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

Submission Title: [France Telecom - IHP Joint Physical Layer Proposal for IEEE 802.15 Task Group 3c]
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Abstract: [Proposition of a high data rate wireless system in the 60 GHz range, providing data rates ranging from 335 Mbps to 3 Gbps.]

Purpose: []

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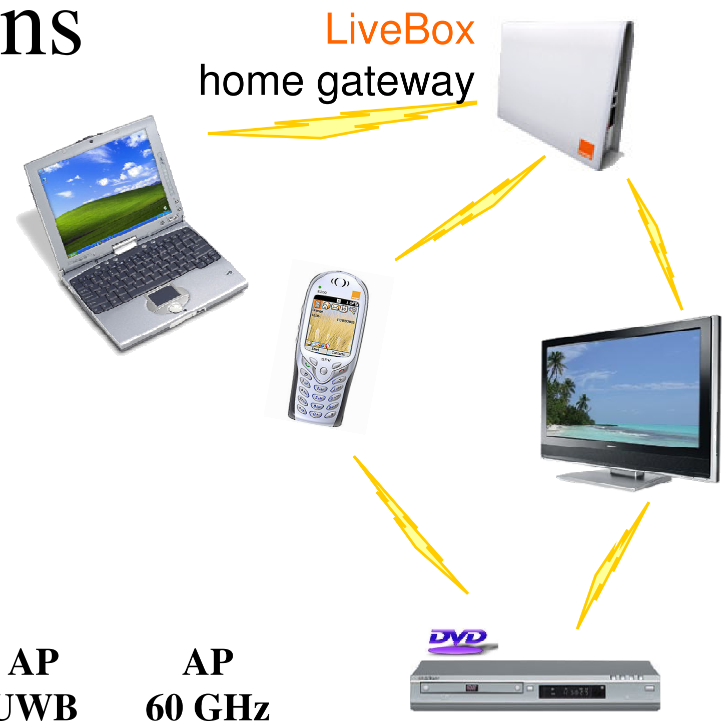
Overview

- Proposal for high data rate, 60 GHz PHY layer for 802.15.3 MAC
- Main features
  - Data rates from 335 Mbps to 3 Gbps for applications such as video streaming, file transfer, home network distribution or in-vehicle media supply
  - Efficient channelization adapted to worldwide regulation
  - OFDM based system providing high spectrum efficiency
  - Scalable parameters for increased robustness
  - Low power and cost-effective implementation

Applications and Frequency Band Plan

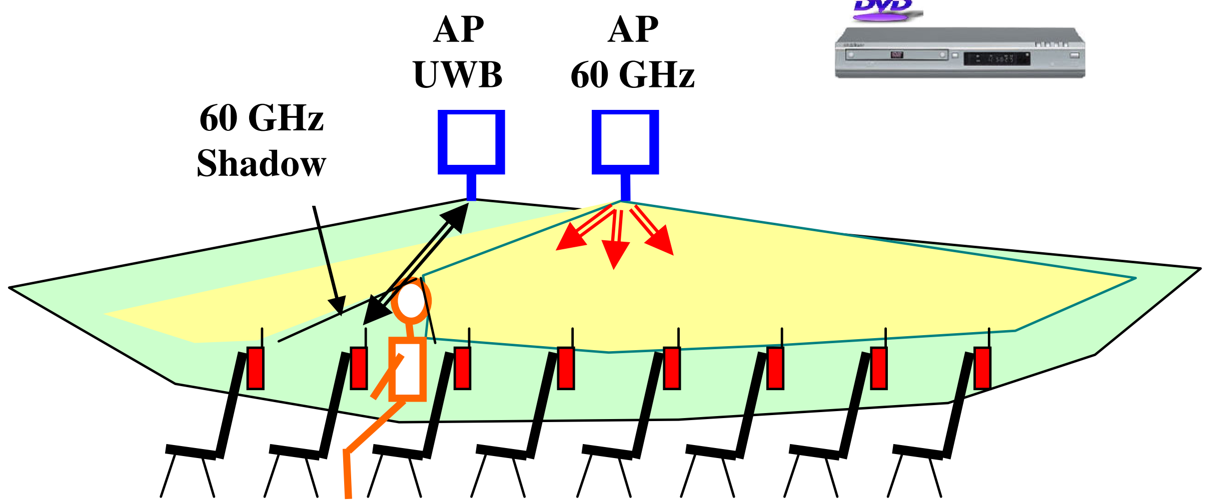
Applications



- Uncompressed video streaming (UM1)
- Kiosk file downloading (UM5)

- High data rate WPAN distribution
  - Multiple user high data rate networking
  - Home or office video streaming
  - Express file transfer

- Media supply in trains, busses and aircraft
  - Possibly use of secondary system (e.g. UWB) for 100% coverage



Applications

- Environments
  - Indoor environments (Residential / Office / Library)
  - Hot spots
  - Confined environments (train, aircraft, …)
  - Potential nomadic mode within coverage area

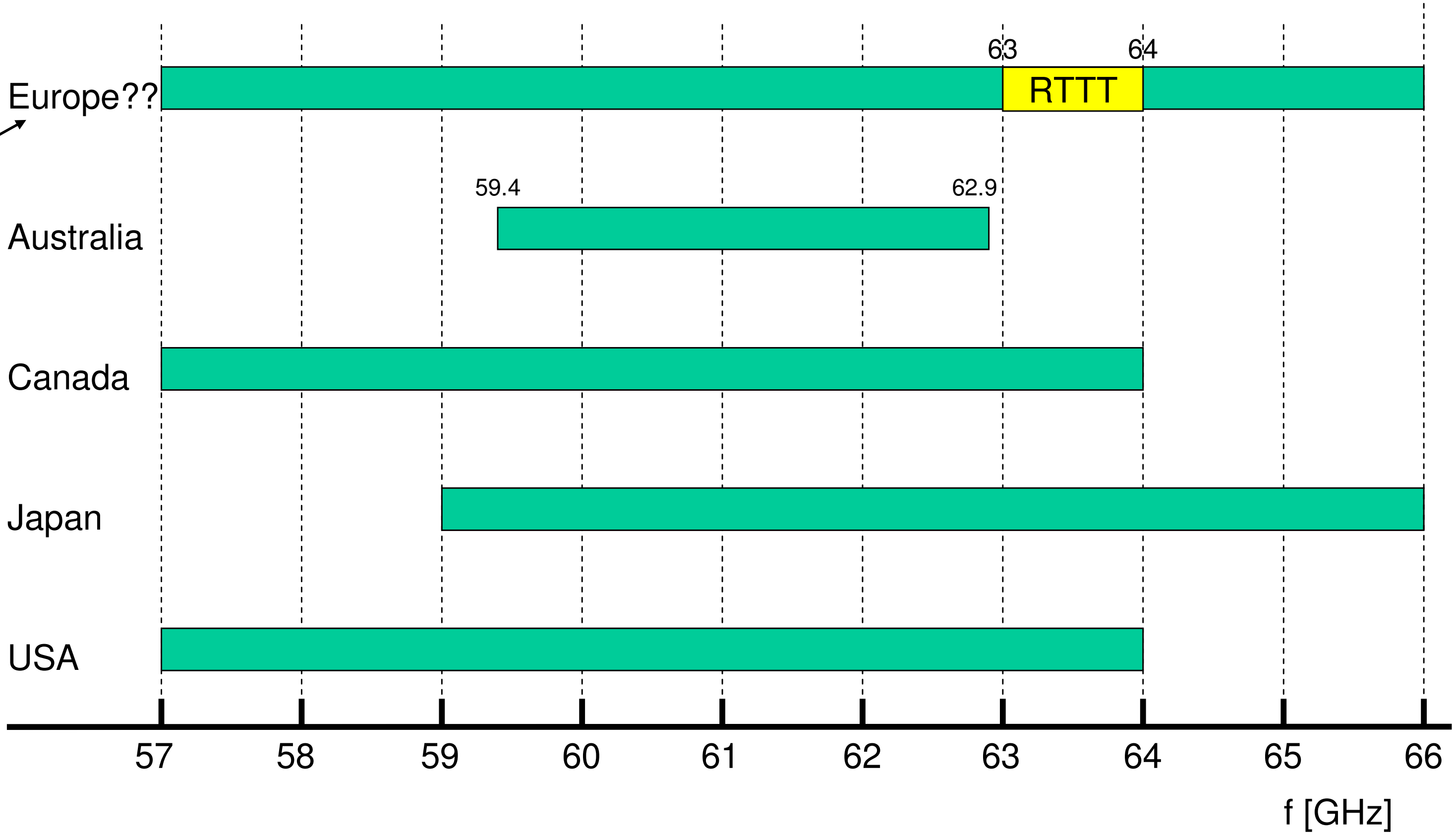
- Cell mode coverage
  - Envisioned usage requires radio coverage within one (or more) cell
  - Antennas with wide beamwidth are preferred (30° to 60° beamwidth)
  - Robust modulation scheme required to deal with channel distortion and related ISI ⇨ solution based on OFDM

Frequency Channels

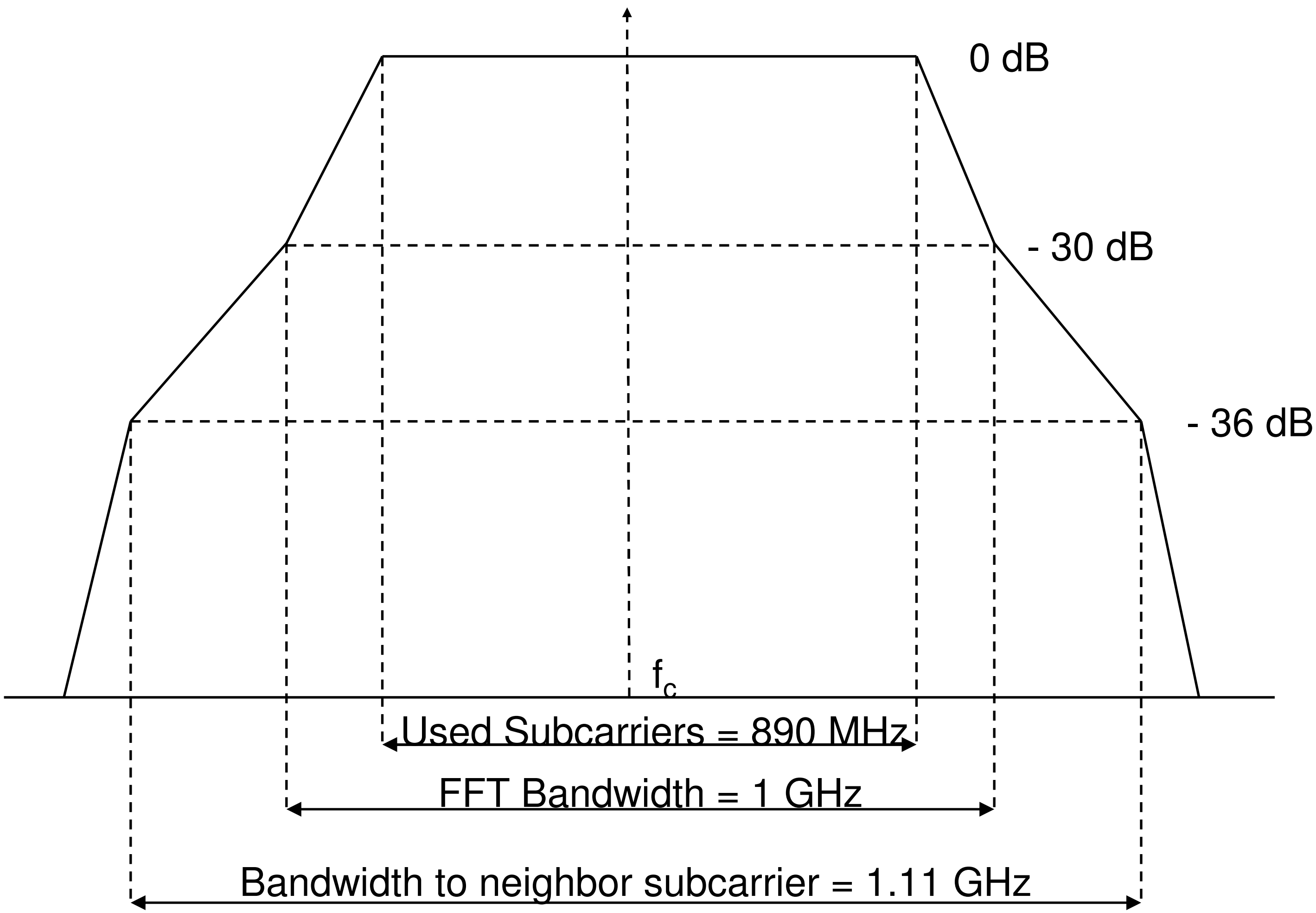
- Channel bandwidth: 1 GHz (500 MHz and 2 GHz optional)
- Efficient utilization of international ‚frequency grid'
- Nine channels allocated from 57 GHz up to 66 GHz

