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

Submission Title: Filtering for TG4m OFDM PHY

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Source: Soo-Young Chang (SYCA) and Cristina Seibert (Silver Spring Networks)
Voice: +1 530 574 2741, E-maill: sychang@ecs.csus.edu

Re: [802.15.4m]

Abstract: Raised cosine and root raised cosine filters are examined to apply them for TG4m OFDM signals. It is found that these filters make the signals meet the regulatory spectral requirements of white space bands and improve BER performance.

Purpose: To provide information on filtering OFDM signals to the 802.15 TG4m group

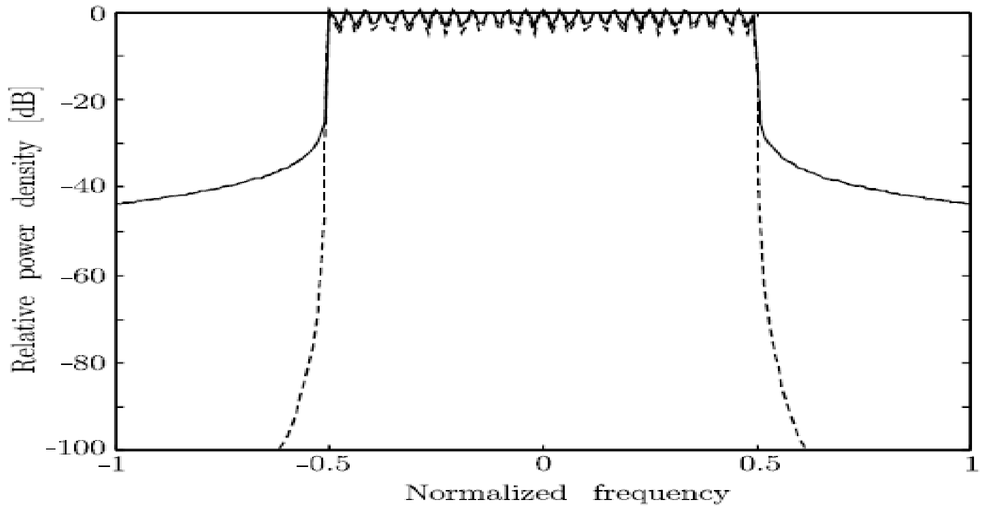
TG4m OFDM OVERVIEW AND INTRODUCTION

PROBLEMS TO BE SOLVED (1)

Problem 1: Pulse shaping is applied for frequency band limiting.

- Filtering is needed at transmitter and probably at receiver.
  - For TG4m applications, -55.4 dBr attenuation is necessary at the edge of a channel band to satisfy white space out-of-band emission rules.

Spectrum with rectangular pulse (solid) and raised cosine pulse (dashed)



What type of filtering is the best at transmitter and at receiver respectively for TG4m OFDM?

PROBLEMS TO BE SOLVED (2)

Problem 2: Filtering may improve BER performance.

- Three issues causing symbol errors
  - **ISI**: signal spill-over in time domain
  - **White noise**: uniformly distributed interference in frequency domain
  - **Fading**: delayed signals caused by different reflected paths

What type of filtering is the best at transmitter and at receiver respectively for TG4m OFDM?

PROBLEMS TO BE SOLVED (3)

Solution for these problems?

- One issue for frequency band limiting
  - **Pulse shaping**: The **raised-cosine filter** is a filter frequently used for pulse-shaping in digital modulation due to **its ability to minimize inter-symbol interference (ISI)**. *
- Three issues causing symbol errors
  - **ISI**: **raised cosine filtering** is inherently effective to ISI even with mild delay spreads.
  - **White noise**: **matched filtering** mitigates white noise effects
  - **Fading**: delayed signals caused by different reflected paths

What type of filtering is the best at transmitter and at receiver respectively for TG4m OFDM?
→ **Raised cosine filters or root raised cosine filters** are strong candidates for TG4m pulse shaping.

* http://en.wikipedia.org/wiki/Raised-cosine_filter

TYPES OF FILTERS

Filter: a device or process that removes from a signal some unwanted component or feature. Most often, this means **removing some frequencies and not others in order to suppress interfering signals and reduce background noise**.

