Evaluation and Analysis of Influence from Other Radio Systems in Wideband Non-Contiguous OFDM Receiver

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Advanced Telecommunications Research Institute International (ATR)

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This research was performed under research contract of "Research and Development on Wideband Non-Contiguous OFDM", for the Ministry of Internal Affairs and Communications, Japan

Introduction

We are making progress of research for

Wideband Non-Contiguous OFDM

- Allocates subcarriers (SCs) onto many dispersed idle bands,
- Aggregates, Obtains high data traffic.

Previous Paper :

Evaluate influence of interference from other radio systems (the Most Serious Issue in WNC-OFDM system)

BER were quite different from Gaussian noise environment.

↓

This Paper conducts :

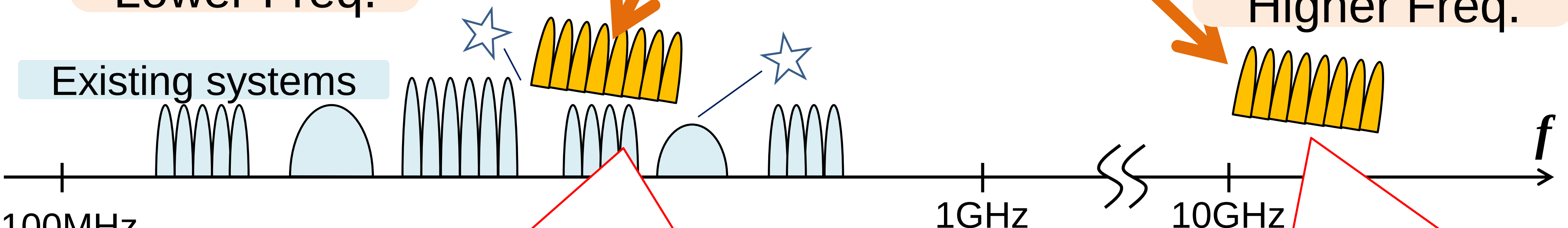
conducts Theoretical analysis in order to Confirm validity of the interference characters observed in the previous evaluation.

Overview of WNC-OFDM

To Obtain New Frequency Band

2) Deploy on Lower Freq.

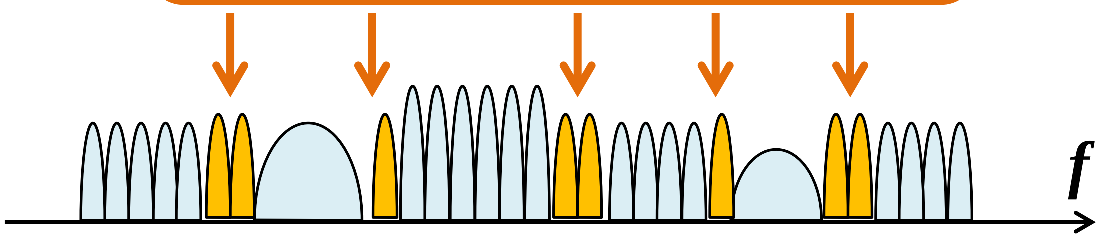
1) Deploy on Higher Freq.



Difficult to obtain Consecutive band

Large propagation loss, High cost

Allocate Subcarriers onto many dispersed idle bands



Aggregate, obtain high data traffic

WNC-OFDM

Wideband Non-Contiguous OFDM

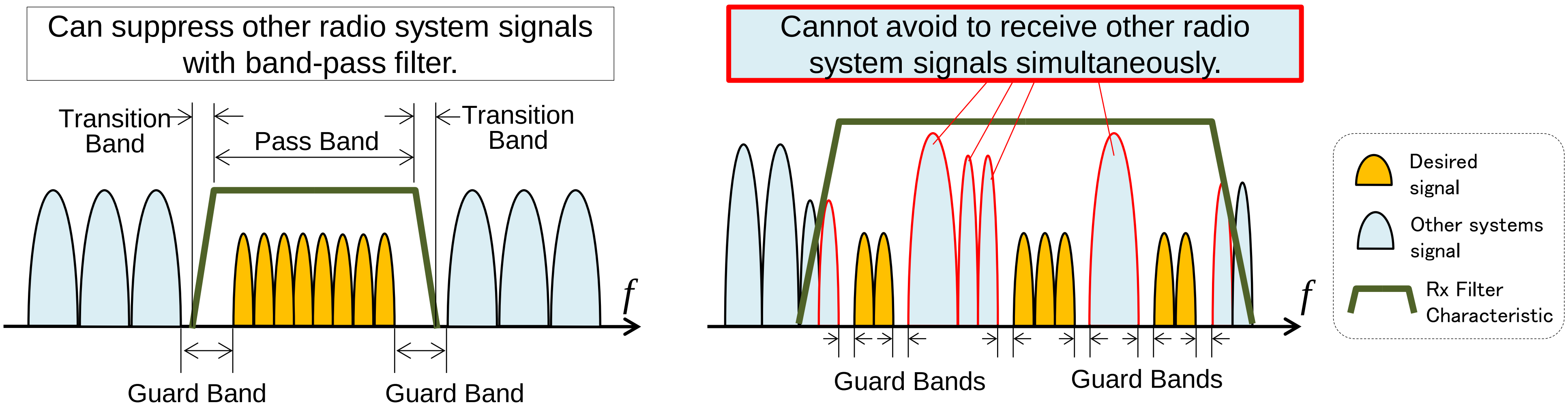
Supports Extremely Wide Band (170MHz ～ 1GHz)

→ Advantageous to gather dispersed idle bands

Interference from other systems signal

RF-units cannot be implemented independently for each dispersed SC block. Required to Cover some SC blocks together with a RF-unit of wider bandwidth.

→ Cannot avoid to receive other radio systems signal simultaneously. (WNC-OFDM's characteristic difficulty)



Signal reception in usual radio systems

Signal reception in WNC-OFDM systems

Important to comprehend the influence of interference from other radio systems and tolerance for the interference

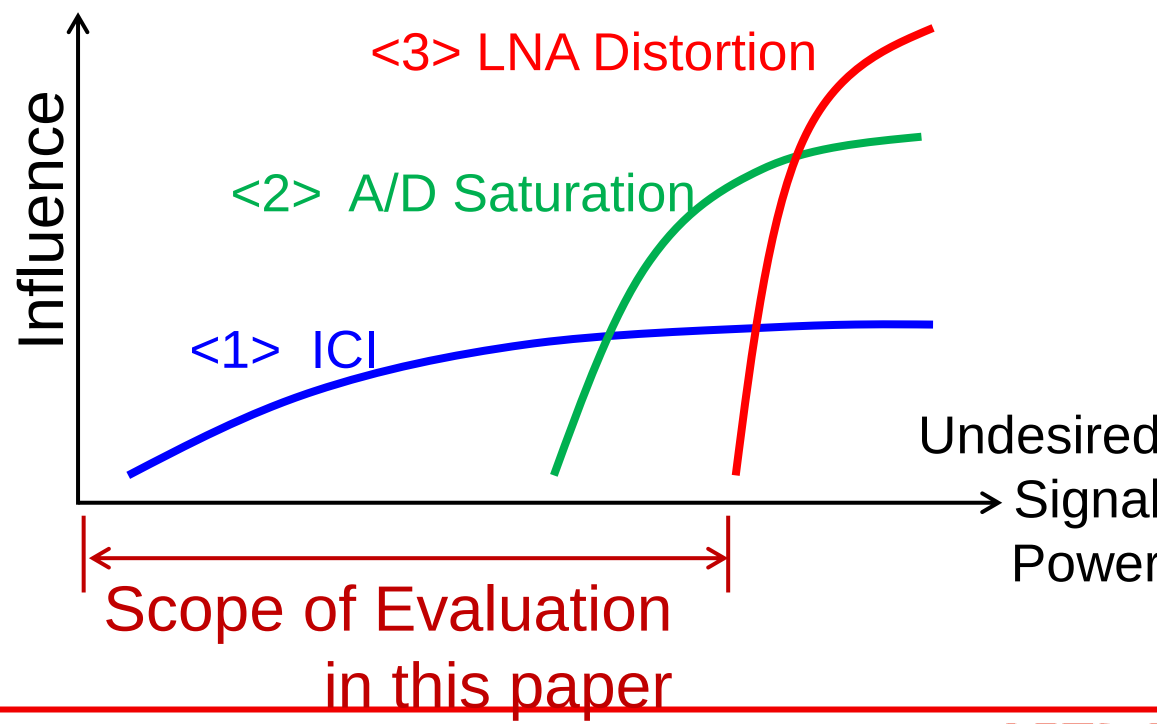
Interference from other systems signal

Issues caused by simultaneous reception of large undesired signals

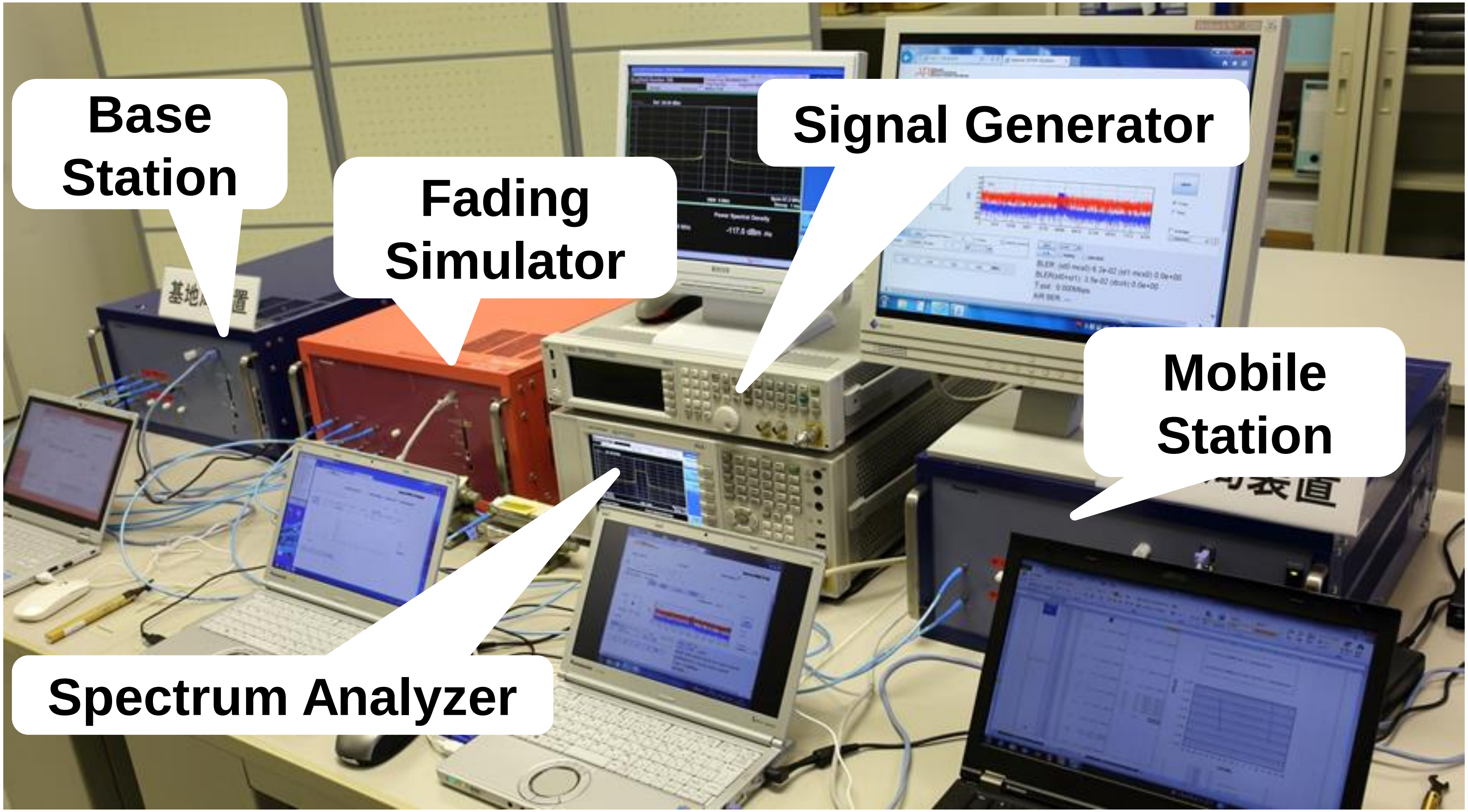
<1> Collapse of Orthogonality at FFT (→ ICI)

