Non-orthogonal signals for spectral and energy efficient transmission;

are these the ideal candidates for 6G?

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Radio Access Network Techniques for 6G

July 2021

Why does radio/modulation change from generation to generation?

We would like radio signals that can carry ***all the information****, maintaining data* ***quality*** *and integrity in smallest possible* ***bandwidth*** *and lowest possible* ***energy*** *using* ***simplest*** *equipment.*

- **Use**: think of 1G, GSM, UMTS and then LTE and 5G
- Data **rate**: kb/s to Gb/s
- **Bandwidth** and radio
- Signal quality and errors:
  - Channel physics: delay spread, environment, user speed
  - Channel use: noise and interference
- Equipment, **energy** and **complexity**

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FM GMSK CDMA/QAM OFDM/QAM

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- Signal quality and errors:
  - Channel physics: delay spread, environment, user speed
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OFDM concept has not changed since 1958!!

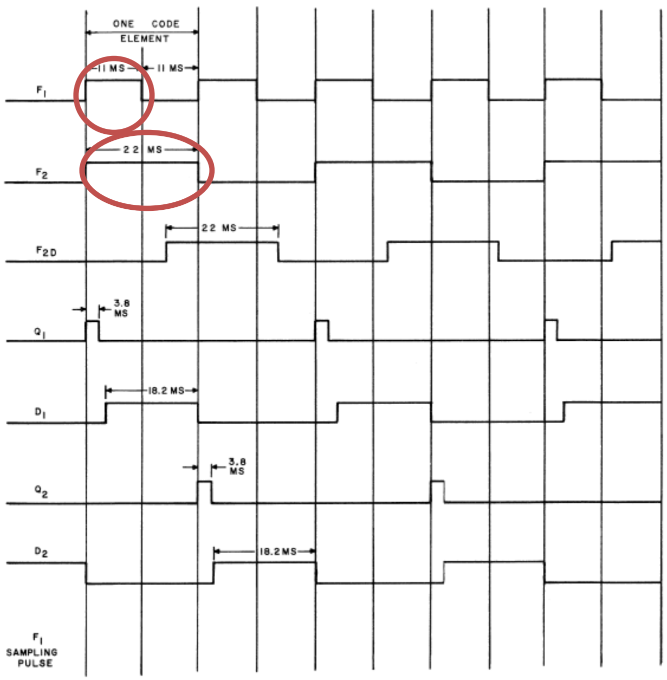


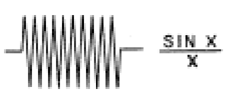
Figure 12-6. Timing Pulse Relation

- A binary bit stream is divided into N-binary bit streams.
- Bit duration is extended from T_b to N x T_b

  What does this do to the spectrum?

- Each of the N sub-streams modulates a sinusoidal carrier known as (sub-carrier)
- The carriers are at different frequencies and are separated by

  $\Delta f = 1/N \times T_b$
- The sub-streams are added together and transmitted



The concept has not changed since 1958!!

Total BW 2090 + 110 = 2200 Hz
20 sub-carriers
Sub-carrier separation = 110 Hz
= 1/18.2 ms

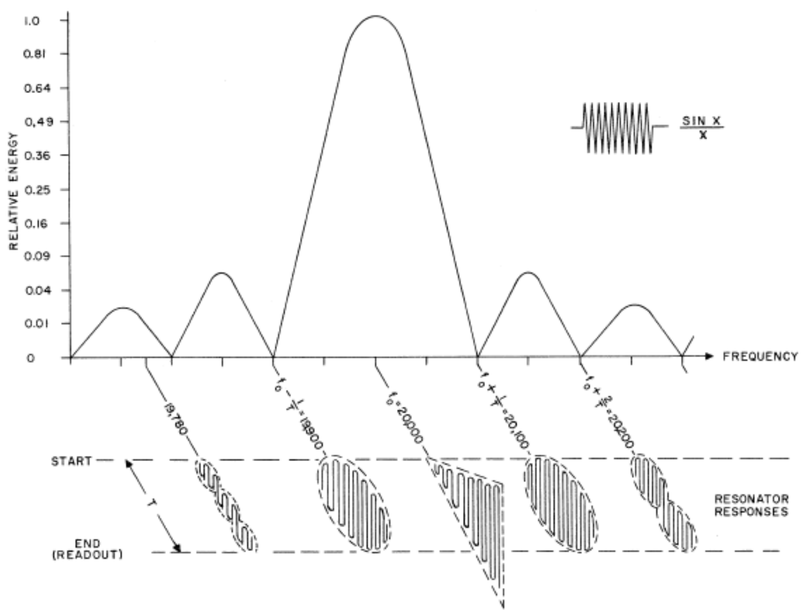


Figure 12-5. Energy Versus Frequency Distribution of Transmitted Pulses and Infinite Q Resonator Responses

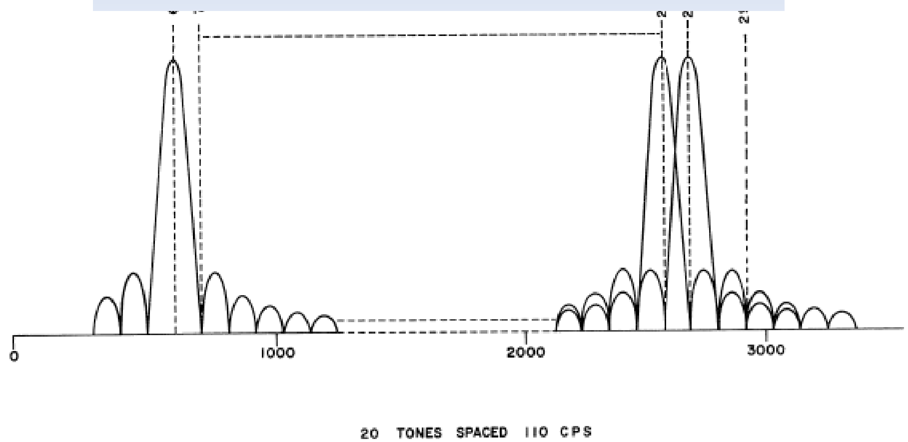
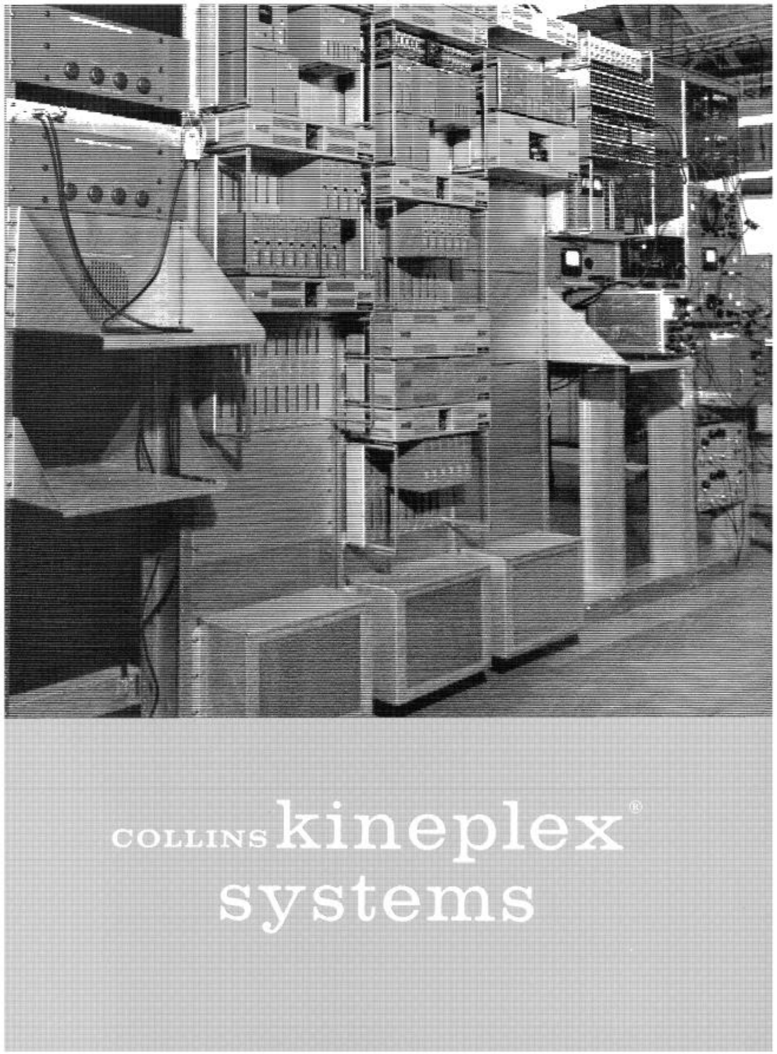


Figure 12-7. Channel Allocation at 100 WPM

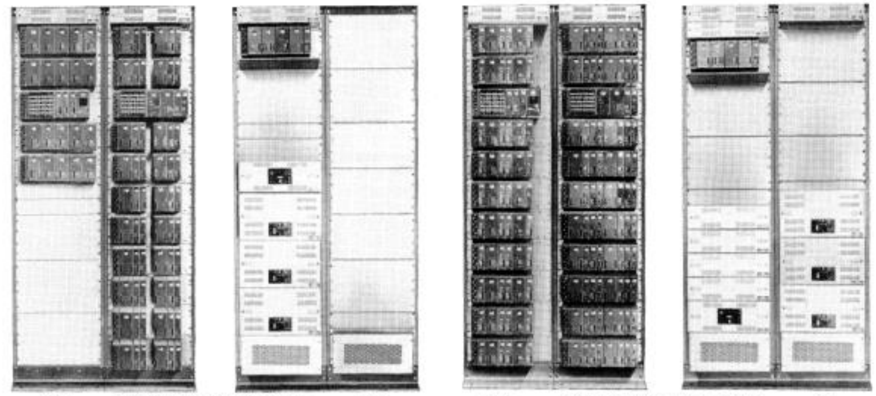
This is an FSK system, but a special one!!

OFDM circa 1959

KINEPLEX



KINEPLEX® DATA SYSTEMS

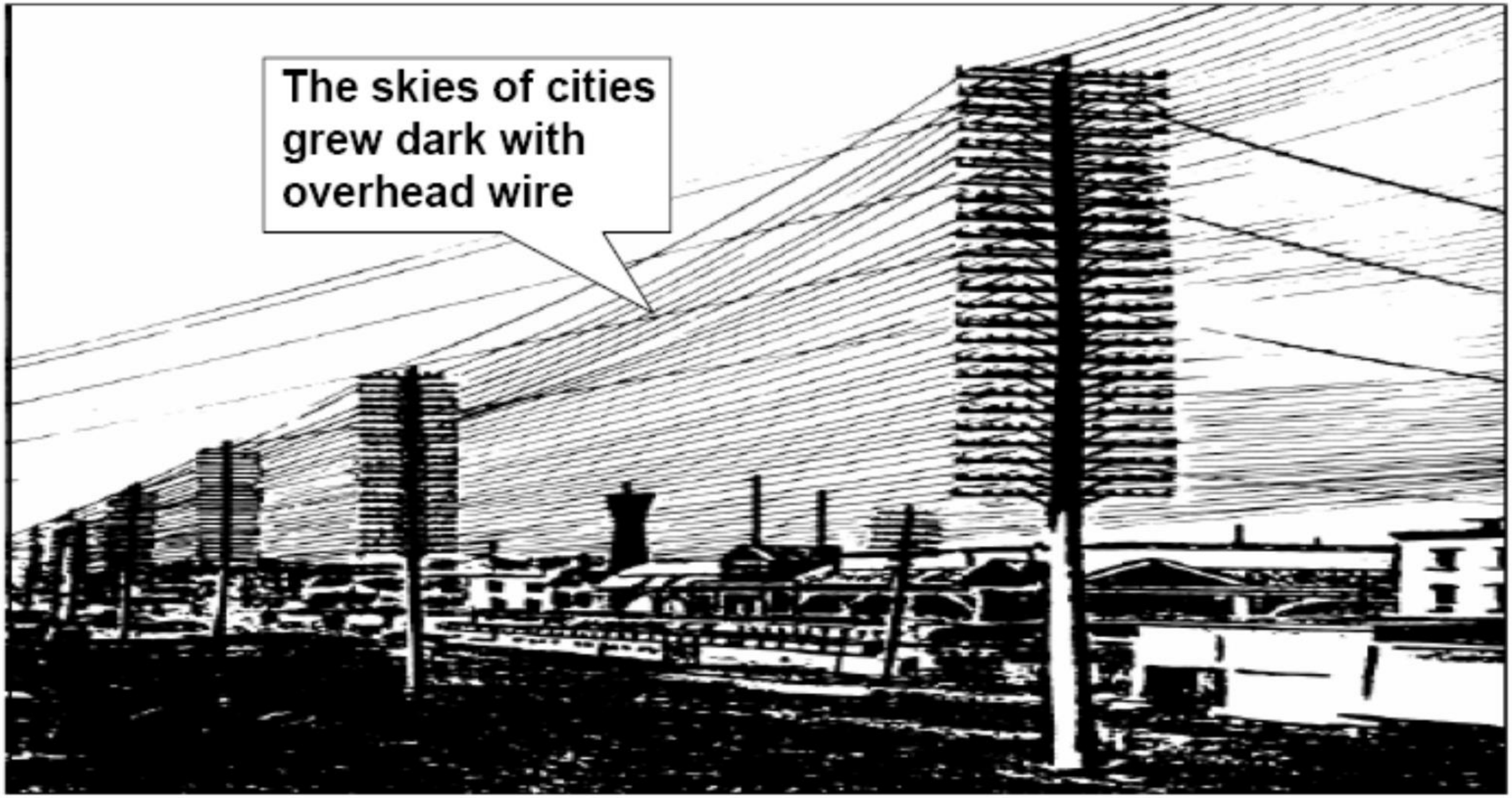


	Type	Dimensions (inches) W	D	H	Weight (lbs.)	Channels	Operational Rate
Kineplex Data System	TE-202	41	20	86⅛	400	40	75 bits per second per channel 3,000 bits per second total
Kineplex Data System with Teletypewriter Converters	TE-202	41	20	86⅛	700	40	60, 75 or 100 words per minute per channel
Kineplex Data System	TE-206	25	18	58	175	8	300 bits per second per channel 2,400 bits per second total
Kinecard Converter	768G-1	25	20	66	300		100 cards per minute
Kinetape Converter	768H-1	25	20	66	350		300 eight-bit characters per second
Kinetape Converter	768H-2	25	20	66	350		300 seven-bit characters per second

