Spectrum Shared Synchronous Cognitive Wireless Distributed Networks

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Cognitive MIMO Mesh Network (CMMN)

Research project called SCOPE funded by Japanese ministry of internal affairs and communications from 2006 to 2009

Joint research project among four universities

- Tokyo Institute Technology
- The University of Electro-Communications
- Tokyo University of Agriculture and Technology
- Yokohama National University

Very high speed wireless mesh networks are achieved over the primary wireless communication system by using dynamic spectrum access (DSA) and MIMO technologies

From 2009, we started new research project funded by SCOPE with Tokyo University of Science, for the research about "Intelligent MAC Layer Techniques for Cognitive Radio"

Today's Presentation

- Introduction and Problem of Current Wireless LAN
- Research Summary of this Project
- Analysis of Potential Ability Spectrum Sharing by using Primary Sensing Function
- Synchronous MAC Protocol for Wireless Distributed Networks

1. INTRODUCTION

One method of establishing flexible wireless networks

WDN

(Wireless Distributed Networks)

are focused

"High speed high reliability wireless distributed network"

Current Wireless LAN system

CSMA/CA protocol is utilized for accessing distributed spectrum resource (IEEE802.11-DCF)

→ This protocol is used all over the world

However,

Utilization efficiency of spectrum of CSMA/CA is not high

- Backoff period of CSMA/CA, IFS(Inter Frame Space) for distributed access
- Packet loss due to random access
- Performance degradation due to hidden node problem
- In-flow hidden node problem in multi-hop network

⇒ Post CSMA/CA Protocol is required without considering traditional backward compatibility of current CSMA

Synchronous Wireless Distributed Networks

In order to realize synchronous WDN

Spectrum sharing with conventional wireless LAN is required.

Co-existence of CSMA based conventional wireless LAN and TDMA based synchronous WDN

➡ Different policy networks should share the spectrum

In this research

Conventional WLAN: Primary system
Synchronous WDN: Secondary system } Cognitive system

High speed reliable synchronous wireless distributed networks over conventional wireless LAN is considered.

What is Cognitive Radio?

Cognitive radio

- Communication method
- Modulation method
- Frequency
- Data rate

} Transceiver is reconfigured by recognizing the surrounding radio environment

↓

Unused frequency can be used for communication by reconfiguration not to interfere to the primary systems

Cognitive radio is expected to be a solution for the shortage of the frequency resource

Types of Cognitive Radio

There are two main research streams of Cognitive Radio

- **Multi-mode System (Heterogeneous Network)**

  Adaptive selection of multiple wireless systems for improving the efficiency of radio resource

- **Dynamic Spectrum Access (Spectrum Sharing)**

  Flexible frequency use for secondary communication without interference toward the primary system

Multi-mode System

- Multiple wireless communication systems are adaptively selected according to the radio environment
- The frequency assignment of each system is the same as the conventional frequency allocation plan
- Multi-mode terminals are used

Examples

Data →

Data →	802.11a (WLAN)	5GHz
Data →	802.11g (WLAN)	2.4GHz
Data →	802.16 (WiMAX)	2.5GHz?

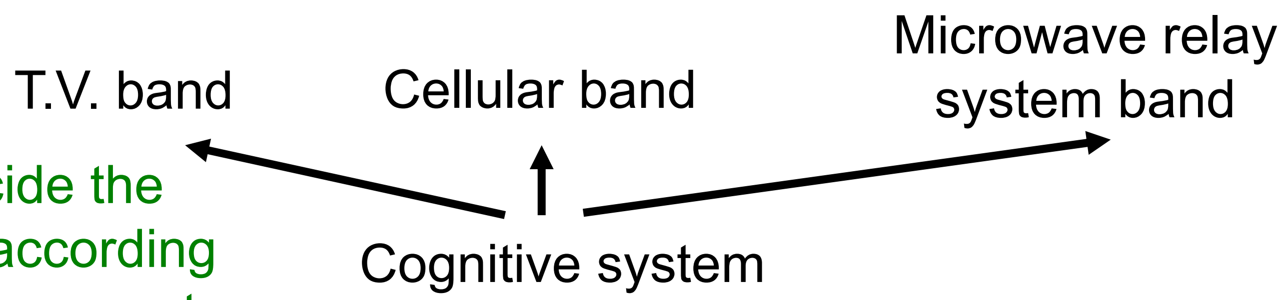
Selection according to the radio environment

Easy feasibility but improvement of frequency usage is not high

Dynamic Spectrum Access

- Secondary cognitive system uses the frequency band assigned to the primary systems
- Dynamic frequency utilization can be realized if we can realize suppressing the interference toward the primary system
- Ultimately, wireless communication can be freely used without frequency allocation plan

Example



Adaptively decide the frequency band according to the radio environment

High efficient frequency usage can be realized but the spectrum allocation policy should be changed

Spectrum Sharing System

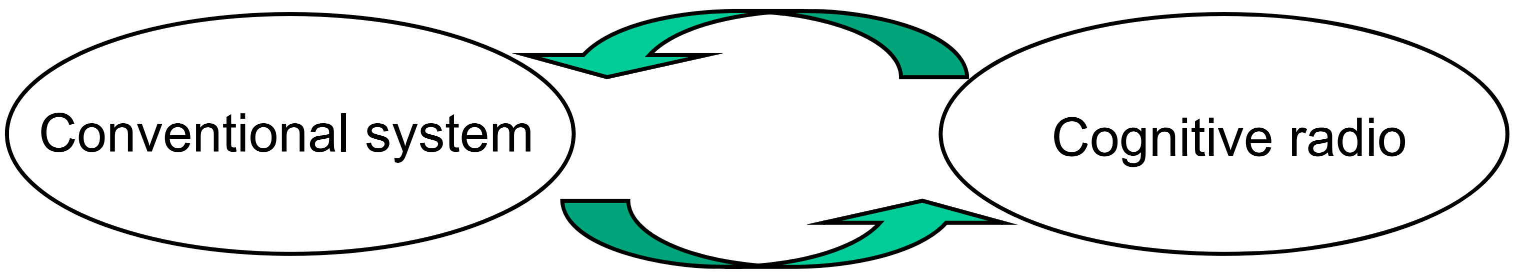
Even in metropolitan area, it is expected that 80% spectrum is not used instantly

White space spectrum

→ Such spectrum can be used for secondary system

Inter system interference avoidance between the primary system and the secondary system is required

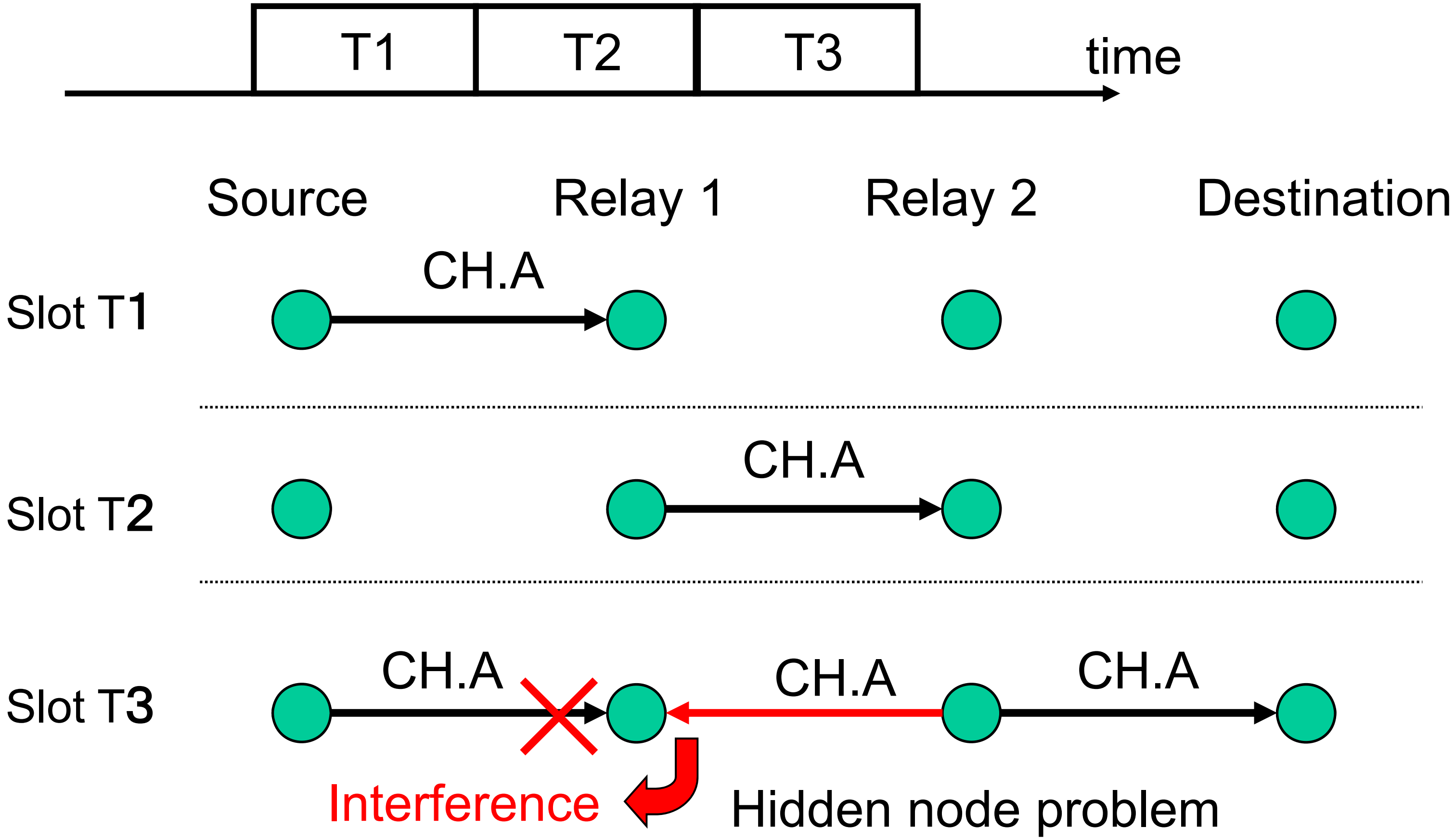
Conventional Wireless LAN Giving interference **Synchronous WDN**



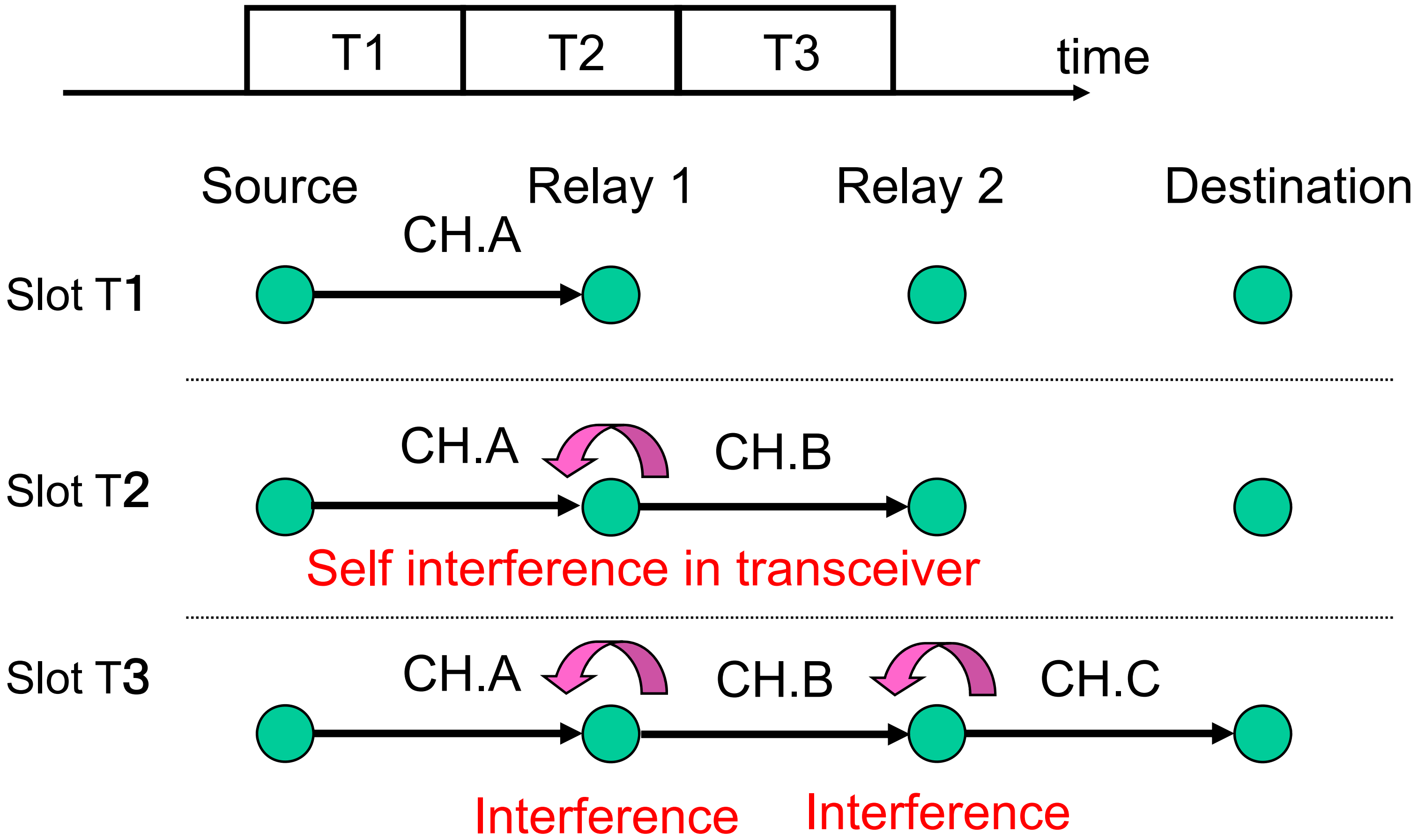
Primary system Given interference Secondary system