<2> Saturation at A/D converter

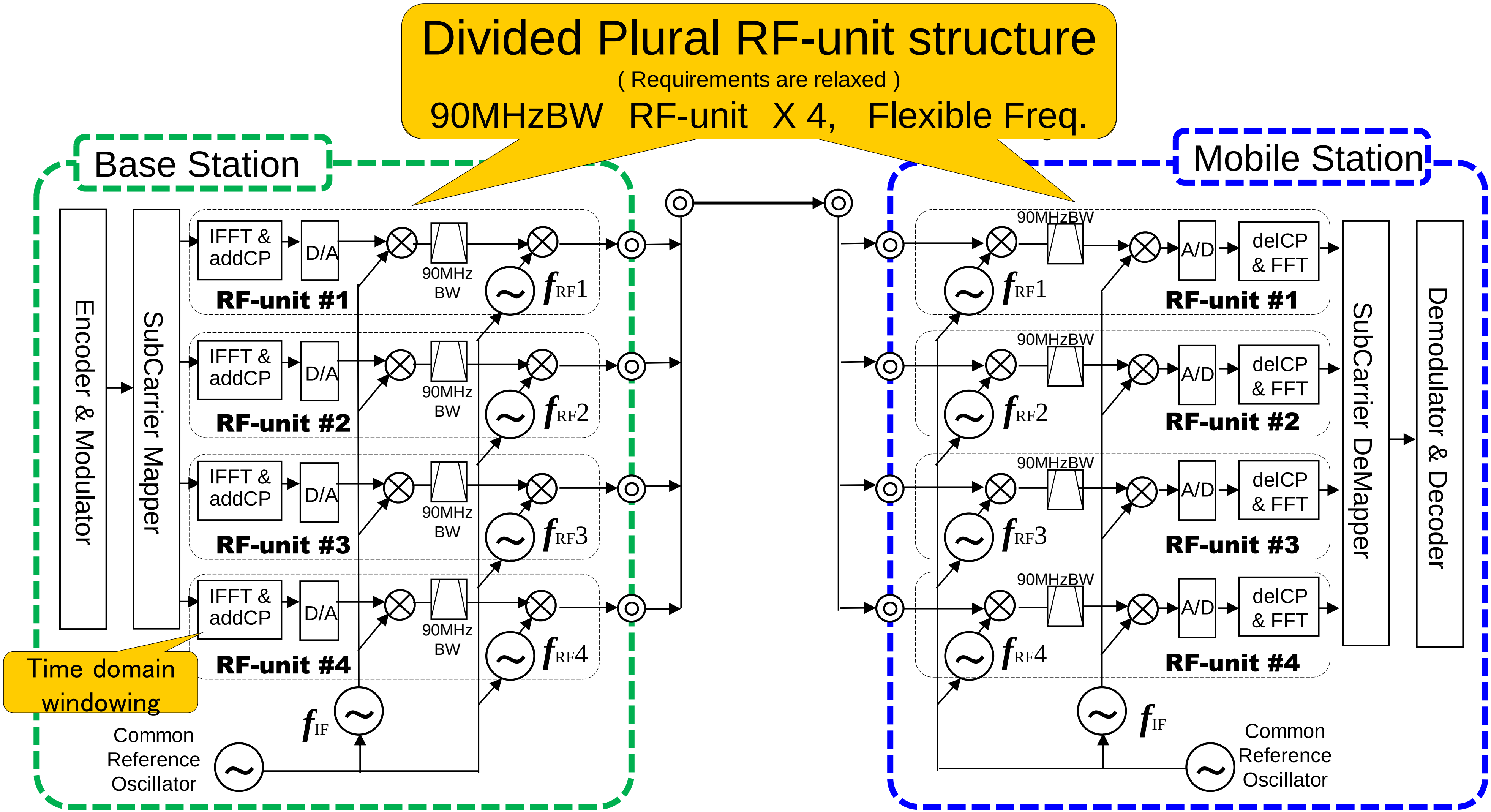
<3> Nonlinear Distortion at frontend LNA



External view of Experimental Equipment

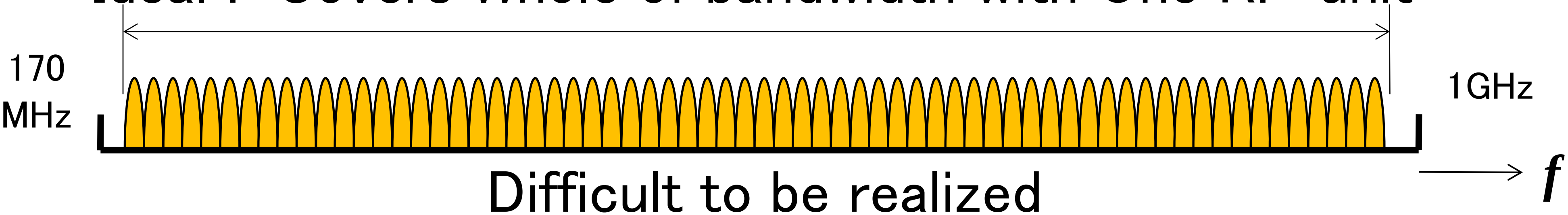


Block diagram of Experimental Equipment (downlink)



RF circuit structure for wideband

Ideal : Covers Whole of bandwidth with One RF-unit



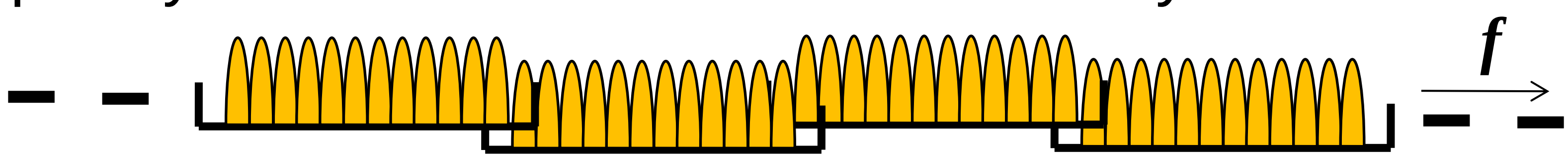
Difficult to be realized

(due to its High specifications : performance, cost, size etc.)

◎ Divided Plural RF-units structure

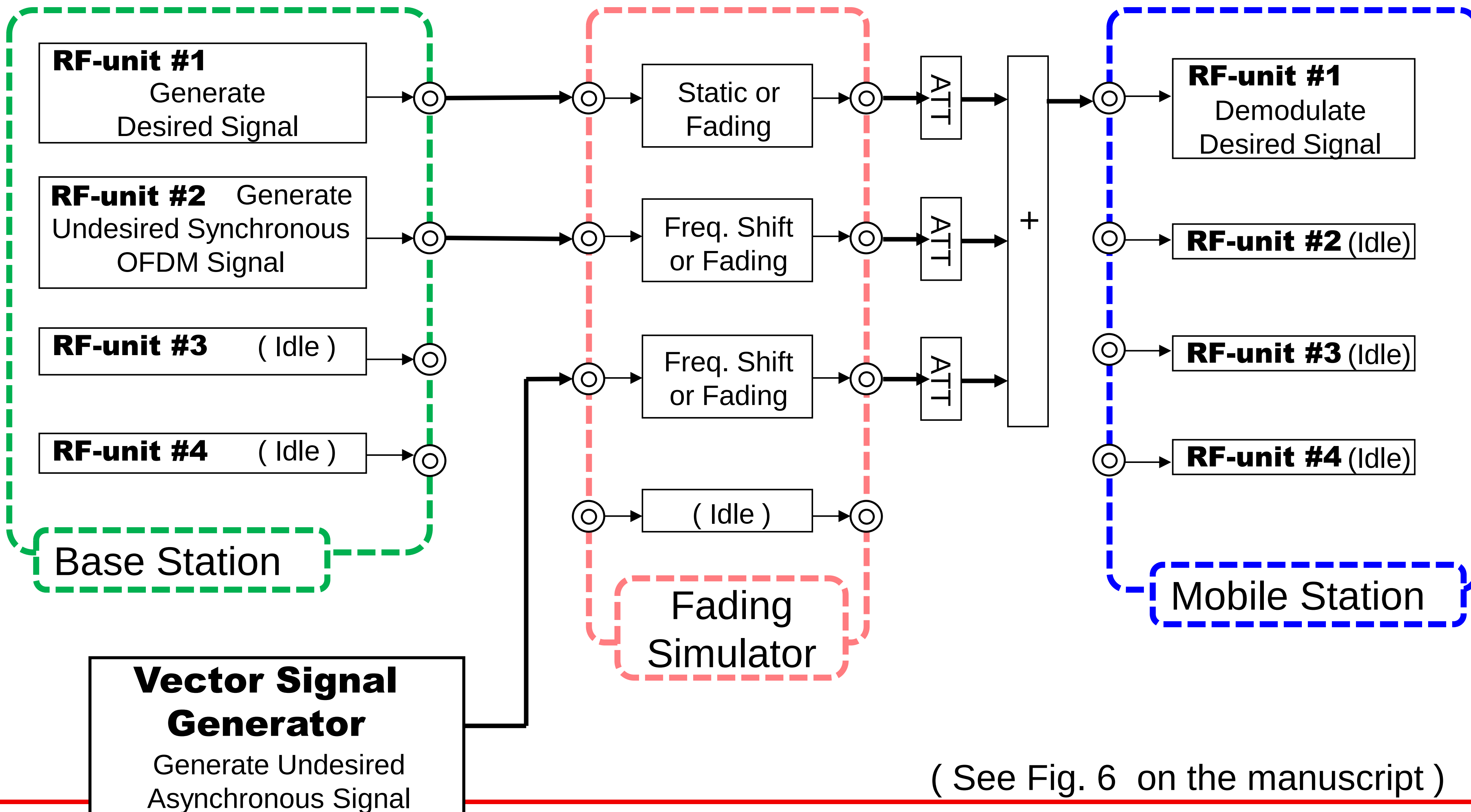
Requirements are relaxed and facilitate the implementation

Frequency of each RF-unit can be set flexibly



Also Consecutive wide band can be supported

Experimental Environment



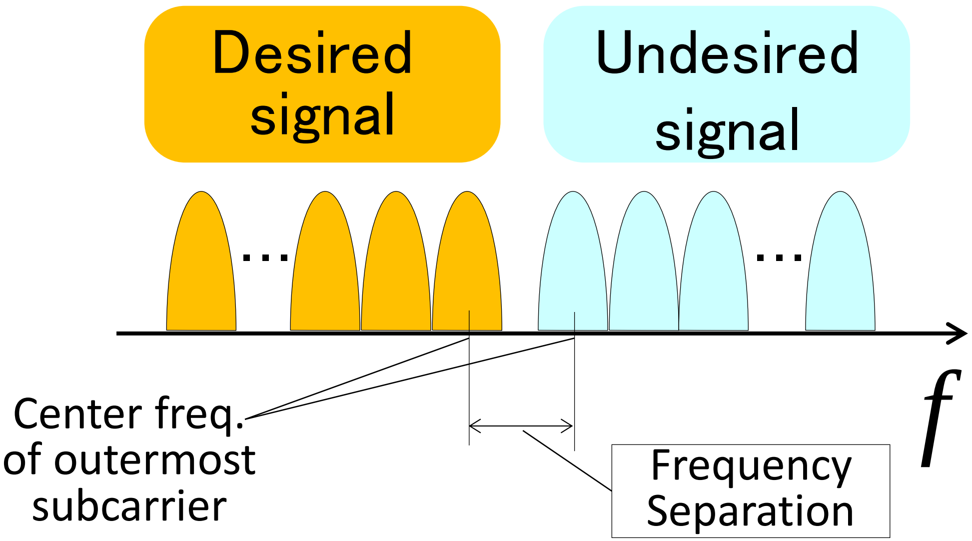
(See Fig. 6 on the manuscript)

Specification of Signals for Evaluation

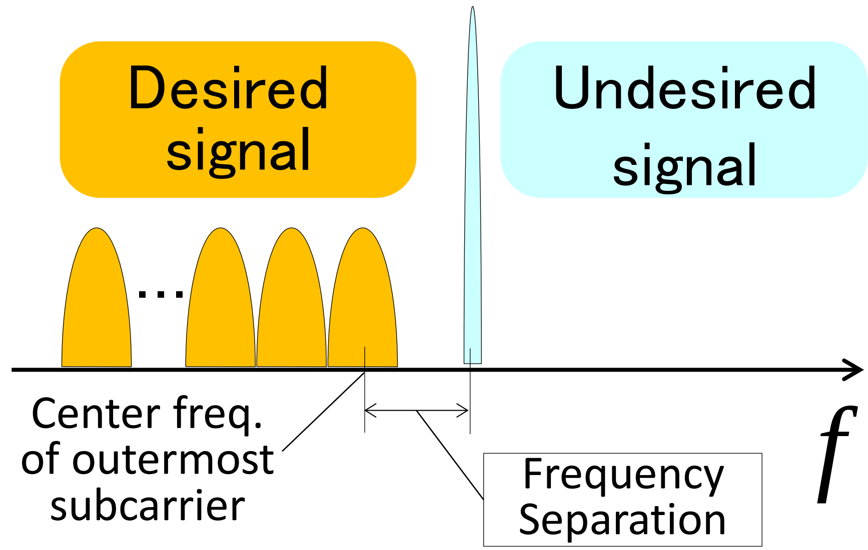
			Signal Format	Band width	Synchro-nization between desired signal	Generated by
Desired Signal	WNC-OFDM		Based on 3GPP-LTE Rel.8 downlink, 15kHz SC spacing, QPSK, No FEC,	9MHz (600 SCs)	-	WNC-OFDM Equipment RF-unit #1
Undesired Signal	OFDM	*Synchronous*			Synchronous	WNC-OFDM Equipment RF-unit #2
		Asynchronous			Asynchronous (different symbol length and timing)	Vector signal generator
	CW		Continuous wave	-	-	