- Butterworth filter – no gain ripple in pass band and stop band, slow cutoff
- Chebyshev filter (Type I) – no gain ripple in stop band, moderate cutoff
- Chebyshev filter (Type II) – no gain ripple in pass band, moderate cutoff
- Bessel filter – no group delay ripple, no gain ripple in both bands, slow gain cutoff
- Elliptic filter – gain ripple in pass and stop band, fast cutoff
- Optimum "L" filter
- Gaussian filter – no ripple in response to step function
- Hourglass filter
- Raised-cosine filter

* http://en.wikipedia.org/wiki/Filter_(signal_processing)

TYPES OF FILTERS CONSIDERED

Filtering at transmitter

- Raised cosine filter
- Root raised cosine filter
- Brick-wall filter
- Other types of filters

Filtering at receiver

- Matched filter
- Root raised cosine filter
- Simply Brick-wall filter
- No filtering
- Other types of filters

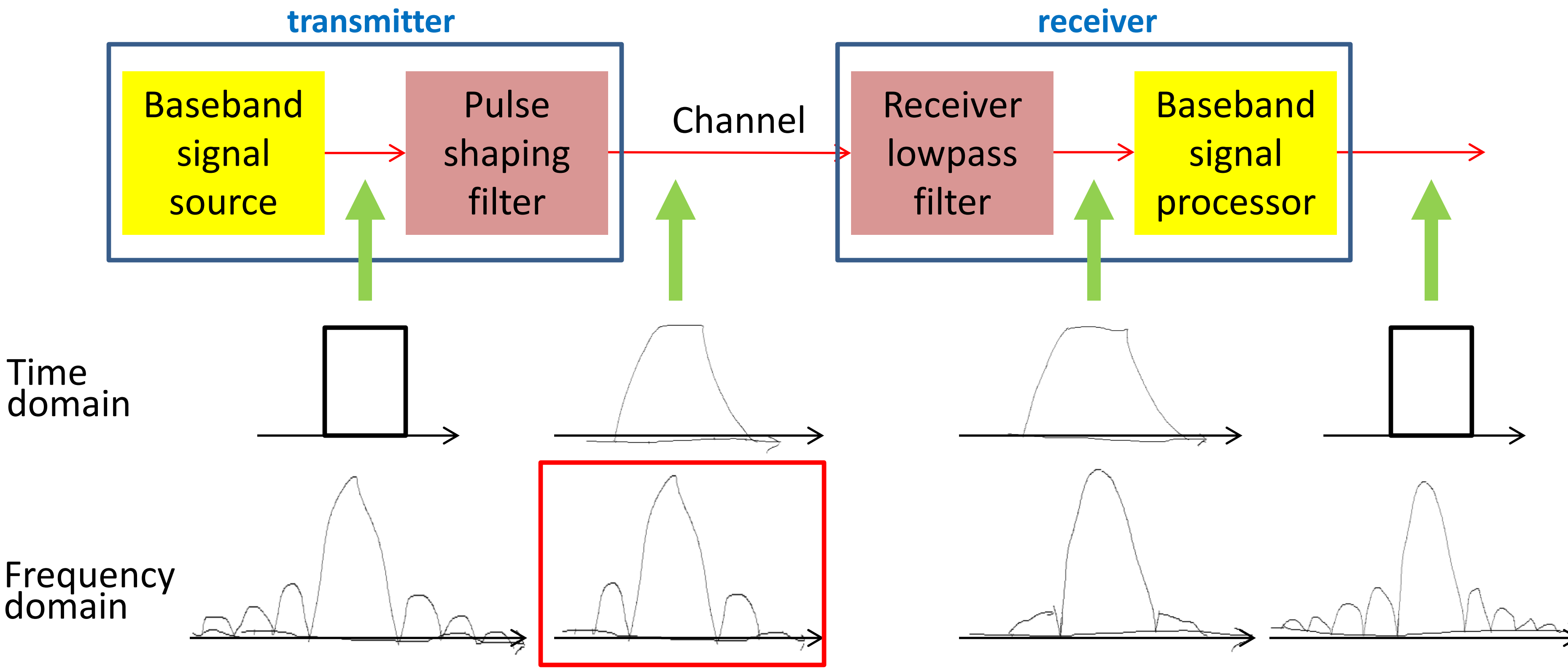
TYPES OF IMPLEMENTATION OF FILTERS

Filter implementation

- analog or digital
- discrete-time (sampled) or continuous-time
- linear or non-linear
- time-invariant or time-variant, also known as shift invariance. If the filter operates in a spatial domain then the characterization is space invariance.
- passive or active type of continuous-time filter
- infinite impulse response (IIR) or finite impulse response (FIR) type of discrete-time or digital filter.