2. PROBLEMS OF CURRENT WLAN FOR MULTI-HOP HIGH SPEED NETEORKS

- In-flow hidden node problem on multi-hop networks



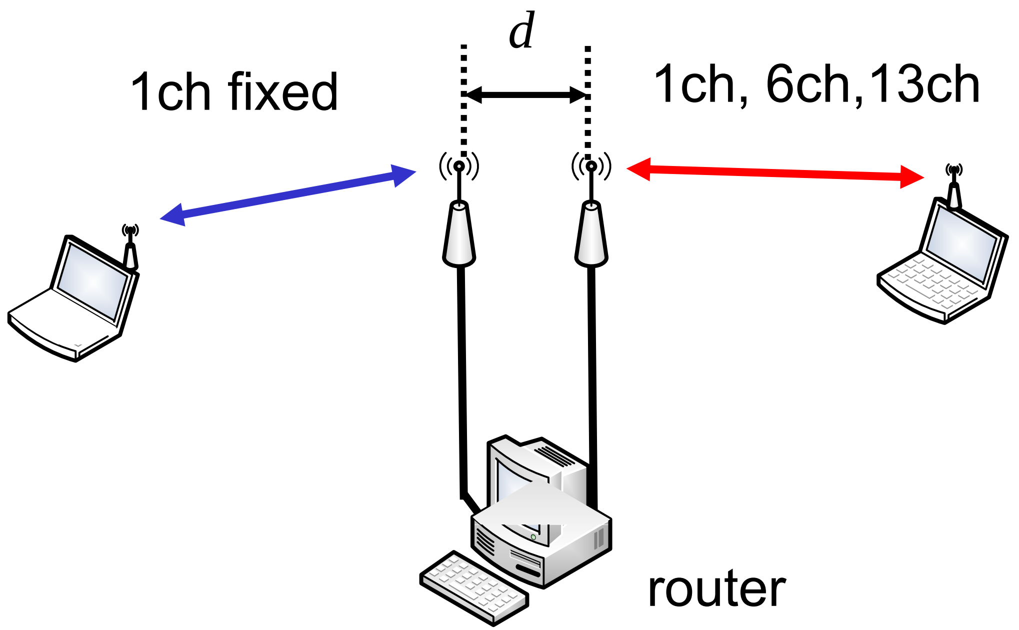
■Adjacent band interference of multi-radio



➡ Current CSMA/CA cannot be directly used for high speed multi-hop networks

Experimental results of multi-hop using multi-radio

Two WLAN access points are prepared.
Two-hop communication is operated in 2.4GHz band



- BUFFALO Air Station WHR-AMPG
- Data rate is measured by using the throughput measurement software Netperf

Data rate through two-hop communication

Normal throughput with one hop in 11g : around 20Mbps

	d=7.5cm	d=70cm	d=250cm
1ch-1ch	10.11Mbps	10.05Mbps	10.38Mbps
1ch-6ch	7.52Mbps	7.95Mbps	12.78Mbps
1ch-13ch	7.7Mbps	12.22Mbps	13.89Mbps

Large interference occurs due to small separation of antenna of Tx and RX

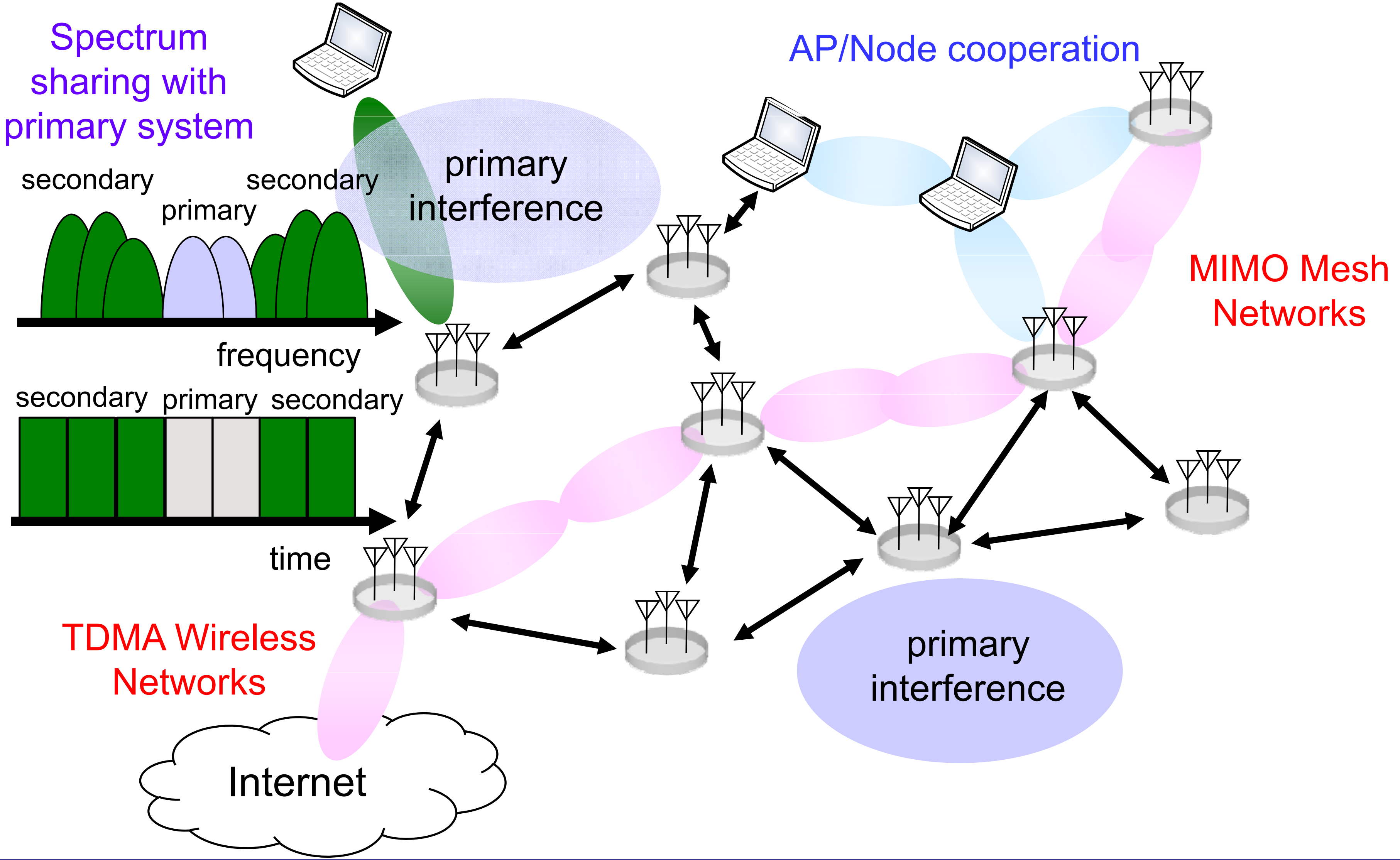
Interference can be mitigated by taking separation between antenna

Multi-radio cannot perfectly solve CSMA interference problem in multi-hop relay

3. SYNCHRONOUS WIRELESS DISTRIBUTED NETWORKS BASED ON COGNITIVE CONCEPT

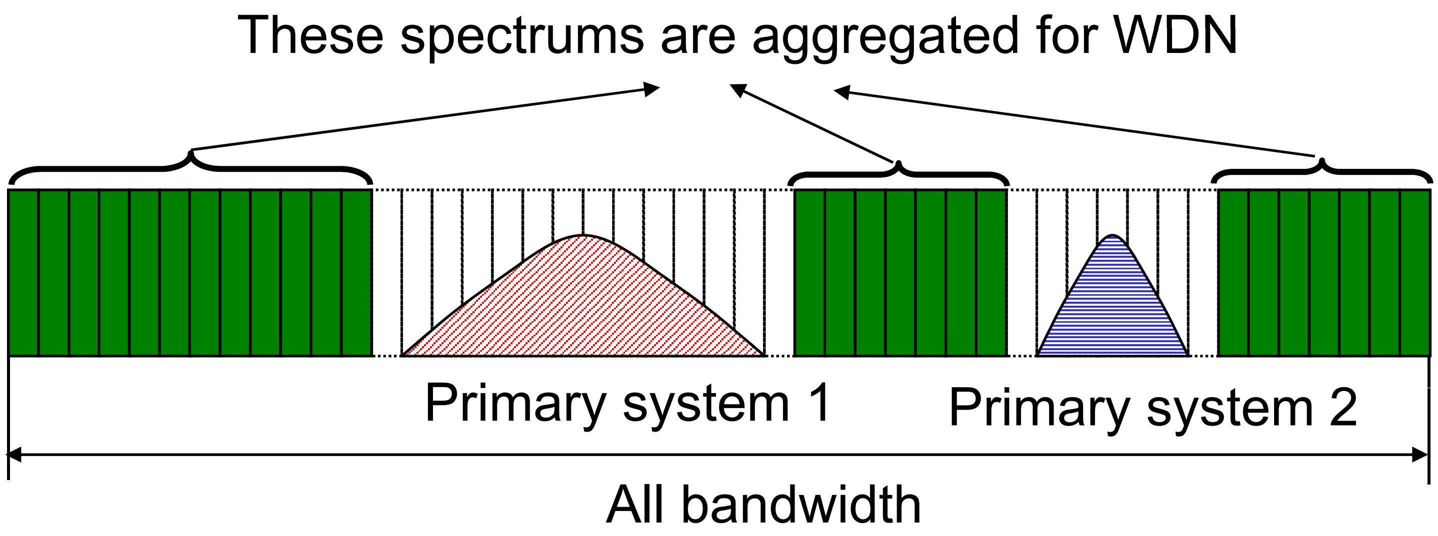
- **Synchronous wireless networks** are overlaid to the primary wireless LAN systems
- The performance of the primary system is protected by **keeping the throughput**
- MAC level redundancy is removed by using **synchronous TDMA networks** within the self flow
- Throughput of the flow can be improved by using **MIMO antenna signal processing**
- **Dynamic spectrum access by using OFDMA** for realizing the high spectrum efficiency networks

System Image of Cognitive Wireless Distributed Networks



Dynamic Subcarrier Control throughout Wide Band

Spectrum is shared by setting null subcarriers on the primary utilized spectrum band for avoiding inter-system interference