(See TABLE 1 on the manuscript)

Definition of frequency separation in evaluation



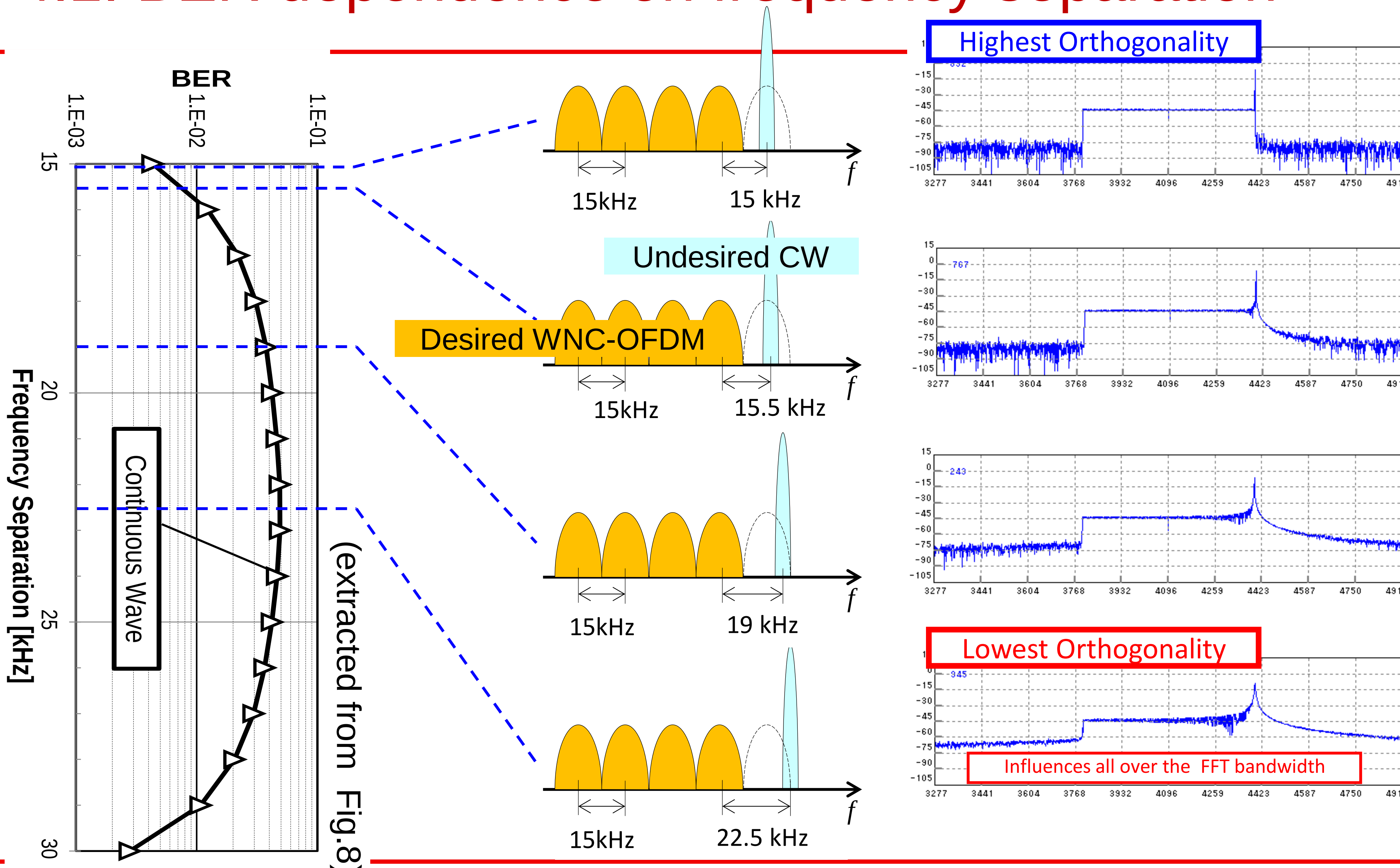
(a) Case of OFDM signal



(b) Case of continuous wave

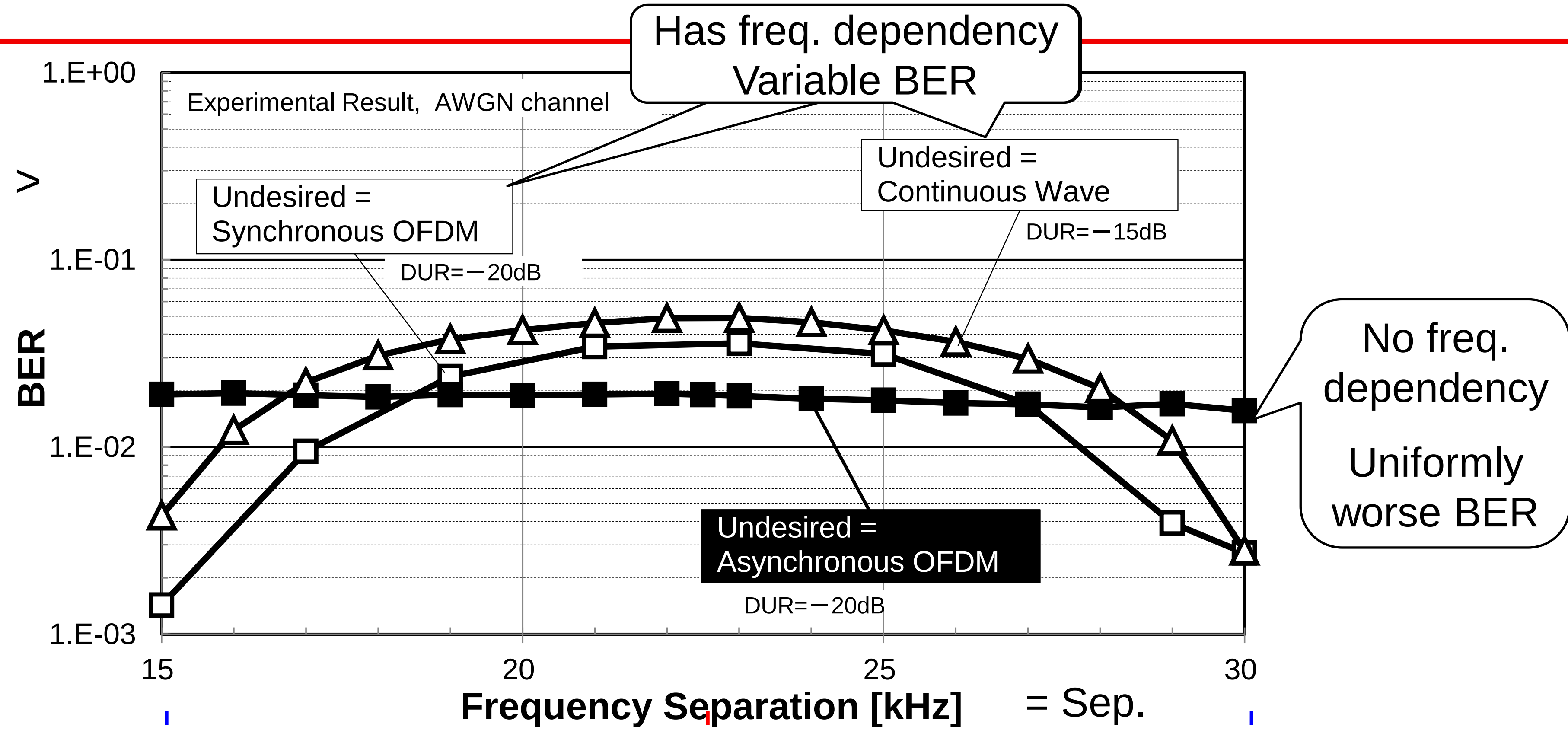
(See Fig. 7 on the manuscript)

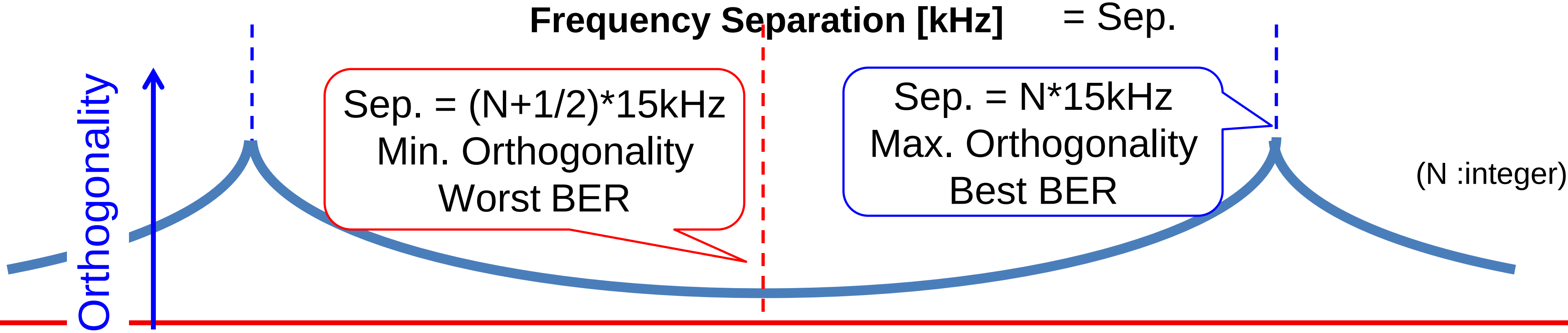
4.1. BER dependence on frequency separation



4.1. BER dependence on frequency separation

< Fig.8 >





4.2. BER vs. DUR with undesired synch. OFDM

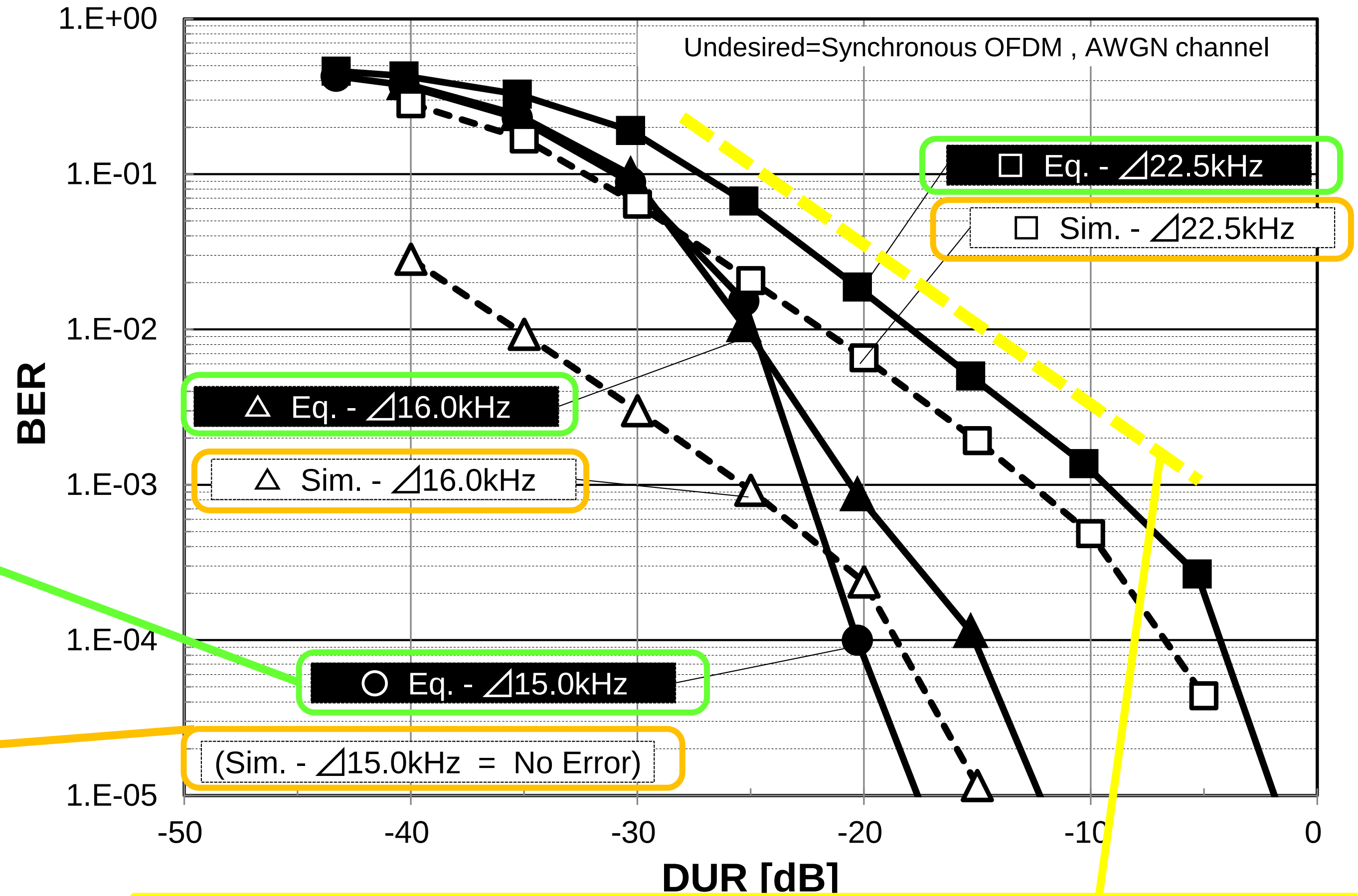
Experimental Result & Simulation Result w/o A/D

< Fig.9 >

When ⊿(freq. separation) =15.0kHz, No Error occurs theoretically.