* http://en.wikipedia.org/wiki/Filter_(signal_processing)

TYPES OF FILTERS APPLIED FOR COMMUCATIONS



For each case, this spectrum needs to be reviewed to check whether the spectrum of the transmitted signal meets emission requirements.

SUMMARY OF PROPOSED TG4m OFDM PARAMETERS *

- Subcarrier spacing
  - (9765 and 5/8) Hz or (78125/8) Hz
- OFDM symbol rate
  - 7.8125 ksymbols/s, which corresponds (4/5)x(78125/8) or 128 µs per symbol
  - a quarter-duration cyclic prefix (CP; 25.6 µs) + a base symbol (102.4 µs)
- Two OFDM modes

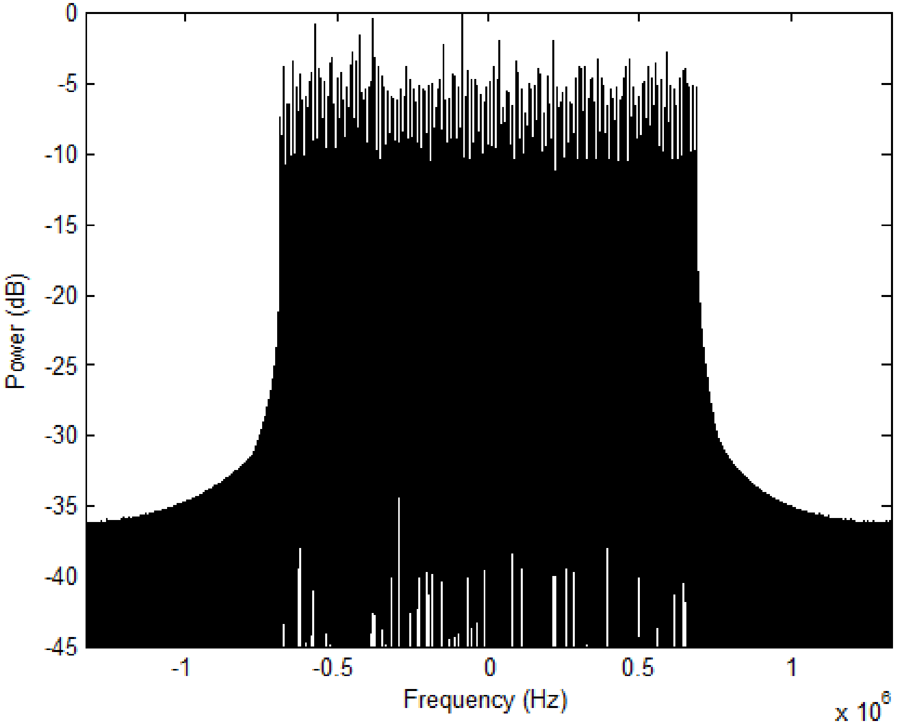
Simulations only for this mode

Parameter	Mandatory mode	Optional mode (4 times overclock mode)
Channel spacing (kHz)	1250	4*1250
Nominal bandwidth (kHz)	1064.5	4248
DFT size	**128**	**128**
modulation	**BPSK, QPSK, 16QAM**	**BPSK, QPSK, 16QAM**

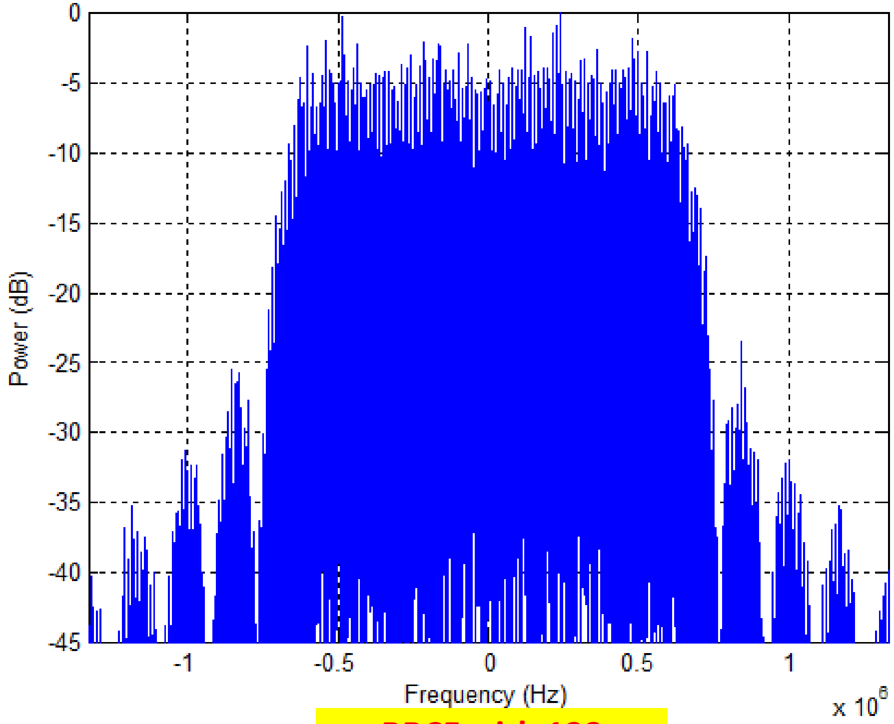
* 15-12-0481-01-004m-Ofdm-PHY-Merged-Proposal-for-tg4m