All spectrum is adaptively controlled by the unit of subcarrier at WDN system

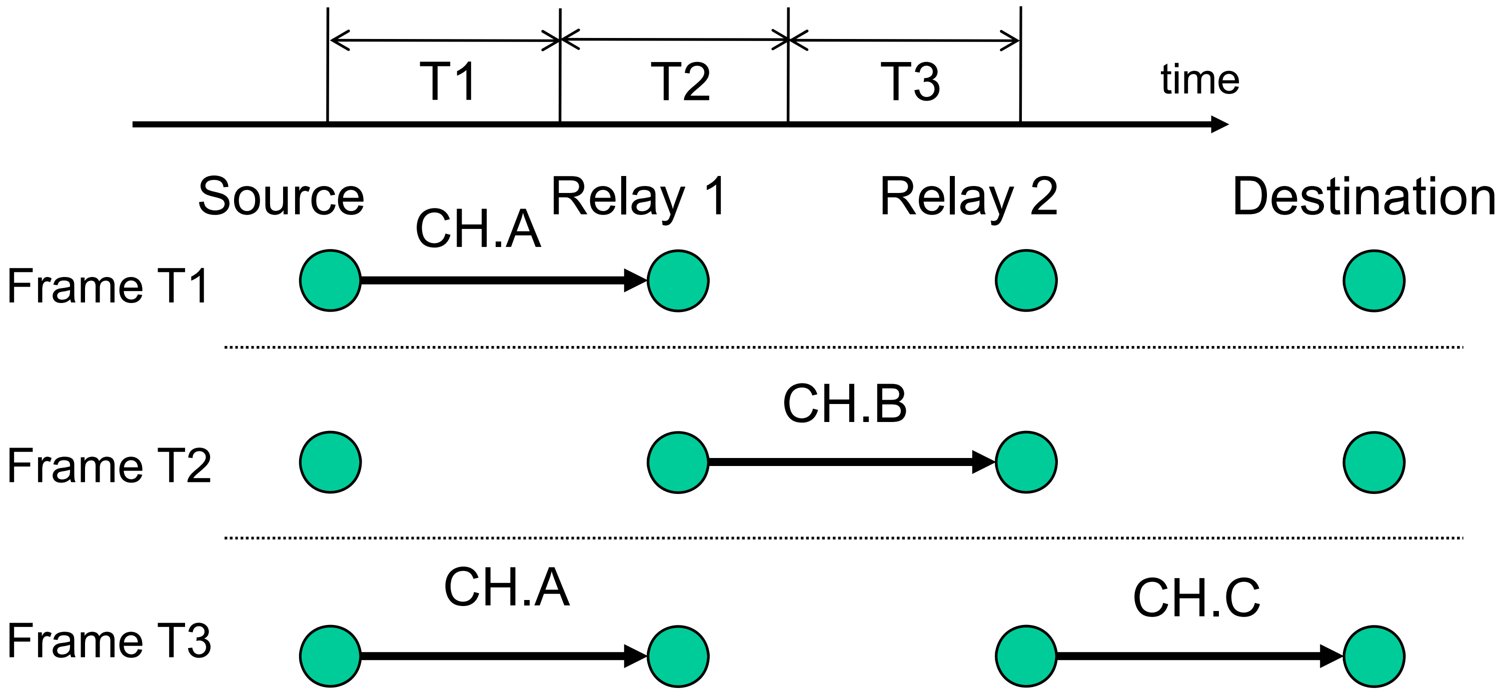
TDMA Multi-hop Wireless Networks

•Transmit timing of the nodes in a flow is synchronized:

Transmit timing is scheduled by the source node

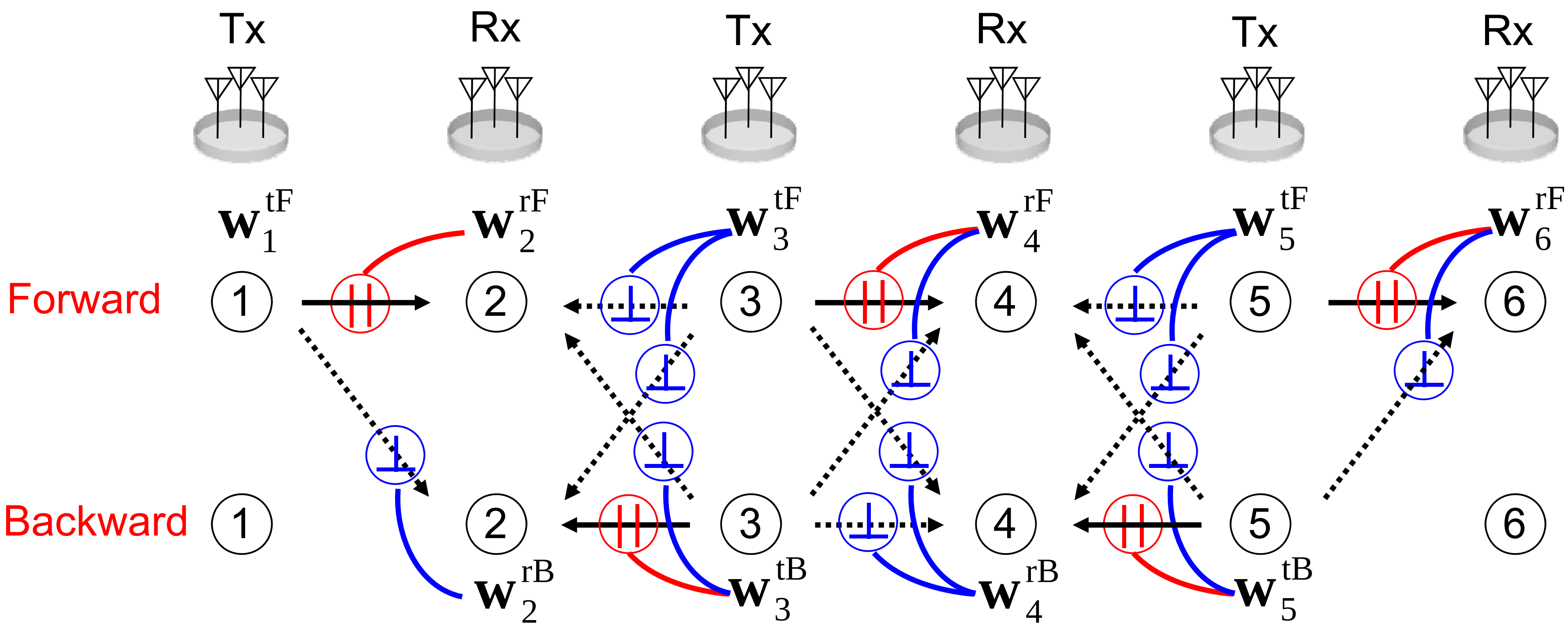
⇨ Packet transmission timing can be controlled not to occur the hidden node problem

•Two-way transmission can be realized with high efficiency by using MIMO technique in the TDMA multi-hop networks



High Speed Two-way Wireless Multi-hop Networks using MIMO Mesh

- Two-way forward link and backward link is multiplexed by space division in a flow
- Interference among the next next hop can be removed
- Diversity, interference cancellation and space multiplexing can be realized



4.ANALYSIS OF POTENTIAL ABILITY SPECTRUM SHARING BY USING PRIMARY SENSING FUNCTION

Typical spectrum shared cognitive radio on primary system

➡ Secondary nodes avoid interference toward primary system.

- ✓ Transmission interruption according to the sensing results of spectrum sensing
- ✓ Setting protection area by using Geolocation information
- ✓ Interference limitation toward primary receiver by using power control of secondary node
- ✓ Interference avoidance by using adaptive array antenna

Power control method for avoiding interference toward primary receiver is typical solution of spectrum sharing.

Some primary systems have CSMA function at transmitter

ISM band device for considering spectrum sharing

➡ Typical system: Wireless LAN

These devices have carrier sense function

These primary systems can share the spectrum by using low sensitive sensing function but not perfect.

We can select two types of sharing spectrum method if we assume the primary system with carrier sense function.

- ✓Secondary power control method (Space Division)
- ✓Time sharing by using sensing (Time Division)

Which method can achieve more efficient spectrum sharing?

- Primary System ➡ Low sensitive sensing
- Secondary System ➡ High sensitive sensing

Spectrum sharing methods

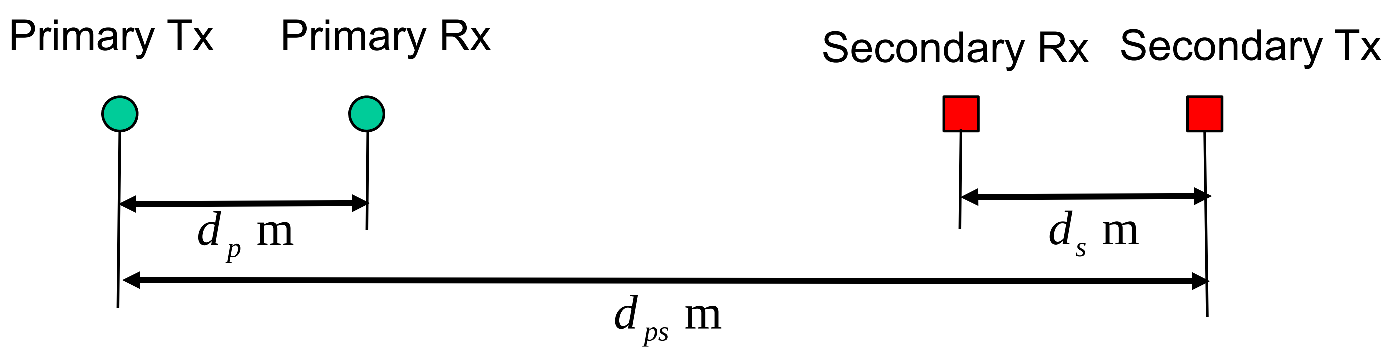
Time Sharing?	Power Control?
CSMA or TDMA	Space Division

We analyze the performance of both systems for confirming suitable situation to apply.

In particular, we evaluate the secondary capacity performance by considering the sensing level.

System Model
Primary and Secondary Model

- Worst case interference scenario is considered
- Only the transmitter signals can be sensed
- Perfect spectrum sensing and perfect power control are assumed in the first step



Power Control : Interference level mitigation at Primary Rx
Carrier Sense : Both communication pairs detect each other

Propagation Model

Simple propagation model based on n exponent model

- Primary transmit power P_p
- Primary max transmit distance d_p
- Primary permission interference I_p
- Secondary sensing level γ_s
- Secondary transmit power P_s
- Secondary max transmit distance d_s
- Secondary carrier sense range d_{scs}
- Path loss factor n
- Reference distance d_0
- Wave length λ

Propagation loss based on dB domain

$$L_{s,dB} = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 10n\log_{10}\left(\frac{d}{d_0}\right)$$

When antenna gain of Tx and Rx is $G_{s,dB}$ $G_{r,dB}$, respectively and the transmit power is $P_{s,dB}$, the received power is

$$P_{r,dB} = P_{s,dB} + G_{s,dB} + G_{r,dB} - L_{s,dB}$$

The above equation can be converted to

$$P_r = P_s \cdot G_s \cdot G_r \cdot \left(\frac{\lambda}{4\pi d_0}\right)^2 \cdot \left(\frac{d_0}{d}\right)^n$$

Constant part can be unified

$$P_r = P_s \cdot \alpha \cdot \left(\frac{1}{d}\right)^n$$

α constant part

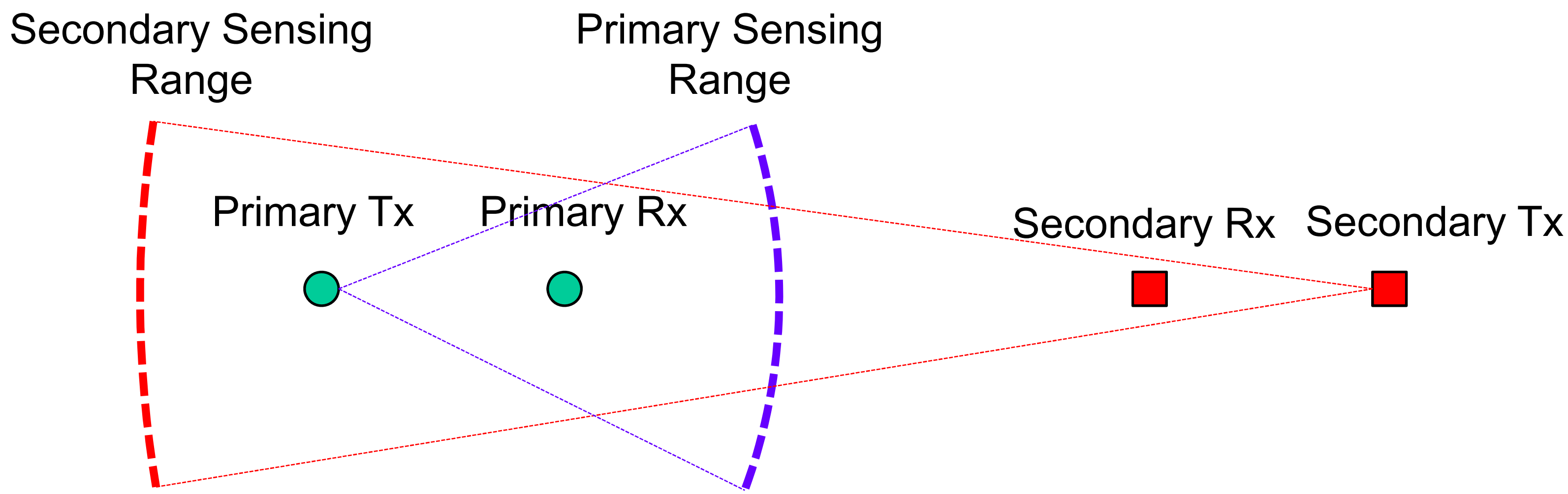
2.4GHz, Antenna gain 1, $d_0 = 1$

⇨ $\alpha = 9.89 \times 10^{-5}$

Sensing Model

Sensing level Signals more than γ : sensing succeeded
Signals less than γ : sensing failed

Primary node : Low sensitive device ⇨ sensing area is small
Secondary node: High sensitive device ⇨ sensing area is large



Different sensing area brings hidden node problem occurs one way

⇨ One way hidden node problem

Perfect interference avoidance can be achieved by removing one way hidden node problem.