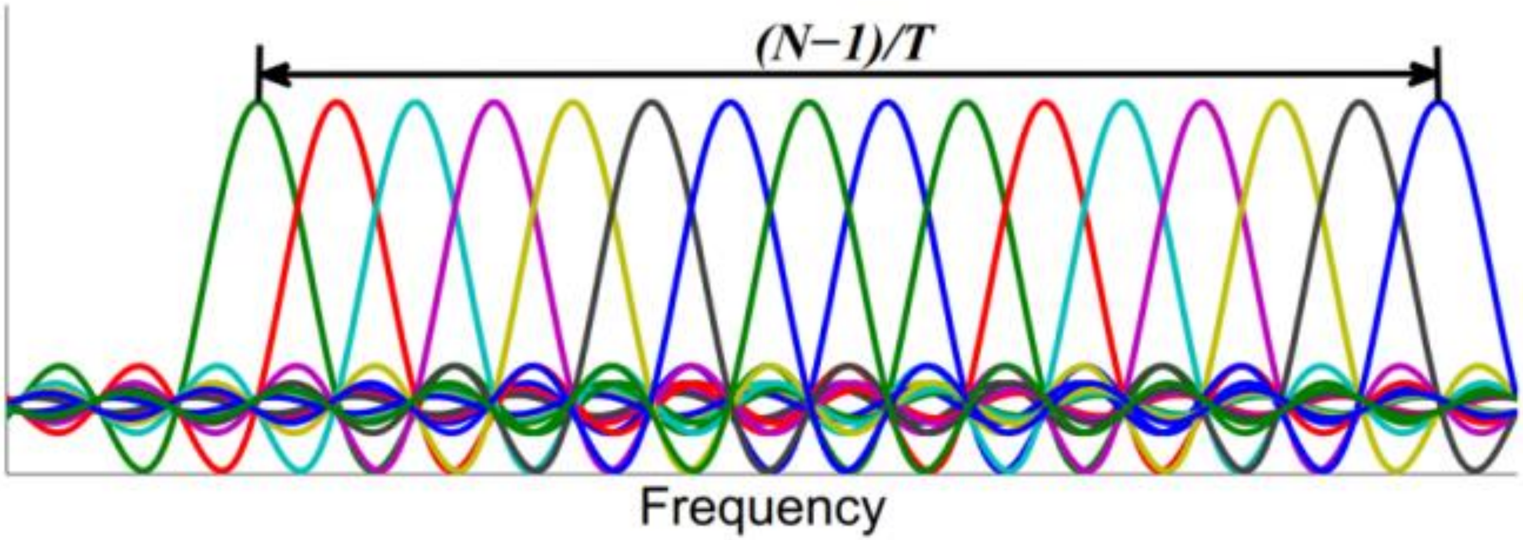
768H-1, -2

R. Mosier and R. Clabaugh, ***Kineplex, a bandwidth efficient binary transmission system***, AIEE Proceedings, Vol. 76, January 1958

Parallel Communications methods are not new!!



Orthogonal FDM



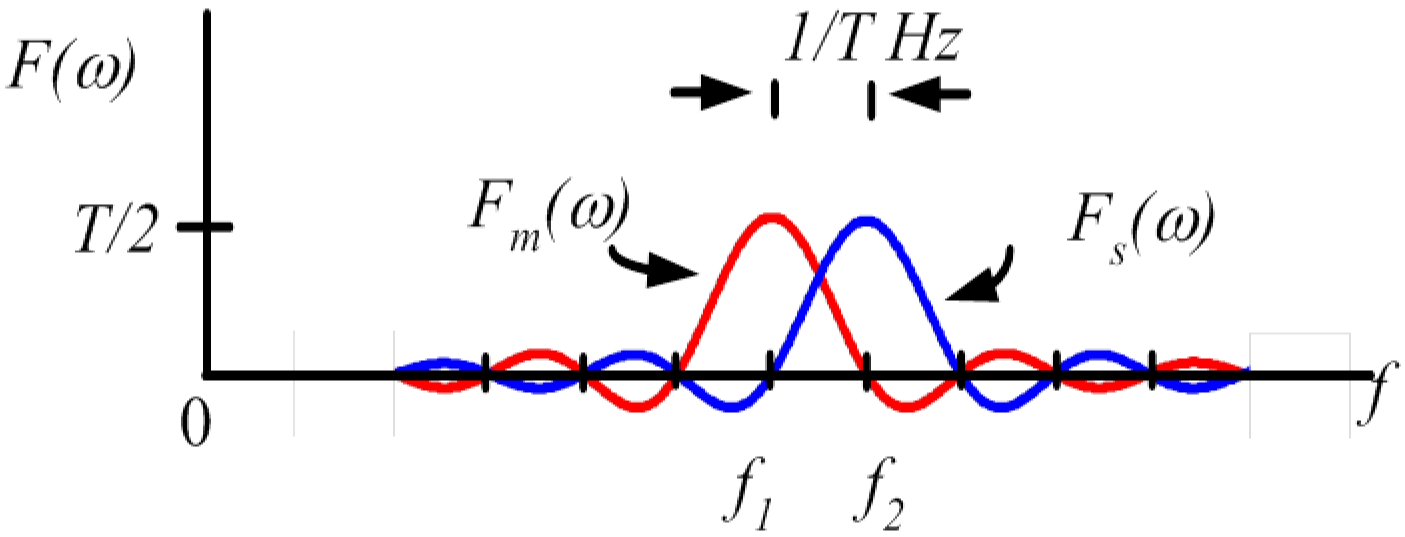
(a) OFDM Spectrum

LTE and 5GNR
Where else is OFDM used?

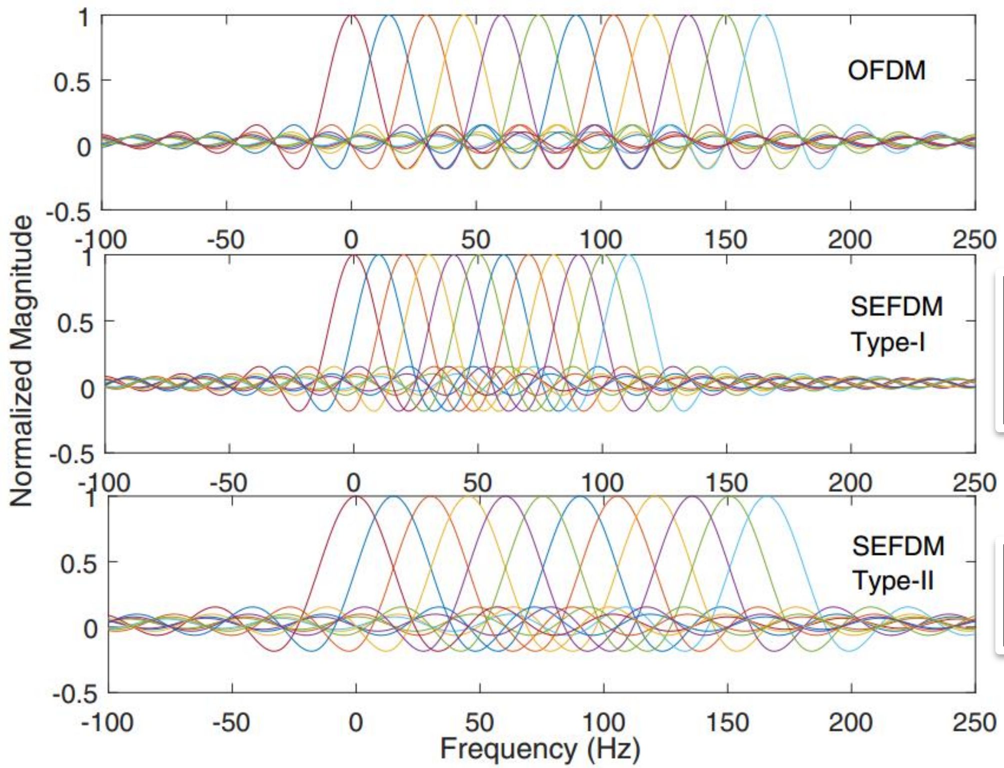
System	Transform Size	Number Carriers	Channel Spacing kHz	Bandwidth MHz	Sample Rate MHz	Symbol Duration μsec	Data Rate Mbits/s
HyperLAN/2	64	52 4	312.5	16.25	20	3.2 0.8	6-54
802.11a	64	52 4	312.5	16.56	20	3.2 0.8	6-54
DVB-T	2048 1024	1712 842	4.464	7.643	9.174	224	0.68-14.92
DAB	2048 8192	1536	1.00	1.536	2.048	24/48/96 msec	3.072
ADSL	256 (down) 64 (up)	36-127 7-28	4.3125	1.104	1.104	231.9	0.64-8.192

Minimum Shift Keying

Used in GSM



The non-orthogonal signal waveform



Existing

Proposed:
Bandwidth saving
Connection increase

Proposed:
Data rate increase

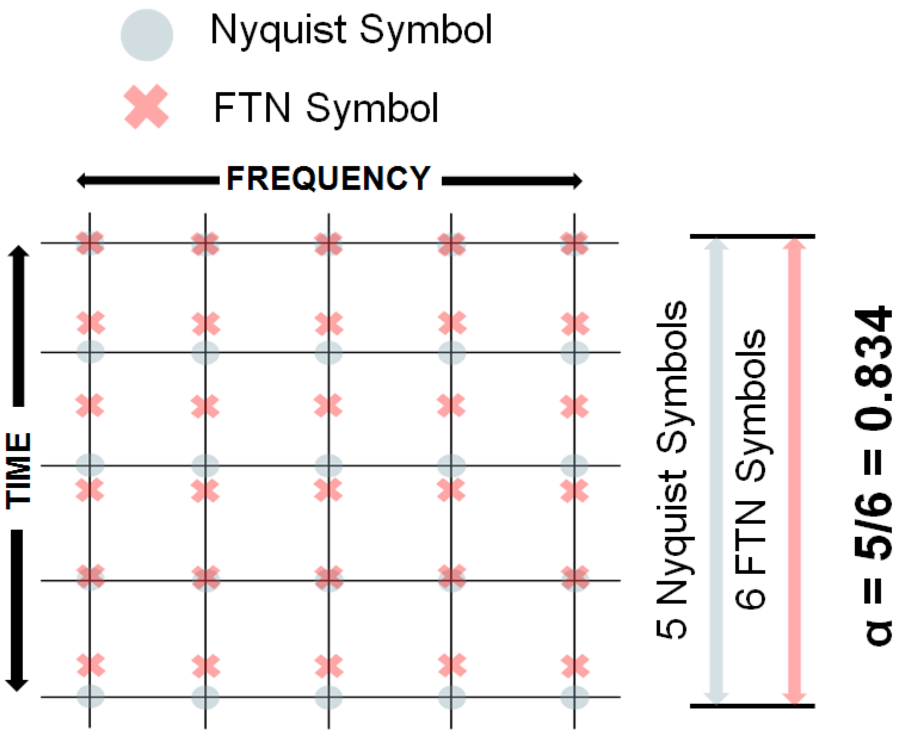
- OFDM (12 sub-carriers, data rate is Rb).
- SEFDM Type-I (12 sub-carriers, bandwidth compression factor α=0.67, data rate is Rb).
- SEFDM Type-II (12 sub-carriers, bandwidth compression factor α=0.67, data rate is 1.5Rb).

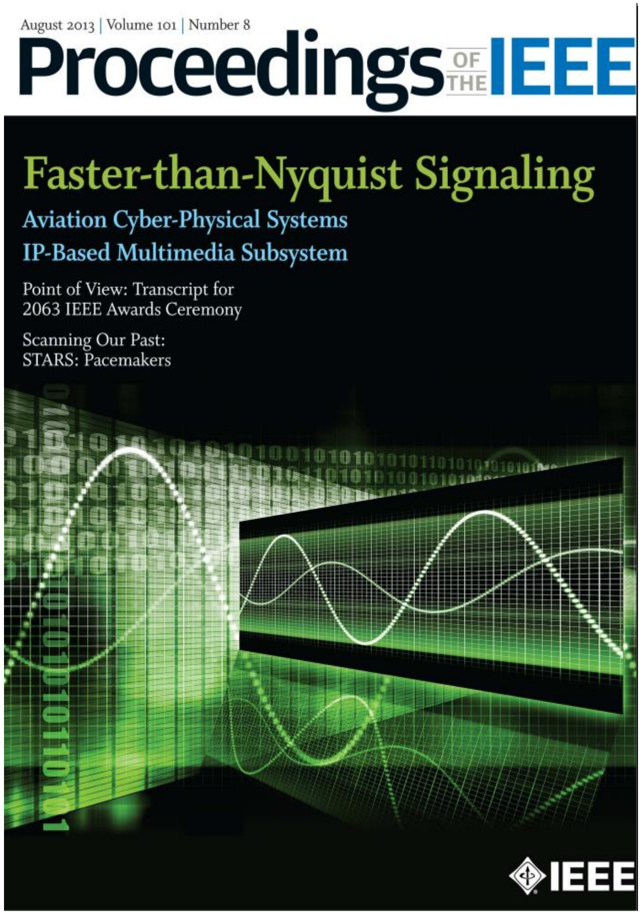
M. Rodrigues and I. Darwazeh, "A spectrally efficient frequency division multiplexing based communications system," in Proc. 8th Int. OFDM Workshop, Hamburg, 2003, pp. 48 – 49.

Mutistream Faster Than Nyquist (FTN)

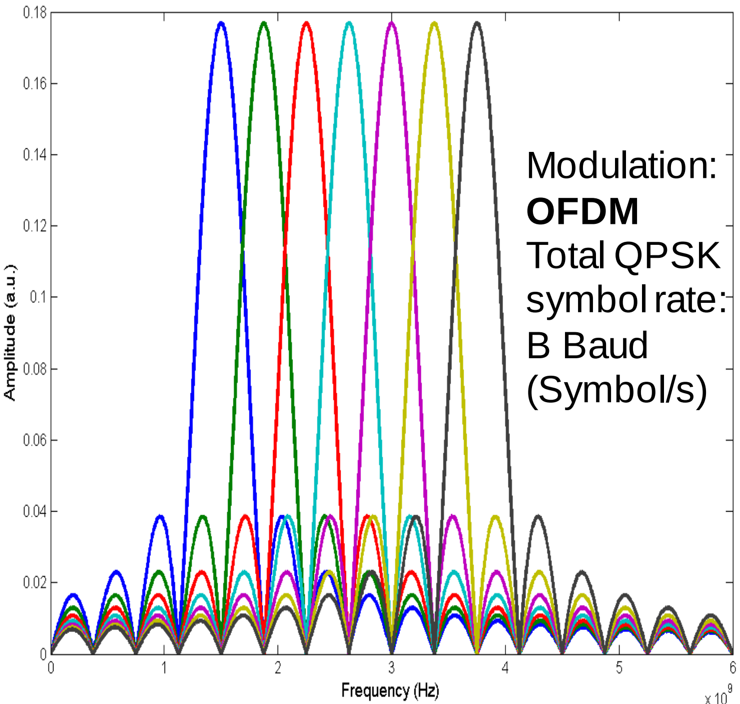
(D. Dasalukunte, F. Rusek, and V. Owall, “An iterative decoder for multicarrier faster-than-Nyquist signaling systems,” in Communications (ICC), 2010 IEEE International Conference on, May 2010, pp. 1–5)

FTN: increase spectral efficiency by transmitting data faster than Nyquist criterion.