RTTT: Road Transport and Traffic Telematics

Frequency Regulation in Europe is in Progress



Proposed Spectral Mask per Channel



System Architecture

System Architecture

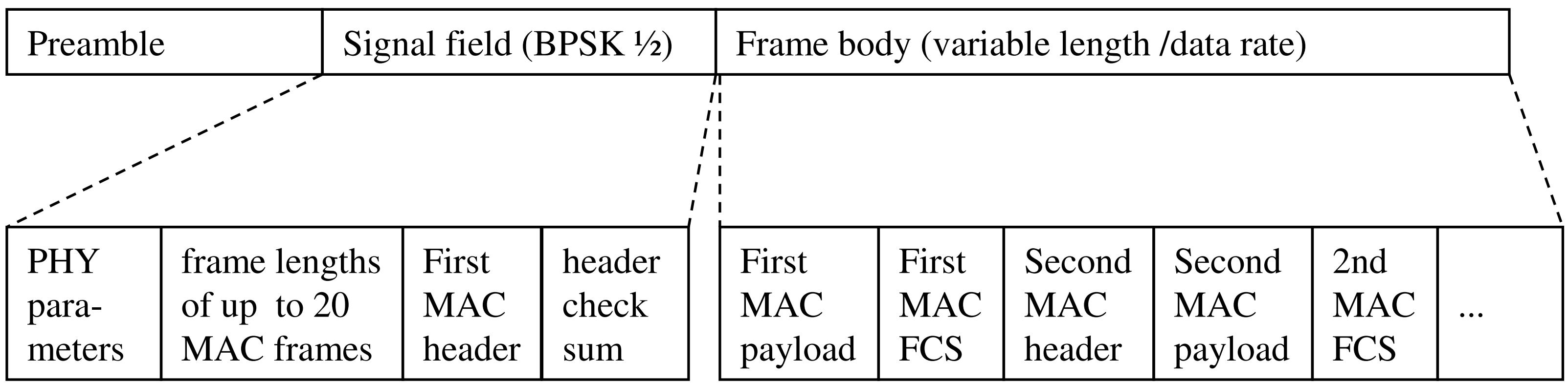
Basic MAC features:

- Standard IEEE 802.15.3 MAC
  adapted to 60 GHz PHY
- Centrally controlled TDMA scheme
  Piconet controller + several terminals
- QoS (Quality of Service) support
- Authentication, privacy, dynamic channel selection, power management, etc.
- Unicast, Multicast and Broadcast capabilities
- Point to point and point to multipoint connection

PHY-Dependent MAC Parameters

Parameter name	proposed value – 60 GHz
pPHYMIFSTime	1 µs
pPHYSIFSTime	8 µs
pCCADetectTime	2 µs
pPHYChannelSwitchTime	500 µs
pPHYClockAccuracy	+/- 15 ppm
pMaxFrameBodySize	4082 octets
pMaxTransferUnitSize	4066 octets
pMinFragmentSize	128 octets

Frame Format



- Preamble of about 6.6 µs duration.
- First OFDM symbol = Signal Field.
  Always sent at the lowest data rate of 375 Mbit/s (BPSK ½).
  Contains PHY header, lengths of up to 20 MAC frames, 1st MAC header.
  Protected by header check sum (HCS) = 16 bit CRC.
- More OFDM symbols = Frame body .
  Variable length and modulation scheme / data rate
  Contains up to 20 MAC payloads, FCS, and MAC headers (except 1st)
- If required, the last OFDM symbol is filled with arbitrary stuff bytes.

Definition of Signal Field

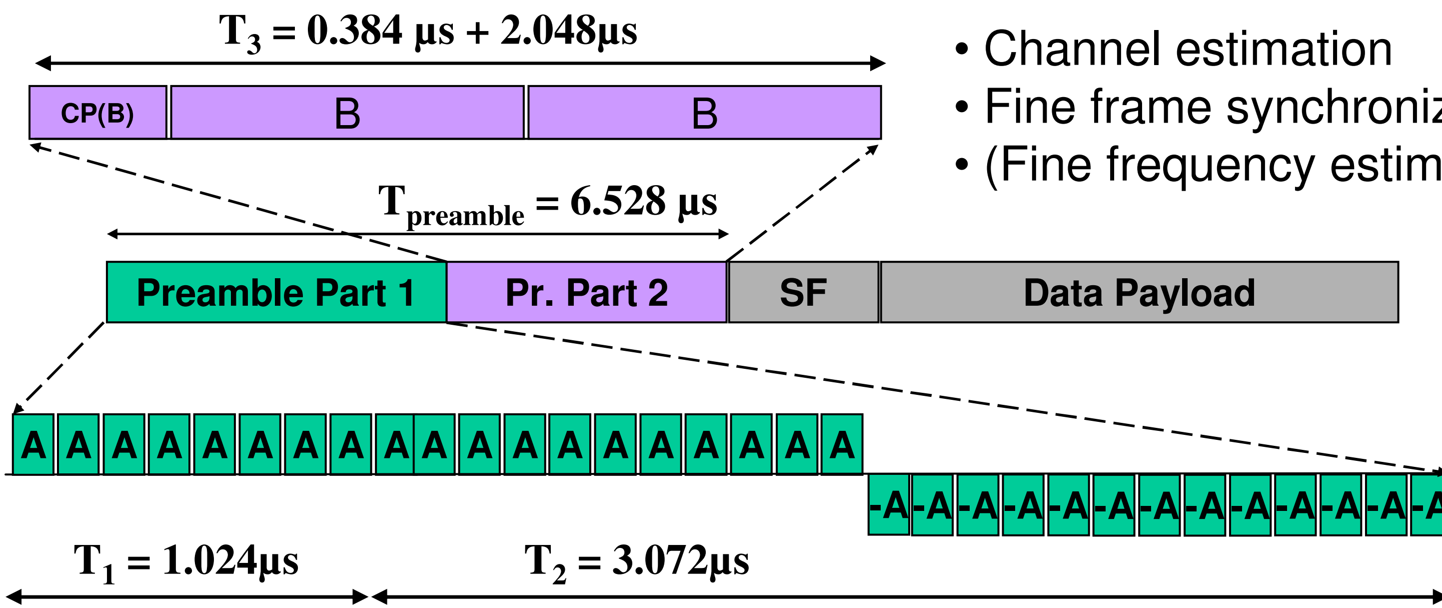
One OFDM symbol BPSK ½ (375 Mbit/s) = 52.5 bytes

Assigned bits	Length	Logical name	Description and range
Byte 0, bits 0-2	3 bits	PHY_VERSION	PHY version (currently set to zero)
Byte 0, bits 3-7	5 bits	PD_MODE	Transmission mode for data payload (see table 2)
Byte 1, bits 0-2	3 bits	N_PERM	N_PERM+1 specifies the interleaver size in multiples of OFDM symbols, range = 1…8
Byte 1, bits 3-5	3 bits	N_STREAM	N_STREAM+1 = number of parallel coding streams
Byte 1, bit 6	1 bit	FRM_FOLLOW	1 = after the MIFS time, a subsequent frame is intended to be sent, 0 = no subsequent frame is intended to be sent
Byte 2, bits 0-4	5 bits	N_MAC_FRM	N_MAC_FRM+1 = number of transmitted MAC frames in this physical frame, range = 1…20
Byte 3, bits 0-7 Byte 4, bits 0-6	15 bits	PD_SCR_INIT	Initial state for data scrambler
Byte 5, bits 0-7 Byte 6, bits 0-3	12 bits	NDATA_1	NDATA_1 = packet length in MAC frame 1
• • •	• • •	• • •	• • •
Byte 33, bits 4-7 Byte 34, bits 0-7	12 bits	NDATA_20	NDATA_20 = packet length in MAC frame 20
Byte 35-Byte 44	10 bytes	MHD_1	MAC header of packet 1
Byte 49, bits 0-7 Byte 50, bits 0-7	16 bits	CRC_HD	PHY header checksum (16-bit CRC)
Byte 51, bits 6-7 Byte 52, bits 0-3	6 bits		6 Viterbi tail bits

Preamble Format and Utilization

Two long B-symbols for:

- Channel estimation
- Fine frame synchronization
- (Fine frequency estimation)



8 A-symbols for

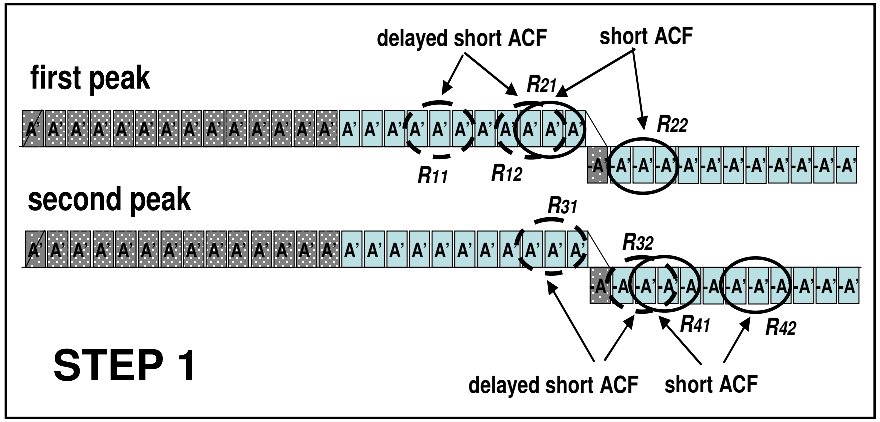
- AGC settling

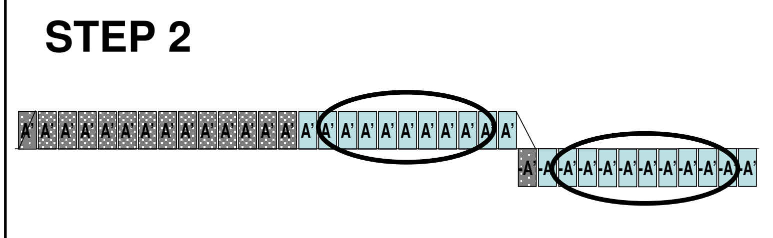
11 A-symbols + 13 inverted A-symbols for:

- Frame detection
- Frequency correction
- Coarse frame synchronization

Frame Detection Mechanism

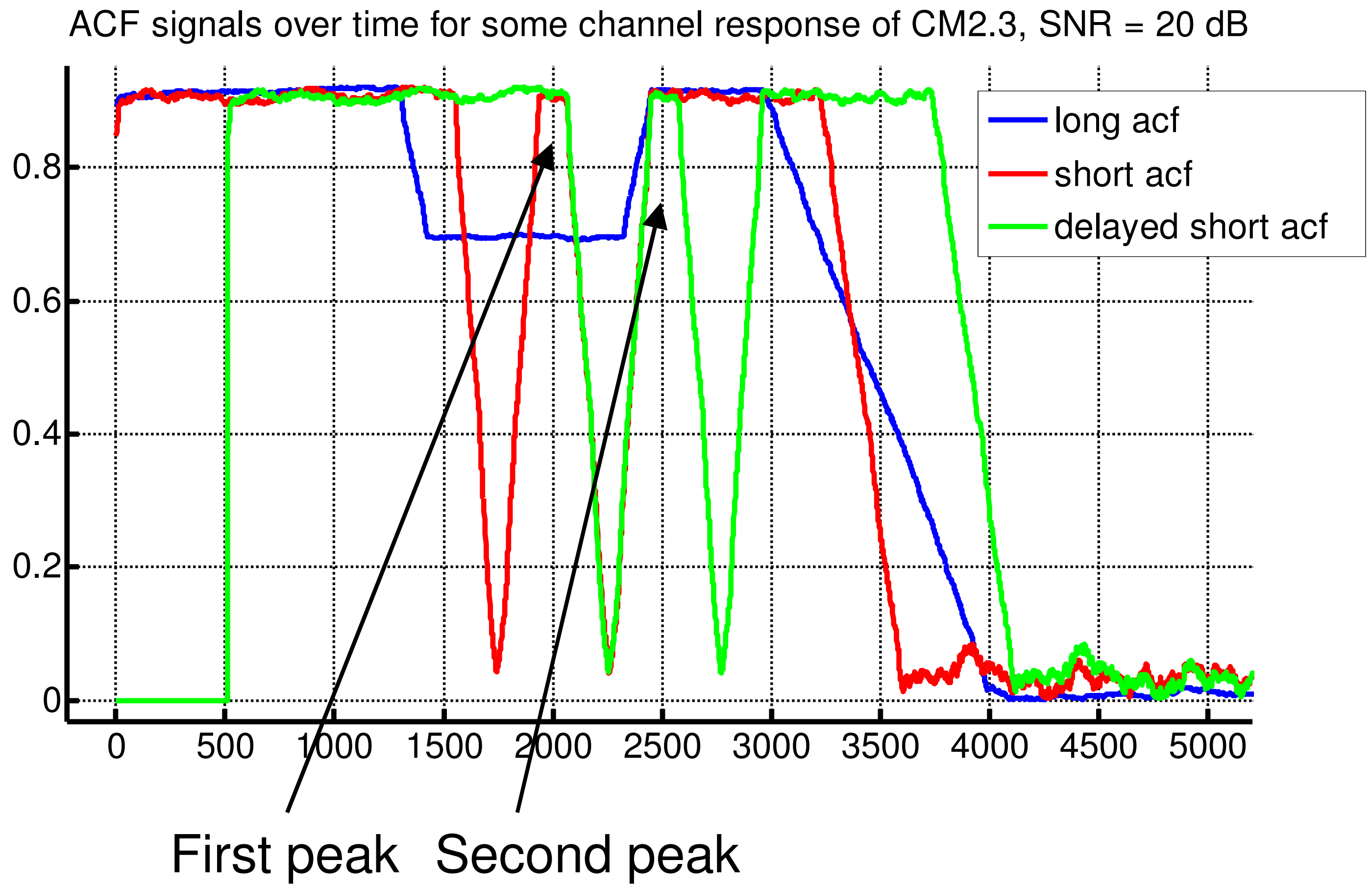
- A normalized autocorrelator is related to a delayed version
- Samples satisfying an "antiphase-condition" are marked
- Marked samples are grouped in clusters, such that the distance of adjacent cluster samples is below some value d
- The middle point in each cluster is defined as a peak at position x_k
- Two peaks must be found in the frame with a distance $|x_{k+1} - x_k| \in [D_{\min}, D_{\max}]$
- With the first peak as a time reference, a second ACF is evaluated for final frame detection and frequency offset correction





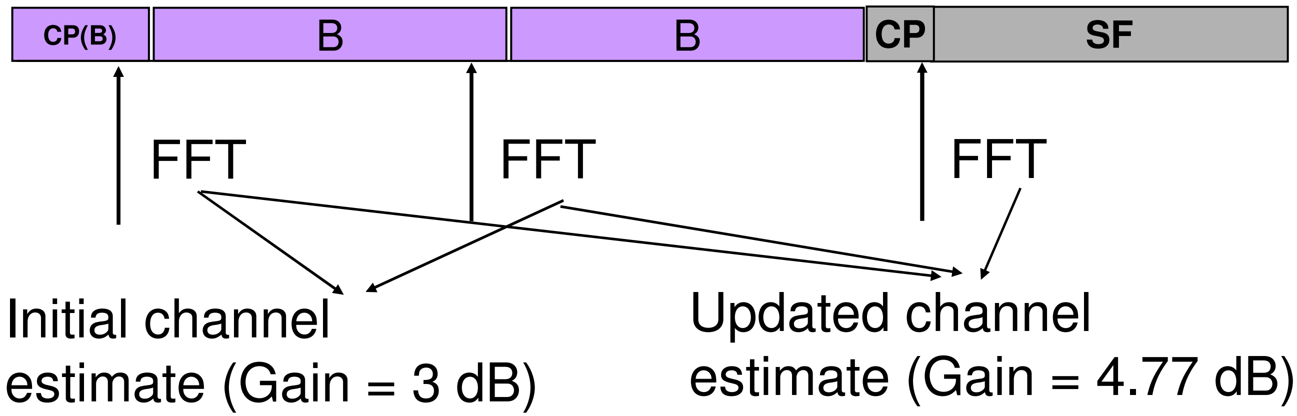
Applying second (long) ACF for frequency correction and final frame detection

Signal Waveform of Synchronizer-ACFs

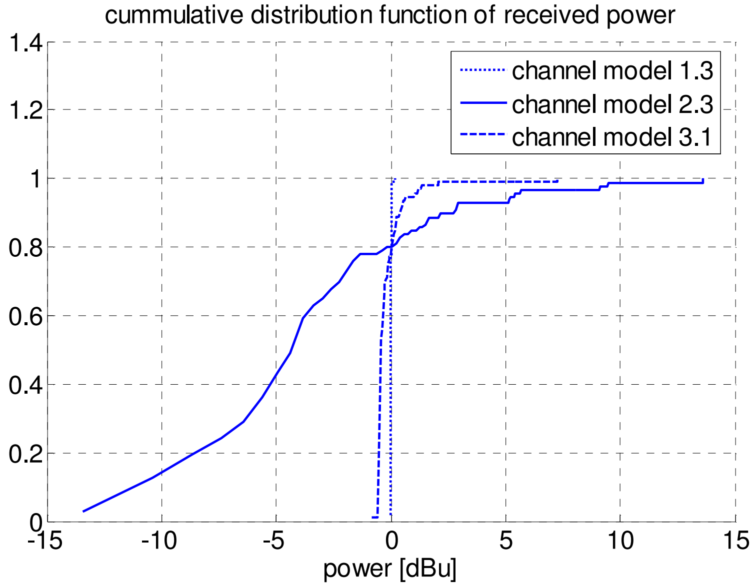


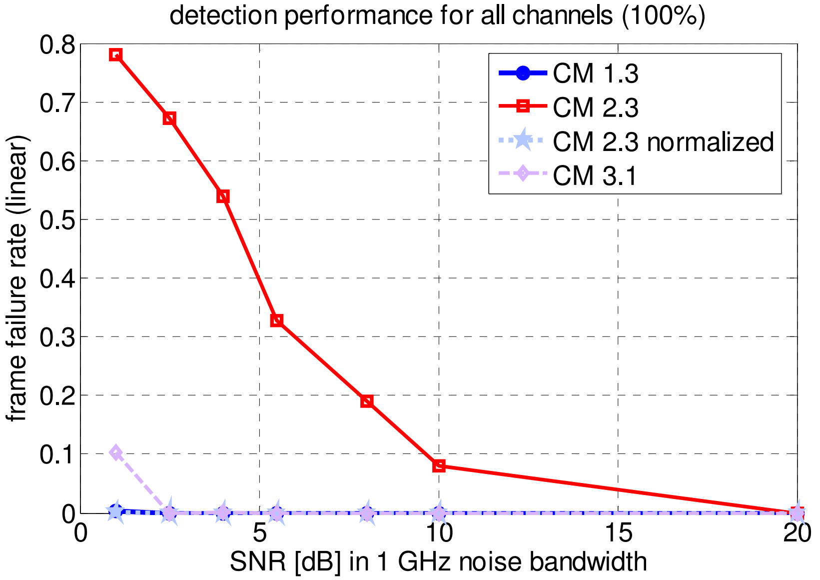
Channel Estimation and Time Synchronization

- Two FFTs are applied on the second preamble part for initial channel estimation
- A phase-unwrapping method is used to estimate the position of the centroid of the channel impulse response in the frequency domain
- The frame FFT start position is taken at a fixed offset position from the estimated centroid
- The BPSK modulated OFDM symbol for the signal field (SF) is exploited after SF decoding to improve channel estimation (DFE)