Analysis of Primary Secondary Spectrum Sharing

Spectrum sharing based on power control

Maximum permissible transmit power by protecting the primary receiver

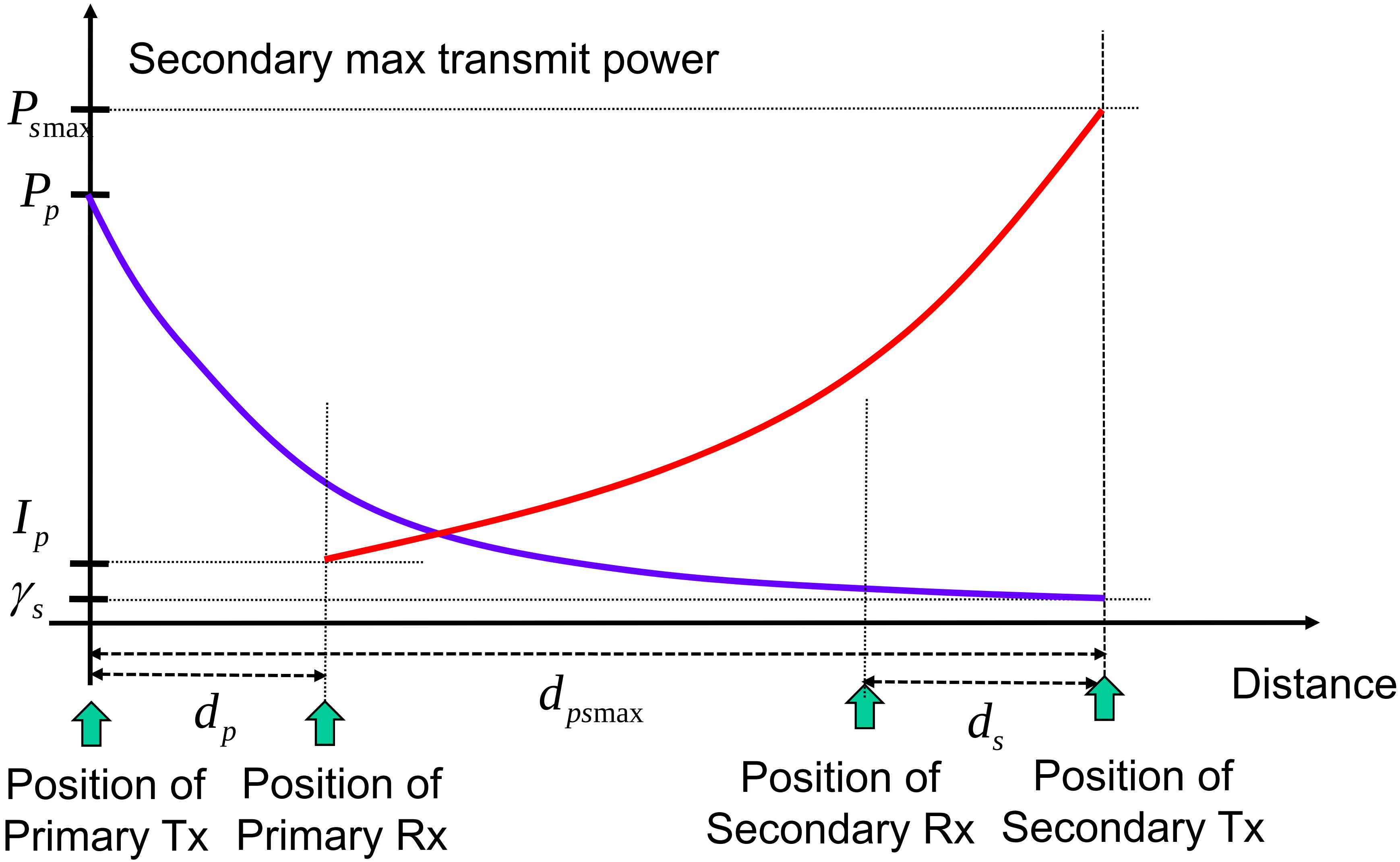
$P_{s\max}$ and $d_{ps\max}$ can be derived by primary transmit power P_p and secondary sensing level γ_s .

$$\gamma_s = P_p \cdot \alpha \cdot \left(\frac{1}{d_{ps\max}} \right)^n$$

$$I_p = P_{s\max} \cdot \alpha \cdot \left(\frac{1}{d_{ps\max} - d_p} \right)^n$$

where I_p is permissible interference power for protecting primary receiver.

Power relation under power control



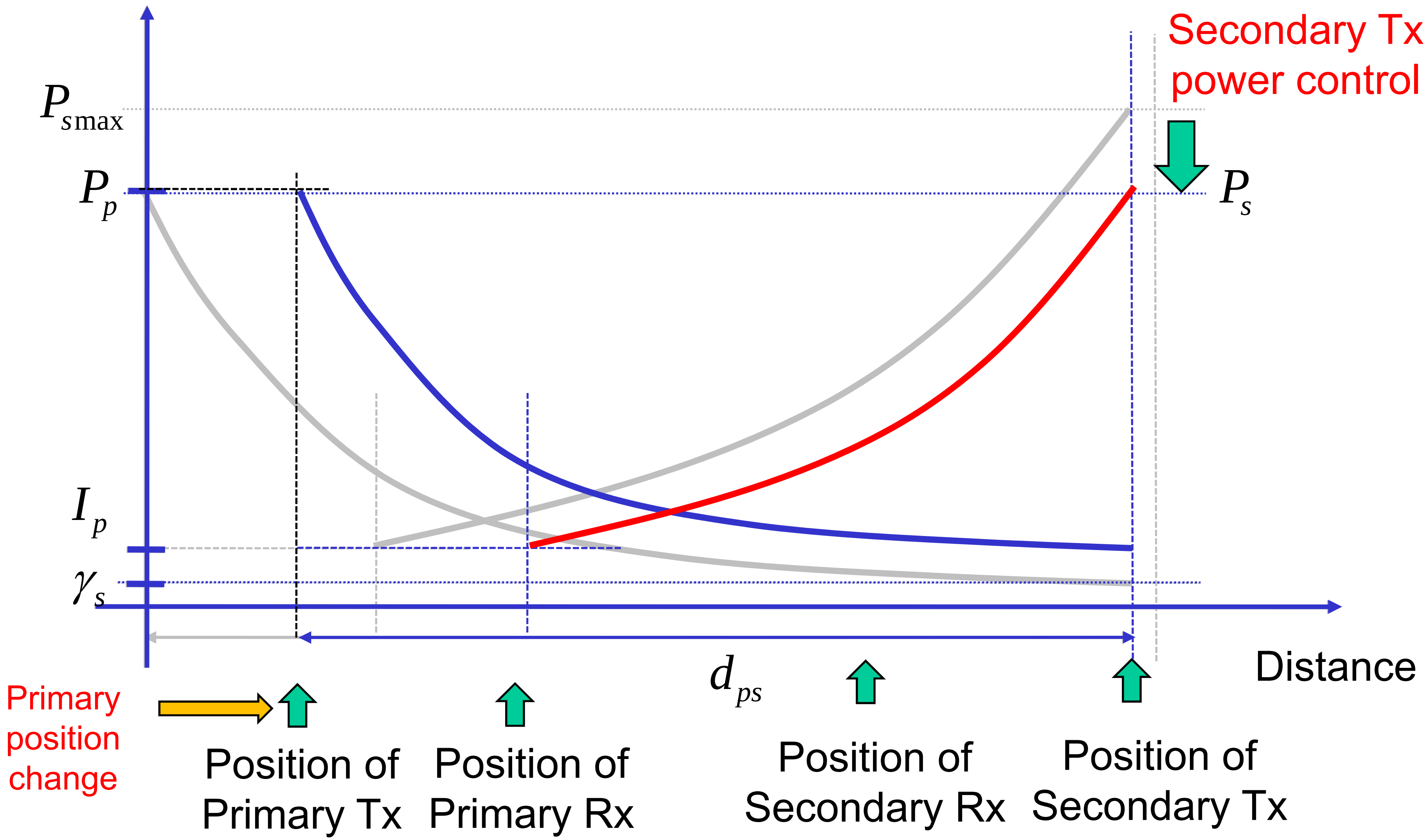
Power control when the distance of both Txs becomes small

In order to keep the giving interference limitation, the distance between both transmitter is d_{ps} the following transmit power limitation should be considered.

$$I_p = P_s \cdot \alpha \left(\frac{1}{d_{ps} - d_p} \right)^n$$

From above equation, we can derive permissible transmit power P_s .

Power relation when both Txs becomes closer



Secondary capacity under transmit power control

Received signal power at the secondary receiver

$$P_{rs} = P_s \cdot \alpha \left(\frac{1}{d_s} \right)^n$$

Noise + Interference power at the secondary receiver

$$P_{\sin} = P_p \cdot \alpha \left(\frac{d_0}{d_{ps} - d_s} \right)^n + P_n$$

P_n Noise power

Secondary capacity under transmit power control

$$C_s = \log_2 \left(1 + \frac{P_{sr}}{P_{\sin}} \right) = \log_2 \left(1 + \frac{P_p \cdot \alpha \left(\frac{1}{d_s} \right)^n}{P_p \cdot \alpha \left(\frac{1}{d_{ps} - d_s} \right)^n + P_n} \right)$$ bits/s/Hz

Spectrum sharing based on time division

Spectrum sharing based on carrier sense to divide the system by time

Max sensing range d_{pscs} is derived from the primary sensing level and max power of secondary $P_{s\max}$

$$\gamma_p = P_{s\max} \cdot \alpha \left(\frac{1}{d_{pscs}} \right)^n$$

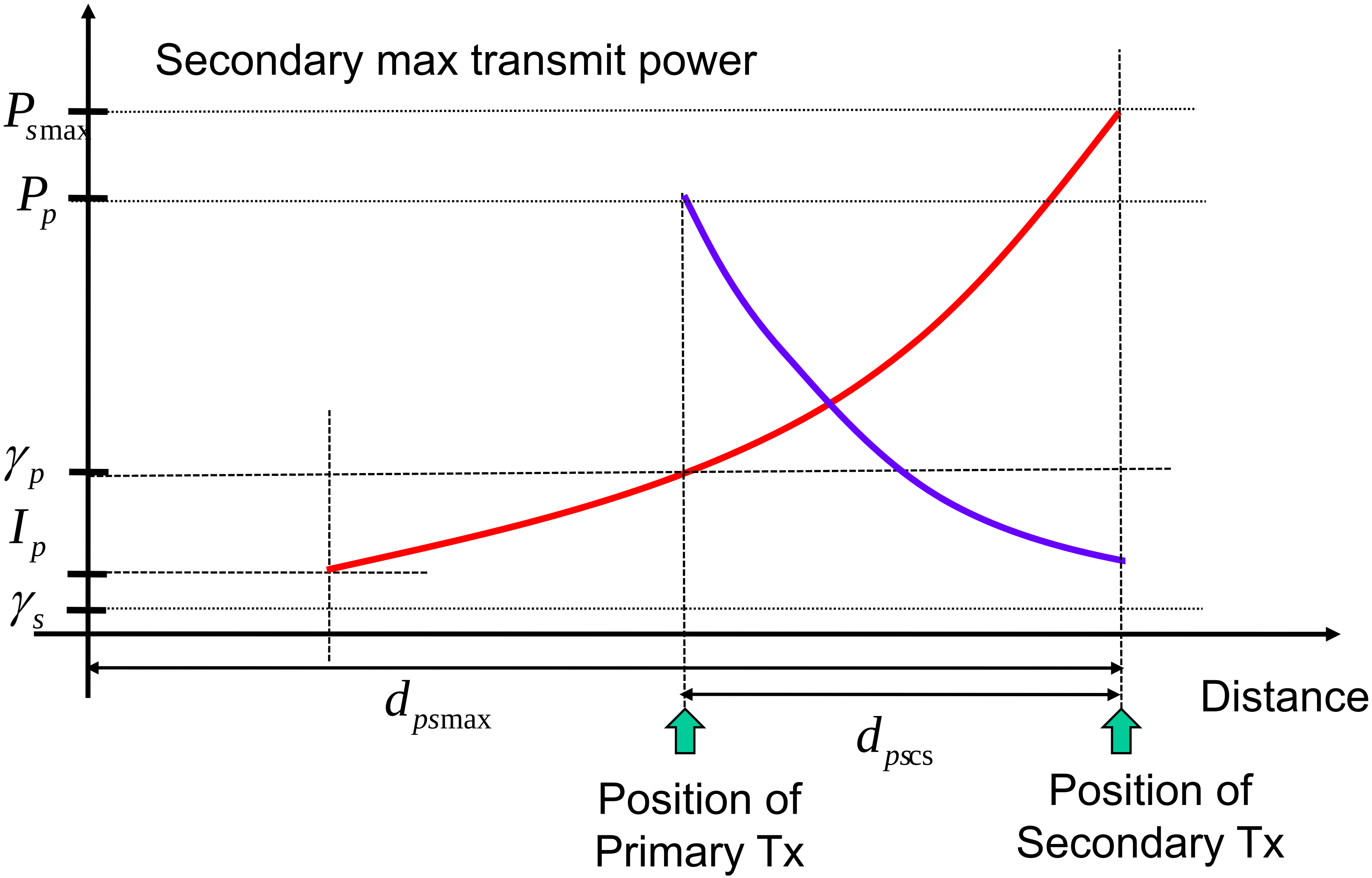
γ_p Sensing level of primary system

One way hidden node problem occurs if the both transmitter nodes are located within the following region,