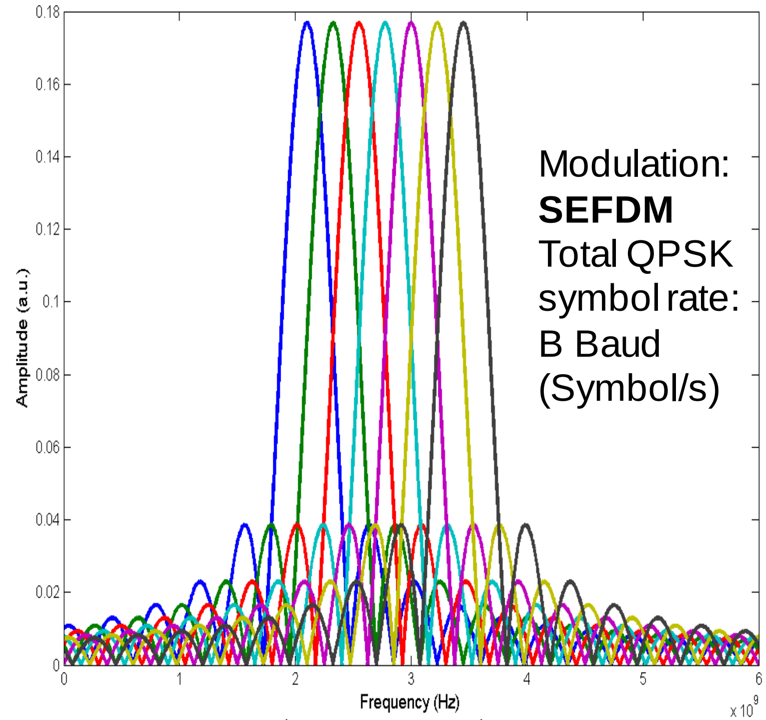


Bandwidth Saving vs. ICI



Bandwidth ≈ B Hz

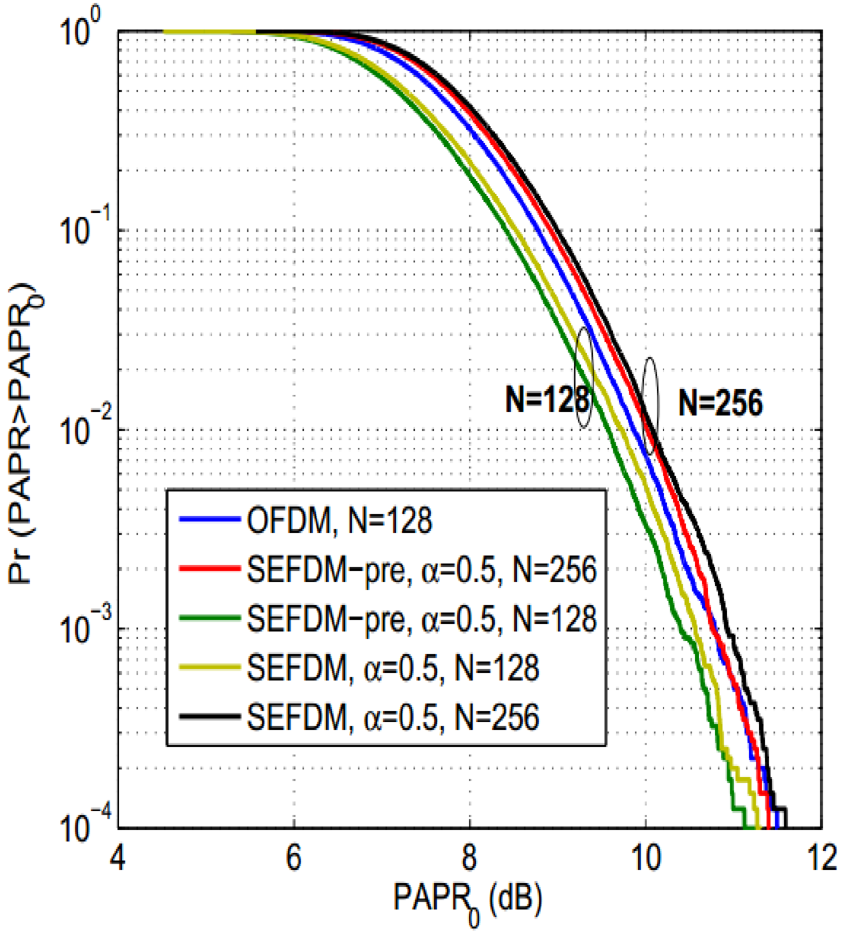
No ICI



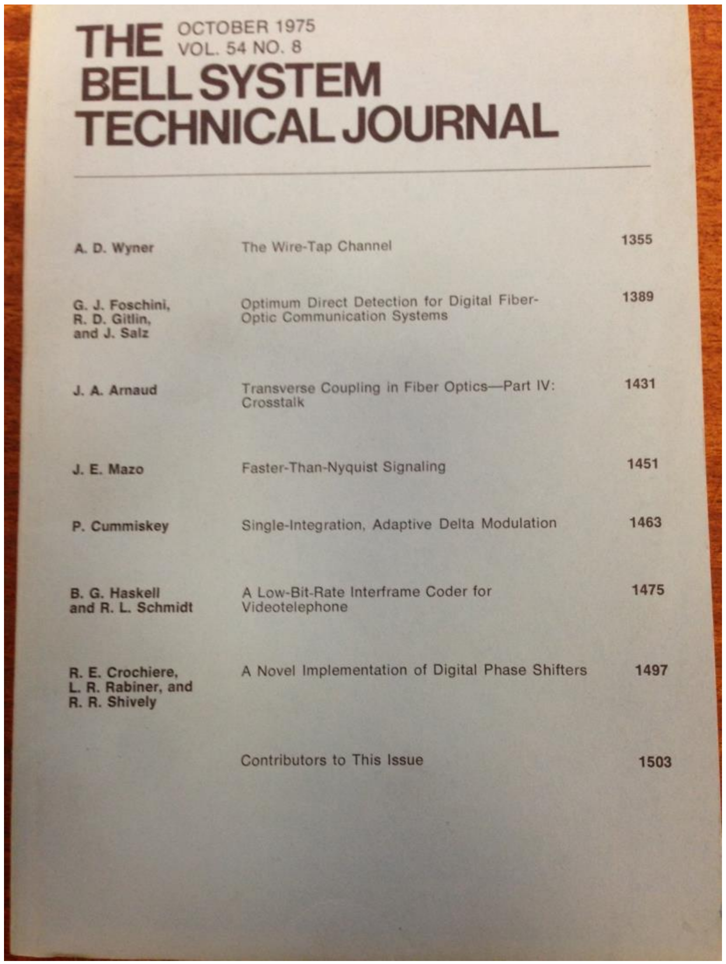
Bandwidth ≈ $\alpha \cdot B$ Hz, $0<\alpha<1$

With ICI

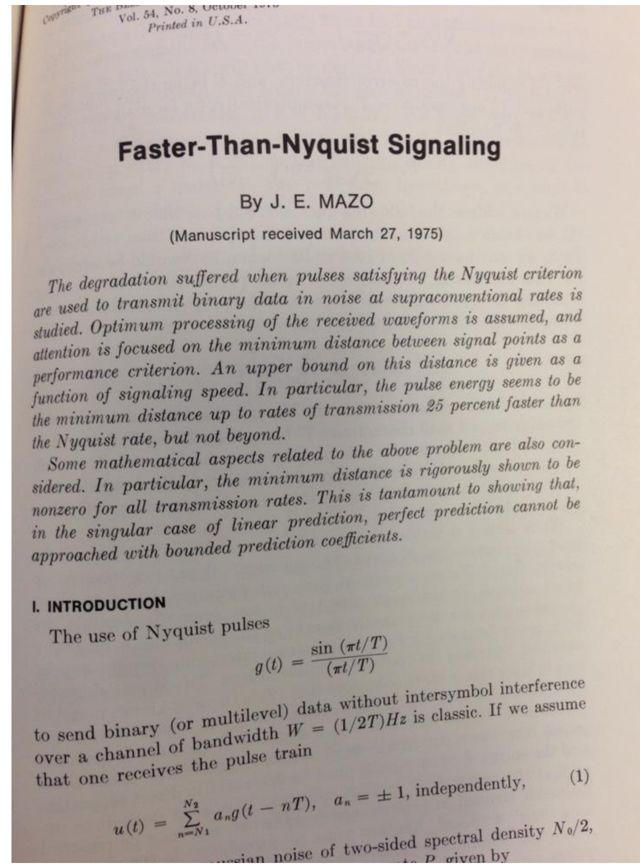
No PAPR penalty



And in 1975…



THE BELL SYSTEM TECHNICAL JOURNAL
OCTOBER 1975
VOL. 54 NO. 8



Vol. 54, No. 8, October
Printed in U.S.A.

Faster-Than-Nyquist Signaling

By J. E. MAZO

(Manuscript received March 27, 1975)

The degradation suffered when pulses satisfying the Nyquist criterion are used to transmit binary data in noise at supraconventional rates is studied. Optimum processing of the received waveforms is assumed, and attention is focused on the minimum distance between signal points as a performance criterion. An upper bound on this distance is given as a function of signaling speed. In particular, the pulse energy seems to be the minimum distance up to rates of transmission 25 percent faster than the Nyquist rate, but not beyond.

Some mathematical aspects related to the above problem are also considered. In particular, the minimum distance is rigorously shown to be nonzero for all transmission rates. This is tantamount to showing that, in the singular case of linear prediction, perfect prediction cannot be approached with bounded prediction coefficients.

I. INTRODUCTION

The use of Nyquist pulses

$$g(t) = \frac{\sin(\pi t/T)}{(\pi t/T)}$$

to send binary (or multilevel) data without intersymbol interference over a channel of bandwidth $W = (1/2T)Hz$ is classic. If we assume that one receives the pulse train

$$u(t) = \sum_{n=N_1}^{N_2} a_n g(t - nT), \quad a_n = \pm 1, \text{ independently,} \tag{1}$$

…noise of two-sided spectral density $N_0/2$, … given by

Simple signal generation using IFFT

$$X_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} s_n \exp\left(\frac{j2\pi nk\alpha}{N}\right)$$

Padding zeros

$$s_i' = \begin{cases} s_i & 0 \le i < N \\ 0 & N \le i < M \end{cases}$$

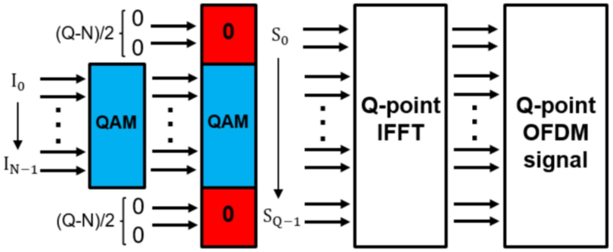
$$X_k' = \frac{1}{\sqrt{M}} \sum_{n=0}^{M-1} s_n' \exp\left(\frac{j2\pi nk}{M}\right)$$