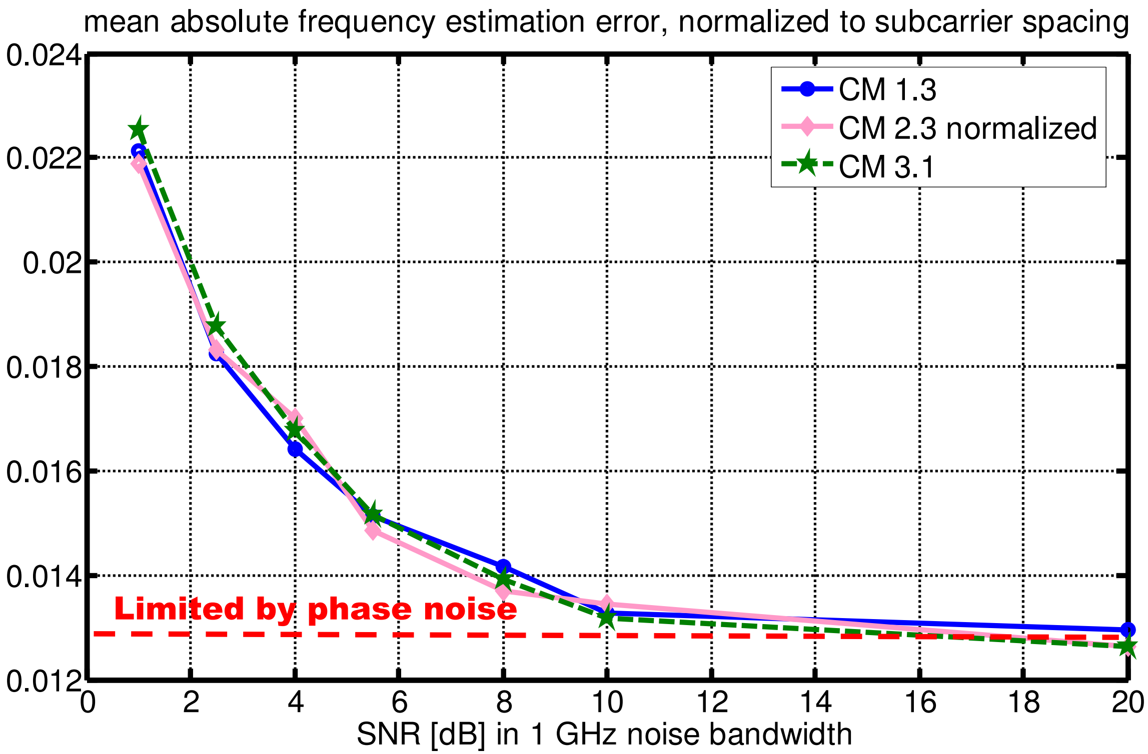
Detection Performance





- Good performance down to SNR = 1 dB for CM1.3, CM3.1 and CM2.3(norm.)
- Bad performance for unnormalized CM2.3 due to strong power fluctuation
- No false alarm was ever observed
- 5000 simulated frames / SNR-value, virtual simulation time / SNR-value = 82ms
- Power amplifier backoff: IBO = OBO = 10 dB
- Phase noise: -92 dBc/Hz@ 1MHz, cutoff (pole) = 100 kHz, noise floor = -130 dBc/Hz

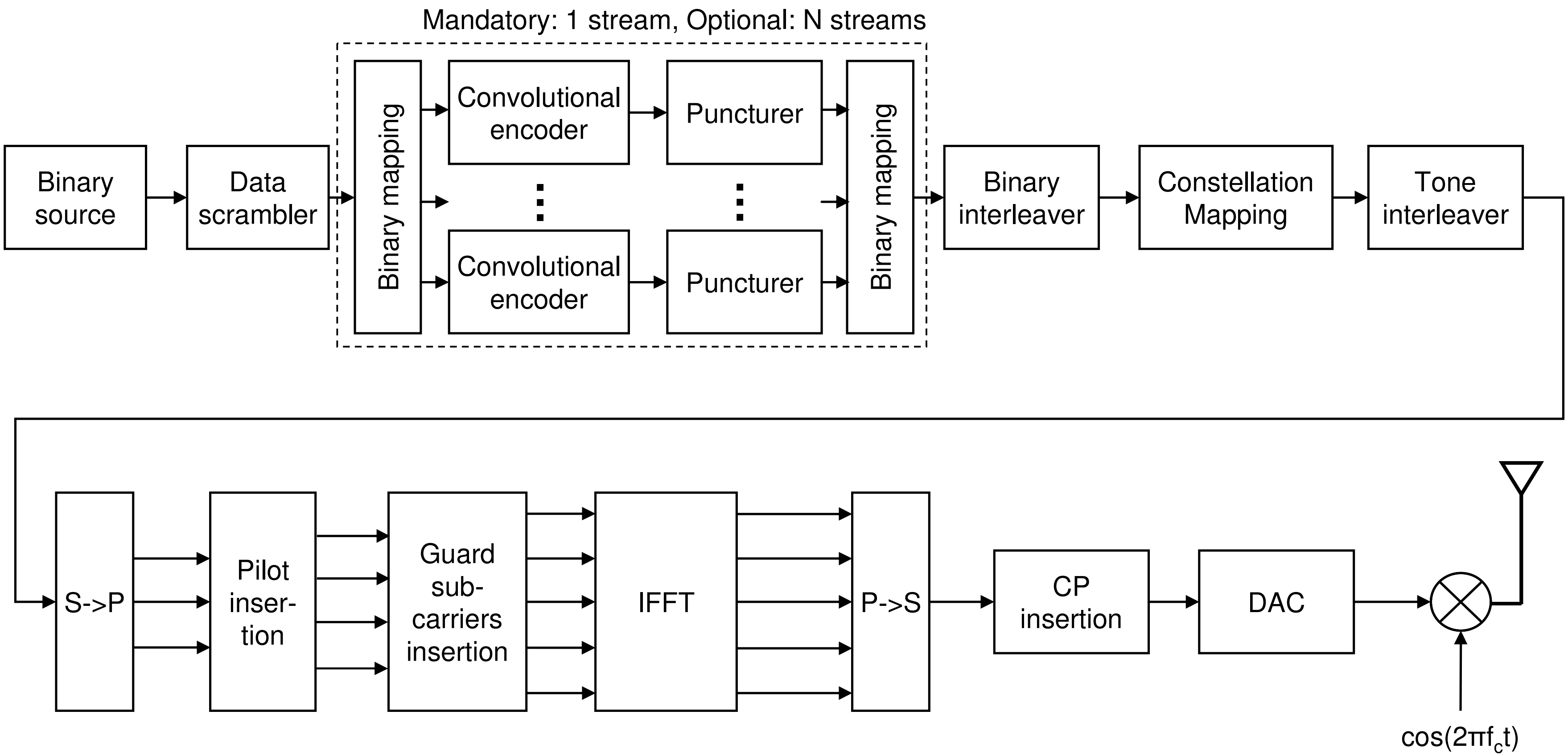
Frequency Synchronization



- Performance can be improved with less phase noise / wider PLL loop bandwidth

PHY Baseband Description

PHY Baseband Architecture



- OFDM system architecture

System Parameters

Parameter	Value
Number of data subcarriers	840
Number of pilot subcarriers	66
Number of DC zero subcarriers	5
Number of guard subcarriers	113
FFT size	1024
Channel bandwidth	1 GHz
Subcarrier frequency spacing	0.977 MHz
IFFT/FFT period	1024 ns
Cyclic prefix duration	96 ns / 160 ns / 220 ns
Symbol interval	1120 ns / 1184 ns / 1244 ns

- Nominal channel bandwidth of 1 GHz
- Compatible with 500 MHz and 2 GHZ channels
- 3 different values of CP duration depending on the channel characteristics

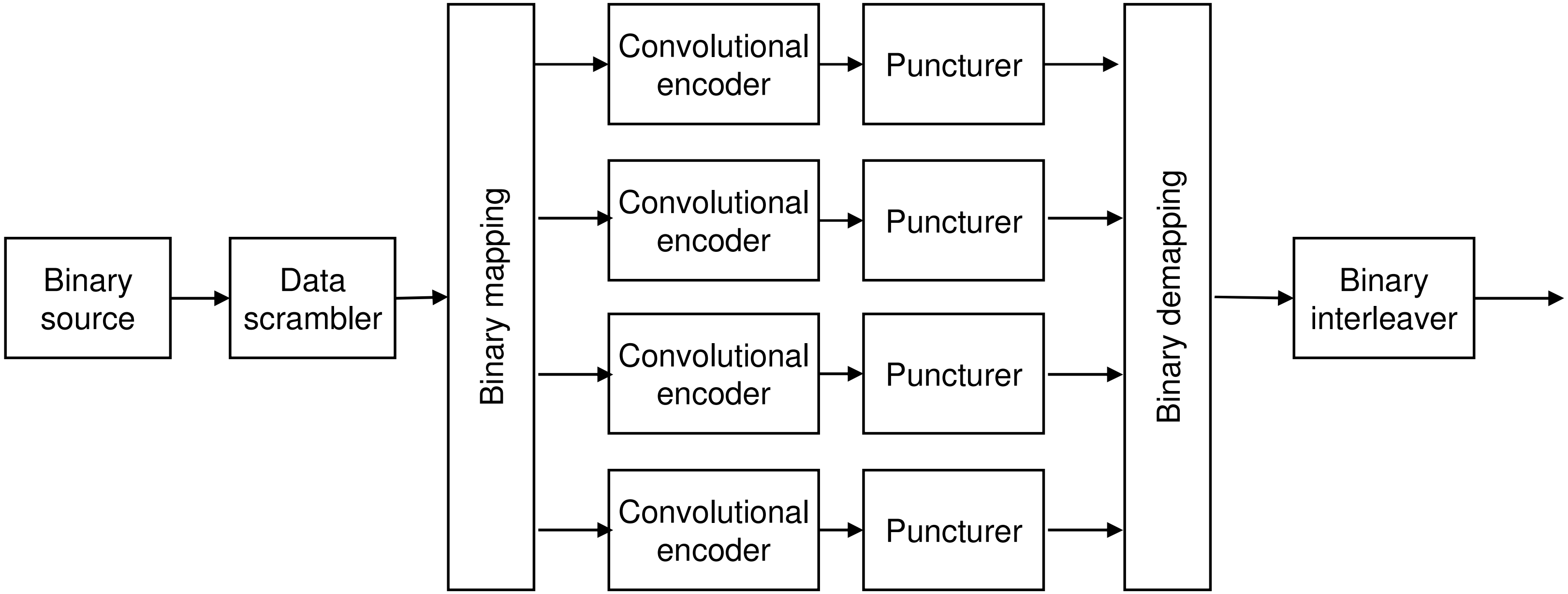
Modulation and Coding Schemes

Data Rate	Modulation	Coding Rate	Data bytes per OFDM symbol
375 Mbps	BPSK	1/2	52.5
500 Mbps	BPSK	2/3	70
750 Mbps	QPSK	1/2	105
1000 Mbps	QPSK	2/3	140
1500 Mbps	16-QAM	1/2	210
2000 Mbps	16-QAM	2/3	280
2500 Mbps	16-QAM	5/6	350
3000 Mbps	64-QAM	2/3	420

Valid for CP duration of 96 ns. See backup slides for longer CP values.