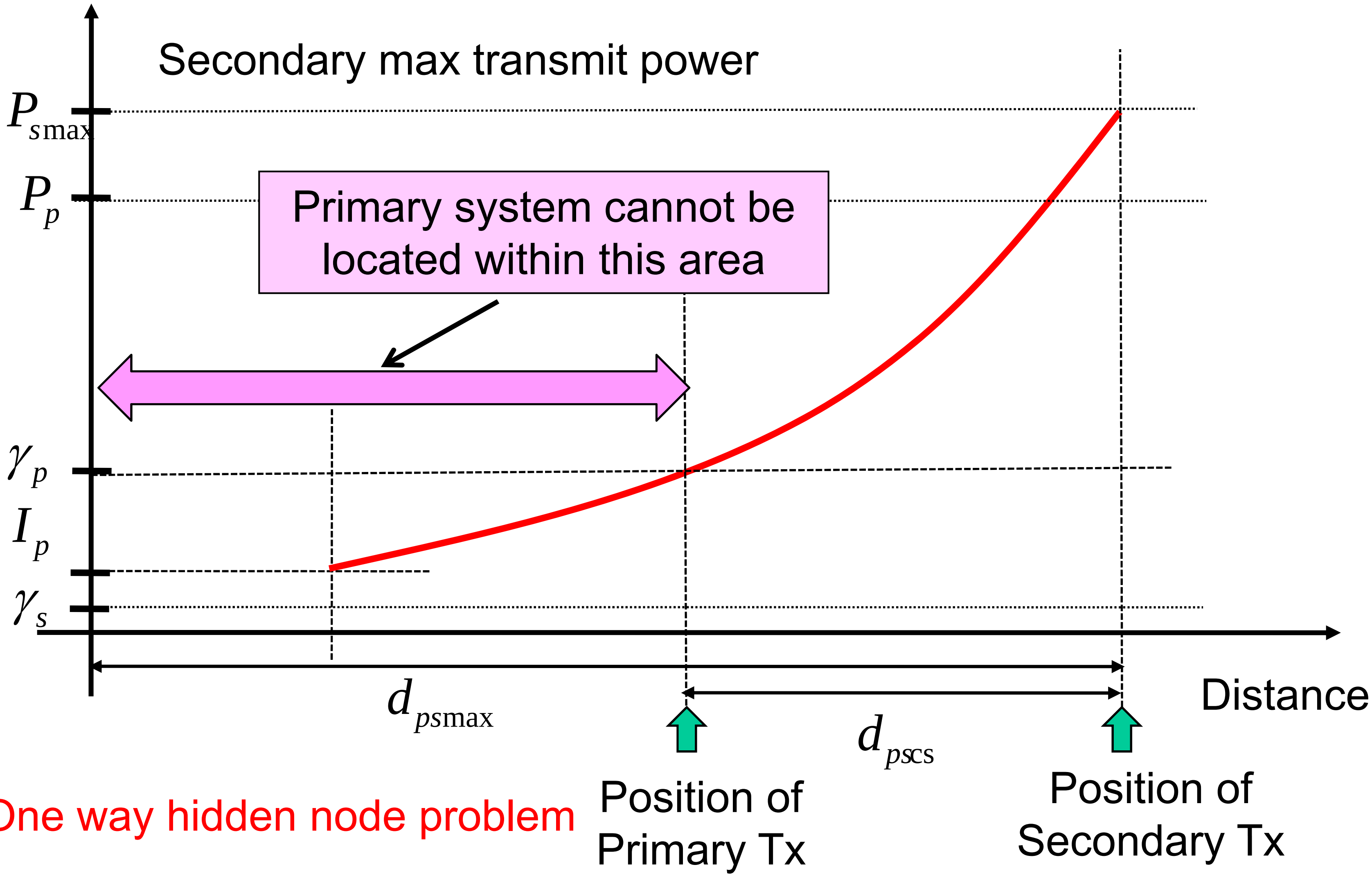
$$0 < d_{ps} \le d_{pscs}$$

We can apply time division spectrum sharing within above region.

Power relation under both side sensing



Primary system prohibited area



One way hidden node problem

Secondary capacity under time division

Maximum secondary transmit power can be used when the time division spectrum sharing is applied. (Orthognality of time separation)

The desired signal received power at secondary receiver

$$P_{sr} = P_{s\max} \cdot \alpha \left(\frac{1}{d_s} \right)^n$$

No interference at the receiver because orthogonality of time domain. Noise power: P_n

Primary channel utilization ratio U_p

$$C'_{\mathrm{std}} = (1 - U_p) \log_2 \left(1 + \frac{P_{sr}}{P_n} \right) = (1 - U_p) \log_2 \left(1 + \frac{P_{s\max} \cdot \alpha \left(\frac{1}{d_s} \right)^n}{P_n} \right)$$

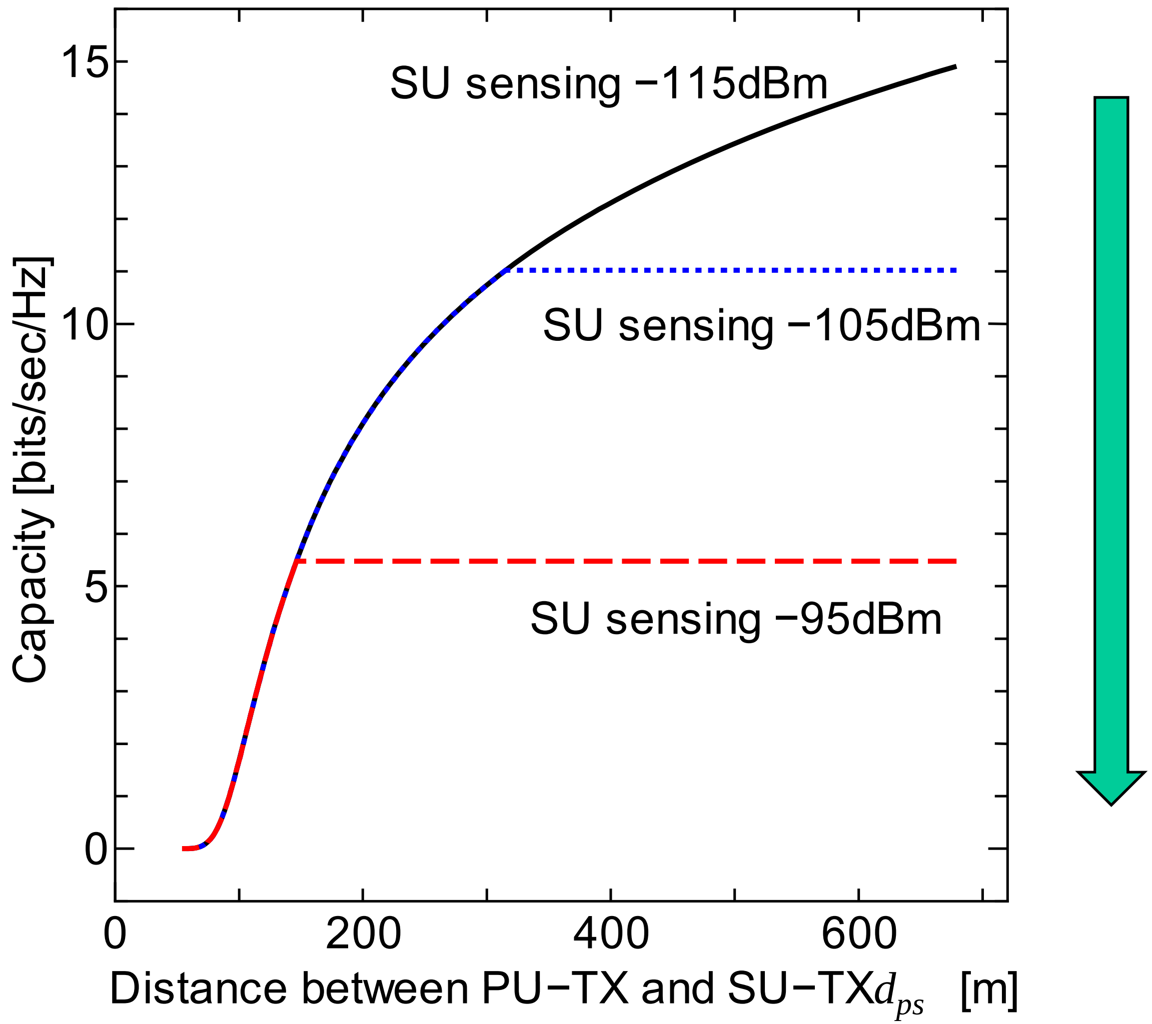
bits/s/Hz

Numerical Example of Primary and Secondary Spectrum Sharing

Parameter Conditions

Frequency Band	2.4GHz
Transmit Power of Primary	P_p=10mW
Transmit Range of Primary	d_p=50m
Transmit Range of Secondary	d_s=20m
Path loss Factor	n=3
Reference Distance	d_0=1m
Primary Maximum Interference Level	$I_{p,dB}$=-95dBm

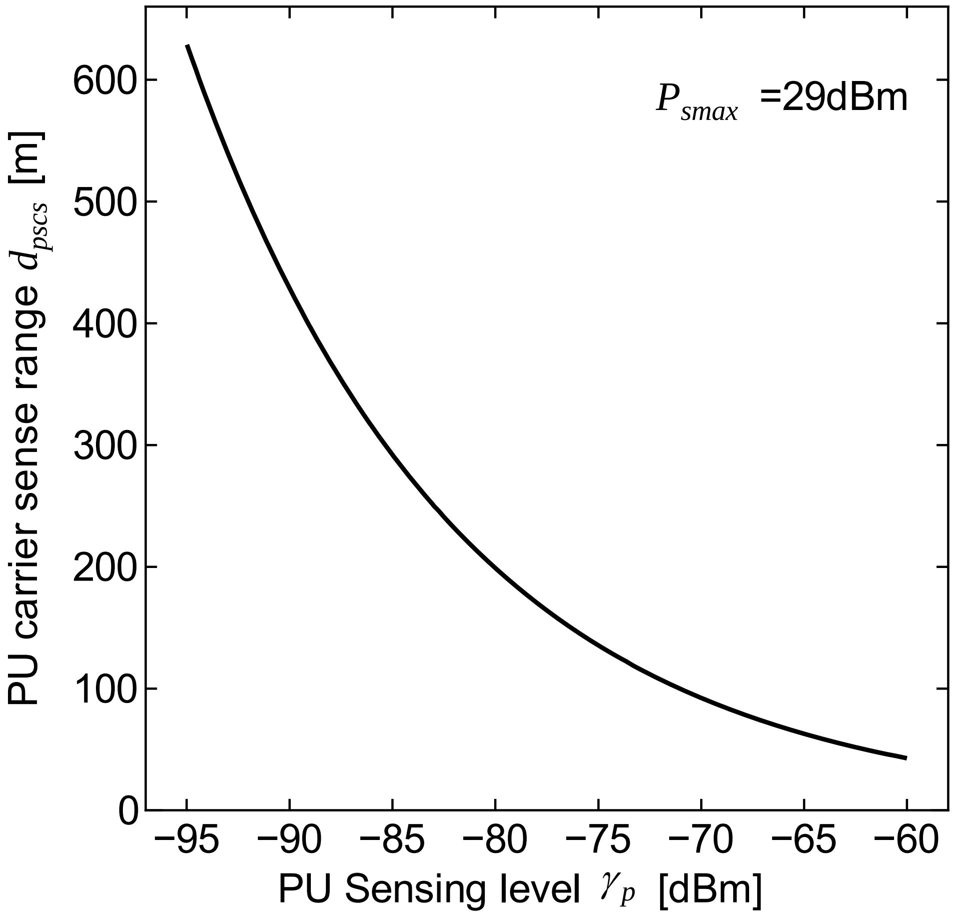
Secondary Capacity based on Power Control



Secondary capacity degrades by decreasing sensing level.