Truncate to N samples

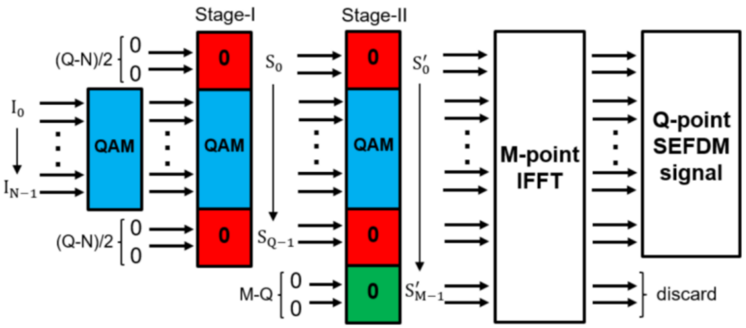
❖ IFFT is applicable to SEFDM

SEFDM signal generation

❖ Similar to OFDM signal generation



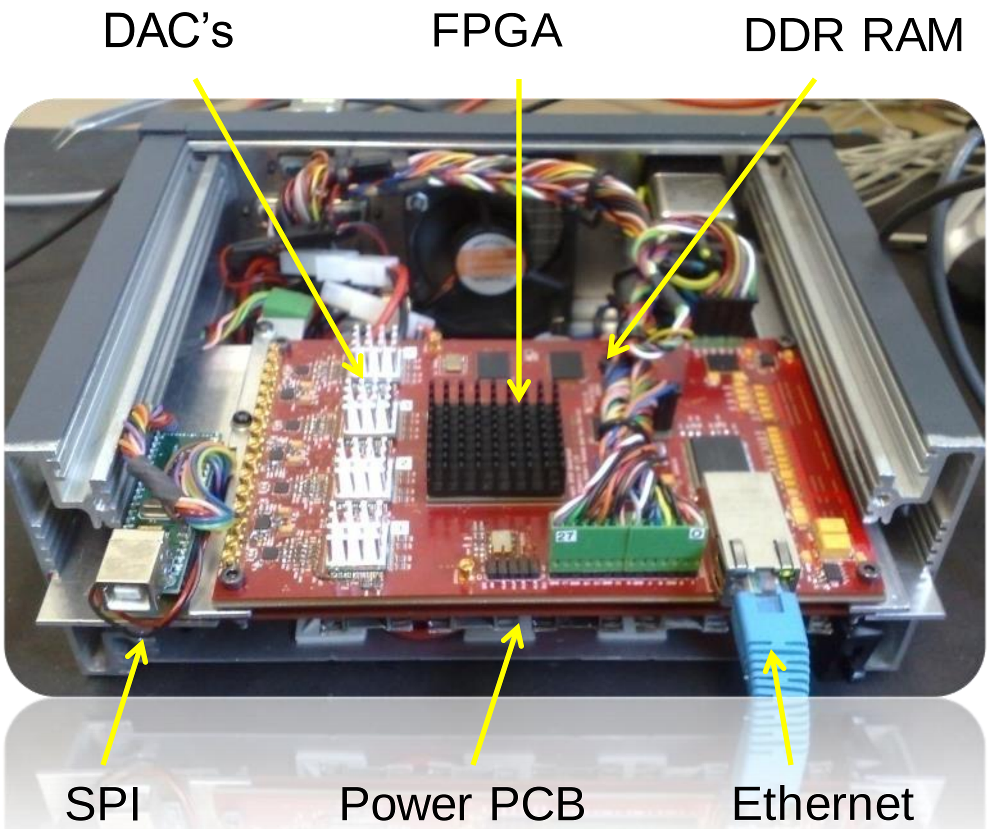
→ **OFDM**



→ **SEFDM (SigGen-I)**

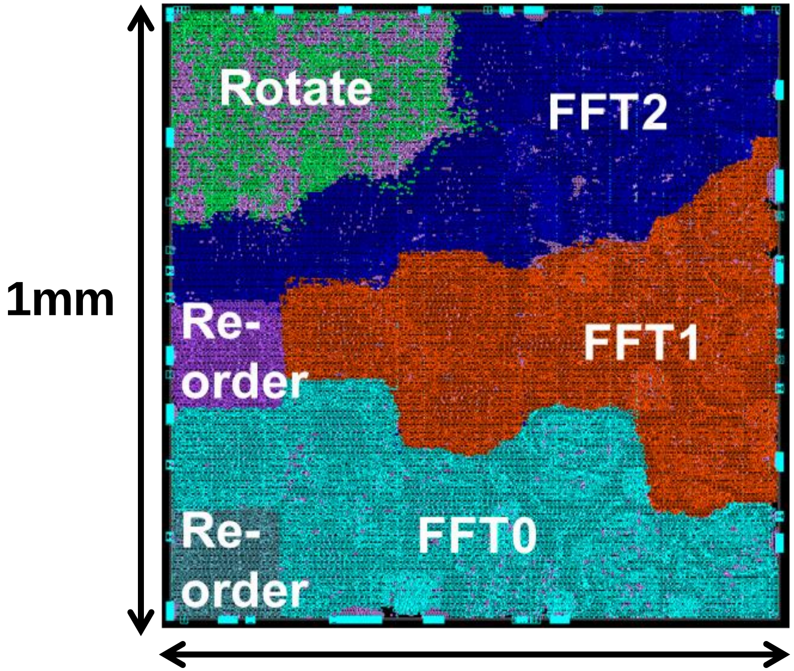
Customized Hardware Transmitter

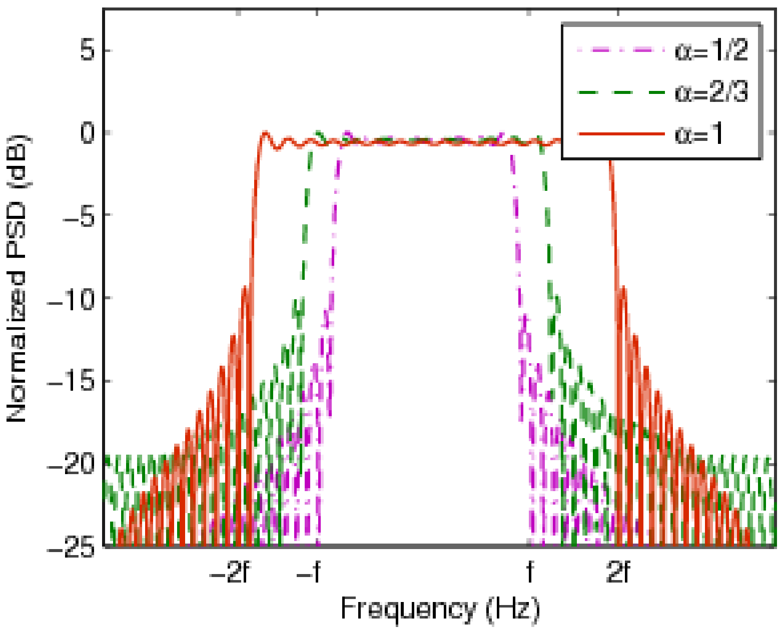
Metric	Value
Analogue Bandwidth with buffering PER DAC (8 in total)	150MHz
DAC Resolution	16-Bit
Max SNR	106dB
Max sample length/DAC	300mS
Live streaming – 1 DAC Analogue bandwidth	31.25MHz
Live streaming – 4 DAC Analogue Bandwidth	7.125MHz



VLSI Transmitter Implementation

[1]. P. Whatmough, M. Perrett, S. Isam, and I. Darwazeh, "VLSI architecture for a reconfigurable spectrally efficient FDM baseband transmitter," Circuits and Systems I: Regular Papers, IEEE Transactions on, vol. 59, no. 5, pp. 1107 –1118, may 2012

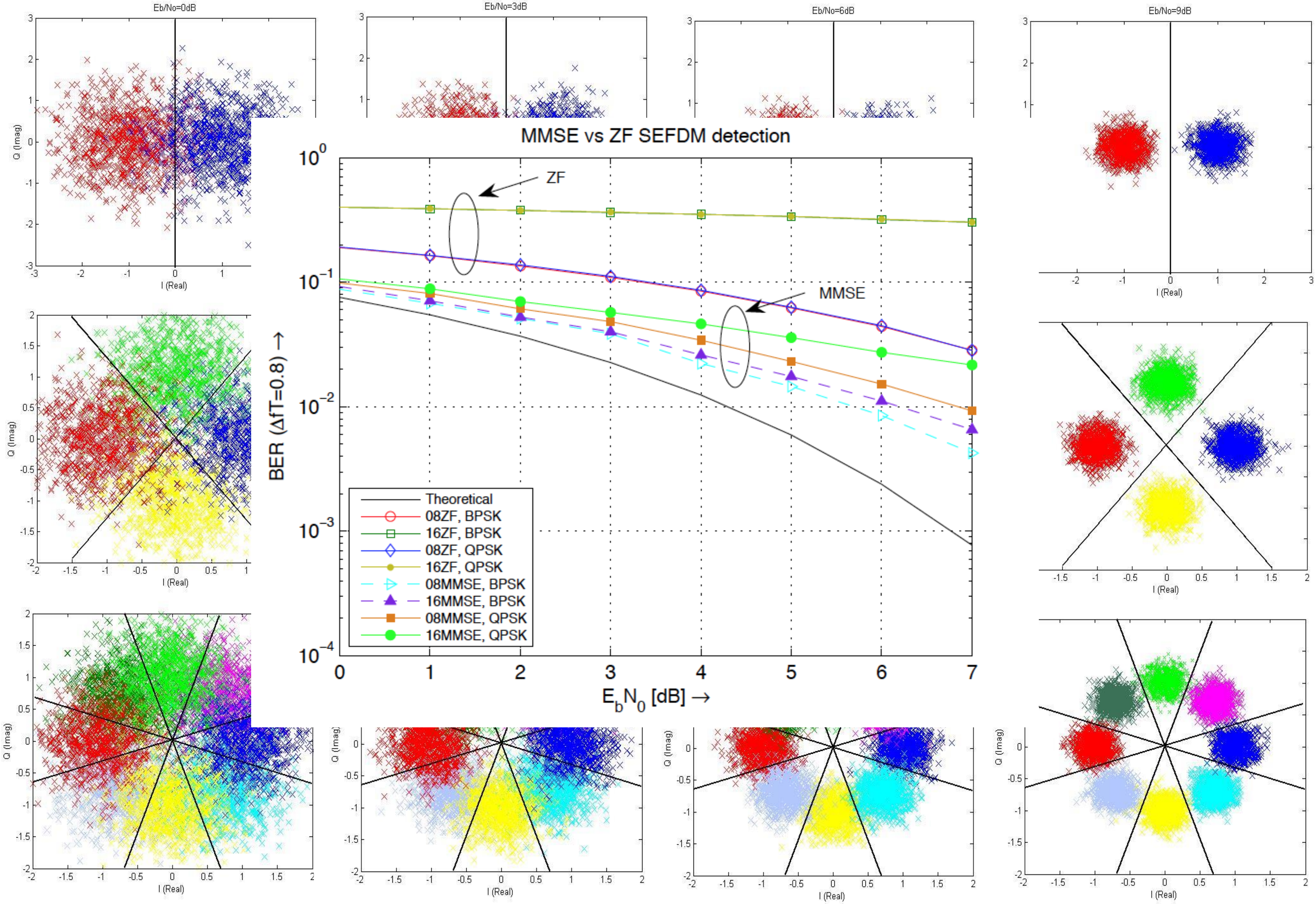




- Reconfigurable SEFDM modulator
- 32nm CMOS process
- Throughput of 250 Mbps to 750 Mbps for QPSK – 64QAM

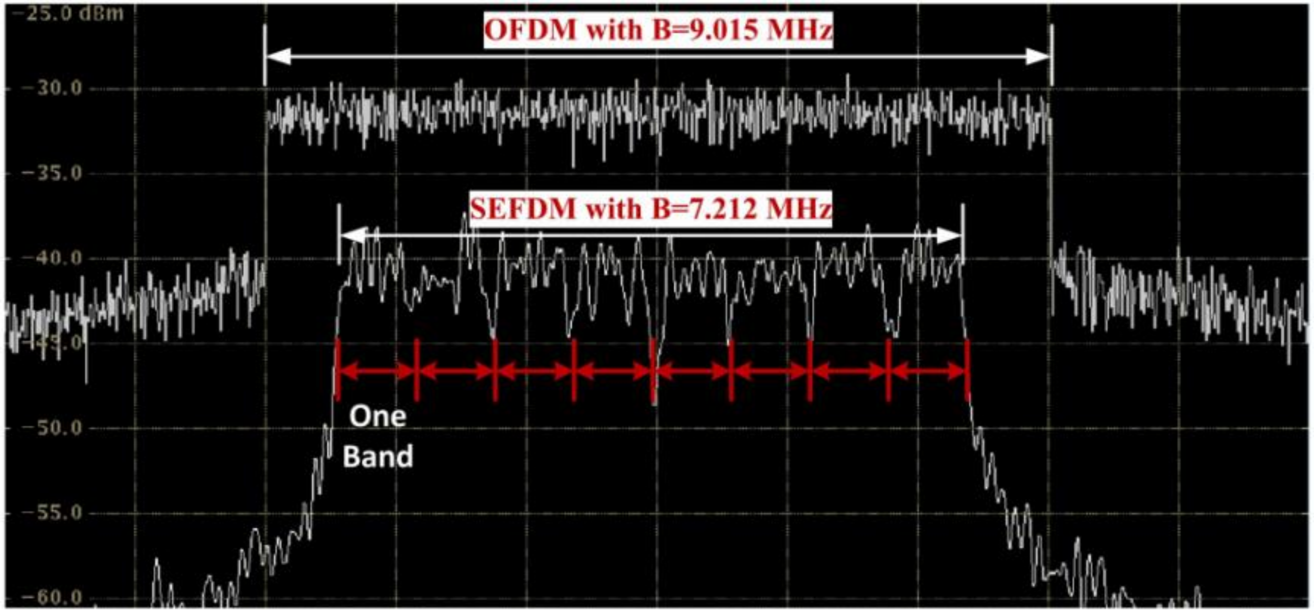
The detection problem

Different colours indicate different symbols. The dark lines indicate the decision boundaries



B-SEFDM vs. OFDM

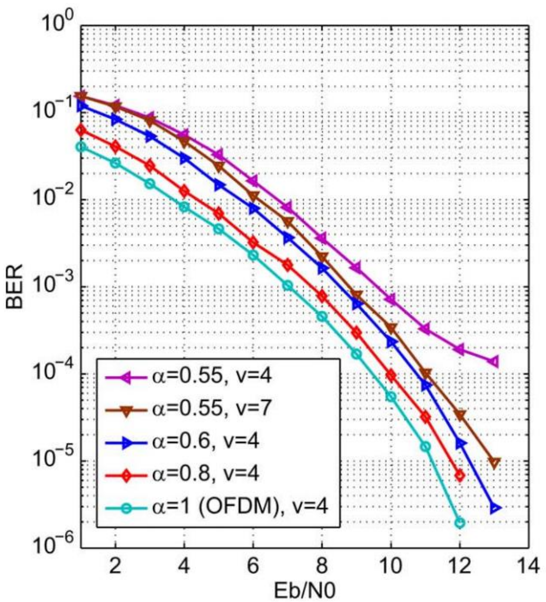
Experimental bandwidth comparison of B-SEFDM (α= 0.8) versus OFDM. By transmitting the same amount of data, B-SEFDM requires a bandwidth of 7.212 MHz while OFDM needs 9.015 MHz. Carrier frequency is 2 GHz, frequency span is 15 MHz and resolution bandwidth (RBW) for OFDM and B-SEFDM are 3 KHz and 60 KHz, respectively.



Results measured in a static frequency selective channel

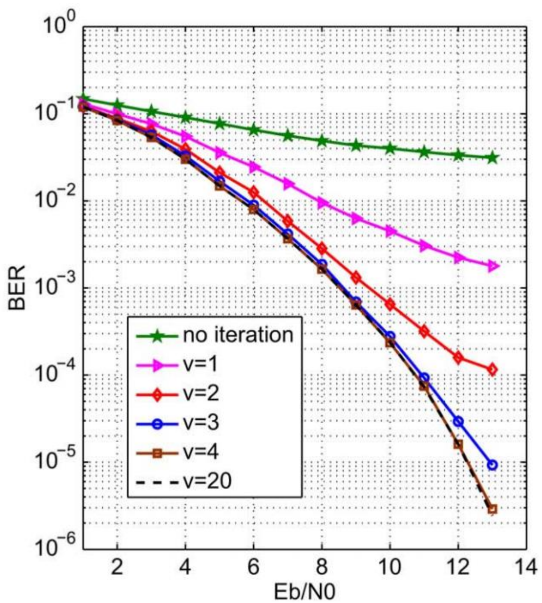
Channel characteristic:

$$h(t) = 0.8765\delta(t) - 0.2279\delta(t - T_s) + 0.1315\delta(t - 4T_s)$$
$$-0.4032e^{\frac{j\pi}{2}}\delta(t - 7T_s)$$



(a)

BER performance



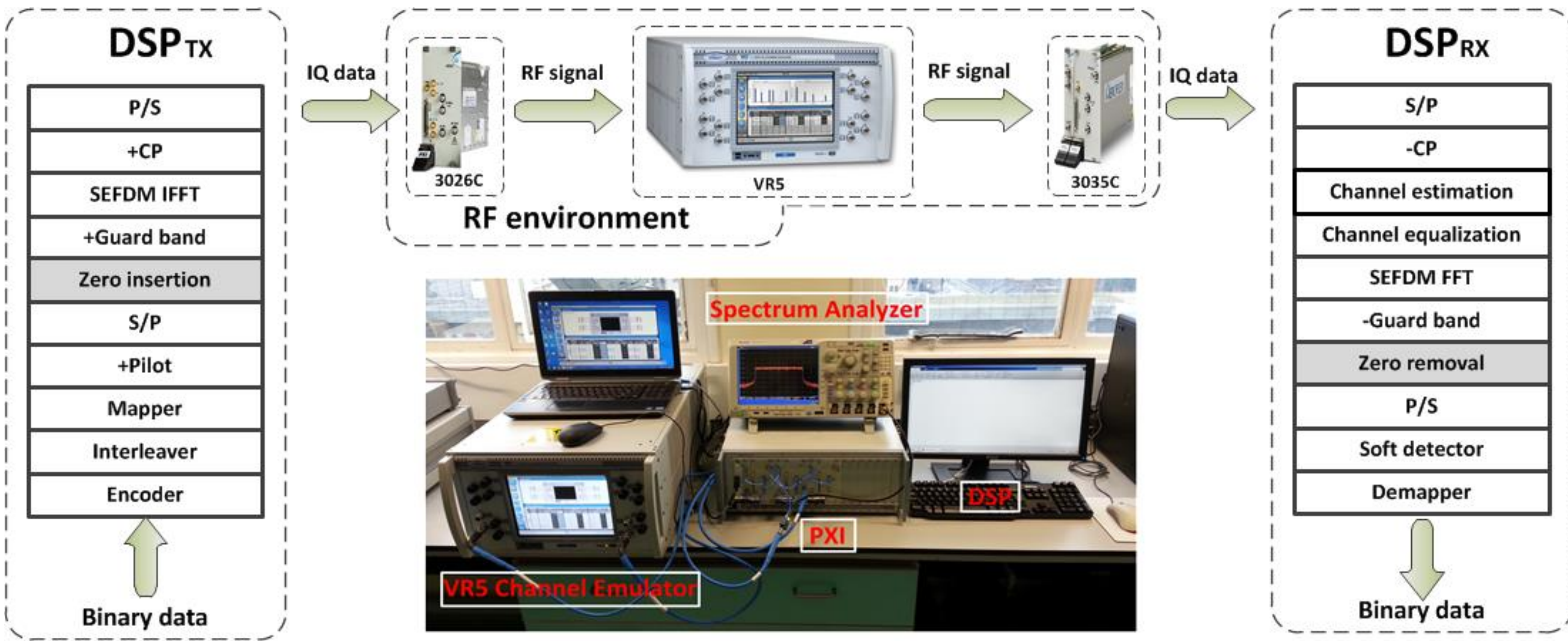
(b)

Convergence performance

- Fig (a) shows systems with different bandwidth compression factors. For high values, curves can converge to the OFDM one. But with small values, it will not converge due to high ICI.
- Fig. (b) shows the convergence performance with α=0.6. It is clearly seen that 4 iterations are sufficient to get converged BER performance.