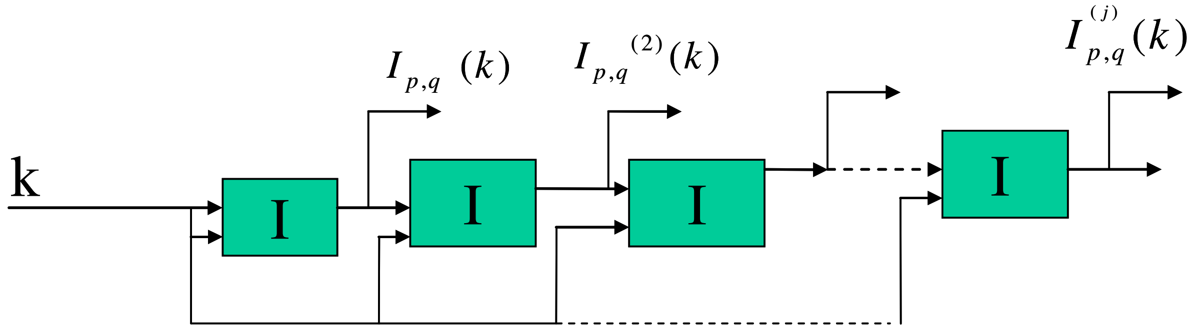
Coding Scheme

- Convolutional encoder, with code rate R = 1/2 and generator polynomials $g_0 = (133)_8$ and $g_1 = (171)_8$
- Parallel encoding for high data rates



Binary Interleaving

- Optimized binary interleaver to increase encoder performance
- An iterative structure of the algorithm generates different permutation rules in a scalable way



$$X_{OUT}(k) = X_{IN}\left(I_{p,q}^{(j)}(k)\right)$$

$$I_{p,q}^{(0)}(k) = [\alpha + k + q \cdot p \cdot [-k - p \cdot k]_K]_K$$

$$I_{p,q}^{(j)}(k) = \left[\alpha + k + q \cdot p \cdot \left[-k - p \cdot I_{p,q}^{(j-1)}\right]_K\right]_K$$

K : Block size,

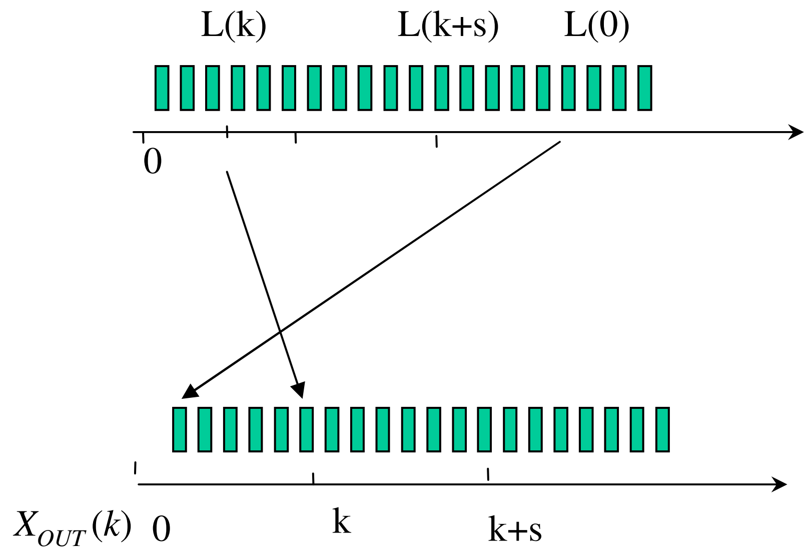
p, q, j : Interleaver parameters

$\alpha < \frac{K}{p}$: Offset parameter

Interleaving Process

- $L(k)$ gives the position of the k-th output sample in the input sequence

$$L(k) = I_{p,q}^{(j)}(k)$$



$$X_{OUT}(k) = X_{IN}(L(k))$$

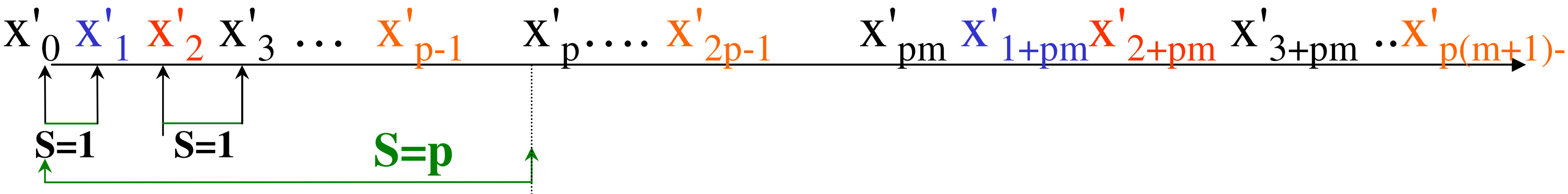
- Selection of interleaving patterns
  - Targeted values for s to maximize $\Delta L(s)$
  - Parameters $\{p, q, j\}$ are selected when

$$Max\left\{\Delta L(s) = \underset{0 \le k \le K-1}{Min}\left\{\left|I_{p,q}^{(j)}(k+s) - I_{p,q}^{(j)}(k)\right|\right\}\right\}$$

Binary Interleaving Properties [1], [2]

❶ *Controlled interleaving spreading $\Delta L(s)$* between bits separated by (s-1) bits.

- ✓ s depends on the maximisation criterion of $\Delta L(s)$



- ✓ $\Delta L(s)$ maximisation in each data symbol ➔ s={1,…,m-1}
  m :number of encoded bits per sub-carrier
- ✓ $\Delta L(s)$ maximisation between adjacent sub-carriers ➔ $[s]_m=0$

❷ *Preservation of an interleaving mapping pattern*

- ✓ Adapted to parallel encoding of independent bit streams and special binary mapping

❸ **2 interleaving sizes** K_1 and K_4 (1 and 4 OFDM symbol lengths)

- ✓ A common interleaving pattern for binary and sub-carrier interleaving
- ✓ Binary interleaving located in the parallel FEC structure ➔ generates additional interleaving depths with common interleaving patterns
- ✓ Overall interleaving depths {1, 2, 4, 8 OFDM symbol length}

Binary Interleaving Parameters

- Setting of parameters {*p*, *q*, *j*}

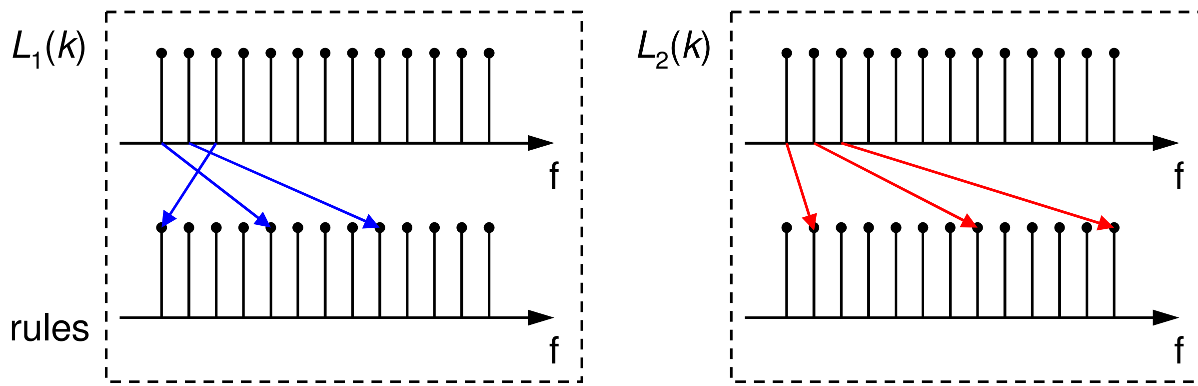
Interleaving set up	Interleaving depth *K*	Interleaving parameters			Interleaving spreading Δ*L*(*s*)				
		p	***q***	***j***	***s*=1**	***s*=2**	***s*=3**	***s*=4**	***s*=6**
BPSK (binary) Sub-carrier, 1 OFDM	840	12	2	3	143	286	411	268	18
16-QAM (binary) Sub-carrier, 4 OFDMs	840x4	96	2	1	1537	286	1251	572	858
64-QAM (binary)	840x6	36	2	3	2089	862	1227	1724	2454
16-QAM (binary)	840x4x4	21	2	3	3949	5942	1593	2356	3186
64-QAM (binary)	840x4x6	288	2	3	7487	5186	2301	9788	4602

Tone Interleaving

- After constellation mapping, the complex symbols assigned to different frequency tones are interleaved over 1 or 4 OFDM symbols
- Purpose is to increase the system frequency diversity and reduce interference from narrow band interferers
- Similar interleaving scheme is used as for binary interleaving
- Dynamic implementation: two different permutation rules are used cyclically

$Y_{OUT}(k)=Y_{IN}(L(k))$

Two different permuation rules



	Permutation rule #1	Permuation rule #2	Permutation rule #1	Permuation rule #2
OFDM symbol	#1	#2	#3	#4

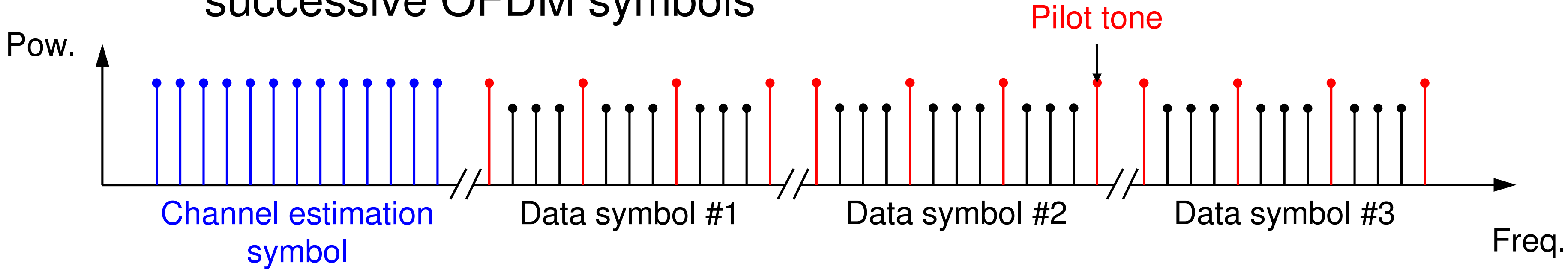
Tone Interleaving Parameters

- Setting of parameters {*p*, *q*, *j*}

Interleaving set up	**Interleaving depth *K***	**Interleaving parameters**			**Interleaving spreading Δ*L*(*s*)**				
		p	***q***	***j***	***s*=1**	***s*=2**	***s*=3**	***s*=4**	***s*=6**
Sub-carrier, 1 OFDM symbol	840	12	2	3	143	286	411	268	18
Sub-carrier, 4 OFDM symbols	840x4	96	2	1	1537	286	1251	572	858

Boosted Pilots

- Two full OFDM symbols are used in each frame for channel estimation
- Additionally, in each OFDM symbol, 66 pilot tones are inserted to mitigate phase noise and frequency offsets
- The information carried by these symbols / pilots is highly sensitive for an efficient compensation of channel impairments
- It is recommended to allocate more power to these signals
- Assymetric pilot positions can also be considered over successive OFDM symbols