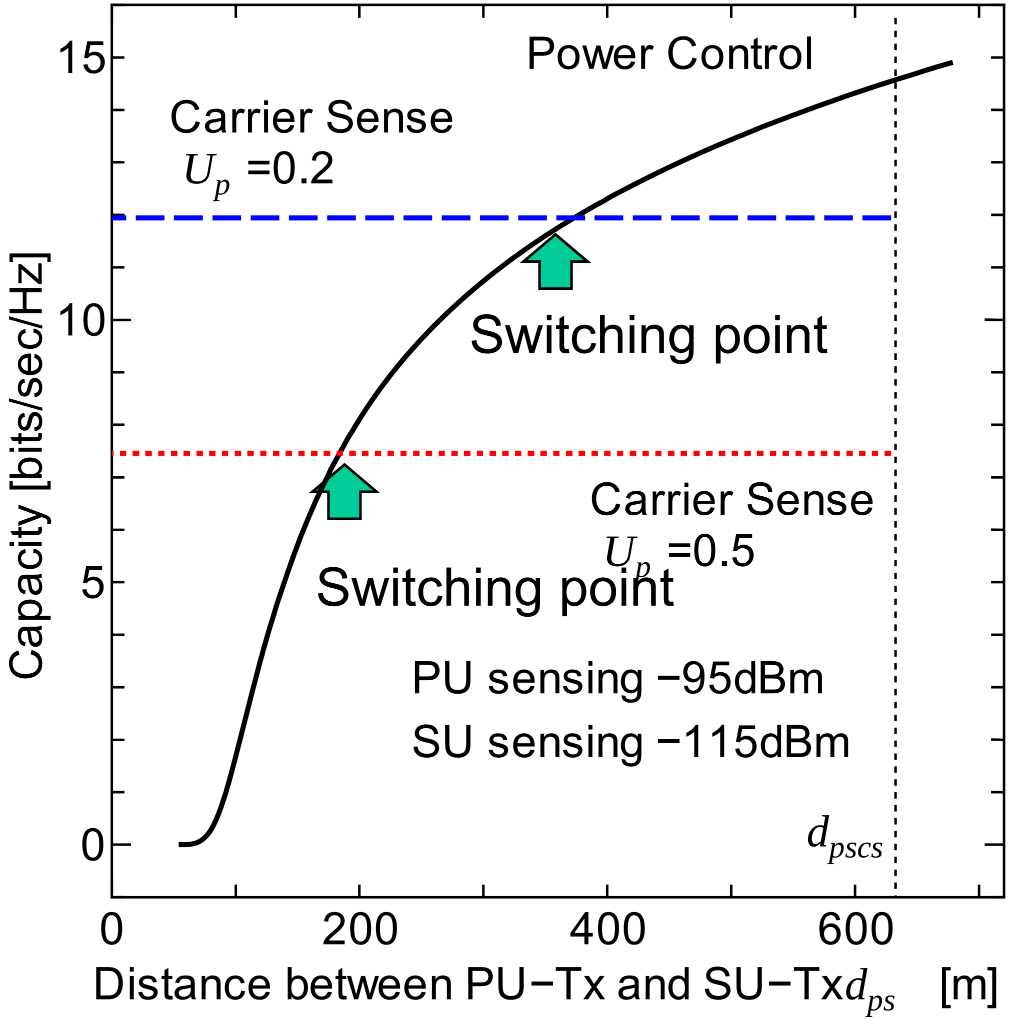
Maximum power limitation of secondary node by decreasing sensing range.

Primary Sensing Range



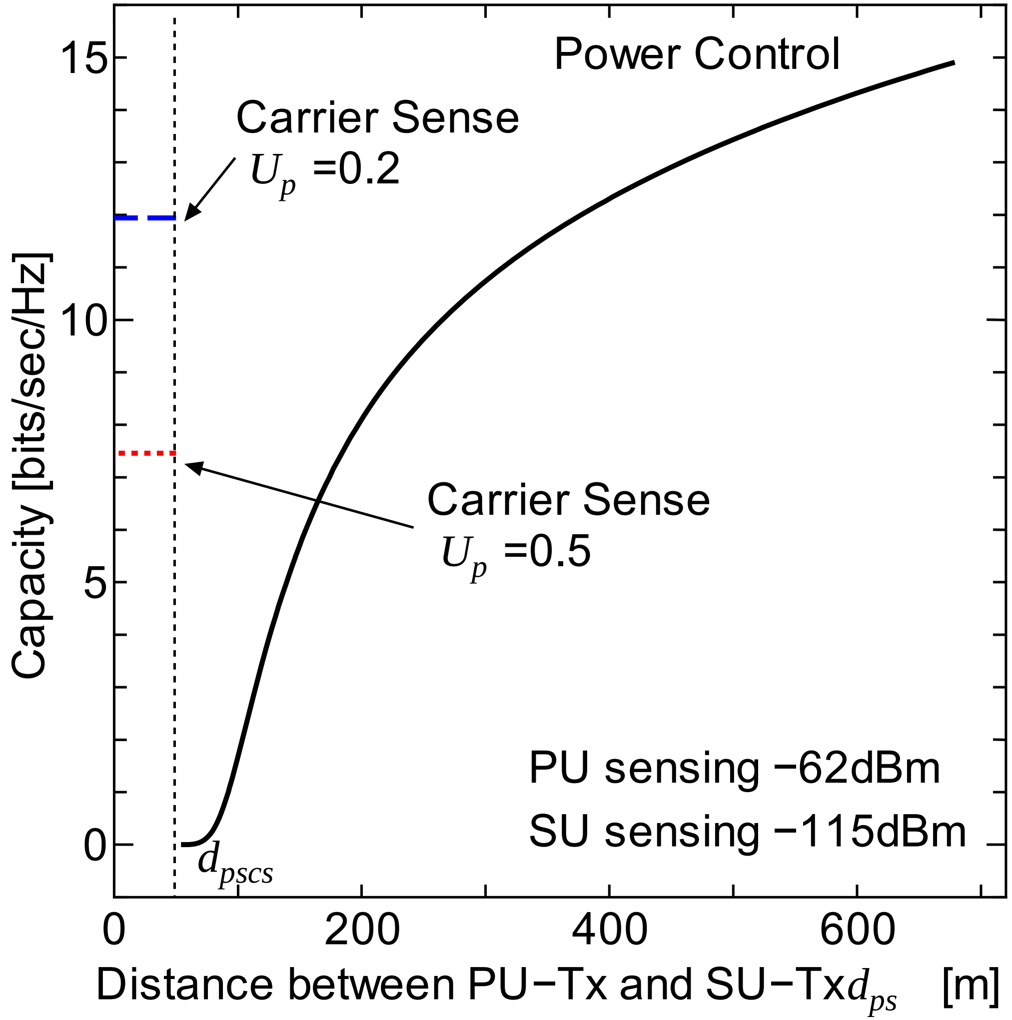
Primary sensing range depends on sensing level of primary node.

Secondary Capacity based on CSMA (1)



Optimal method is changed by primary utilization ratio and primary secondary distance.

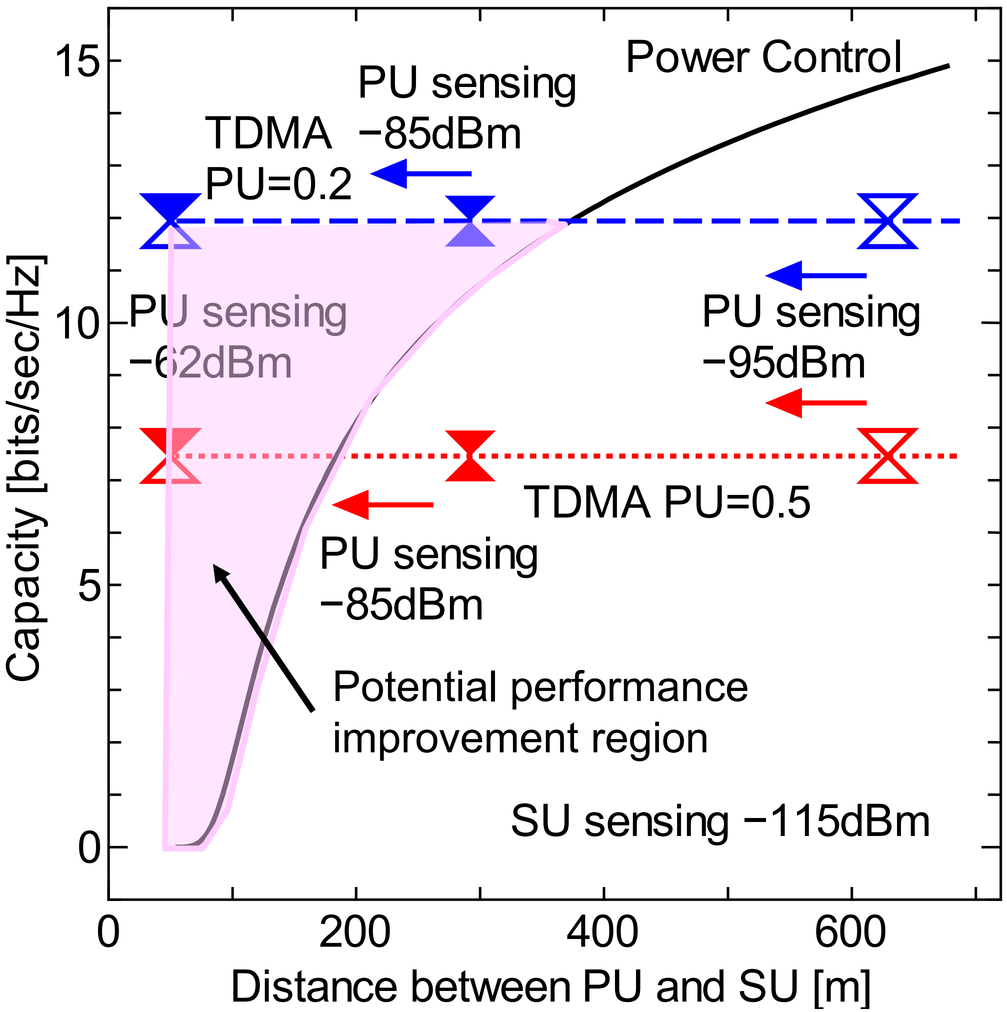
Secondary Capacity based on CSMA (2)



When primary sensing level is set to -62dBm, CSMA effective range is removed.

Spectrum sharing performance based on CSMA with low sensitive sensing device at primary system is limited to use.

Secondary Capacity based on CSMA (3)



I f we apply primary nodes with low sensitive sensing device, the potential communication ability is remained.

Other spectrum sharing method like probabilistic access intelligent MAC protocol is required.

Conclusion of Analysis

Comparing spectrum sharing method under the condition of primary nodes have carrier sense function

- ◆Spectrum sharing based on power control
- ◆Spectrum sharing based on time sharing using sensing

Environment 1

✓Low channel utilization ratio of primary system
✓High sensitive spectrum sensing ability in primary system
✓Distance of primary Tx and secondary Tx is close

➡ Spectrum sharing based on time sharing is effective by considering “maximum power transmission” and “orthogonalization of channel by time sharing.”

Environment 2

- ✓High channel utilization ratio of primary system
- ✓Low sensitive spectrum sensing ability in primary system
- ✓Distance of primary Tx and secondary Tx is apart

➡ Spectrum sharing based on power control is effective.

Environment 3

- ✓Low channel utilization ratio of primary system
- ✓Low sensitive spectrum sensing ability in primary system
- ✓Distance of primary Tx and secondary Tx is middle range

➡ It is difficult to utilize potential vacant spectrum if power control or time sharing is used.
In this region, the other techniques like **intelligent MAC protocol** is required.