Error occurs caused by A/D saturation or freq. error

No Error as theory



- Straight Shaped Graph
  BER x10 / DUR -10dB
- Rapidly fadeout @<1e-3

Different from usual Gaussian interfered environment

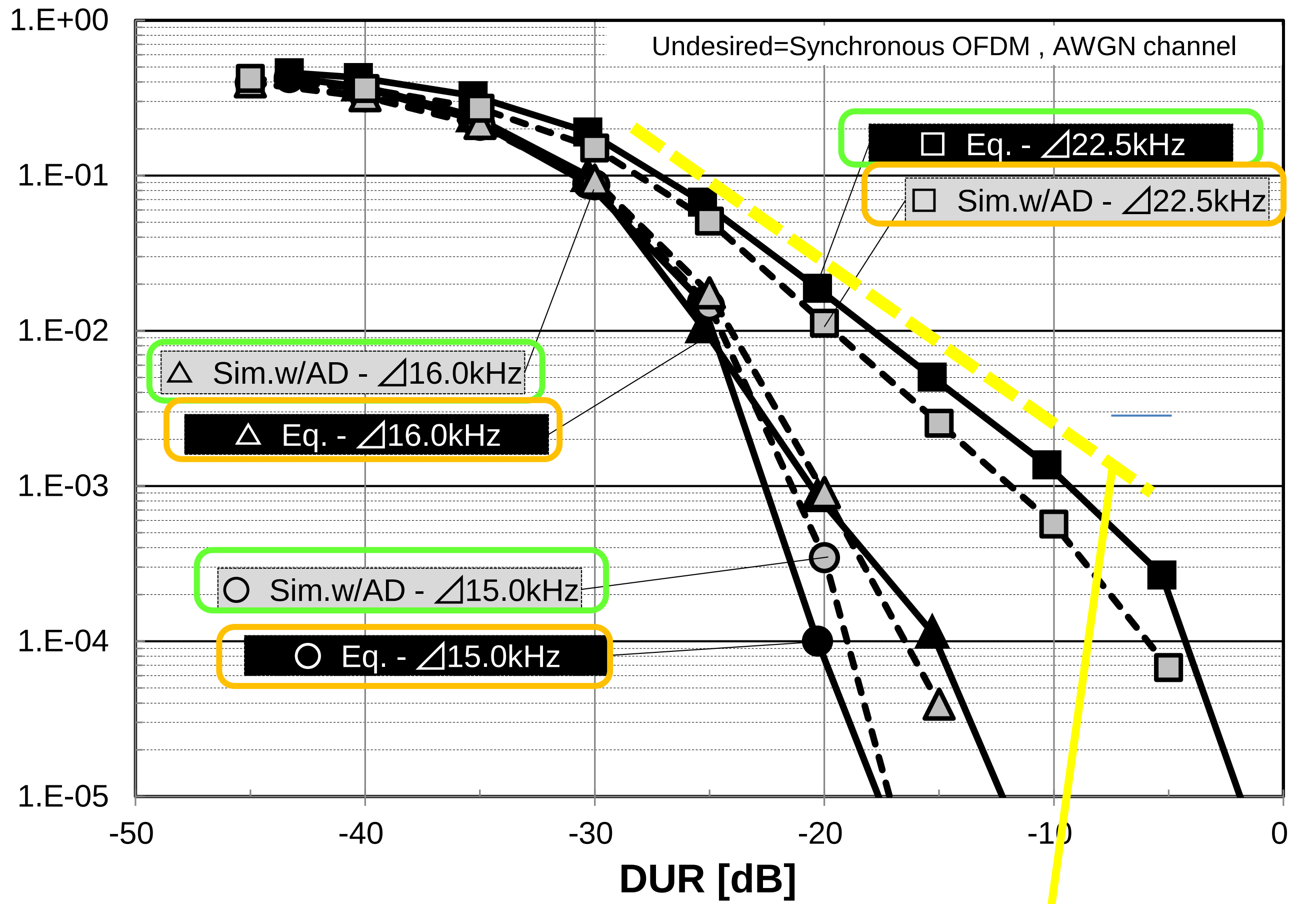
4.2. BER vs. DUR with undesired synch. OFDM

Experimental Result & Simulation Result w/ A/D

< Fig.10 >

Experimental Result and Simulation Result become very CLOSE

Confirmed that the dominant cause of the performance difference between Exp. and Sim. is quantization noise in A/D converter.

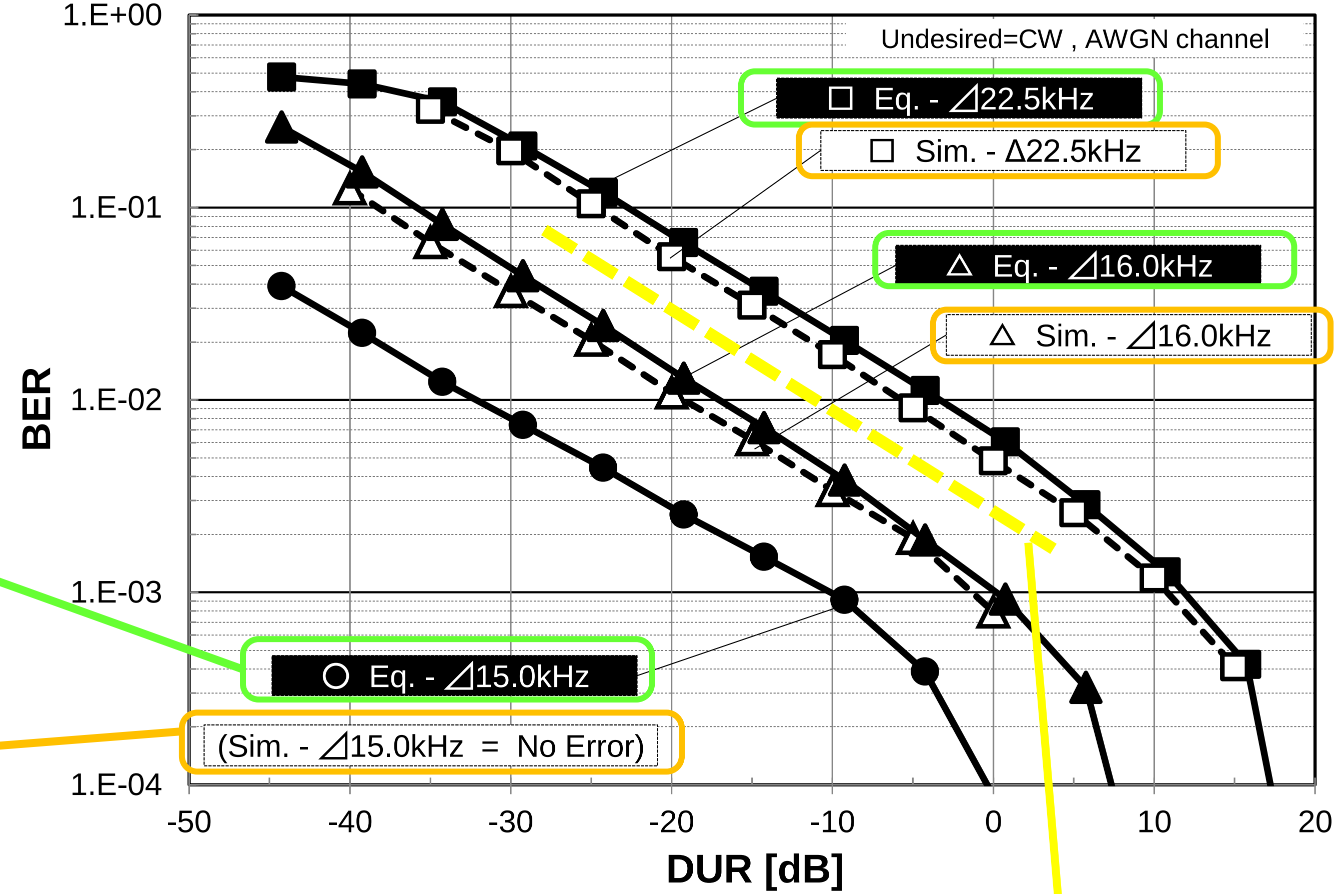


- Straight Shaped Graph
  BER x10 / DUR -10dB
- Rapidly fadeout @<1e-3

4.3. BER vs DUR with undesired CW

Experimental Result & Simulation Result w/o A/D

< Fig.11 >



When ⊿(freq. separation) =15.0kHz, No Error occurs theoretically.

