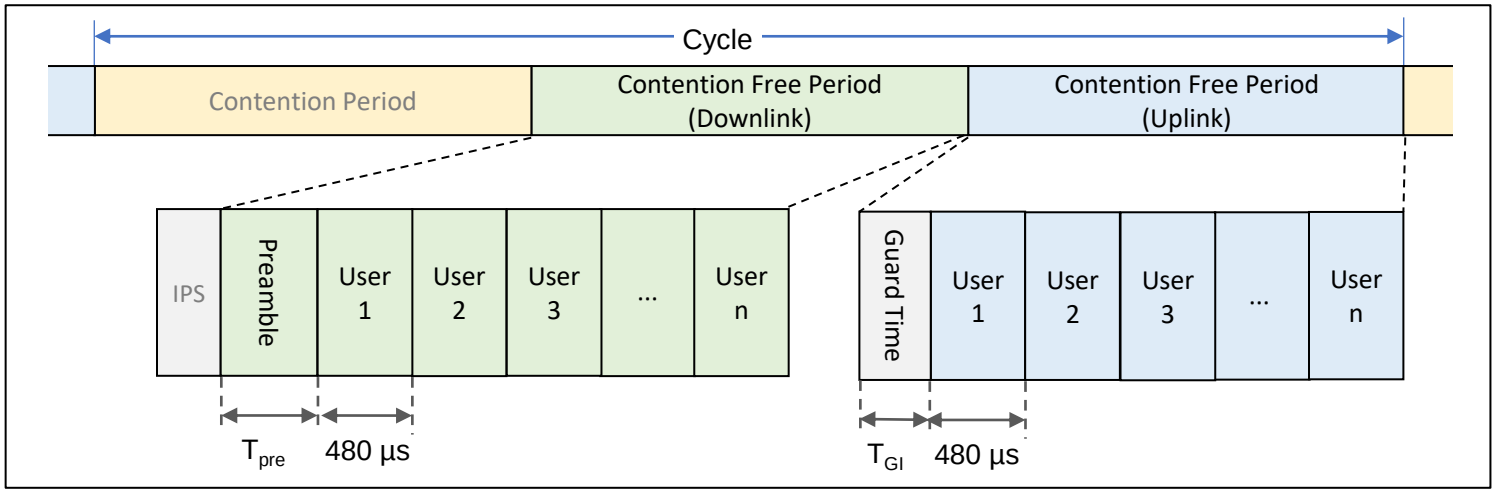
Expectation of NG-SUN(1)

- When applied to MR-OFDM with current 1094 KHz bandwidth
  - The symbol rate is 8-1/3 ksymbol/s, which corresponds 120 μs per symbol.

LTF(1 Symbol)	PSDU	PSDU	PSDU

* Resizable to integer multiples(*n*) of unit frame size : 4 x *n* Symbols (480 x *n* μs)

1 Slot : 4 Symbols (480 μs)



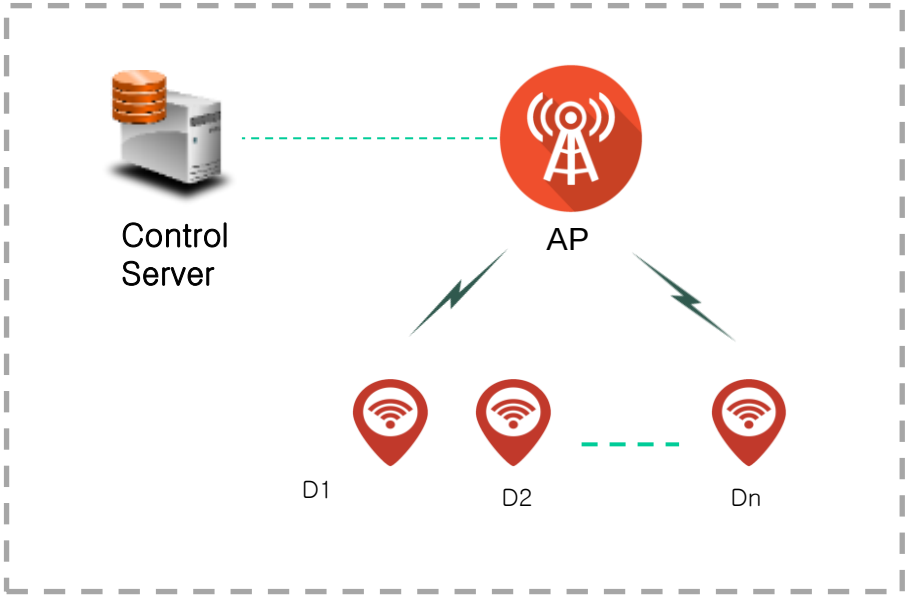
$$T_{Cycle} > T_{pre} + 480 \times N_{DownLinkUserCount} + T_{GI} + 480 \times N_{UpLinkUserCount}\ [\mu s]$$

Expectation of NG-SUN(2)

❖ When applied to MR-OFDM with current 1094 KHz bandwidth

- Update Rate : 50 Hz , # of links : 40
- Utilize for Isochronous Real Time service for limited levels of wireless TSN

Bandwidth	Active tones	# of links	Update Rate (Hz)
1094KHz (MR-OFDM)	104	40	50



Ex> $N_{DownLinkUserCount} = N_{UpLinkUserCount} = 20$

$T_{Cycle} > T_{pre} + T_{GI} + 19.2$ [ms]

20 devices can upload and download data simultaneously at 20ms cycle time (50 times per second)

OR

40 devices can upload or download data simultaneously at 20ms cycle time (50 times per second)

Expectation of NG-SUN(3)