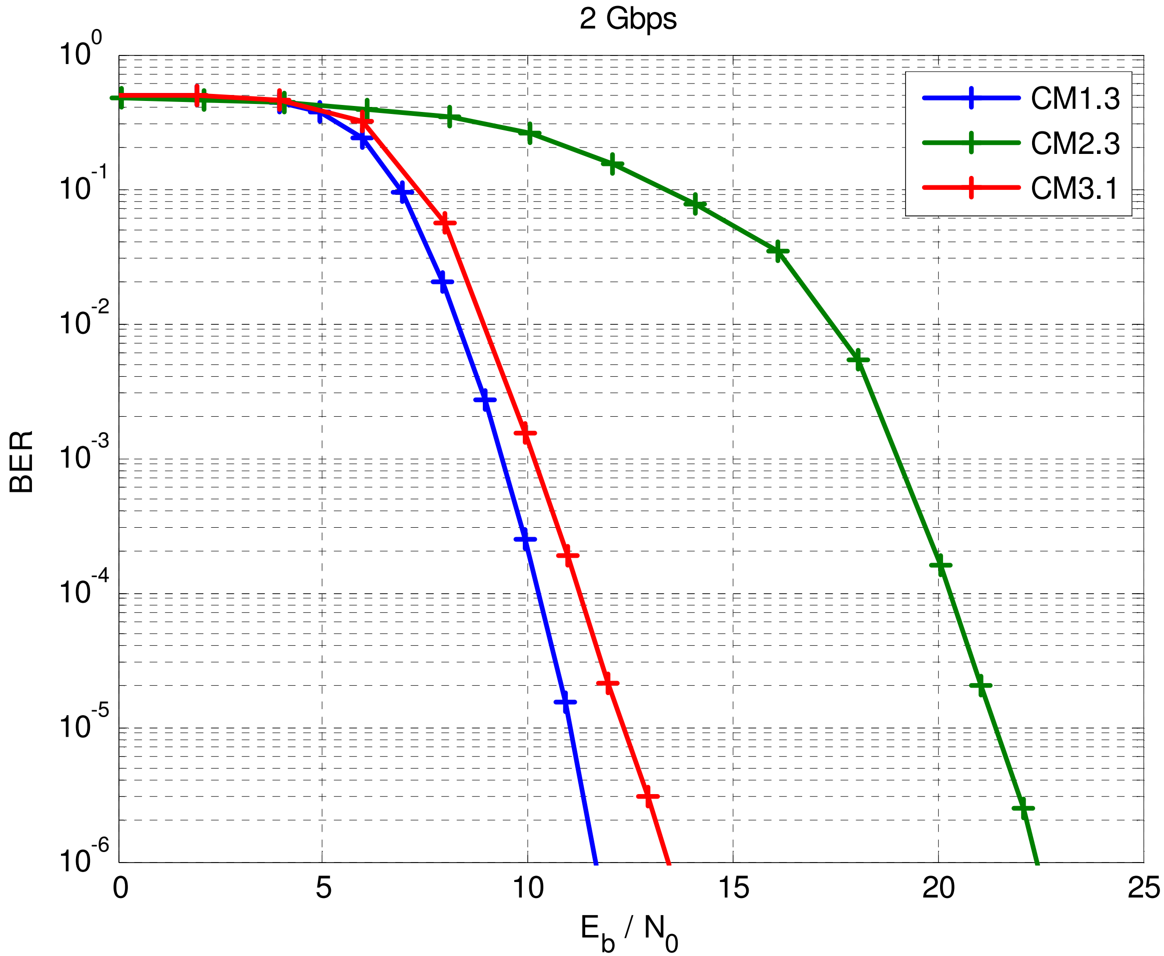
System Performance

Simulation Assumptions

- TG3c channel models (Golden Sets)
  - Residential LOS (CM1.3), NLOS (CM2.3), Office LOS (CM3.1)
  - Spatial filtering: 30° HPBW at Rx
- Simulation scenario
  - 64 packets (payload 2048 bytes) for 100 different channel realizations (a total of about 10^8 transmitted bits)
  - Computation of 90% BER/PER link success probability
- Other simulation assumptions
  - Realistic channel estimation
  - Phase noise: single-zero, single pole model
    - fp = 1 MHZ, fz = 100 MHz, PSD(0)=-87dBc/Hz (-92dBc/Hz for 3 Gbps)
  - Amplifier non-linearities: Rapp model without AM-PM distortion
    - OBO = 10 dB, p = 2

Simulation Results – 2 Gbps

Parameter	Value
RF bandwidth	1 GHz
Number of subcarriers	1024
Data subcarriers	840
Guard time	96 ns (CP)
Modulation	16-QAM
Channel coding, rate	Convolutional code, R = 2/3
Interleaver depth	4 OFDM symbols
Channel models tested	CM1.3, CM2.3, CM3.1
Data rate	2 Gbps



- 90% BER link success probability

Simulation Results – 2 Gbps

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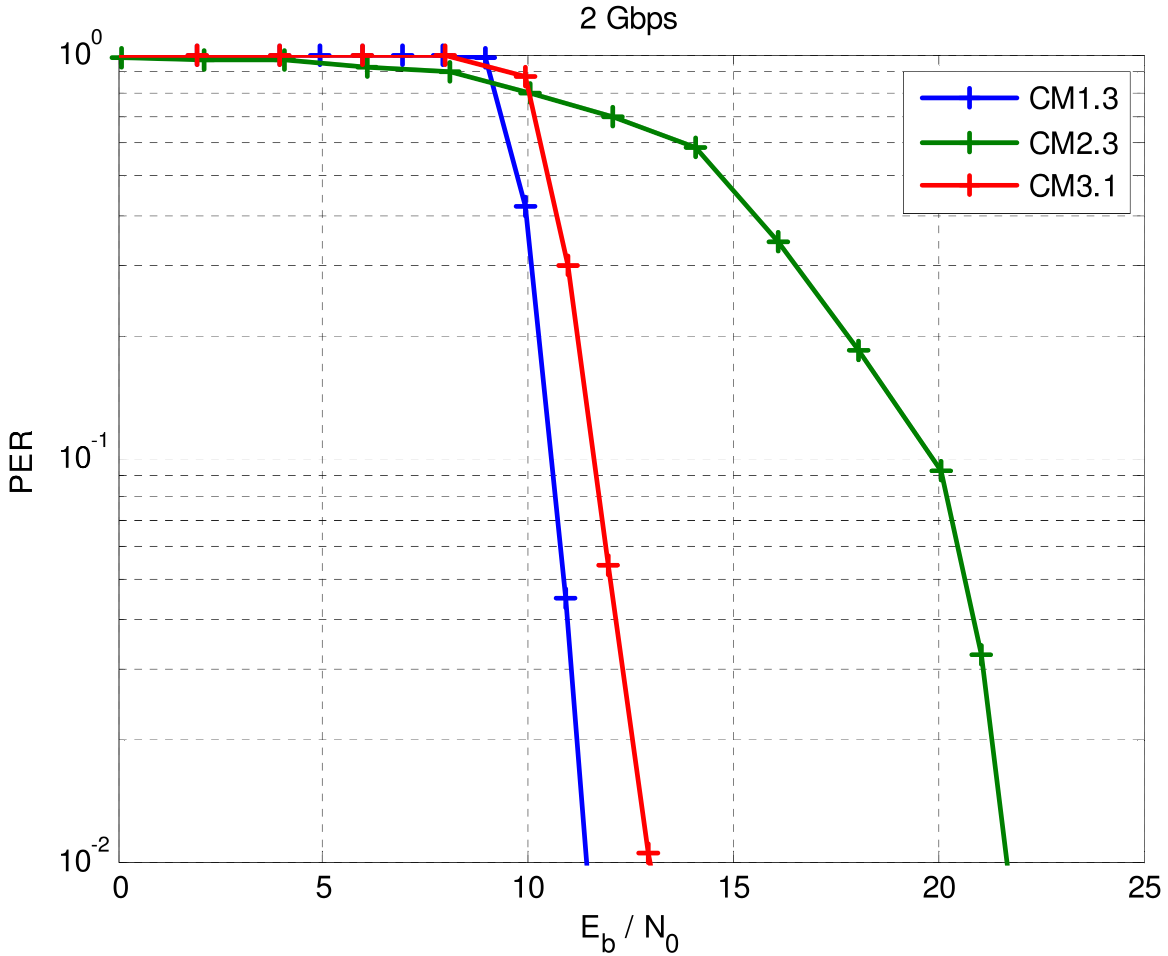
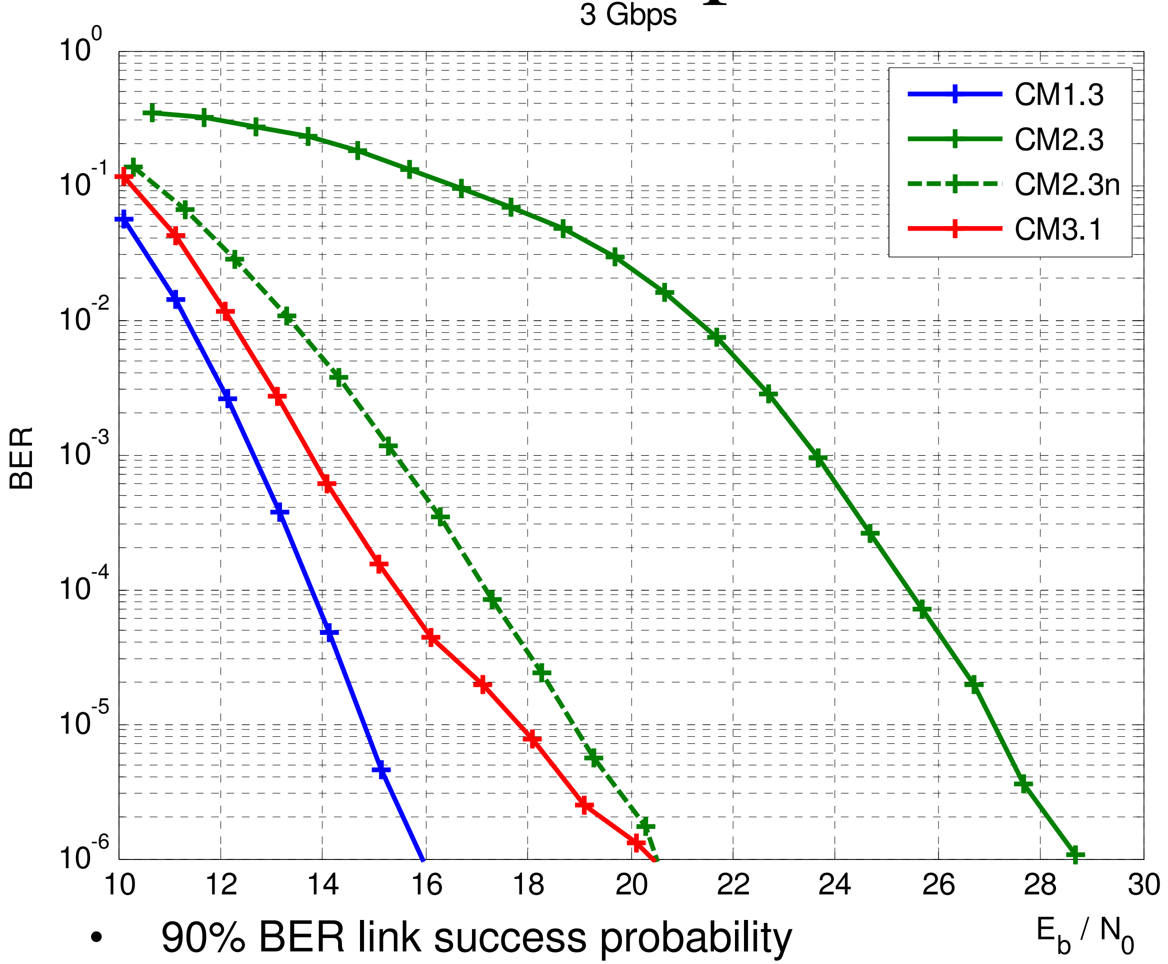