Wireless

[1]. T. Xu and I. Darwazeh, “Bandwidth compressed carrier aggregation,” in IEEE ICC 2015 - Workshop on 5G & Beyond - Enabling Technologies and Applications (ICC’15 - Workshops 23), London, United Kingdom, Jun. 2015, pp. 1107–1112.
[2]. T. Xu and I. Darwazeh, “Practical Implementation of Bandwidth Compressed Carrier Aggregation,” Wireless Communications, IEEE Transactions on. (second revision)
[3]. T. Xu and I. Darwazeh, “Nyquist-SEFDM: Pulse Shaped Sub-Carriers with Frequency Spacing Below the Symbol Rate,” in Wireless Communications and Networking Conference (WCNC), IEEE, 2016 (submitted).



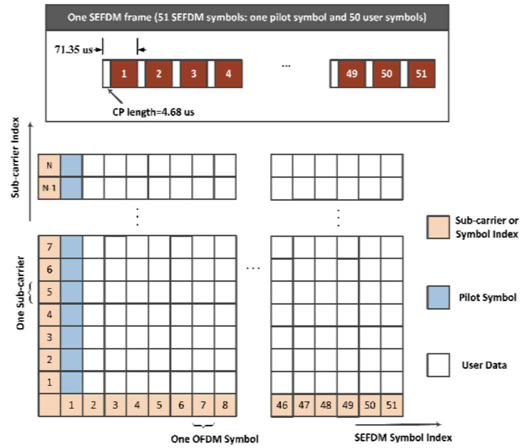
The above experiment testbed is applicable to two scenarios:

1. LTE: Single band SEFDM (excluding zero insertion)
2. LTE-A: Carrier aggregation SEFDM (including zero insertion)

Wireless: LTE format

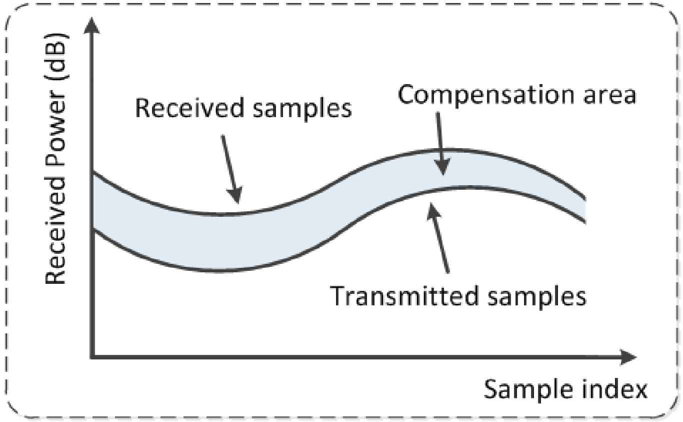
A static frequency selective channel is emulated.

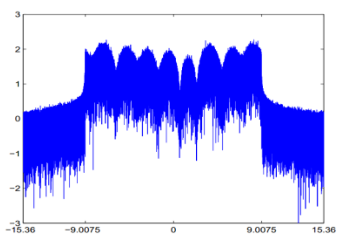
Carrier frequency	2 GHz
Sampling frequency	30.72 MHz
Occupied channel bandwidth	$\alpha\times$18.015 MHz
Sub-carrier modulation bandwidth	30 KHz
Sub-carrier spacing	$\alpha\times$15 KHz
Bandwidth saving	$(1-\alpha)\times$100%
FFT size	2048
Occupied sub-carriers (inc. DC)	1201
Guard sub-carriers	847
Cyclic prefix	144
Frame structure	1 preamble, 50 SEFDM symbols
Modulation scheme	4QAM
Raw bit rate	36.03 Mbps
Channel coding	(7,5) convolutional code
Coding rate	R=1/2
Interleaver	2400-bit random



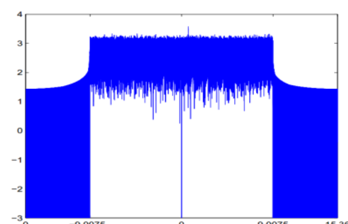
Path	Relative path loss (dB)	Delay values (us)	Phase (degree)
1	0	0	0
2	5.9	$2T_s$=0.0651	180
3	8.2	$8T_s$=0.2604	0
4	3.4	$14T_s$=0.4557	270

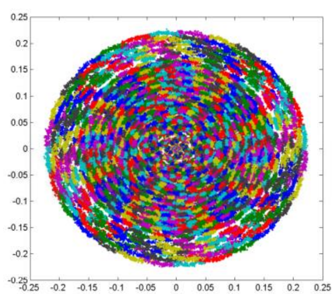
Time-domain channel estimation and equalization



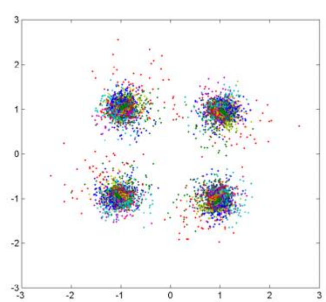


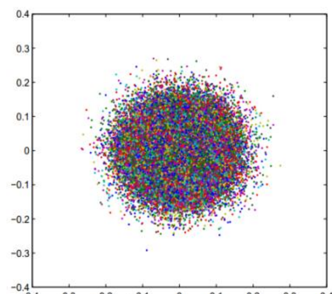
Channel Equalization





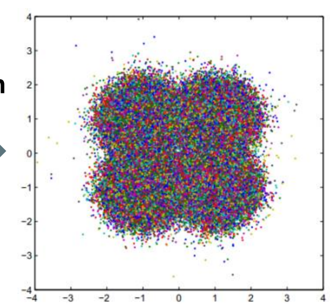
OFDM





Channel Equalization

SEFDM α=0.8



OFDM

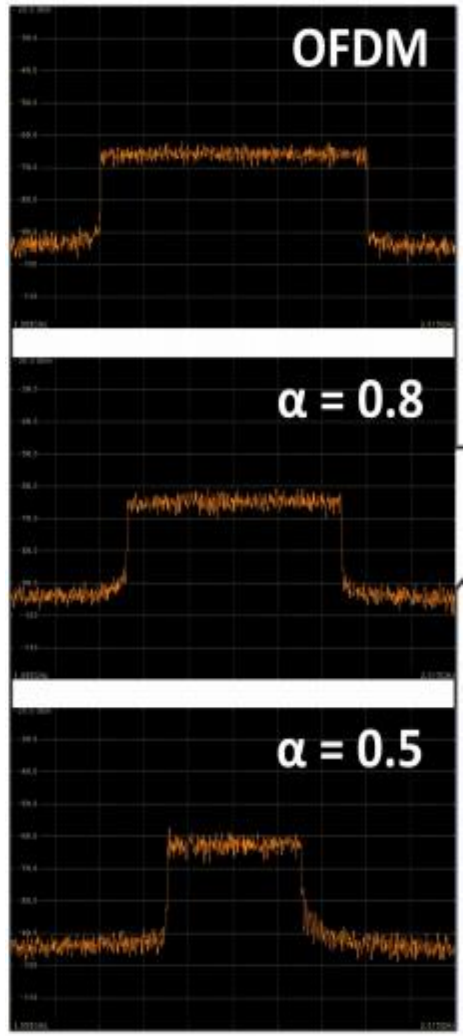
18 MHz

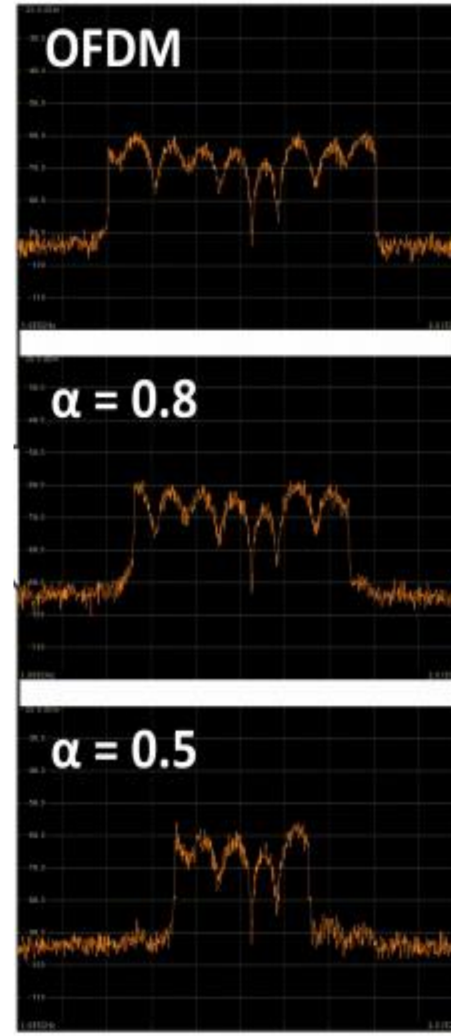
α = 0.8

14.4 MHz

α = 0.6

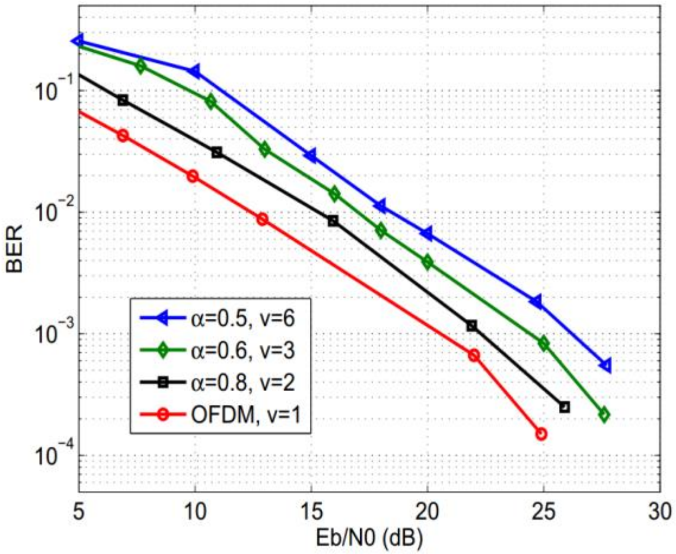
10.8 MHz



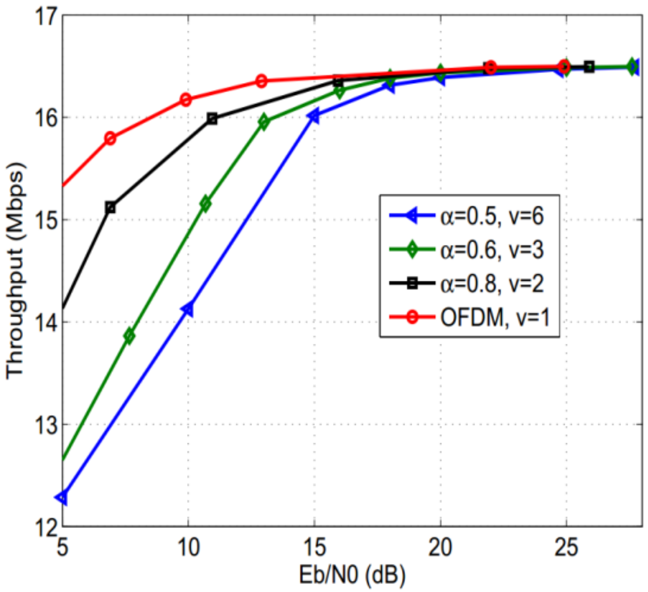


Experimental picture transmission by using SEFDM signal (E_b/N_o=25 dB).

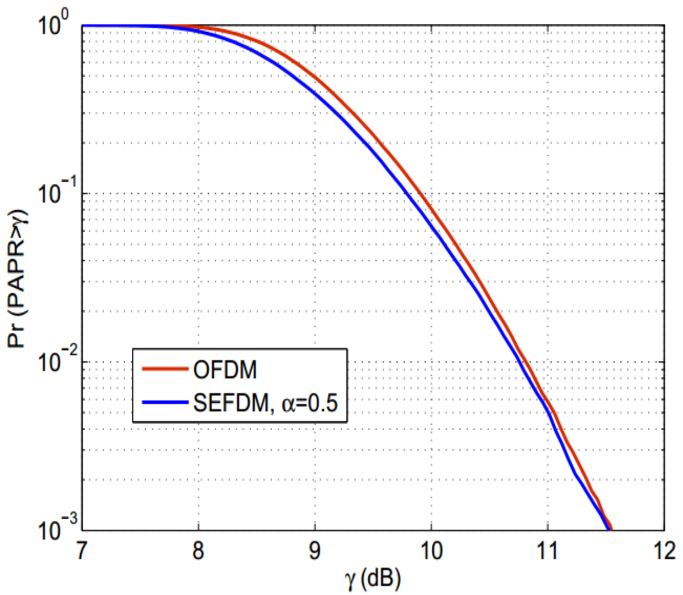
Wireless: LTE



(a). Performance of different Turbo-SEFDM systems with various levels of bandwidth compressions in the RF environment with frequency selective channel. v is the number of iterations.