Error occurs
caused by A/D saturation or freq. error

No Error as theory

- Straight Shaped Graph
  BER x10 / DUR -20dB
- Rapidly fadeout @<1e-3

Different from usual Gaussian interfered environment

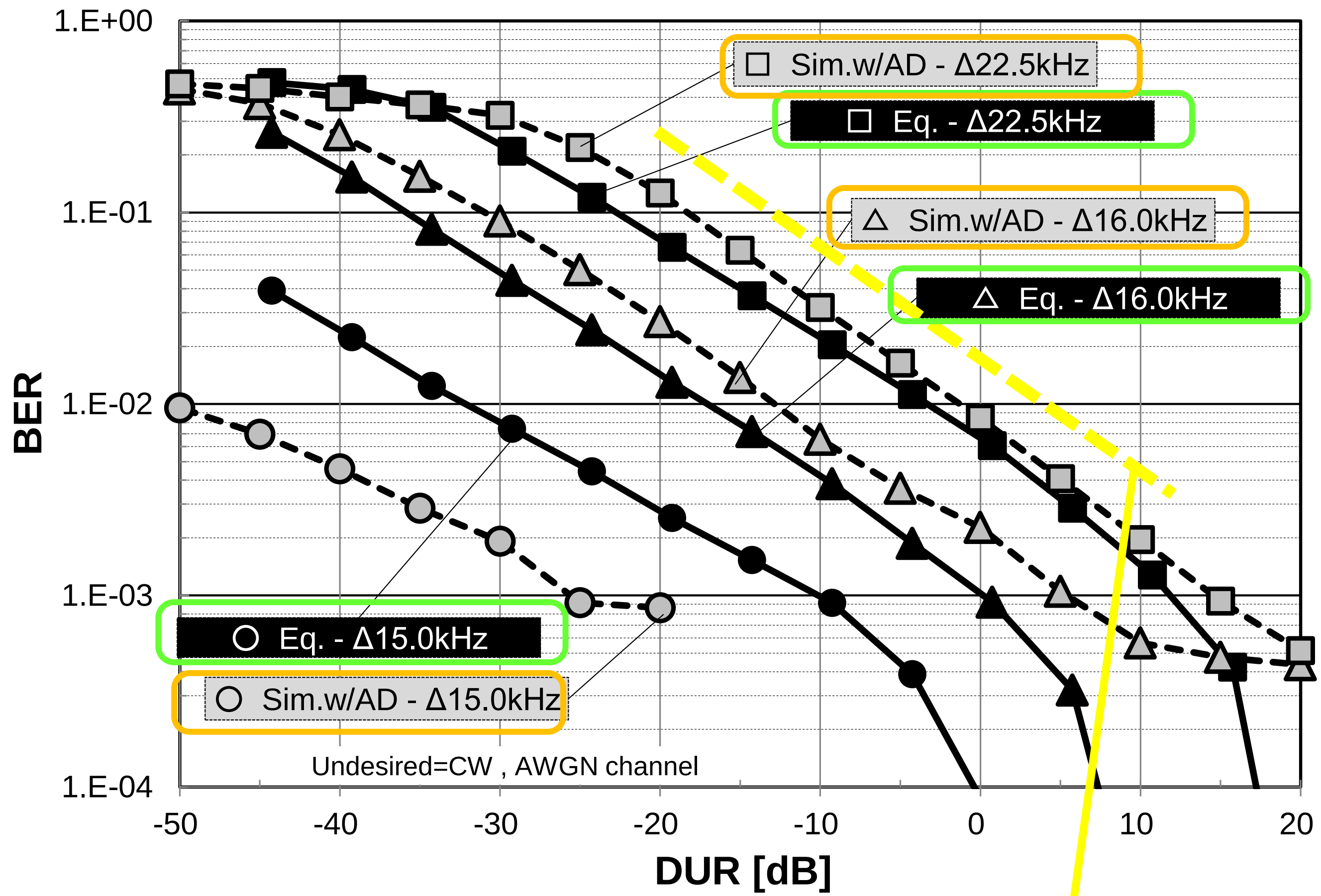
4.3. BER vs DUR with undesired CW

Experimental Result & Simulation Result w/ A/D

< Fig.12 >

Experimental Result and Simulation Result get Closer

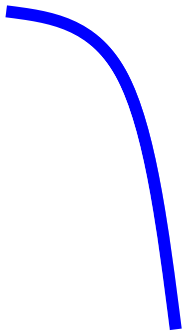
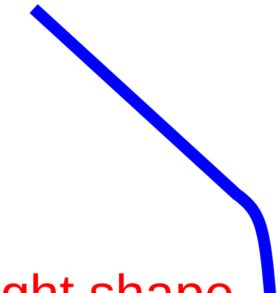
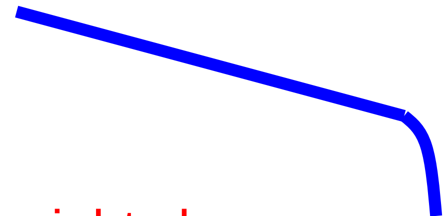
Confirmed that the dominant cause of the performance difference between Exp. and Sim. is quantization noise in A/D converter.



- Straight Shaped Graph BER x10 / DUR -20dB
- Rapidly fadeout @<1e-3

5. Theoretical Analysis

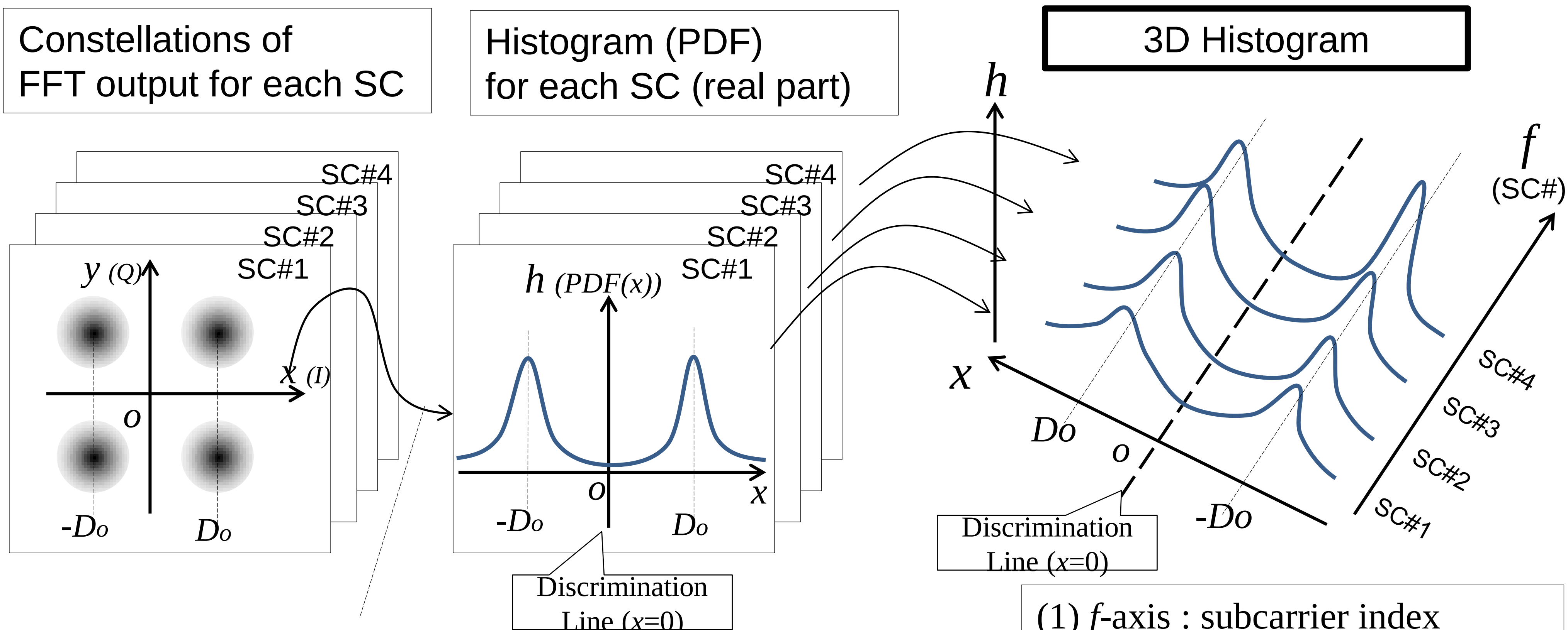
Summary for characteristics of BER vs DUR graph

	Gaussian Noise (AWGN)	**Synchronous OFDM**	**Continuous Wave (CW)**
Shape of graph		 -Straight shape -Fade rapidly @<1e-3	 -Straight shape -Fade rapidly @<1e-3
Slope of graph	Denoted by Error Function	Small Slope: BER 10 times / DUR 10dB	Small Slope: BER 10 times / DUR 20dB

It was considered that these differences were caused by difference of distribution shape of interference.
In this chapter, the different behavior was theoretically analyzed in order to comprehend the characteristics more clearly.

5.1. Histogram of Demodulated Signal

For the sake of observation for received signal distribution caused by interferences, 3D Histograms are drawn by computer simulations.



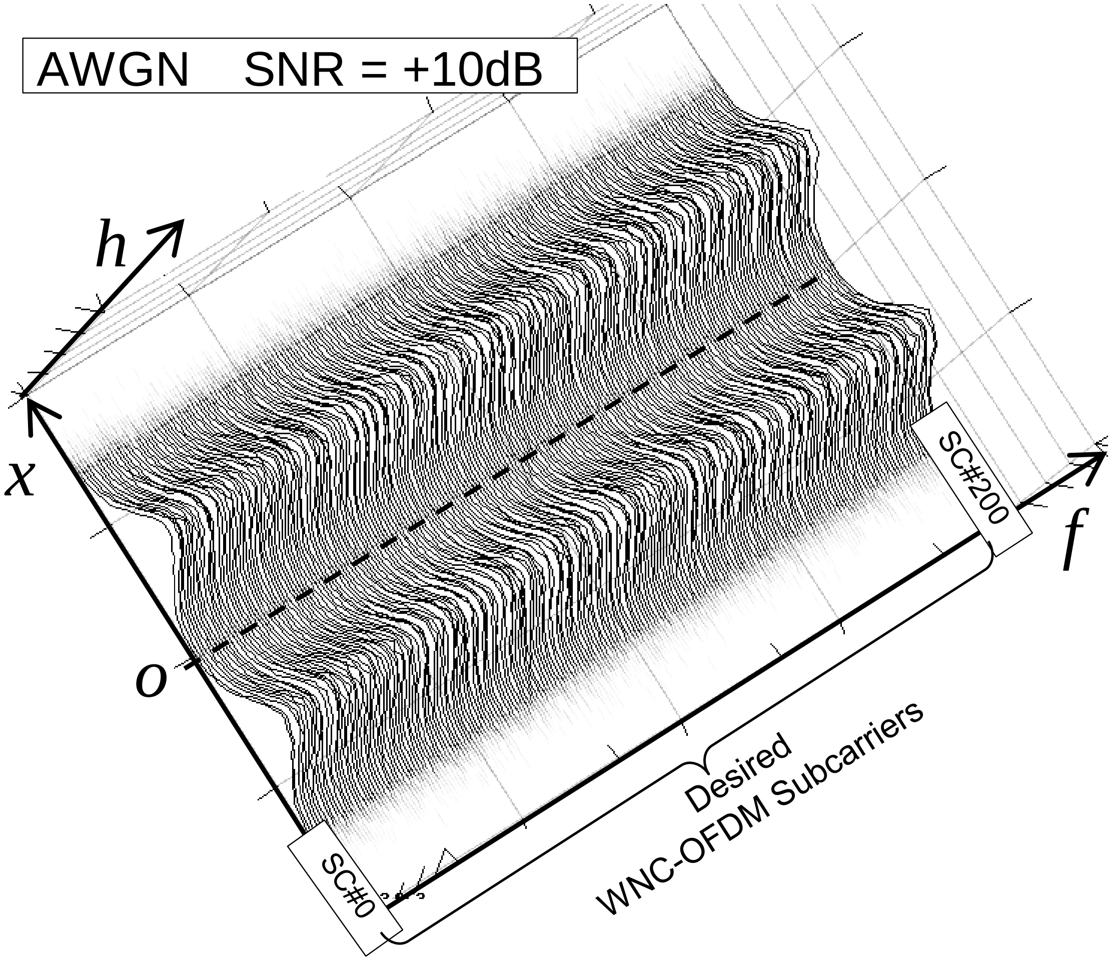
Extract Only Real-part.

(Imaginary-part distribution behaver is similar to Real-part)

(1) *f*-axis : subcarrier index
(2) *x*-axis : magnitude of each SC
(3) *h*-axis : histogram of *x*.

Histogram with AWGN

< Fig.14 >



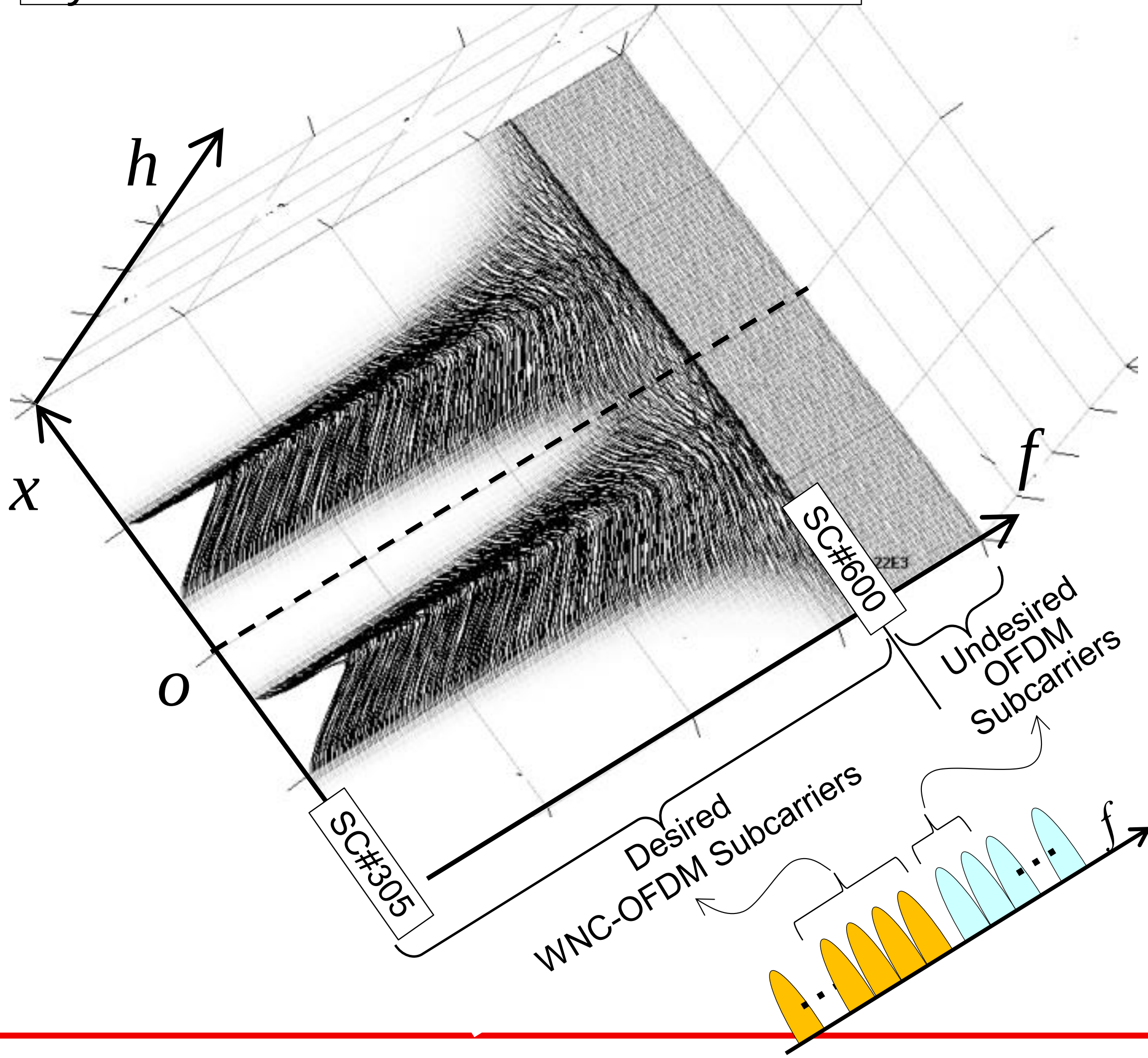
- Gaussian-shape Magnitude Distribution.