PULSE SHAPING FILTERING FOR TG4m OFDM

SPECTRA WITH AND WITHOUT RAISED COSINE FILETERING (1)



No filtering with 128 subcarriers

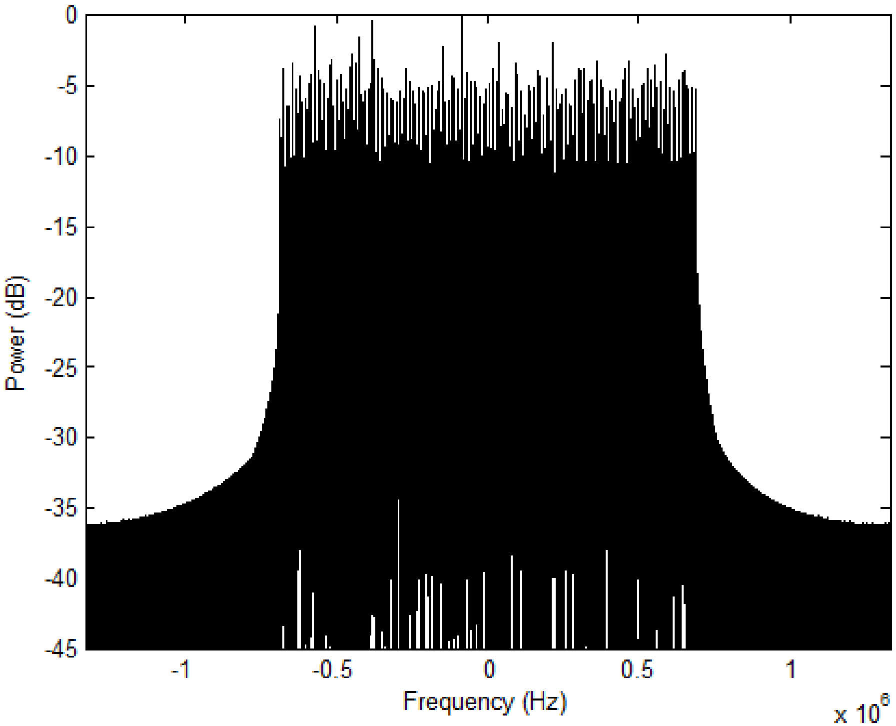


RRCF with 128 subcarriers and filter order of 128

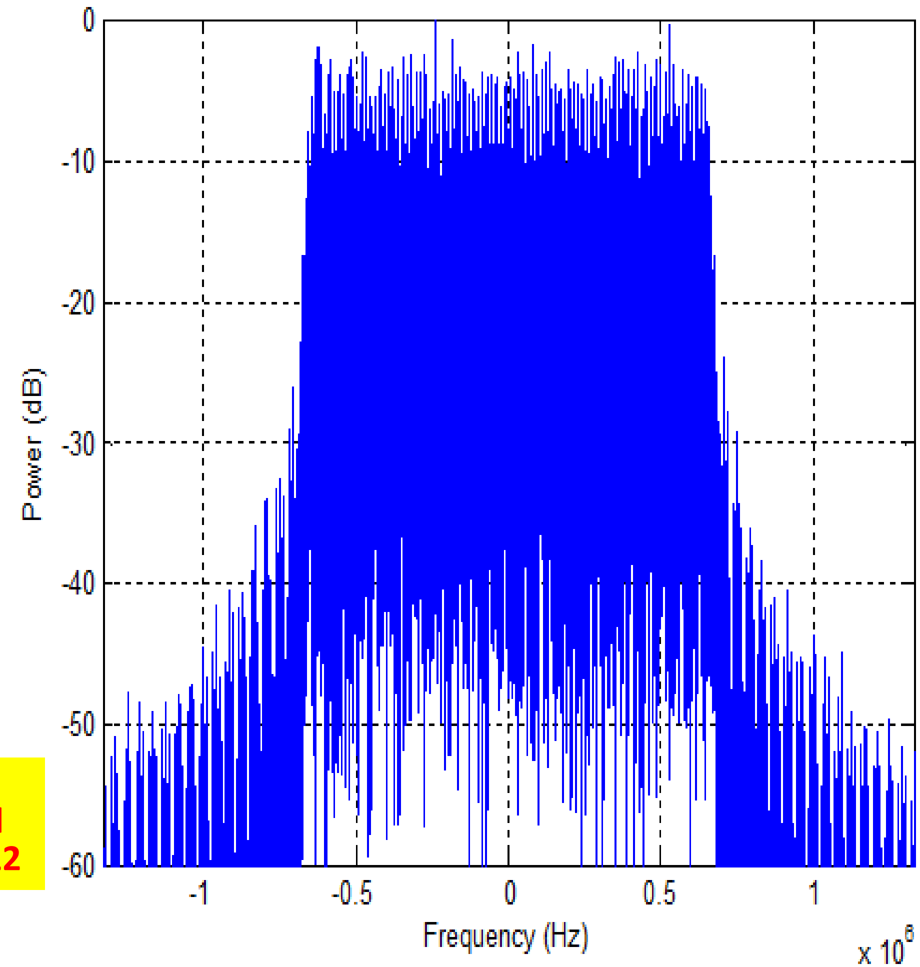
A filter is needed at transmitter to meet spectral mask requirements.

* Similar results can be found in 15-12-0377-00-004m-TG4m-OFDM-filtering.

SPECTRA WITH AND WITHOUT RAISED COSINE FILETERING (2)



No filtering with 128 subcarriers



RRCF with 128 subcarriers and filter order of 512

A filter is needed at transmitter to meet spectral mask requirements.

* Similar results can be found in 15-12-0377-00-004m-TG4m-OFDM-filtering

EFFECT OF FILTER ORDERS AND ROLL OFF FACTORS OF RCF AND RRCF