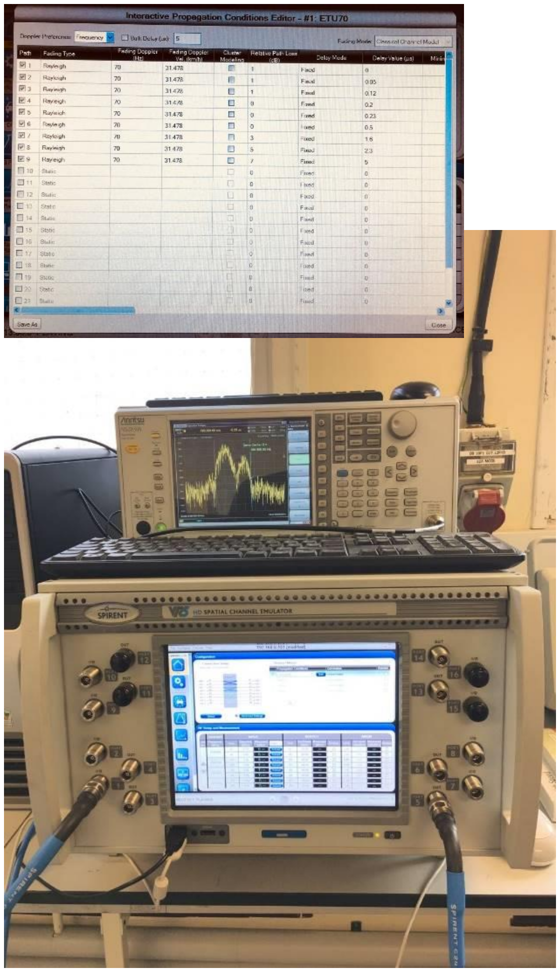


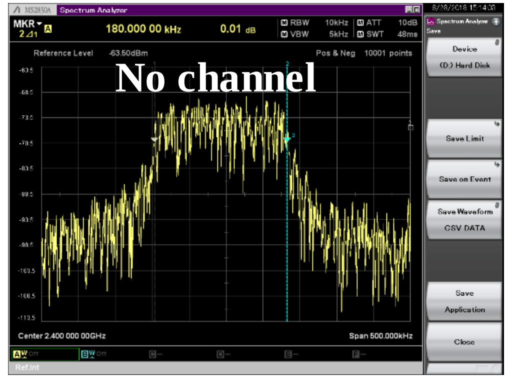
(b). Throughput of different Turbo-SEFDM systems computed based on the BER information in Fig (a) and system specifications. v is the number of iterations.

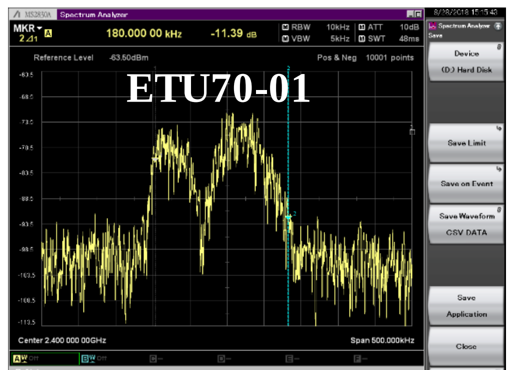


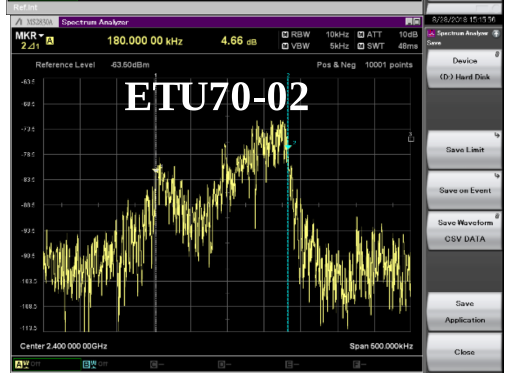
(c). CCDF of PAPR for SEFDM and OFDM systems modulated with 4QAM symbols.

Realistic channel (ETU70) measurements









ETU Delay Profile

Excess tap delay (ns)	Relative power (dB)
0	–1.0
50	–1.0
120	–1.0
200	0.0
230	0.0
500	0.0
1600	–3.0
2300	–5.0
5000	–7.0

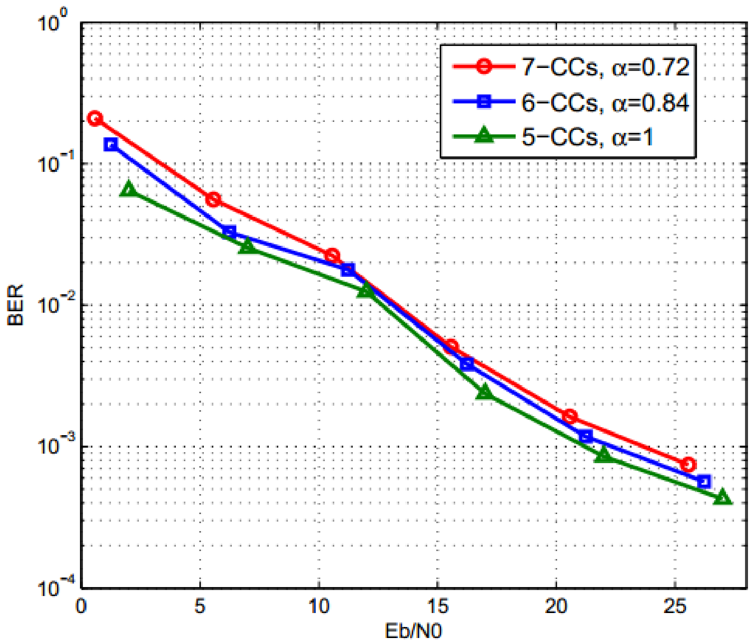
- The number of NB-IoT sub-carriers is 12 with each occupying 15 kHz and overall bandwidth is 180 kHz (one resource block).
- For such a narrow band signal, frequency selective in one resource block exists.

SEFDM with carrier aggregation)

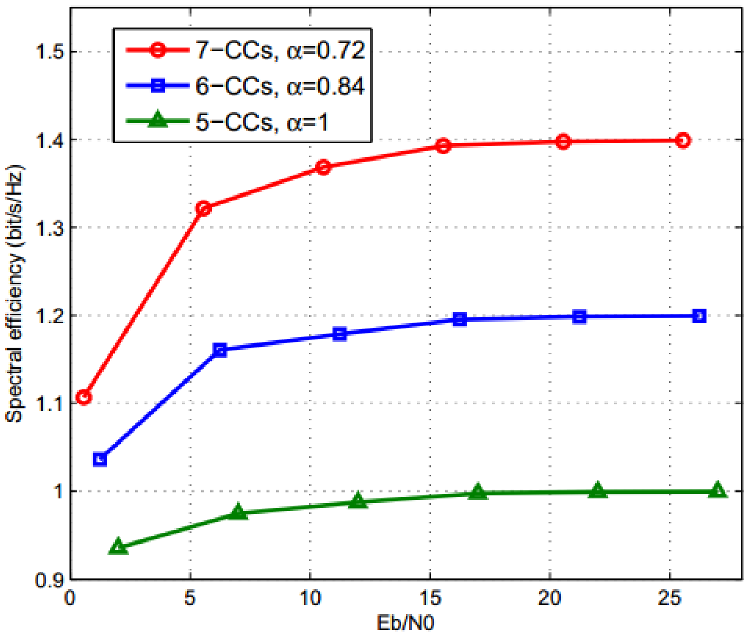
- Realistic LTE defined multipath fading channel with 5 kHz Doppler spread is used.
- Seven signal bands are aggregated in CA-SEFDM while five for CA-OFDM in the same bandwidth.
- 40% more data can be delivered using the CA-SEFDM scheme.

Data rates:

LTE: 50 Mbit/s
SEFDM: 70 Mbit/s



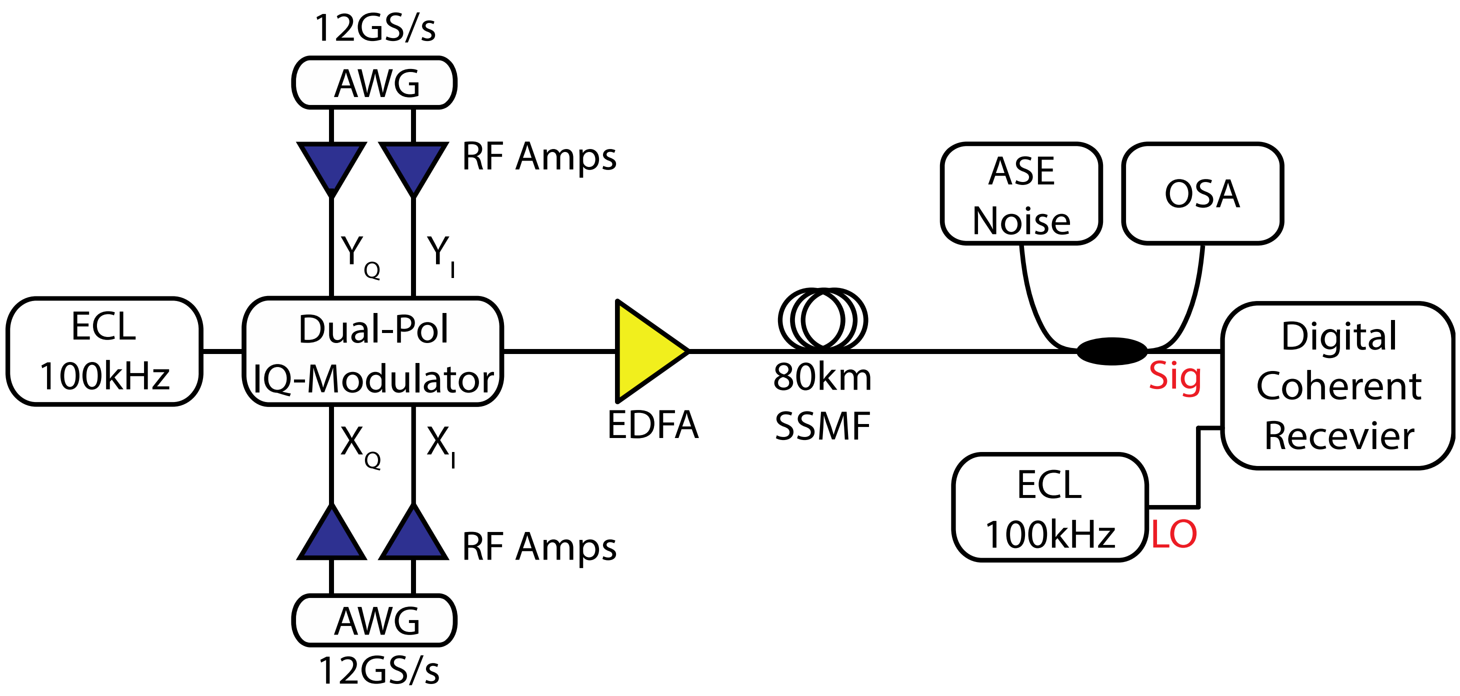
(a). Performance of different CA-SEFDM systems in the condition of real RF environment with the LTE EPA5 fading channel.



(b). Effective spectral efficiency (bit/s/Hz) of different CA-SEFDM systems computed based on the BER information and the system specifications.

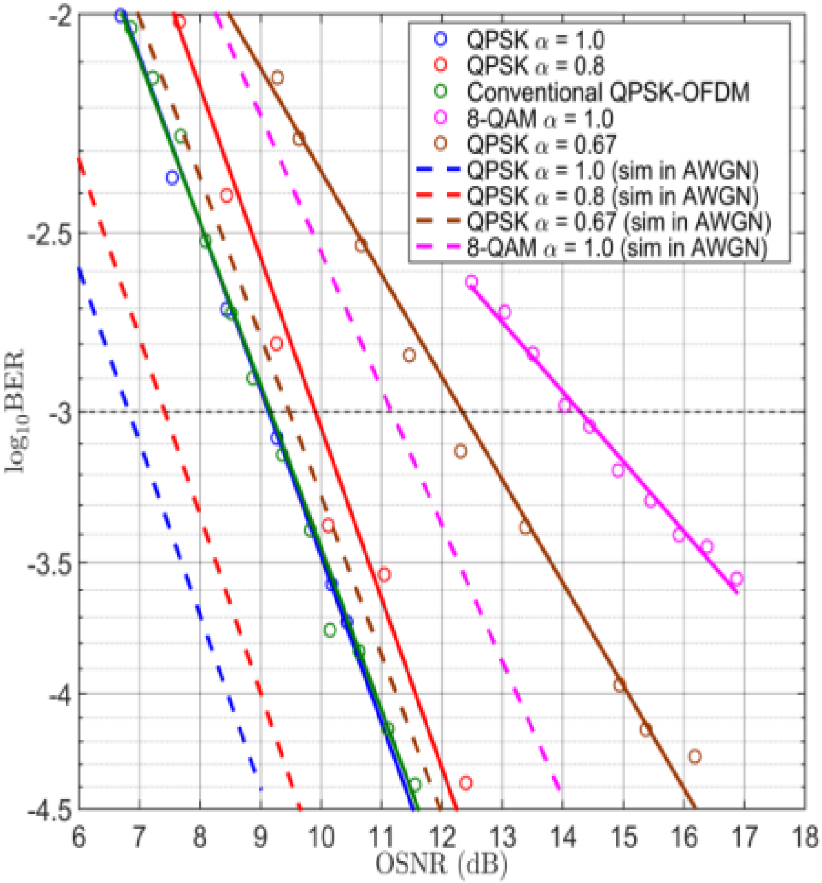
SEFDM over optical channels

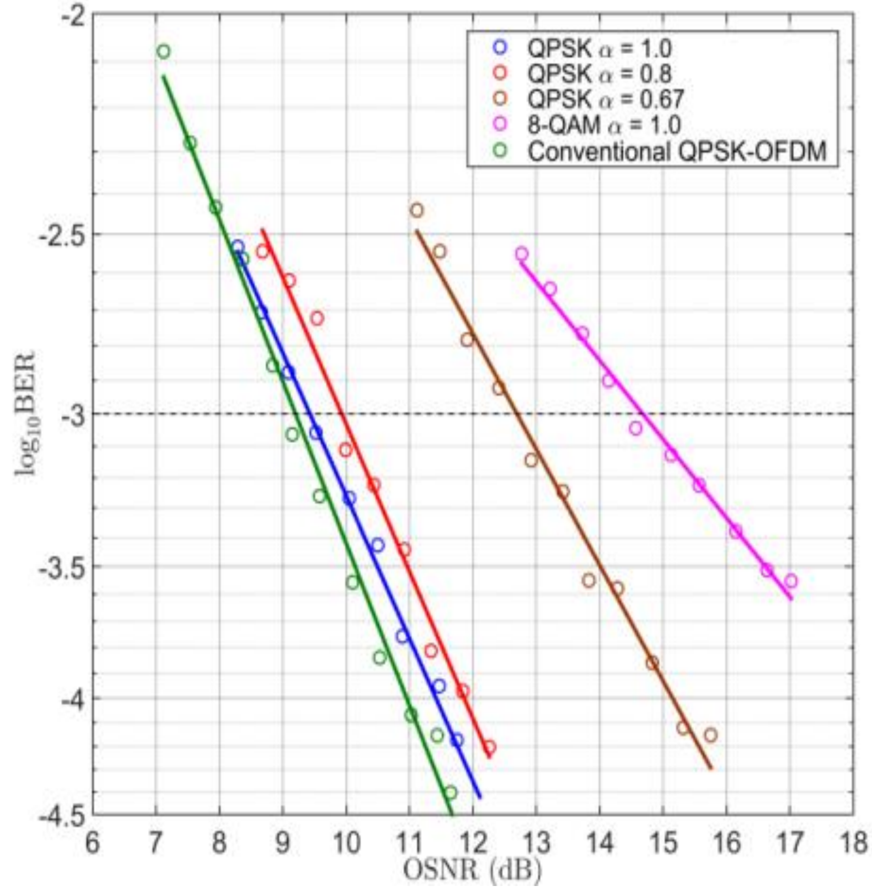
[1]. D. Nopchinda, T. Xu, R. Maher, B. Thomsen, and I. Darwazeh, "Dual polarization coherent optical spectrally efficient frequency division multiplexing," Photonics Technology Letters, IEEE, vol. 28, no. 1, pp. 83–86, Jan 2016.