- Same Size Distribution for all SC's.

Histogram with undesired Synchronous OFDM

< Fig.15 >

Synchronous OFDM DUR = –20dB

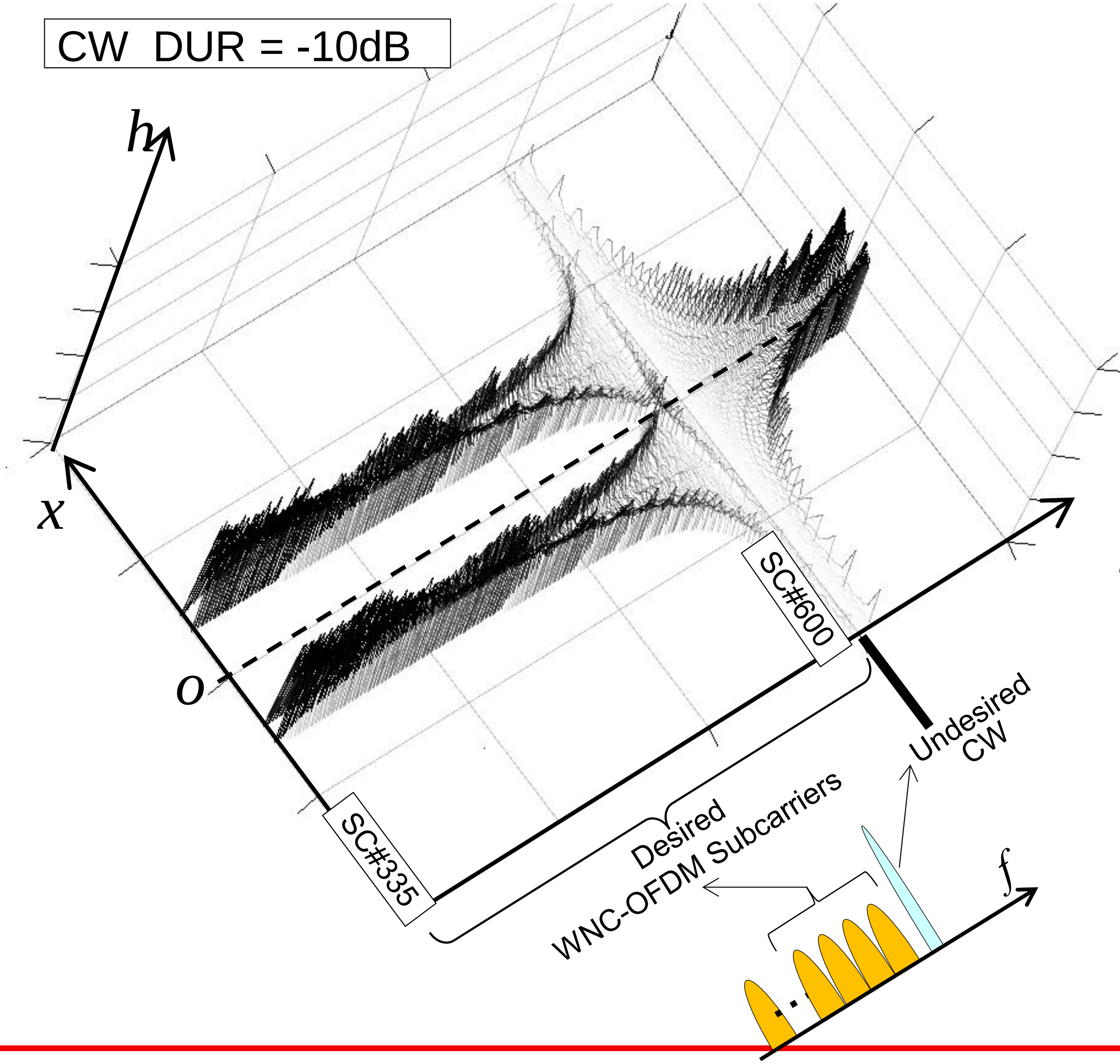


- Magnitude Distributions are different according to SC index, (i.e. frequency). (SCs closer to undesired signal are suffered Larger Interference)

- Distribution shape looks similar to Gaussian

Histogram with undesired CW

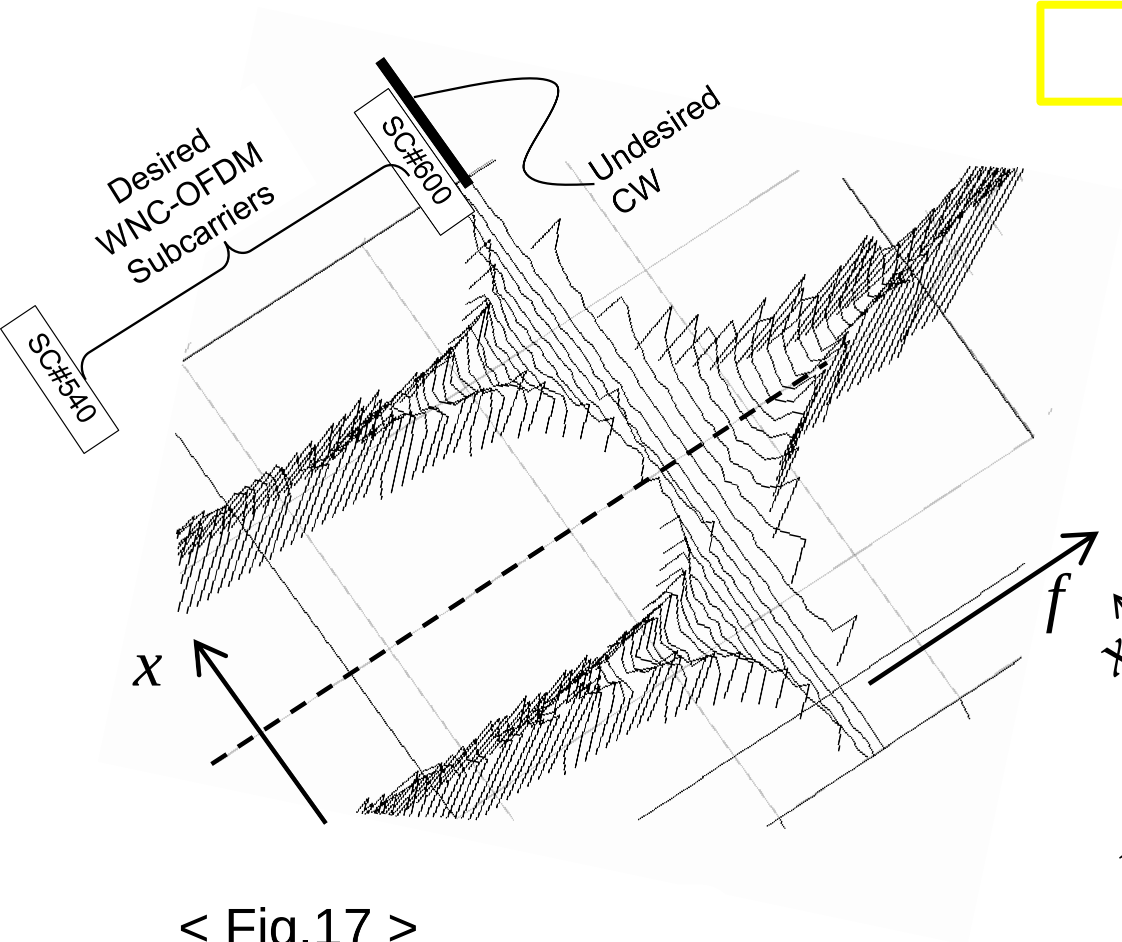
< Fig.16 >



- Magnitude Distributions are different according to SC index, (i.e. frequency). (SCs closer to undesired signal are suffered Larger Interference)

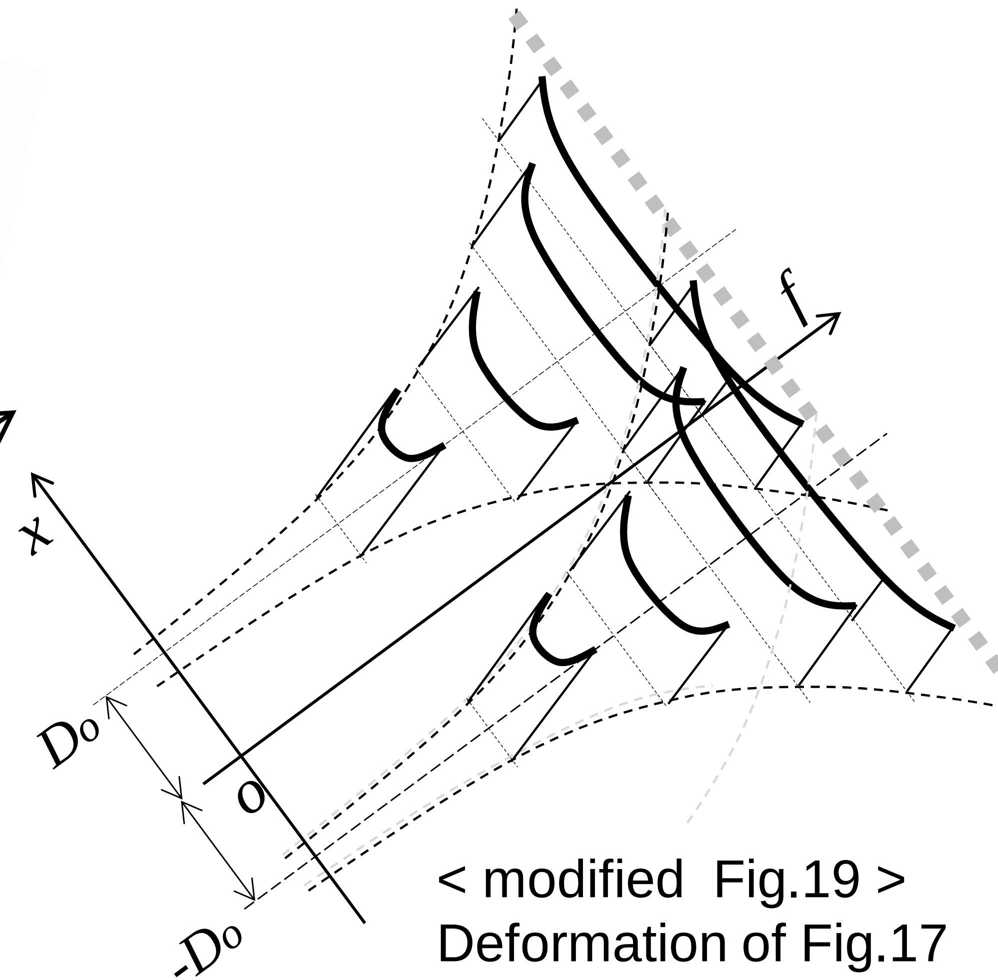
- Distribution shape looks like a letter "M".