		Raised cosine filter (RCF)				Root raised cosine filter (RRCF)			
	Filter order	3dB BW (MHz)	20dB BW (MHz)	-55dBr BW (MHz)	-55dBr from inband edge (MHz)	3dB BW (MHz)	20dB BW (MHz)	-55dBr BW (MHz)	-55dBr from inband edge (MHz)
roll off factor of 0	32	0.5	1.4	>10	>4.5	0.6	1.5	>10	>4.5
	128	**0.95**	**1.15**	**6.1**	**2.55**	**0.95**	**1.2**	**4.5**	**1.75**
	512	1.05	1.05	3.1	1.05	0.95	1.05	2.6	0.8
roll off factor of 0.5	32	0.8	1.4	>10	>4.5	0.65	1.6	>10	>4.5
	128	**0.9**	**1.4**	**2.0**	**0.5**	**1.05**	**1.4**	**3.8**	**1.4**
	512	0.9	1.35	1.45	0.23	1.15	1.4	1.5	0.25
roll off factor of 1	32	0.8	1.6	3.7	0.85	1.05	1.8	>10	>4.5
	128	**0.8**	**1.6**	**1.95**	**0.48**	**1.2**	**1.8**	**2.9**	**0.95**
	512	0.75	1.6	1.9	0.45	1.3	1.85	2.0	0.5