Experimental setup of PDM-CO-SEFDM transmission system

Optical: Coherent





24 Gbit/s 4QAM

BER as a function of OSNR, B2B (left) and 80 km link

60 GHz mm-wave Radio Over Fiber SEFDM

[1]. S. Mikroulis, T. Xu, J. E. Mitchell and I. Darwazeh, ”First demonstration of a spectrally efficient FDM radio over fiber system topology for beyond 4G cellular networking,” in Networks and Optical Communications - (NOC), 2015 20th European Conference on, Jun. 2015, pp. 1–5.

[2]. S. Mikroulis, T. Xu, and I. Darwazeh, “Practical demonstration of spectrally efficient FDM millimeter-wave radio over fiber systems for 5G cellular networking,” in Proc. SPIE, vol. 9772, 2016, pp. 97 720I– 1–97 720I–8.

[3]. T. Xu, S. Mikroulis, J. E. Mitchell and I. Darwazeh, ” Bandwidth Compressed Waveform for 60 GHz Millimeter-Wave Radio over Fiber Experiment,” Lightwave Technology, Journal of. 2016.

85 GHz mm-wave SEFDM

Experimental Demonstration of Spectrally Efficient Frequency Division Multiplexing Transmissions at E-Band Hedaia Ghannam;Dhecha Nopchinda;Marcus Gavell;Herbert Zirath;Izzat Darwazeh IEEE Transactions on Microwave Theory and Techniques Year: 2019 | Volume: 67, Issue: 5

Wireless: E-band (82-68 GHz)

UCL Collaboration with Chalmers University and Gotmic-Sweden

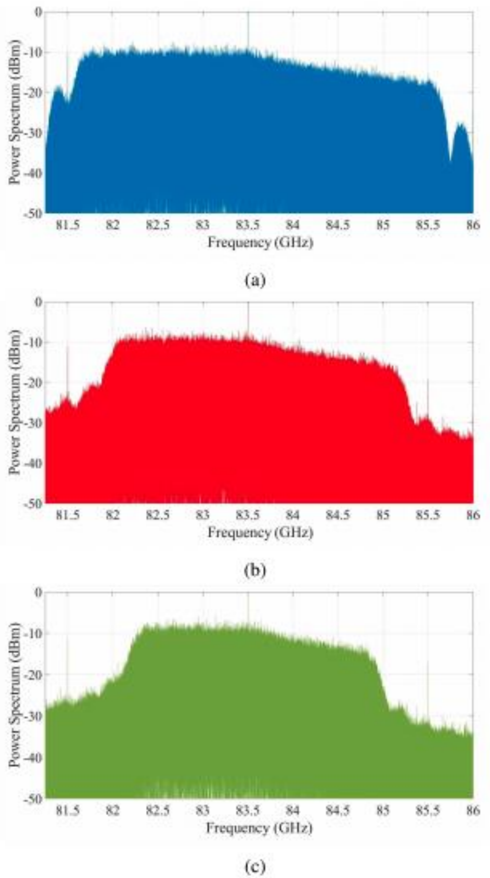


Fig. 7. Spectra of the received samples obtained from the experiment for OFDM ($\alpha = 1$) and SEFDM ($\alpha = 4/5$ and $2/3$) for the same transmission rate 8 Gb/s. (a) OFDM ($\alpha = 1$), BW = 4 GHz. (b) SEFDM ($\alpha = 4/5$), BW = 3.2 GHz. (c) SEFDM ($\alpha = 2/3$), BW = 2.67 GHz.

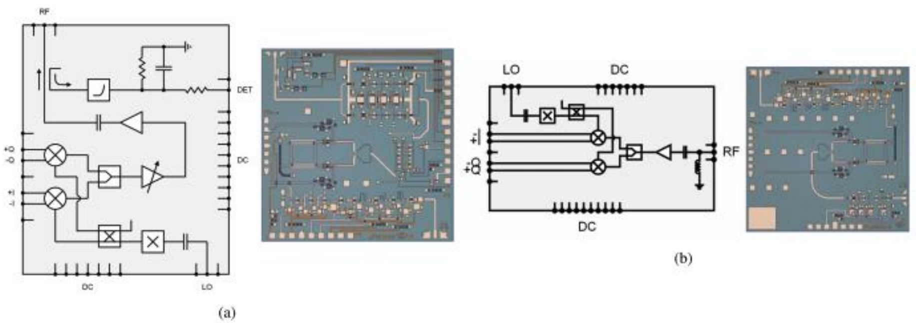


Fig. 2. E-band block diagram [41] and chip photograph. (a) Transmitter, Tx: gTSC0023B. (b) Receiver, Rx: gRSC0014B.

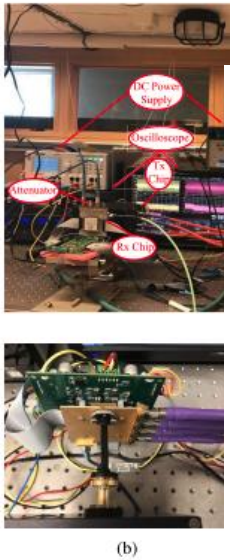


Fig. 4. Photographs of the SEFD
E-band transmission test bed. (b) Transmitter chip. (c) Receiver chip.

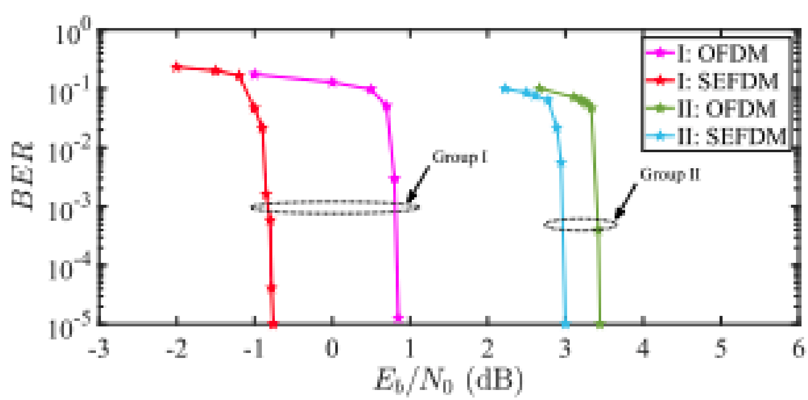
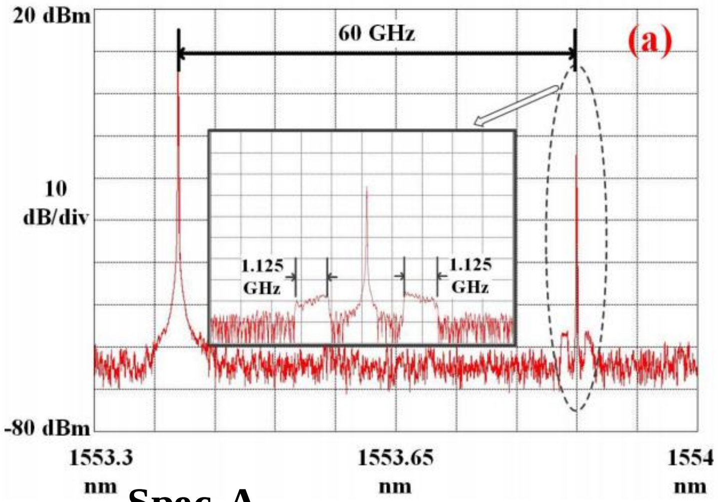


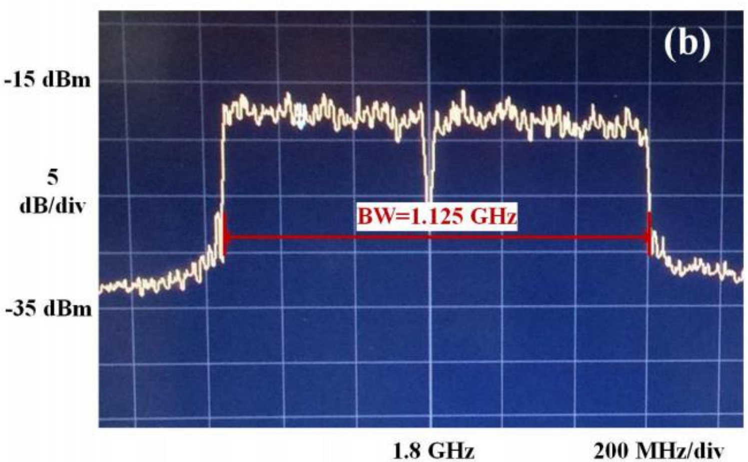
Fig. 8. Comparison of BER results versus E_b/N_0 for a given $(\alpha, \log_2(M), R_c)$.

8 Gbit/s and BW reduced from 4 GHz to 2.67 GHz

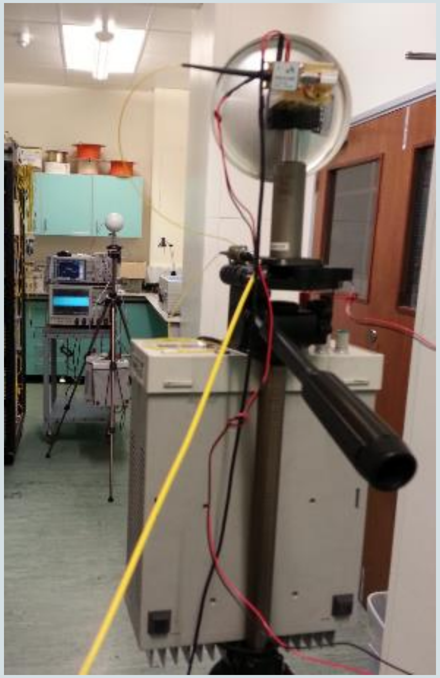
Indoor 60 GHz millimeter-wave signal transmission



Spec-A



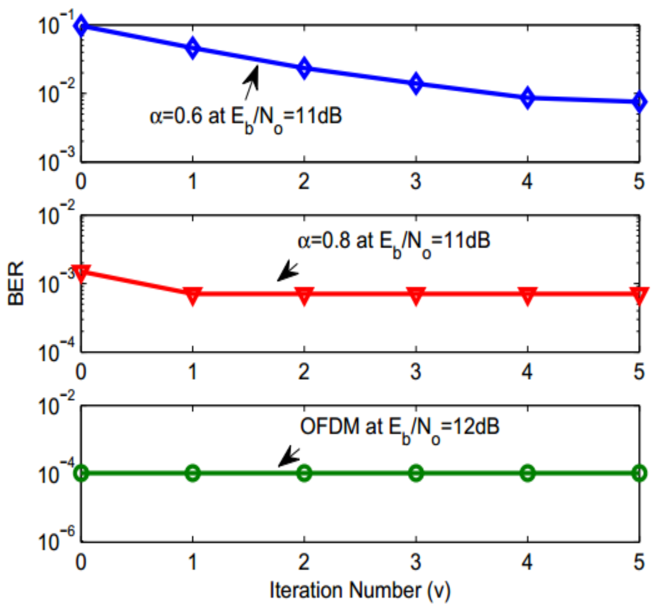
Spec-B



- 60 GHz parabolic antennas have 30 dBi gain; and 3 dB beamwidth of 3.1◦ are employed.
- A 30 dB gain high power amplifier (HPA) at the transmitter and a 30 dB gain low noise amplifier (LNA) at the receiver.
- Transmission distances from few cm to 3 metres.

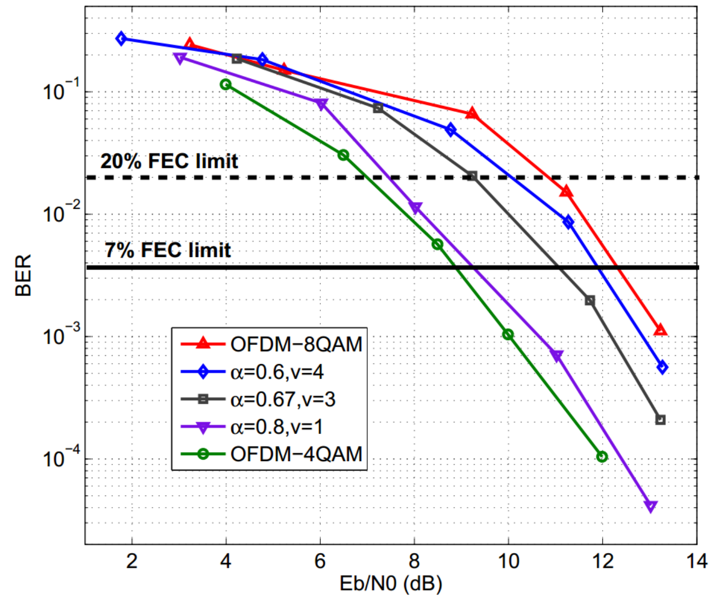
Experimental results for the mm-wave SEFDM-2

Iteration study



- OFDM: no iteration.
- SEFDM: at least one iteration.