5.SYNCHRONOUS WDN MAC PROTOCOL BASED ON COGNITIVE CONCEPT

Policies of the proposed synchronous MAC protocol

- Throughput of WLAN is kept as a primary system (delay may increase)
- TDD frame divided into two types, odd frame and even frame for transmission for reducing the interference of adjacent hop
- Each node has sensing function for recognizing the surrounding wireless environment
- Frame level synchronization is kept among the nodes in a flow

The proposed secondary MAC protocol utilizes the function of CSMA on the primary WLAN for spectrum sharing

Sensing Sensitivity

Two kinds of sensitivity of sensing is considered

◆Conventional Sensing (Carrier Sense on WLAN)

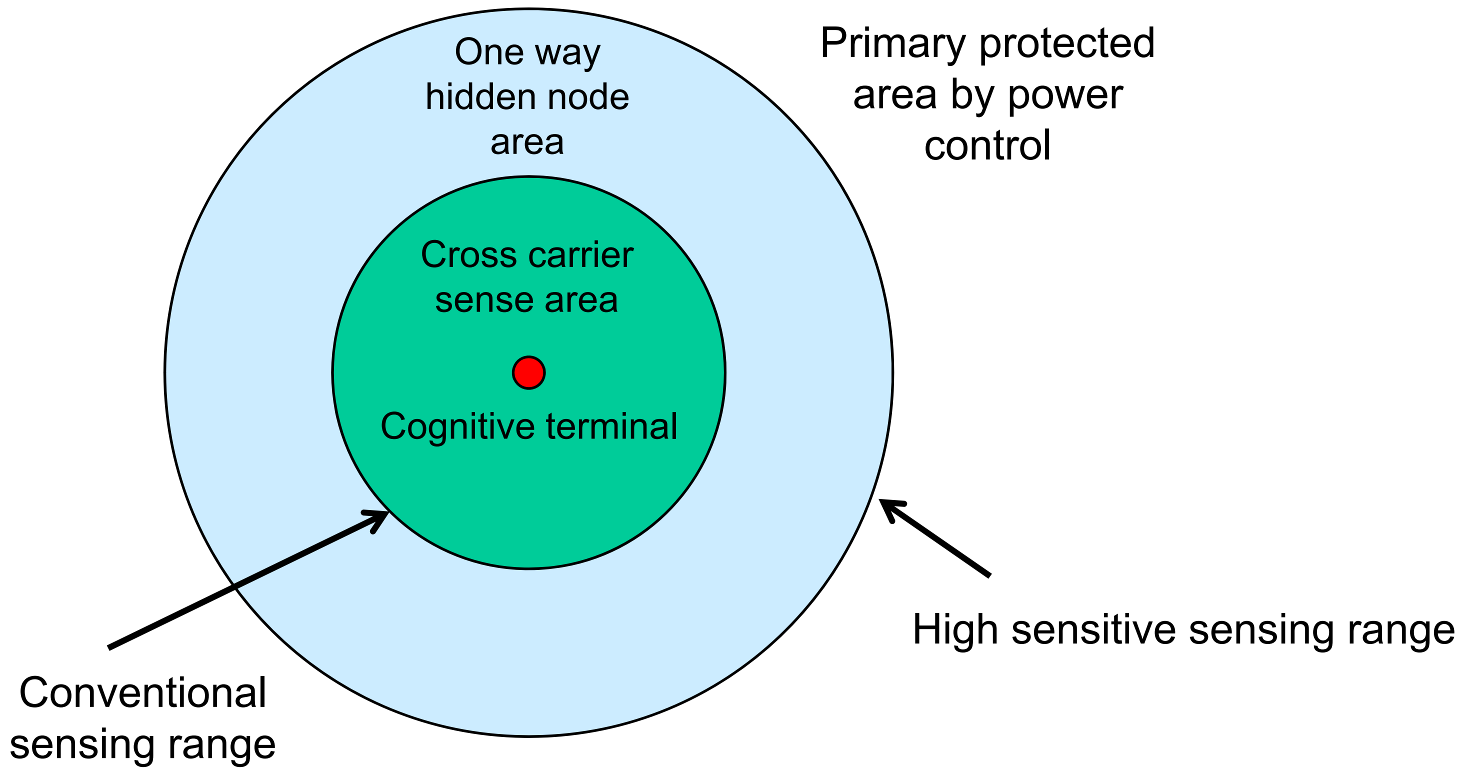
- Carrier sense level is 20dB or more higher than noise level
- Spectrum sharing with near nodes can be achieved but the hidden node problem cannot be avoided

◆High Sensitive Sensing

- Signal around the noise level and below the noise level is detected
- A lot of papers have been proposed such high sensitive sensing for cognitive radio
- Sensing without hidden node problem can be achieved

Sensing Range and Inter-system Interference

Primary Secondary interference situation is different if we use different sensing level



Sensing Level and Sensing Range

Frequency f 2.4GHz
Tx Power P_{pr} 10dBm
Antenna gain 0dBi

Sensing level L_{CS} vs sensing range d_{CS}

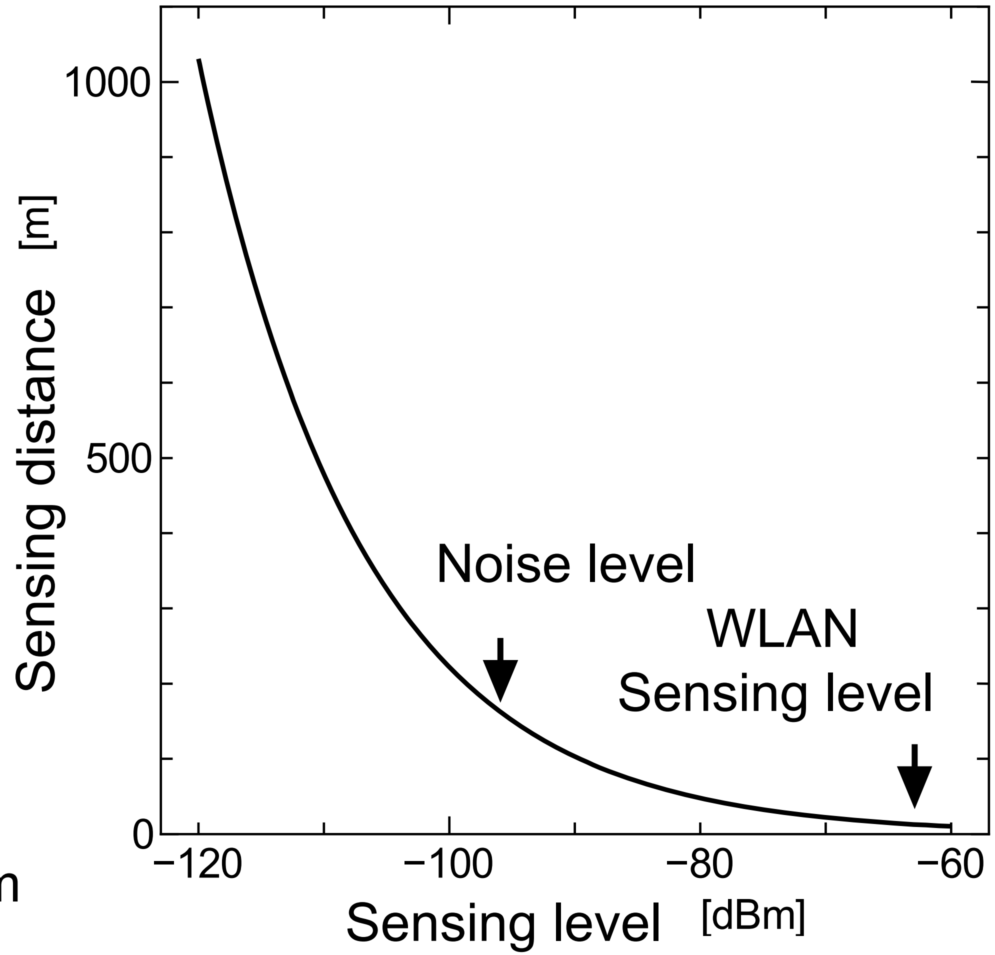
$$L_{CS} = P_{pr} - 20\log_{10}(f) - 30\log_{10} d_{cs} + 28 \text{[dBm]}$$

WLAN Inter-system carrier sense level −62dBm

➡ Sensing range about 10m

Sensing at noise level −95dBm

➡ Sensing range about 150m



Spectrum Sensing considering Inter-system Interference

Primary protected area: Power Control

- Transmit power of WDN transmitter is limited not to interfere to the primary receiver

One way hidden node area: Intelligent MAC

- High sensitive sensing is used for avoiding interference from WDN to primary
  When the interference is detected, the secondary transmission is terminated

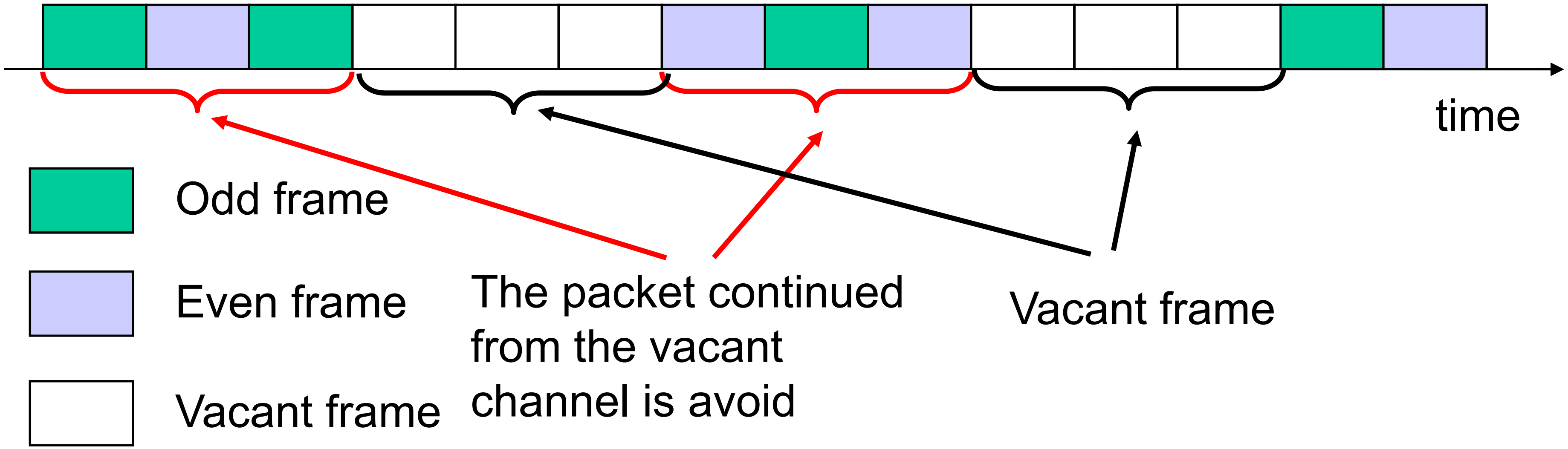
Cross carrier sense area: CSMA

- Carrier sense can be worked each other for sharing the channel by time

TDMA Frame Assignment for Proposed MAC

Vacant frame is prepared according to the channel utilization ratio of primary system

- Odd frame: WDN can use this frame for odd link
- Even frame: WDN can use this frame for even link
- Vacant frame: WDN cannot use this frame and giving priority to primary WLAN



- WDN frames are classified into 3 types of frames per unit
- A vacant frame for primary WLAN is prepared

Number of vacant frame N_{pri} (primary priority frame)

U_{pri} Primary utilization ratio

$$U_{pri} = \frac{N_{pri}}{3 + N_{pri}}$$

$$(3 + N_{pri}) \cdot U_{pri} = N_{pri}$$

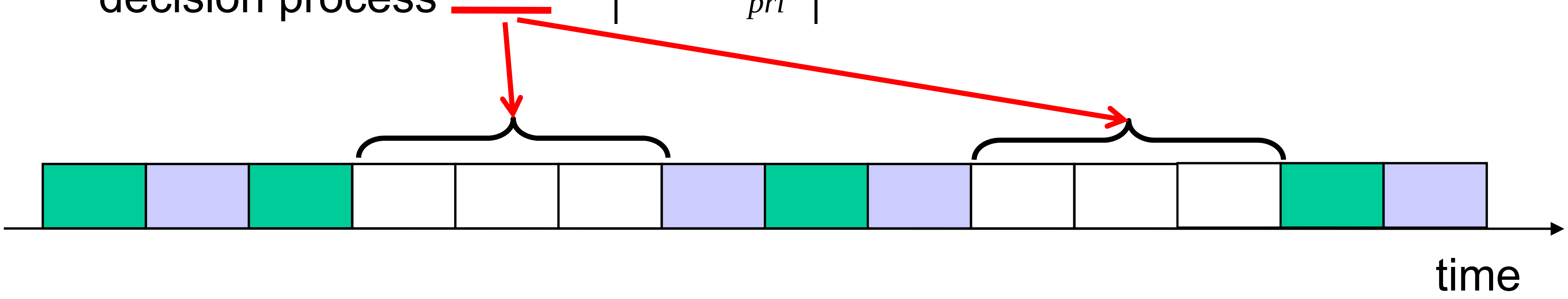
$$N_{pri} = \frac{3U_{pri}}{1 - U_{pri}}$$

Number of vacant frames decision process

$$N_{pri} = \left\lceil \frac{3U_{pri}}{1 - U_{pri}} \right\rceil + N_m$$

$\lceil x \rceil$ Integer no less than x

N_m Margin frame



Spectrum Sharing Method

Primary protected area node

WDN transmission power is controlled
⇒Inter system interference in this area is avoided by transmit power control