Histogram with undesired CW (close up)



< Fig.17 >
Close up for Fig.16

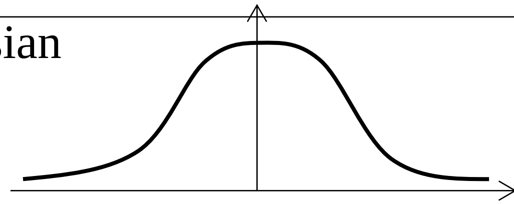
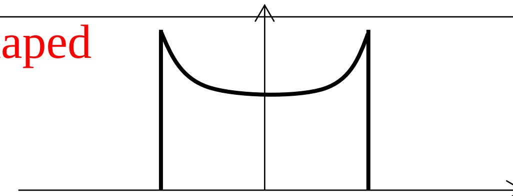
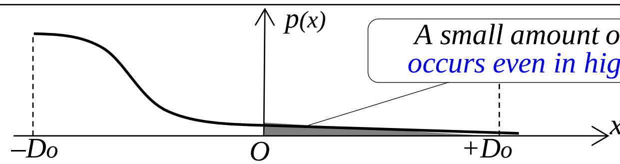
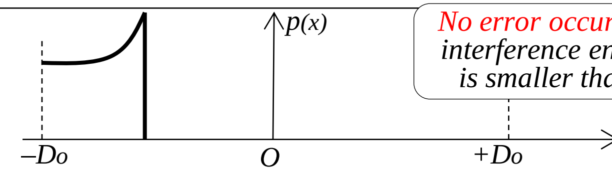
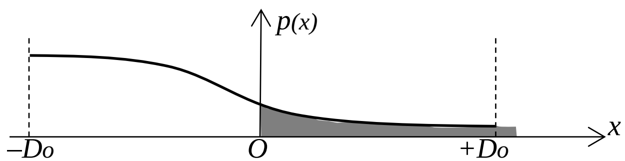
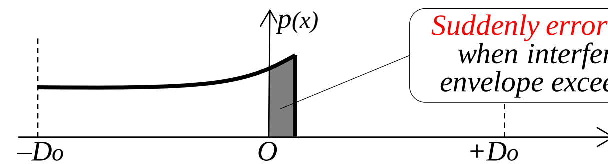
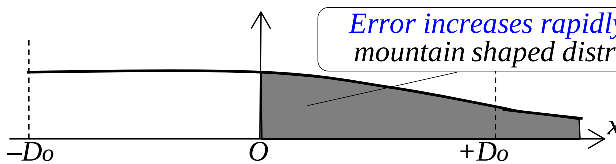
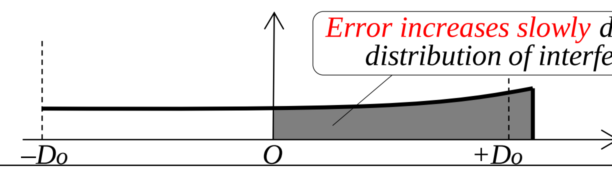
'M' shaped Distribution



< modified Fig.19 >
Deformation of Fig.17

Summary of Histogram Observation

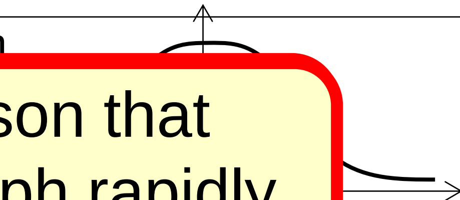
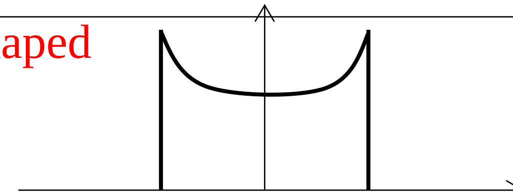
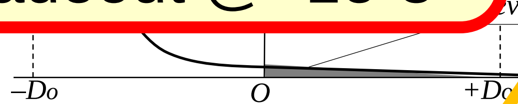
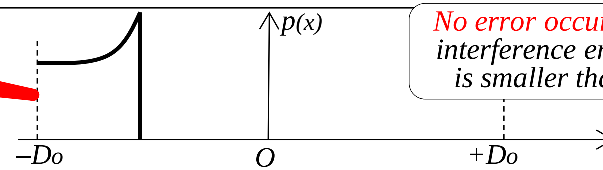
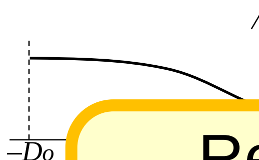
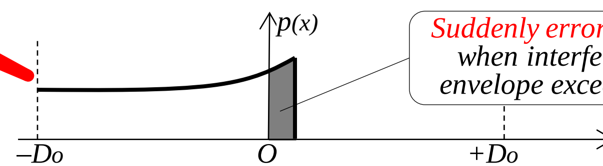
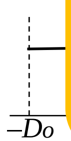
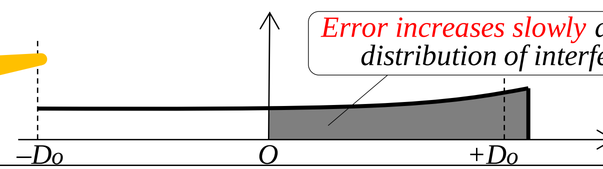
< Extracted from Table 2 >

<table>
<tr><th colspan="2"></th><th>Additive White Gaussian Noise (AWGN)</th><th>OFDM</th><th>Continuous Wave (CW)</th></tr>
<tr><td colspan="2">Uniformity of Interference</td><td>Uniform additive noise
- All SCs are always interfered equally</td><td colspan="2">Unbalanced Interference
(Larger interference for SCs close to undesired signal)
- Number of interfered SCs increases as undesired signal power increases</td></tr>
<tr><td colspan="2">Magnitude Distribution of Interference</td><td>Gaussian
</td><td>Like Gaussian</td><td>"M" shaped
</td></tr>
<tr><td rowspan="3">Bit Error Occurrence at One SC of desired signal</td><td>High DUR</td><td>
</td><td rowspan="3">Bit error rate can be approximated with integration of all interferences from all undesired OFDM SCs. the interference from one undesired SC can be approximated as interference from an undesired CW.</td><td>
</td></tr>
<tr><td>↕</td><td>
</td><td>
</td></tr>
<tr><td>Low DUR</td><td>
</td><td>
</td></tr>
</table>

x = Magnitude of demodulated (FFT output) signal
p(x) = Probability density function of *x*
Do = Constellation magnitude of desired signal at baseband
O = Origin of x, and threshold point for sign discrimination

Summary of Histogram Observation

< Extracted from Table 2 >

		Additive White Gaussian Noise (AWGN)	OFDM	Continuous Wave (CW)
Uniformity of Interference		Uniform additive noise - All SCs are always interfered equally	Unbalanced Interference (Larger interference for SCs close to undesired signal) - Number of interfered SCs increases as undesired signal power increases	
Magnitude Distribution of Interference		Gaussian 	Like Gaussian	"M" shaped 
Bit Error Occurrence at One SC of desired signal	High DUR		Bit error rate can be approximated with integration of all interferences from all undesired OFDM SCs ... interference from one undesired ... can be approximated as ... interference from an undesired ...	No error occurs when interference envelope is smaller than Do
				Suddenly error occurs when interference envelope exceeds Do
	Low DUR			Error increases slowly due to flat distribution of interference

Reason that the graph rapidly fadeout @<1e-3

Reason that slope of the graph is small

x = Magnitude of demodulated (FFT output) signal
p(x) = Probability density function of *x*
Do = Constellation magnitude of desired signal at baseband
O = Origin of x, and threshold point for sign discrimination

5.2. Theoretical Analysis for Interference from CW

It is required to confirm validity for following Quite Strange Characteristics in CW interfered environment;

- "M" shaped Magnitude Distribution
- Straight shaped BER graph

⇒ Theoretical Analysis was executed.

[Theoretical Analysis for Undesired synchronous OFDM environment]

⇒ Future Work

Distribution of the interference and BER can be approximated with Integration of interferences from ALL undesired OFDM subcarriers.
The interference from ONE undesired subcarrier can be approximated as interference from ONE undesired CW.

5.2. Theoretical Analysis for Interference from CW

＜1＞ CW component at FFT output

Down-converted CW signal :

$$U(t) = A_u\{(\cos(2\pi f_\delta t + \varphi_\delta)) + j(\sin(2\pi f_\delta t + \varphi_\delta))\} \qquad (1)$$

n-th SC component at FFT output = Interference Affecting n-th desired subcarrier :

$$F(n) = \int_0^T U(t)\exp(-j2\pi n f_0 t)\,dt \qquad (2)$$

$$= \frac{A_u}{2\pi(f_\delta - nf_0)}\left\{\begin{array}{c}\sin(2\pi f_\delta N + \varphi_\delta) - \sin\varphi_\delta \\ -j\cos(2\pi f_\delta N + \varphi_\delta) + j\cos\varphi_\delta\end{array}\right\} \qquad (6)$$

When $f_\delta = mf_o$, zero.
(Highest Orthogonality)

When $f_\delta = (m+1/2)f_o$, Maximal Magnitude
(Lowest Orthogonality)

$$F_m = \frac{A_u(-\sin\varphi_\delta + j\cos\varphi_\delta)}{\pi f_0\left(m + \frac{1}{2} - n\right)} \qquad (7)$$

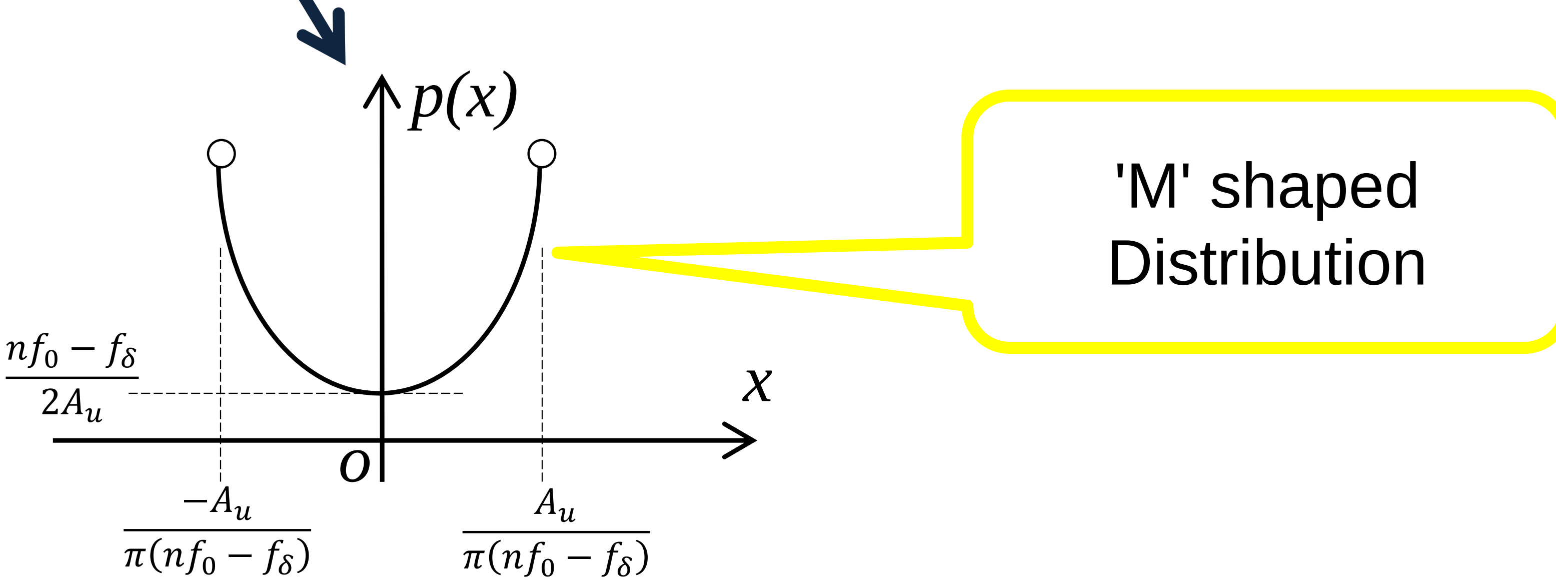
(m= integer)