- 90% PER link success probability

Simulation Results – 3 Gbps

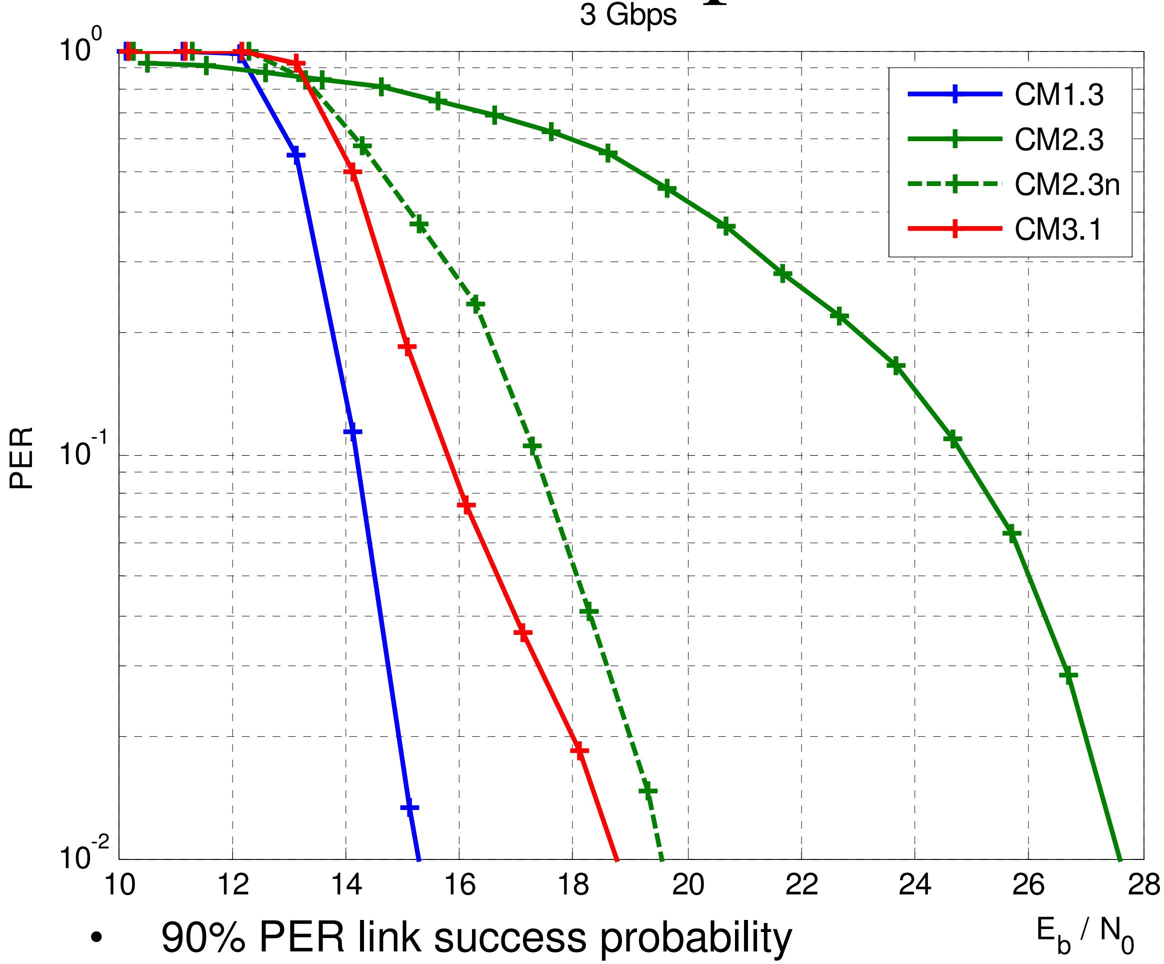
Parameter	Value
RF bandwidth	1 GHz
Number of subcarriers	1024
Data subcarriers	840
Guard time	96 ns (CP)
Modulation	64-QAM
Channel coding, rate	Convolutional code, R = 2/3
Interleaver depth	4 OFDM symbols
Channel models tested	CM1.3, CM2.3, CM3.1
Data rate	3 Gbps



- 90% BER link success probability
- CM2.3n = normalized channels of CM2.3
- Phase noise: PSD(0) = -92 dBc/Hz

Simulation Results – 3 Gbps

Parameter	Value
RF bandwidth	1 GHz
Number of subcarriers	1024
Data subcarriers	840
Guard time	96 ns (CP)
Modulation	64-QAM
Channel coding, rate	Convolutional code, R = 2/3
Interleaver depth	4 OFDM symbols
Channel models tested	CM1.3, CM2.3, CM3.1
Data rate	3 Gbps



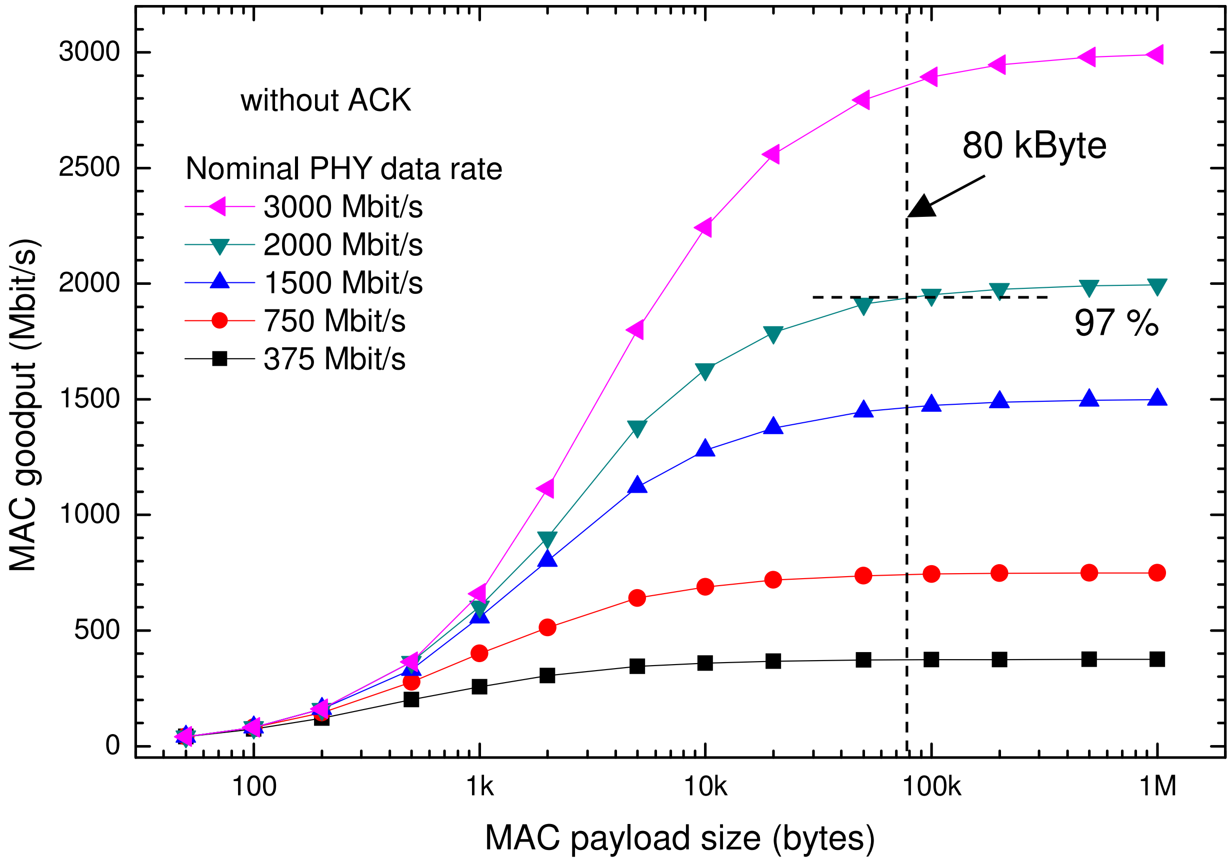
- 90% PER link success probability
- CM2.3n = normalized channels of CM2.3
- Phase noise: PSD(0) = -92 dBc/Hz

Link Budget Example

Parameter	**Value**	**Unit**
PHY-SAP Payload Bit Rate (R_b)	2	Gb/s
Average Tx power (P_T)	10	dBm
Tx antenna gain (G_T)	9	dBi
Center frequency (f_c)	60	60GHz
Path loss at 1 meter ($PL_0 = 20\log_{10}(4*PI*f_c/c)$), $c = 3*10^8$ m/s	68	68.00dB
Rx antenna gain (G_R)	9	dBi
Average noise power per bit (N=-174+10*log$_{10}$(R_b)))	-81	dBm
Rx Noise Figure Referred to the Antenna Terminal (N_F)	6	dB
Average noise power per bit ($P_N = N + N_F$)	-75	dBm
Minimum E_b/N_0 for CM1.3 channel (S) (for BER = 1E-6)	11,6	dB
Shadowing link margin ($M_{shadowing}$)	5	dB
Implementation Loss (I)	3	dB
Tolerable path loss ($PL = P_T+G_T+G_R-P_N-S-M_{shadowing}-I-PL0$)	15,4	dB
Maximum operating range ($d = 10^{PL/10n}$)	5,89	m

- CM1.3, LOS path loss model, 2 Gbps

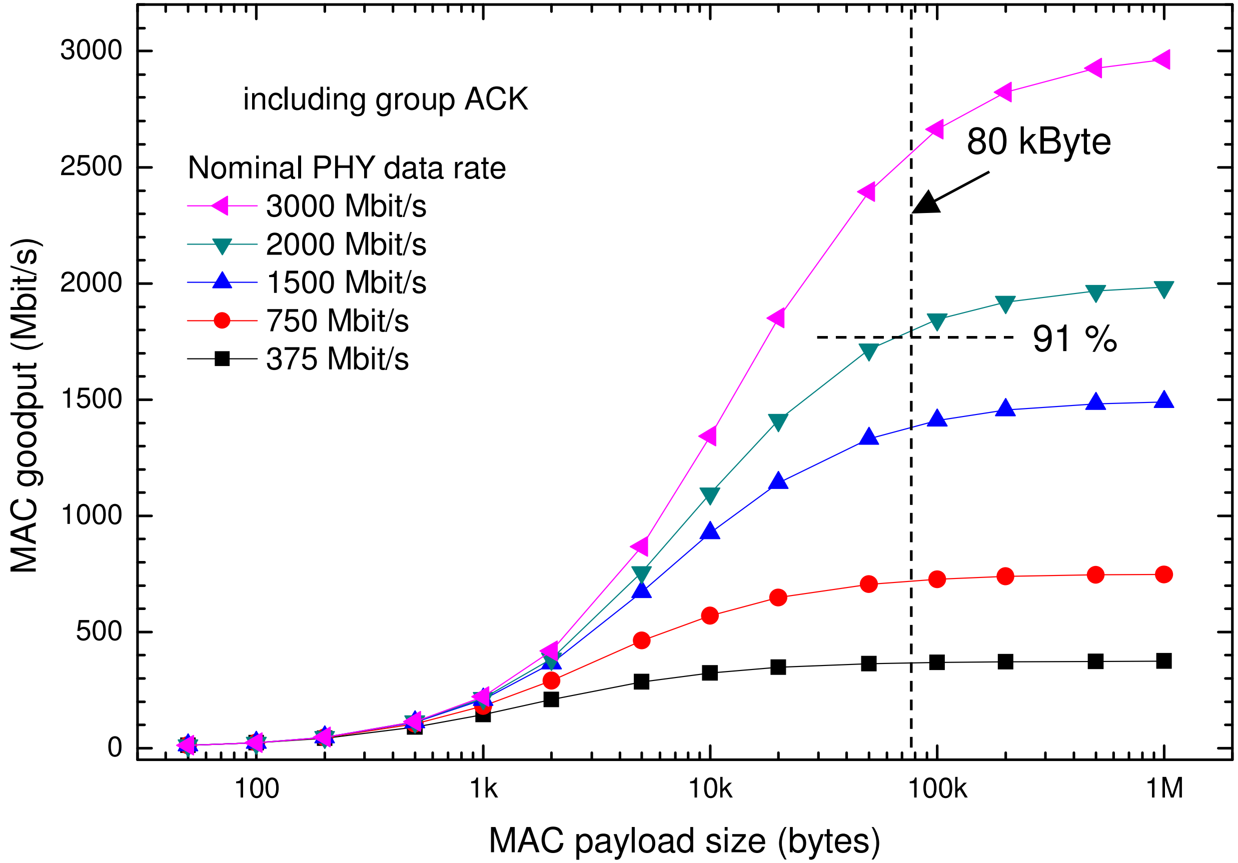
MAC Goodput without ACK



PHY overhead time = 8.8 µs

(6.6 µs preamble + 1.2 µs signal field + 1 µs MIFS time)