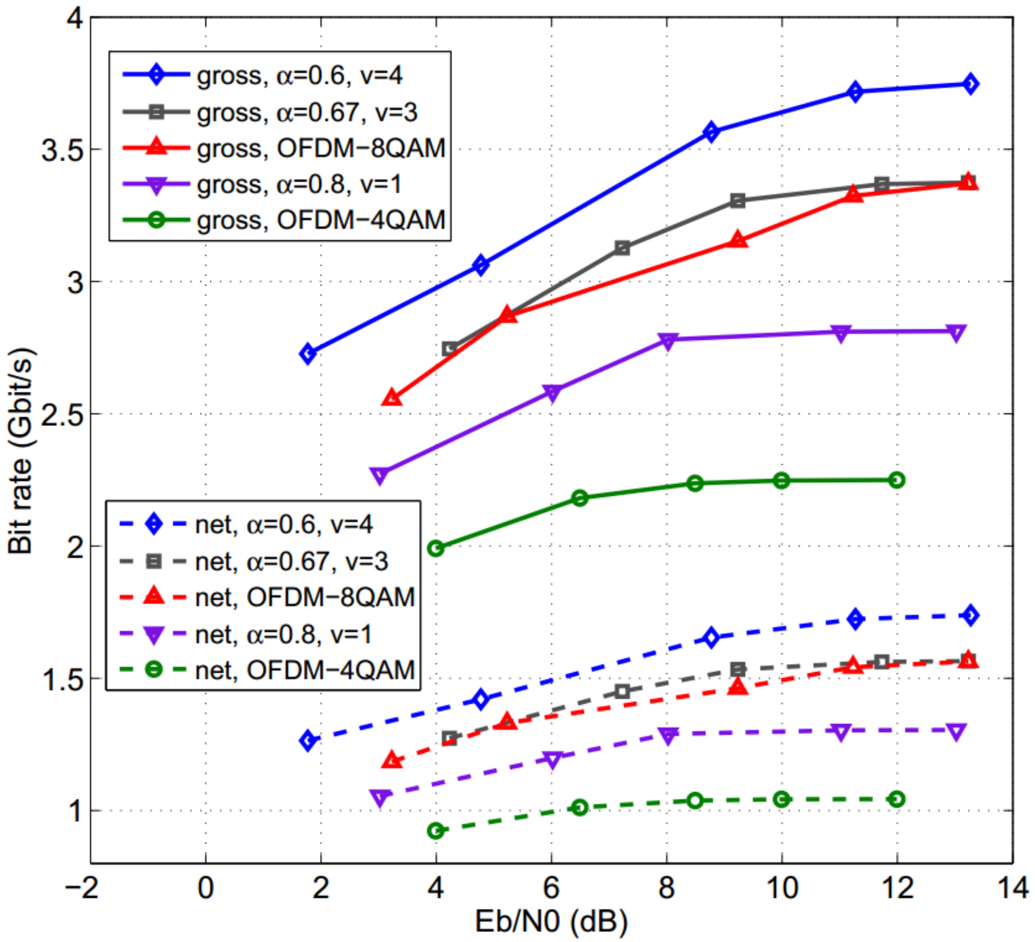
BER measurements



- Within the same bandwidth, bit rate can be increased by up to 67%.
- 4QAM α=0.67 outperforms the 8QAM OFDM have the same spectral efficiency. SEFDM has with 1 dB performance gain.
- The 4QAM α=0.6 outperforms the 8QAM OFDM in both spectral efficiency and BER performance.

Experimental results for the mm-wave SEFDM-3

Bit rate (Gbit/s) measurements



- SEFDM results in better throughput in both net and gross bit rates.
- Gross bit rate: Achievable non-error bits per second including overhead.
- Net bit rate: Achievable non-error bits per second without overhead.
- A lower order modulation format 4QAM shows higher bit rate than a higher order format 8QAM over the same bandwidth.

Complex modulation and probabilistic shaped SEFDM

Use of ML on 5G-like signals to design signal, modulation and constellation

Probabilistic shaping on Non-orthogonal multicarrier-SEFDM: Constellation Diagram (E_b/N_0=12dB)

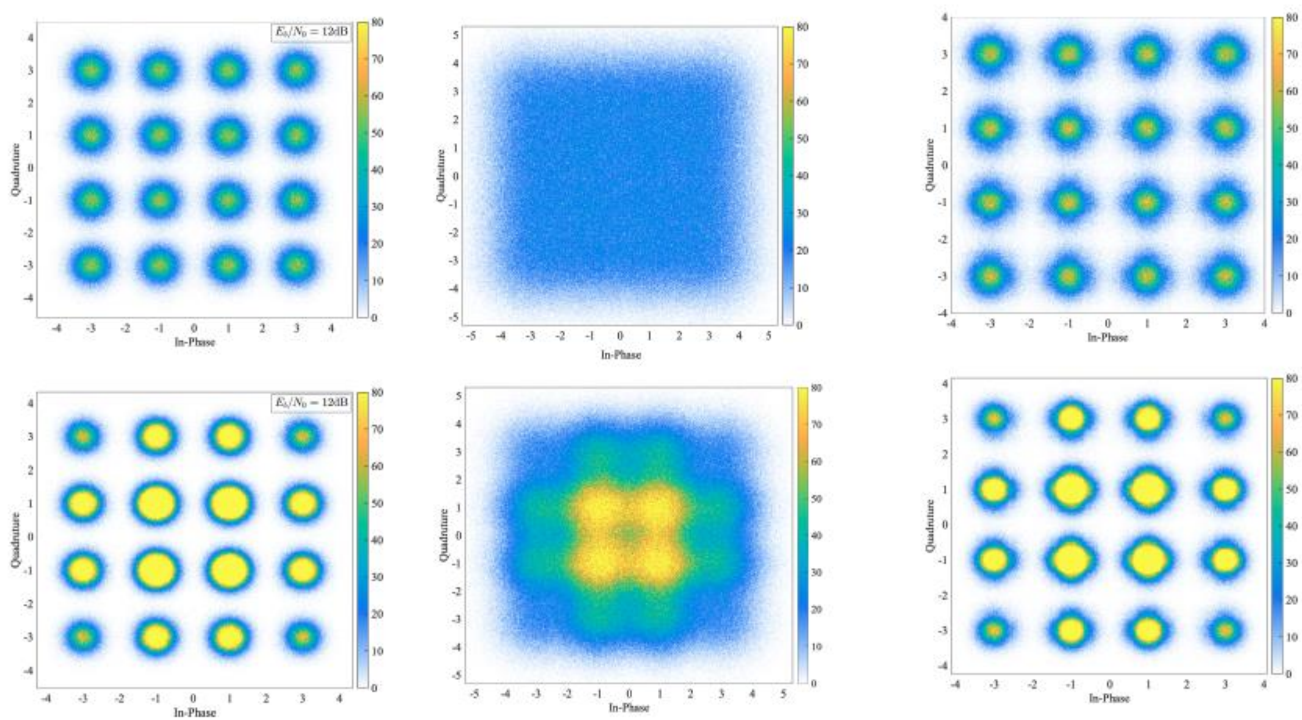
OFDM

SEFDM ($\alpha = 0.8$) before Iterative detection

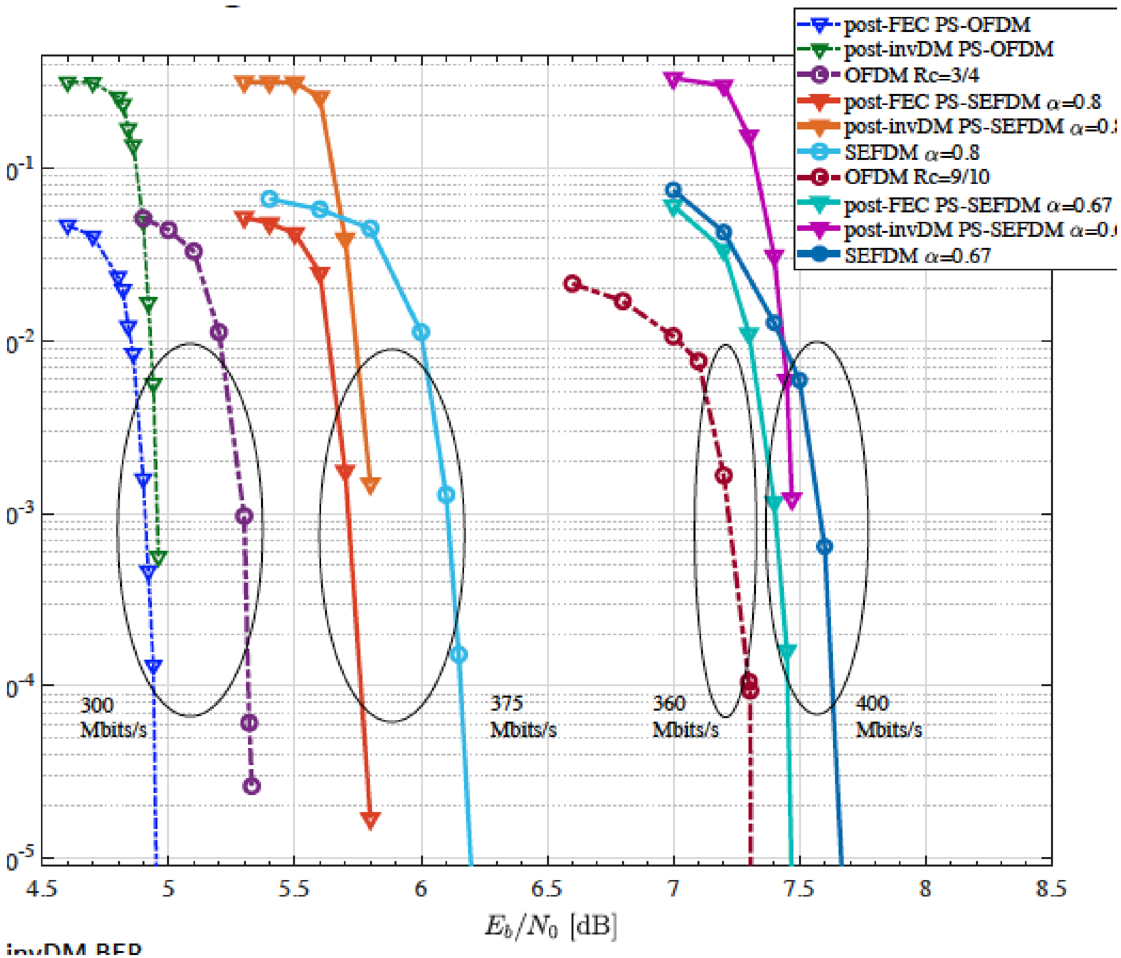
SEFDM ($\alpha = 0.8$) after 5 iterations

Uniform Distributed 16QAM

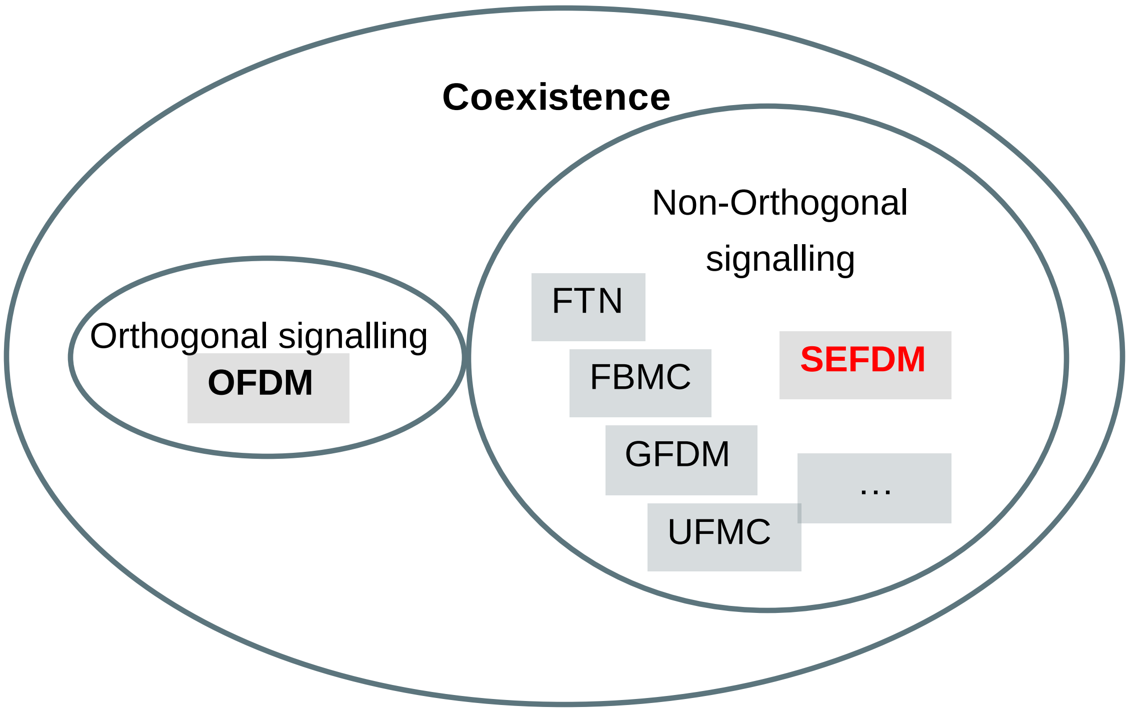
Probabilistic Shaped 16QAM



Same bandwidth but higher rate



Coexistence of orthogonal and non-orthogonal signals



Spectral Efficiency Improvement

Increase bit rate:
FTN

Reduce BW or increase bit rate
SEFDM

Coexistence advantage:
FBMC, GFDM, UFMC

SEFDM

- Data rate improvement
- Bandwidth saving
- Similar signal generation with OFDM
- Easy integration in existing communication systems

Non orthogonal multi carrier satisfies what we need; mm wave, high rates, small cells,

*We would like radio signals that can carry **all the information**, maintaining data **quality** and integrity in smallest possible **bandwidth** and lowest possible **energy** using **simplest** equipment.*

- **Use**: high rates and use of AI
- **Bandwidth** wide available and at mm wave to THz, still not infinite!
- Signal quality and errors:
  - Channel physics: multipath even at point to point
  - Channel use: noise and interference/ high congestion
- Equipment, **energy** and **complexity**

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- Professor Kyle Jamieson
- Professor Herbert Zirath

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Ms Xinyue Liu
Professor Miguel Rodrigues
Dr Dhecha Nopchinda
Dr Ryan Grammenos
Professor John Mitchell

CSNDSP 2018

The First 15 Years of SEFDM: A Brief Survey

(Invited Paper)

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***Abstract*—Spectrally efficient frequency division multiplexing (SEFDM) is a multi-carrier signal waveform, which achieves higher spectral efficiency, relative to conventional orthogonal frequency division multiplexing (OFDM), by violating the orthogonality of its sub-carriers. This survey provides the history of SEFDM development since its inception in 2003, covering fundamentals and concepts, wireless and optical communications applications, circuit design and experimental testbeds. We focus on work done at UCL and outline work done other universities and research laboratories worldwide. We outline techniques to improve the performance of SEFDM and its practical utility with focus on signal generation, detection and channel estimation.**

FTN concepts were effectively combined to create a joint spectrally efficient technique termed time frequency packing (TFP) [12]. Aside from the schemes mentioned above, a non-orthogonal waveform termed generalized frequency division multiplexing (GFDM), where each sub-carrier is pulse shaped, was developed in [13], leading to a novel waveform that has very low out-of-band emission (OOBE) leakage. Other related waveforms such as filterbank based multicarrier (FBMC) [14], universal-filtered multi-carrier (UFMC) [15] and Nyquist-SEFDM [16] aim for the same advantage. Recently a new waveform termed Truncated OFDM (TOFDM) was proposed,