5.2. Theoretical Analysis for Interference from CW

<2> Probability Density Function (PDF) of Interference component

$$q(S) = \frac{nf_0 - f_\delta}{2A_u} \frac{1}{\sqrt{1 - \left(\frac{\pi(nf_0 - f_\delta)}{A_u} S\right)^2}} \quad (10)$$

$$\frac{-A_u}{\pi(nf_0 - f_\delta)} < S < \frac{A_u}{\pi(nf_0 - f_\delta)}$$

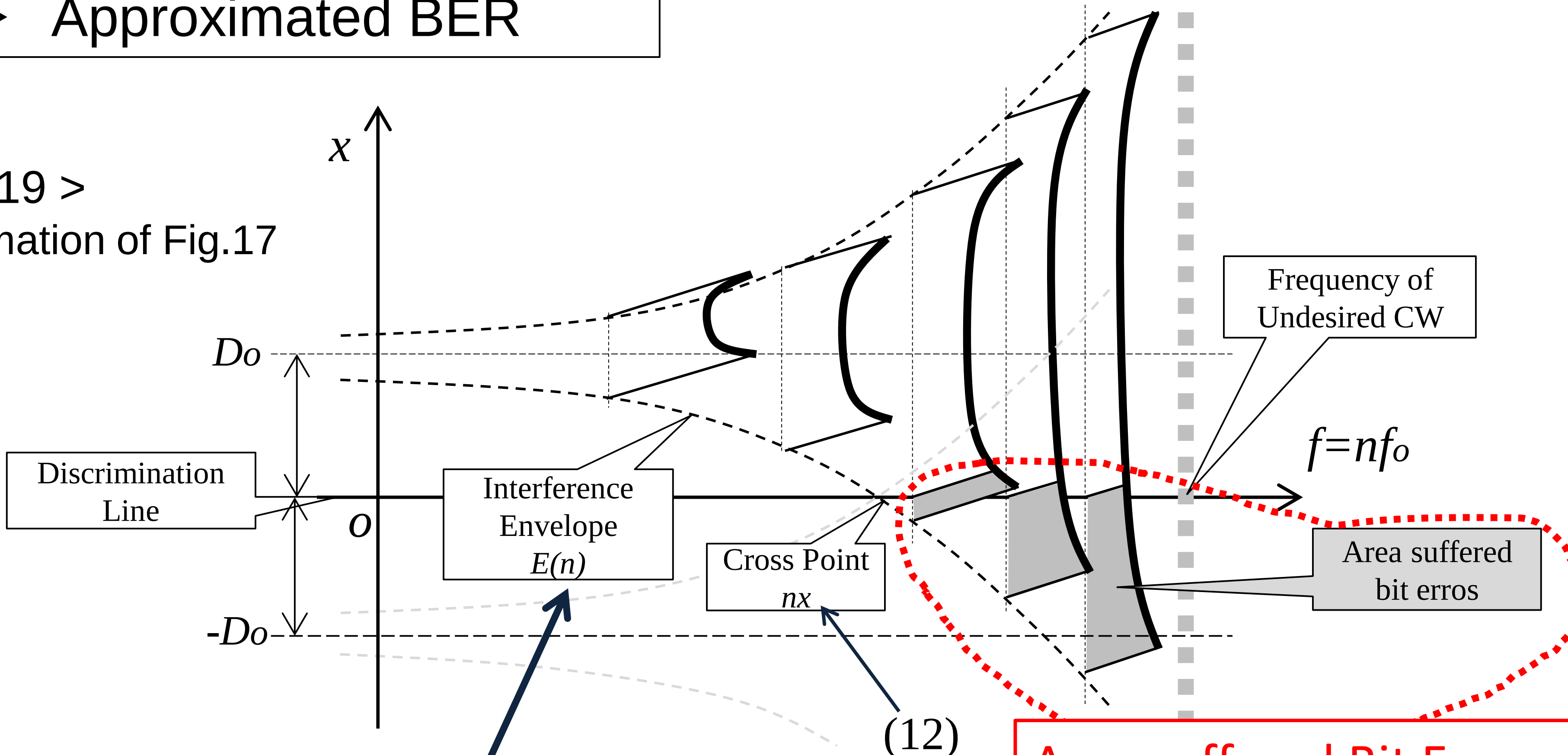


< Fig.19 > PDF of interference from CW

5.2. Theoretical Analysis for Interference from CW

＜3＞ Approximated BER

< Fig.19 >
Deformation of Fig.17



Area suffered Bit Errors
(exceeding Discrimination Line)

(7)

φ_δ = -π/2

"Interference Envelope"

$$E(n) = \frac{A_u}{2\pi f_0\left(m + \frac{1}{2} - n\right)} \quad (11)$$

Integrated at next page (13)

5.2. Theoretical Analysis for Interference from CW

＜3＞ Approximated BER

BER is calculated by Sum of (11)=$E(n)$
for area in which $E(n)$ exceeds the discrimination line.

(PDF of the interference distribution is approximated by rectangular shape)

$$BER = \frac{1}{N}\sum_{n_x}^{N}(E(n) - D_0)\frac{1}{2E(n)} \approx \left(\frac{A_u}{D_0 \pi f_0}\right)\frac{1}{4N} \qquad (13)(16)$$

(16) proves that BER is Inversely Proportional to DUR,
i.e. BER increases 10 times when DUR degrades 20 dB.

(one-tenth in antilogarithm)

Above analysis showed the reason why BER vs DUR graph in undesired CW case had straight shape and small slope (10X BER/20 dB DUR)

Conclusion

Influence of interference from other radio system in WNC-OFDM system were evaluated (both experiments and simulation)

BER vs DUR characteristics was Quite Different compared to Gaussian noise environment.

- straight shape
- small slope (10X BER/20 dB DUR : w/ undesired CW)
- graph rapidly fadeout @<1e-3.

These were Theoretically Analyzed and confirmed validity.

These knowledge is valuable for :

- making System Performance Requirement
- Designing a Link Adaptation Algorithm

Acknowledgment

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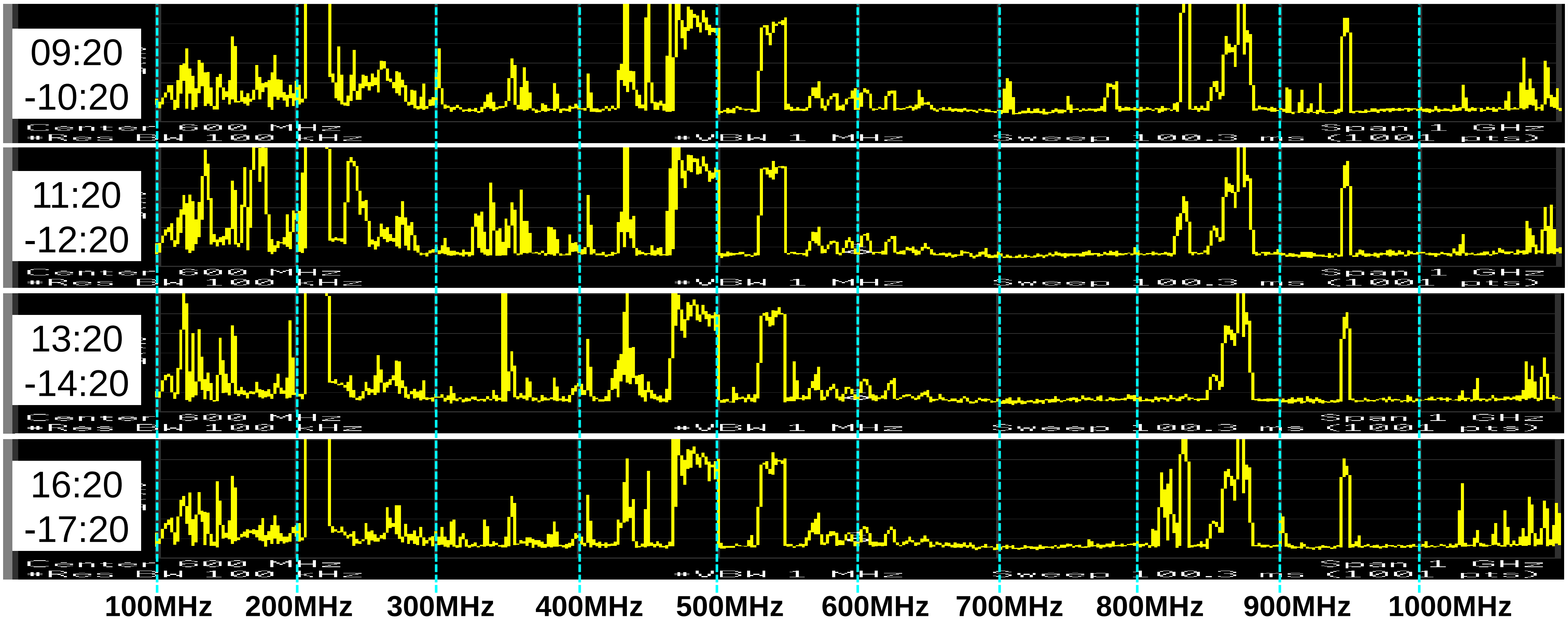
以下　バックアップ

Observation for Actual Usage of Frequency Bands

Measured at ATR Bld., Kyoto, Japan.　3 Dec. 2012.

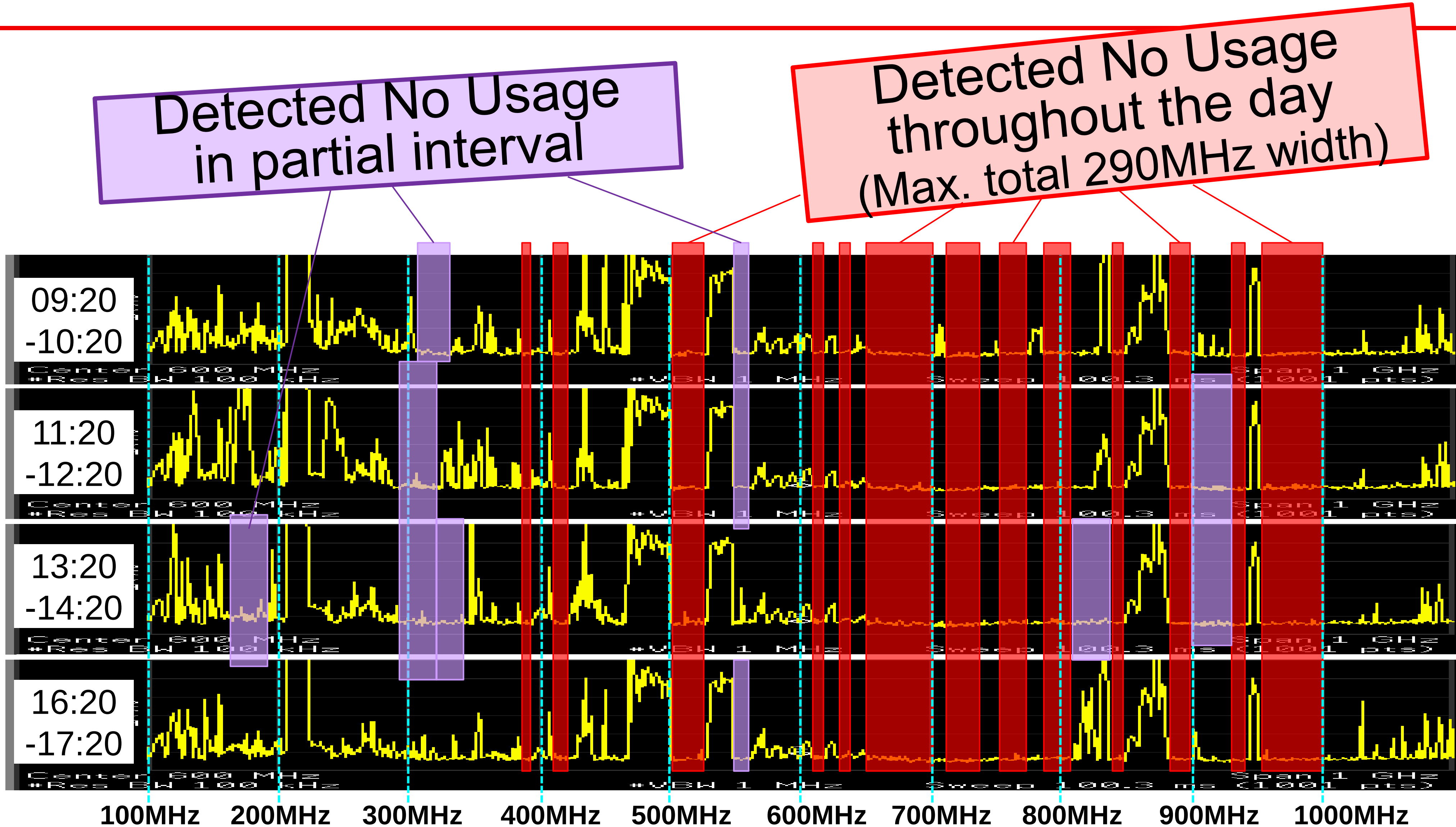
Measured　w/ biconical antenna & spectrum analyzer,（RBW=100kHz,　Max Hold during 1 hour)

Observed many bands whose **Usage Could Not Be Detected.**
Observed variation of usage with time passage.



ATR Advanced Telecommunications Research Institute International

Observation for Actual Usage of Frequency Bands



(Measured at ATR Bld., Kyoto, Japan. 3 Dec. 2012.
RBW=100kHz, Max Hold during 1 hour.)