MAC Goodput with Group ACK



PHY overhead time = 32.8 µs

(2x 6.6 µs preamble + 2x 1.2 µs signal field + 1.2 µs ACK payload + 2x 8 µs SIFS time)

System Implementation

Estimated Chip Area

- Scaling a current FPGA implementation, the following figures can be estimated (4 data streams, max. 500 MHz digital CLK, 65 nm digital CMOS, 130 nm analog SiGe-BiCMOS assumed!):
  - MAC Processor: 10 mm^2 (ca. 10 Mio Gates)
  - Baseband Processor: 15 mm^2 (ca. 15 Mio Gates)
  - Data Converters: 10 mm^2
  - Analog Frontend (incl. PA) 6 mm^2
  - Size Complete Transceiver PCB: 5 cm x 4 cm x 3 cm
  - Size of Antenna (Patch Array): 30 mm x 40 mm x 2 mm

Estimated Power Dissipation

- **Total Power Dissipation at 2 Gb/s (65 nm CMOS digital; 130 nm analog SiGe)**

	TX	**RX**
– MAC Processor:	200 mW	200 mW
– Baseband Processor:	200 mW	350 mW
– Data Converters:	100 mW	150 mW
– Analog Frontend	200 mW	200 mW
– Power Amplifier	150 mW	20 mW

- **Total (continuous): 850 mW 920 mW**

Prototype

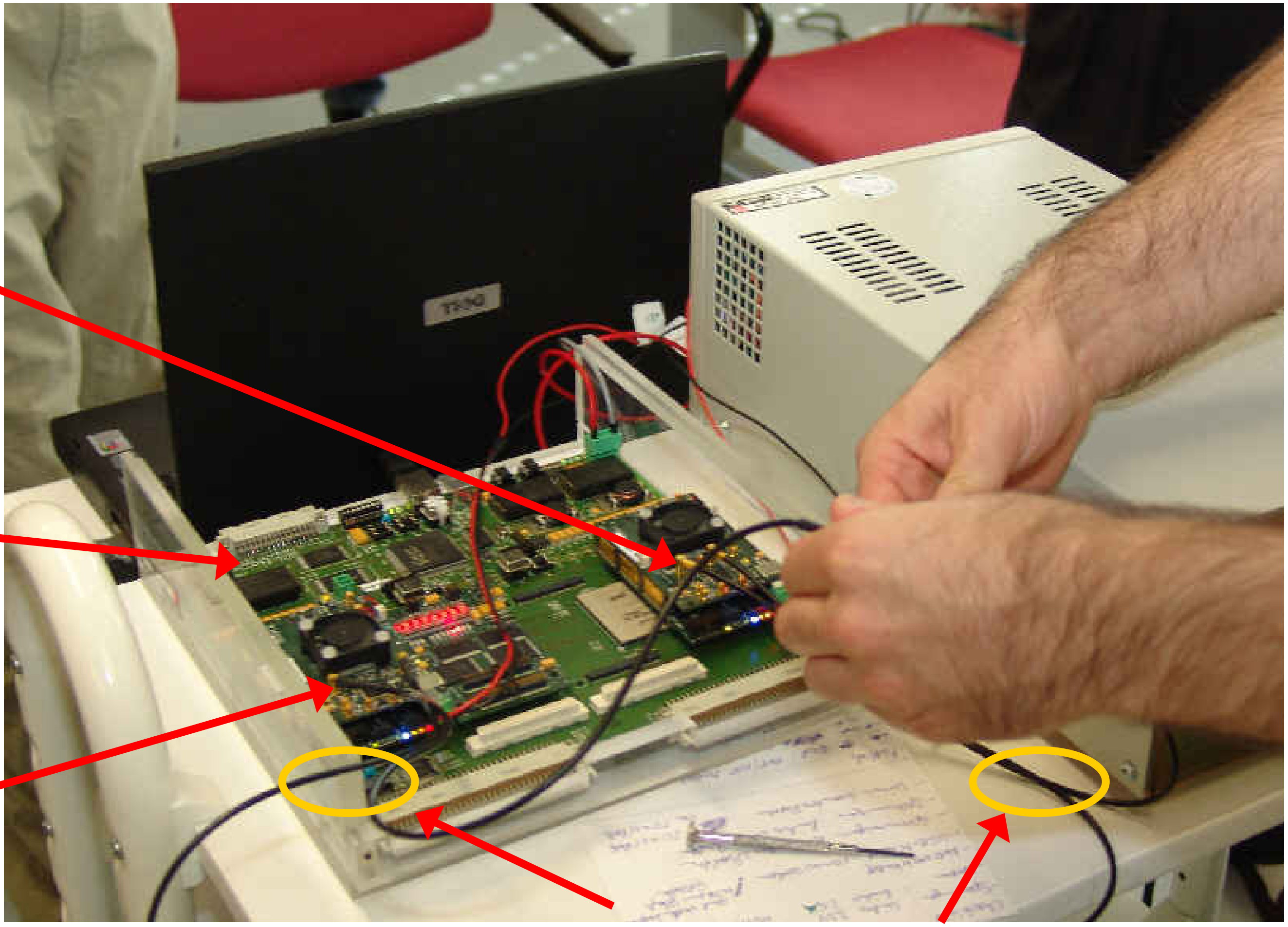
OFDM-Baseband Processor (FPGA)

Signal Bandwidth: 500 MHz; Max data rate: 1 Gbps

A/D Converter

Main FPGA Board for BB Proc.

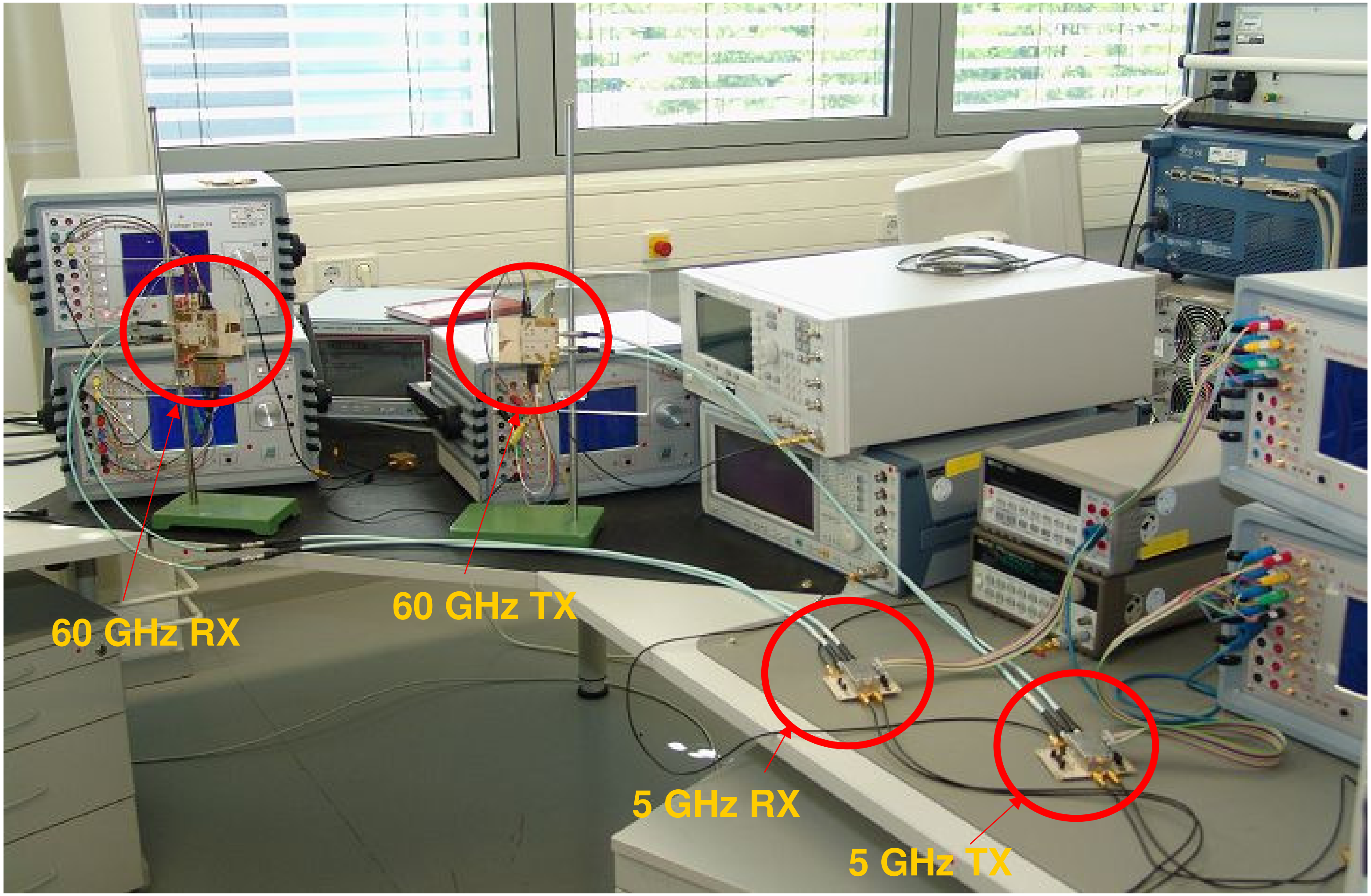
D/A Converter



BB I/Q Signals to/from IF Block

60 GHz Analog Frontend

0.25 um SiGe BiCMOS Technology; Max data rate: 720 Mbit/s @ 500 MHz Bandwidth demonstrated



Open issues

- Addition of a Low Data Rate (LDR) mode for signalling and LDR applications
  - Specific 60 GHz channel
  - Other technology (UWB, 5 GHz, …)
- Compatibility with other techniques for 60 GHz transmission is desirable
  - SC with FDE, SC, …
- Use of multiple antennas could increase efficiency
  - Beamforming
  - MIMO STBC
  - …

Conclusion

- This proposal presents an OFDM based PHY allowing 60 GHz transmission at data rates from 335 Mbps to 3 Gbps
- OFDM presents technical advantages meeting TG3c requirements :
  - Inherently robust against any type of fading channel
  - Providing high spectrum efficiency and allowing to reach high data rates
- OFDM is a future proof technology
  - Mature, widely used technology (WiFi, WiMax, DAB, DVB, ECMA UWB)
  - Large scope of possible applications: from point-to-point data transfer to cell mode coverage
  - Compatible with advanced techniques: beamforming, MIMO STBC, …
- We are in discussions to converge with Wireless HD, and open to discussions with any companies interested in OFDM or compatible technologies

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Thank you !

Questions ?

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Backup slides

Modulation and Coding Schemes

for CP lengths of 160 ns and 220 ns

Minimum Data Rate	Modulation	Coding Rate	Data bytes per OFDM symbol
335 Mbps	BPSK	1/2	52.5
500 Mbps	BPSK	3/4	78.75
675 Mbps	QPSK	1/2	105
1000 Mbps	QPSK	3/4	157.5
1350 Mbps	16-QAM	1/2	210
2000 Mbps	16-QAM	3/4	315
2700 Mbps	64-QAM	2/3	420
3000 Mbps	64-QAM	3/4	472.5