* 15-12-0249-01-004m-OFDM-filtering-for-TG4m, May 2012

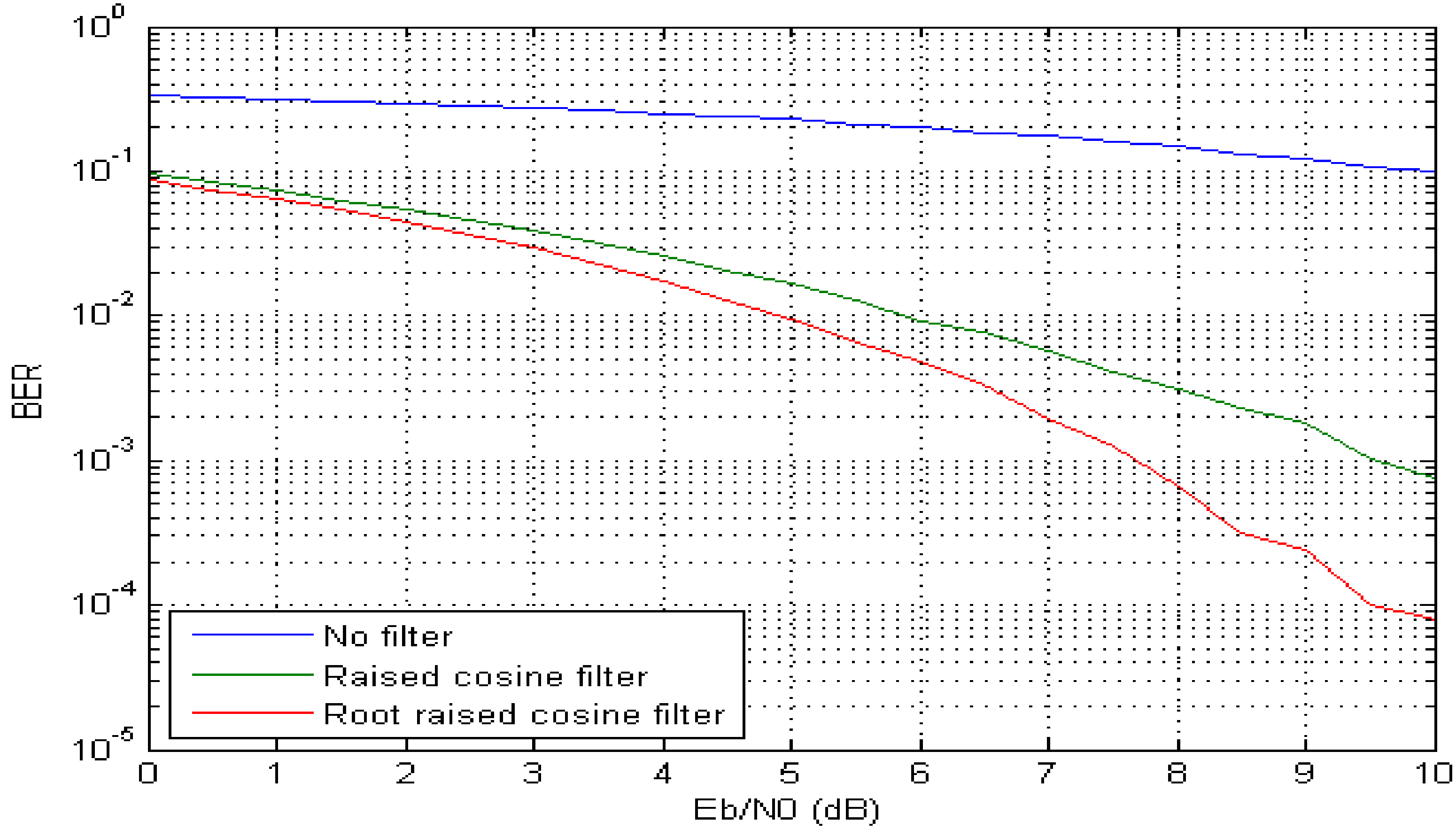
BER PERFORMANCE OF RAISED COSINE FILTERING WITH NO GUARD INTERVALS

TYPES OF FILTERS APPLIED FOR SIMULATIONS

	Filtering at transmitter	Filtering at receiver	
Case 0:	No filter →	No filter	No filter
Case 1:	Raised cosine filter →	No filter	
Case 2:	Raised cosine filter →	Matched filter (raised co	Raised cosine filter
Case 3:	Root raised cosine filter →	Root raised cosine filter	Root raised cosine filter
Case 4:	Raised cosine filter →	Mis-matched raised cosi	Roll-off mismatching