- When more bandwidth is available, NG-SUN can meet the isochronous real-time requirements for wireless TSN.
  - 2.4GHz, 5GHz, 6GHz ISM
  - TVWS

OFDM Parameters	
Signal Bandwidth	20 MHz
Number FFT Size	64
Subcarrier spacing	312.5KHz
The number of active subcarrier	52 for data
OFDM symbol duration	3.2 μs
Guard interval (Cyclic Prefix)	0.8 μs
Total OFDM symbol duration	4.0 μs
Modulation	QPSK

Bandwidth	Active tones	# of links	Update Rate (Hz)
20MHz	52	5	8000
	52	120	500

Bandwidth	Active tones	# of links	Update Rate (Hz)
10MHz	52	5	4000
	52	60	500

Bandwidth	Active tones	# of links	Update Rate (Hz)
5MHz	52	5	2000
	52	30	500

NG-SUN Applications

❖ Applicability in various fields

- Low Rate, Long Range service, such as Smart City : **Multi-slot(repetition)**
- Low Rate, Short Range feedback control of Manufacturing process, such as TSN : **Single-slot, Ultra-short cycle**
- High rate, short range service that mixes A/V and control data, such as in buildings : **Multi-slot(aggregation)**

▣ **Low Rate, Long Range** – Multi-slot(repetition), Smart City

User 1 (PDU 1)	User 1 (PDU 1)	User 1 (PDU 1)	User 2 (PDU 1)	User 2 (PDU 1)	User 2 (PDU 1)	User 3 (PDU 1)	User 3 (PDU 1)	User 3 (PDU 1)	. . .

▣ **Low Rate, Short Range** – Single-slot, Ultra-short cycle feedback control

User 1 (PDU 1)	User 2 (PDU 1)	User 3 (PDU 1)	User 4 (PDU 1)	User 5 (PDU 1)	User 2 (PDU 1)	User 3 (PDU 1)	User 8 (PDU 1)	User 9 (PDU 1)	. . .

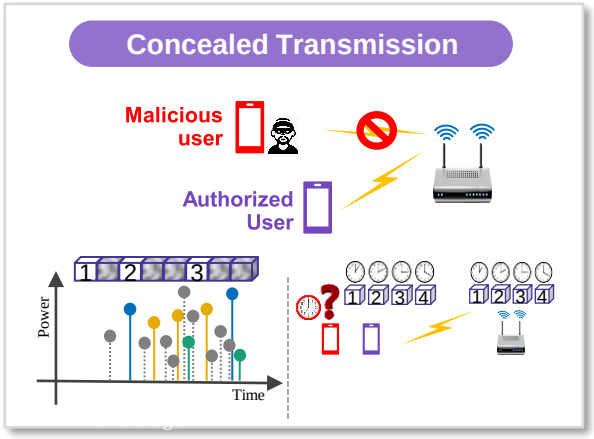
▣ **High Rate, Short Range** – Multi-slot(aggregation) – Smart factory/building(Video, Audio, Control data)

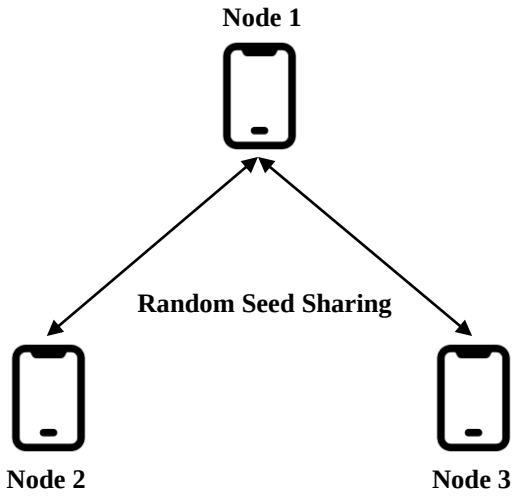
User 1 (PDU 1)	User 1 (PDU 2)	User 1 (PDU 3)	User 2 (PDU 1)	User 2 (PDU 2)	User 2 (PDU 3)	User 2 (PDU 4)	User 3 (PDU 1)	User 3 (PDU 2)	. . .

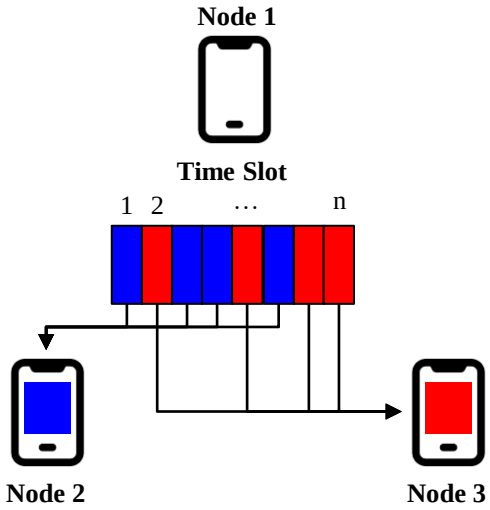
Security

Covert Communications

- Covert Communications for WSN
  - Protect & conceal sensitive packet
    - Generate random seed & share
    - Allocate packet to certain time slot
    - Extract/Reassemble packet







Discussion

- Considering the NG-SUN PHY standard for time-sensitive applications
  - Ultra-Reliable and ultra Low-Latency
  - \Short length, High Update Rate for supporting wireless TSN

- Considering the NG-SUN PHY standard based on wideband OFDM
  - Existing Wi-SUN system based on sub-giga frequency band-
  - The Korean government supplied the 6GHz band as a broadband unlicensed frequency (5,925～7,125MHz, 1.2GHz).

Thanks for Listening !
Q&A