One way hidden node area node

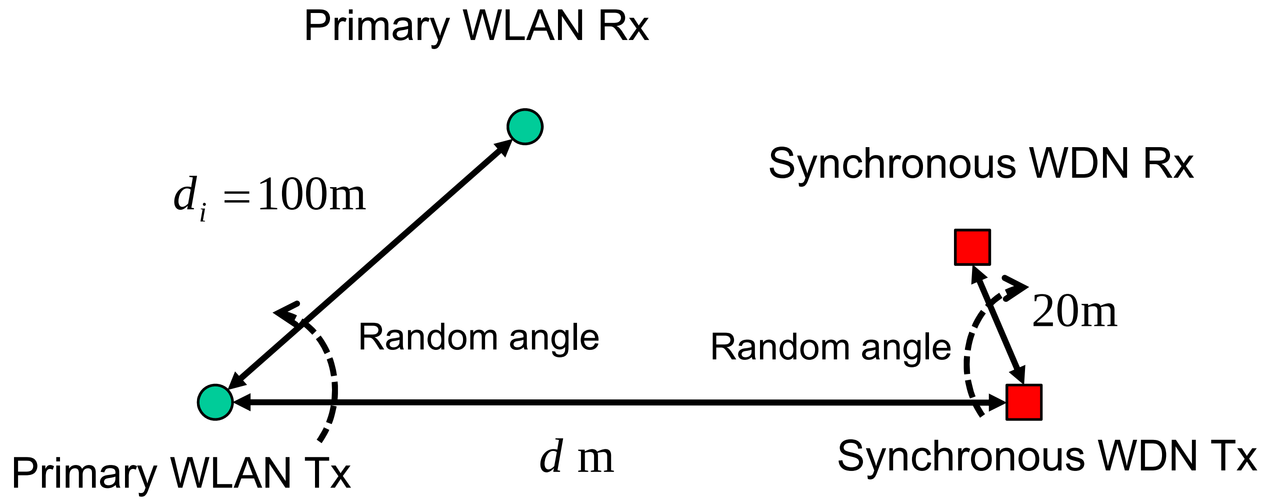
WDN nodes continuously check the existence of the primary system by high sensitive sensing
⇒If primary signal is detected, WDN is terminated to transmit the signal even if the odd or even frames

Cross carrier sense area node

Primary packets are transmitted and share the channel with carrier sense

6.BASIC PERFORMANCE EVALUATION OF PROPOSED WDN MAC PROTOCOL

Assume WDN is overlaid to the CSMA/CA network
Channel occupation is derived by considering the environment shown below by changing the distance between PU and SU

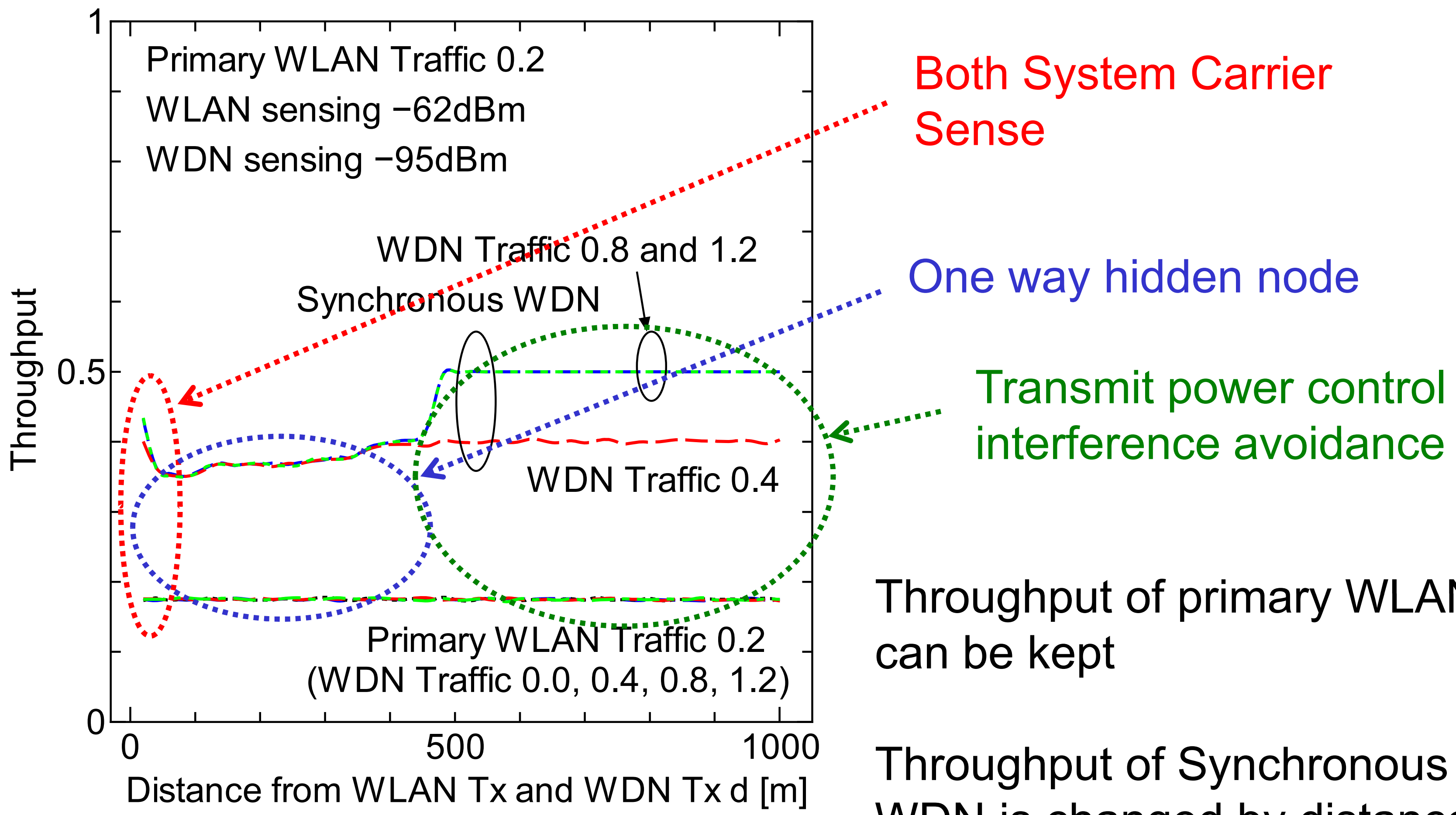


High sensitive sensing level : -95dBm
Conventional WLAN sensing level : -62dBm
TDMA frame length: 1.0ms,
Packet generation : Poisson distrbution

Parameters

Frequency Band	2.4GHz
Transmit Power of Primary WLAN	25dBm
Maximum Transmit Range of Primary WLAN	100m
Synchronous WDN Transmit Range	20m
Required SIR	20dB
Path loss factor	3
TDMA frame length	1ms
Synchronous WDN Packet Length	1ms
Primary WLAN Packet Length	0.7ms
Primary WLAN ACK Length	0.1ms
DIFS	0.025ms
SIFS	0.009ms

Throughput Performance of Primary WLAN Traffic= 0.2

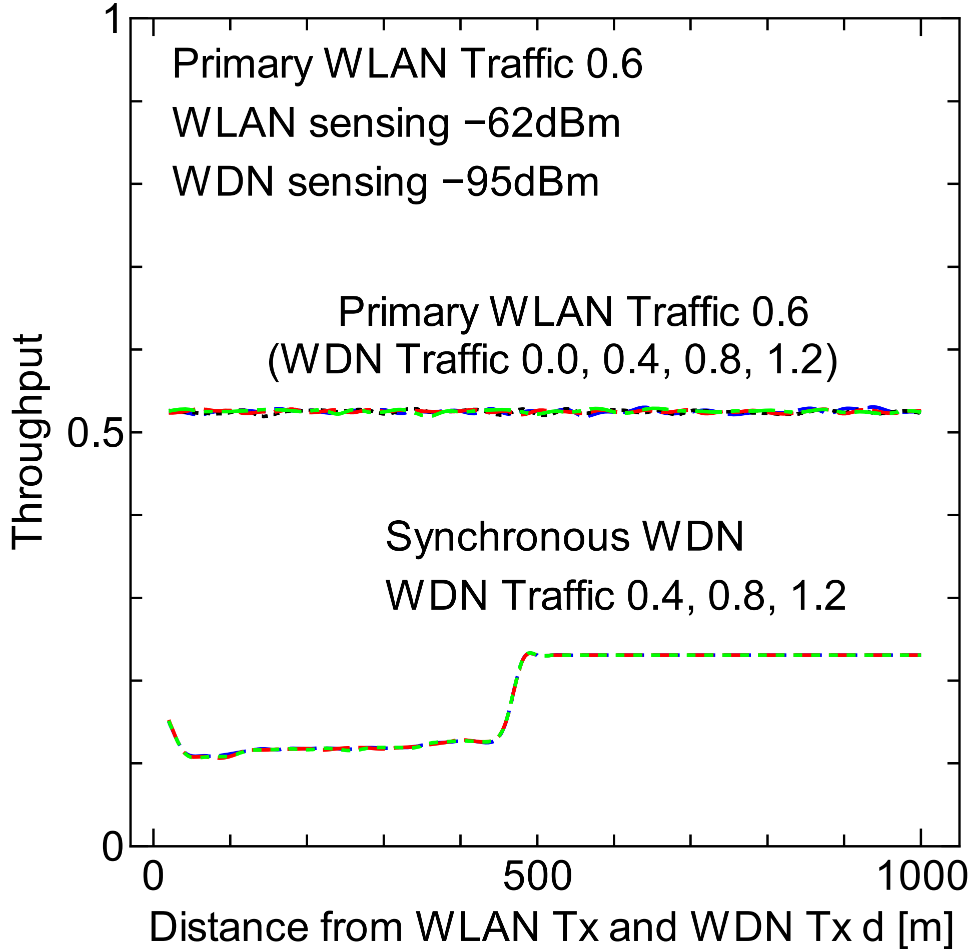


Margin slot Nm=1

Throughput of primary WLAN can be kept

Throughput of Synchronous WDN is changed by distance of two systems

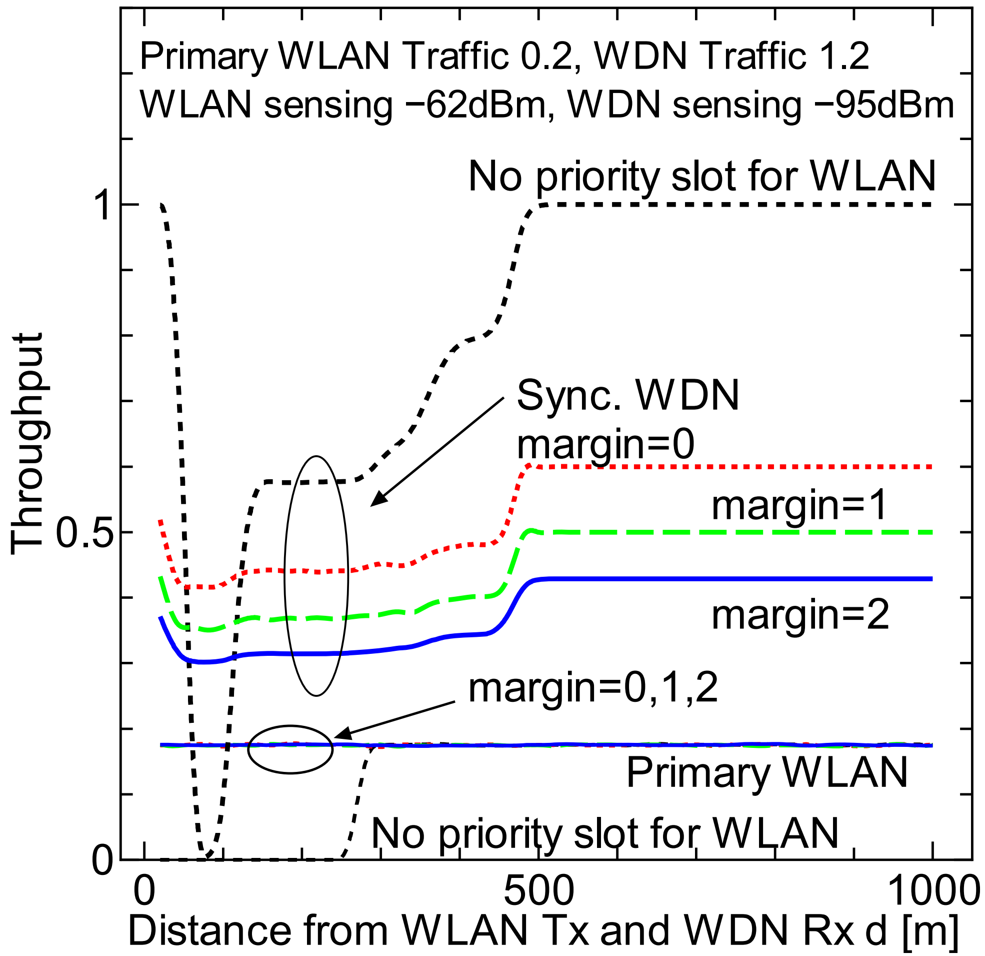
Throughput Performance of Primary WLAN Traffic= 0.6



Margin slot Nm=1

If the primary traffic increases, throughput of primary WLAN can be kept by using the proposed protocol

Throughput Performance with and without the Proposed Protocol



Vacant slot is changed

- No vacant slots
- Margin slot Nm=0
- Margin slot Nm=1
- Margin slot Nm=2

No vacant slot degrades the performance on the one way hidden node area

7. CONCLUSIONS

One of the future wireless distributed networks

High speed high reliability synchronous wireless distributed networks based on cognitive concept

- Solution for hidden node problem in multi-hop network
- Dynamic spectrum management considering whole spectrum
- MAC protocol with keeping the performance of primary
- MIMO Mesh System for supporting two-way communication

⇒ By checking the situation of the primary system, we can realize higher spectrum resource management for high speed high reliability wireless distributed networks