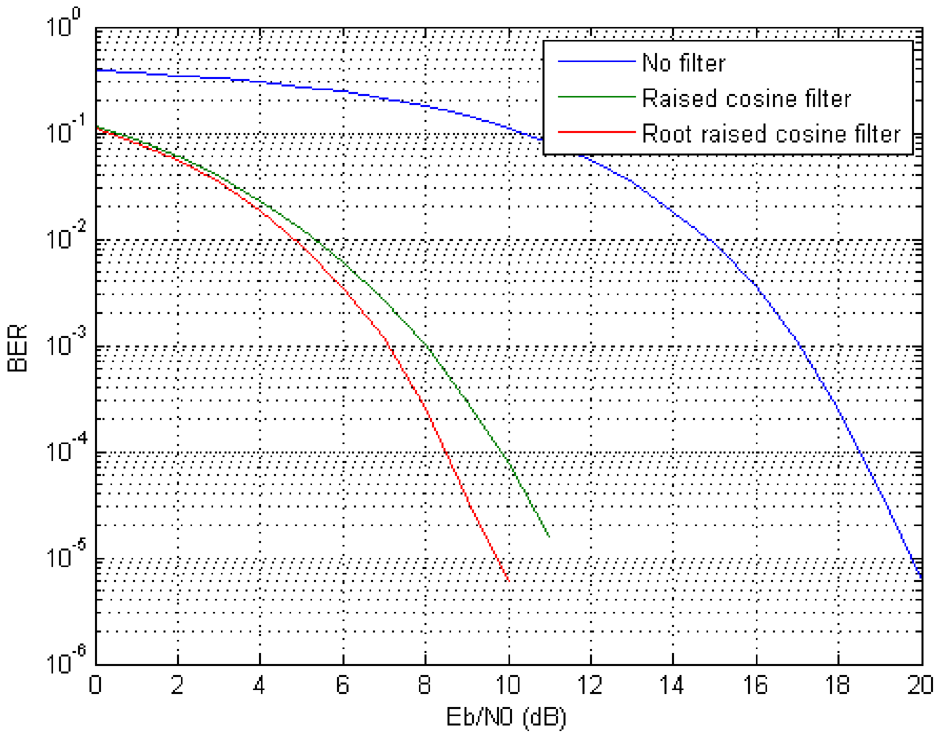
BER PERFORMANCE WITH NO MULTIPATH AND ONLY WITH AWGN

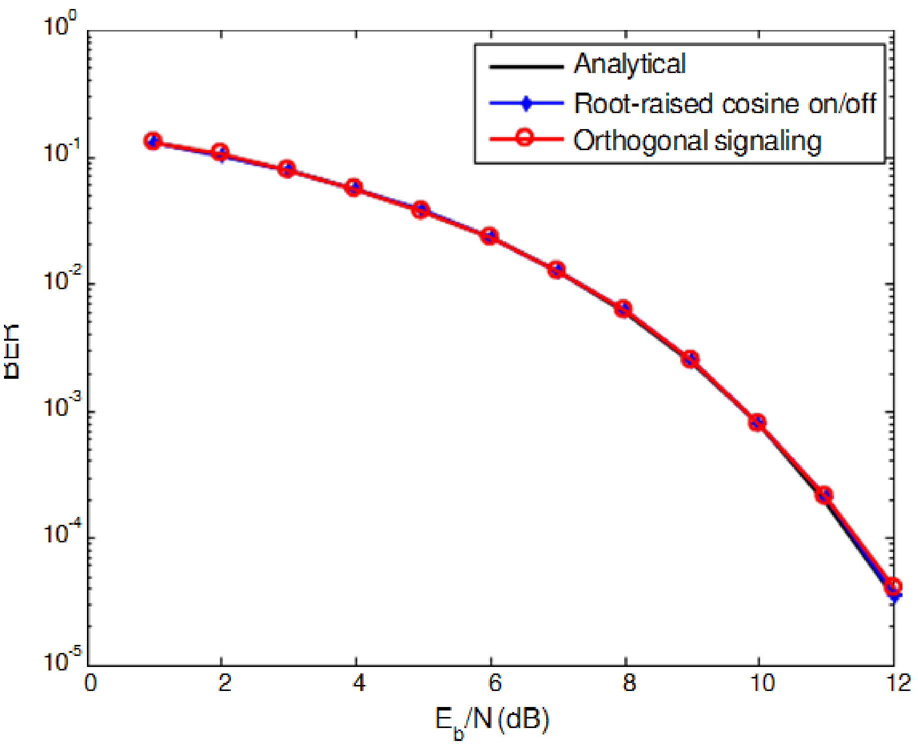
- **Without applying multipath fading and only with AWGN**



RAISED COSINE AND WHITE NOISE

From our simulation results with no fading





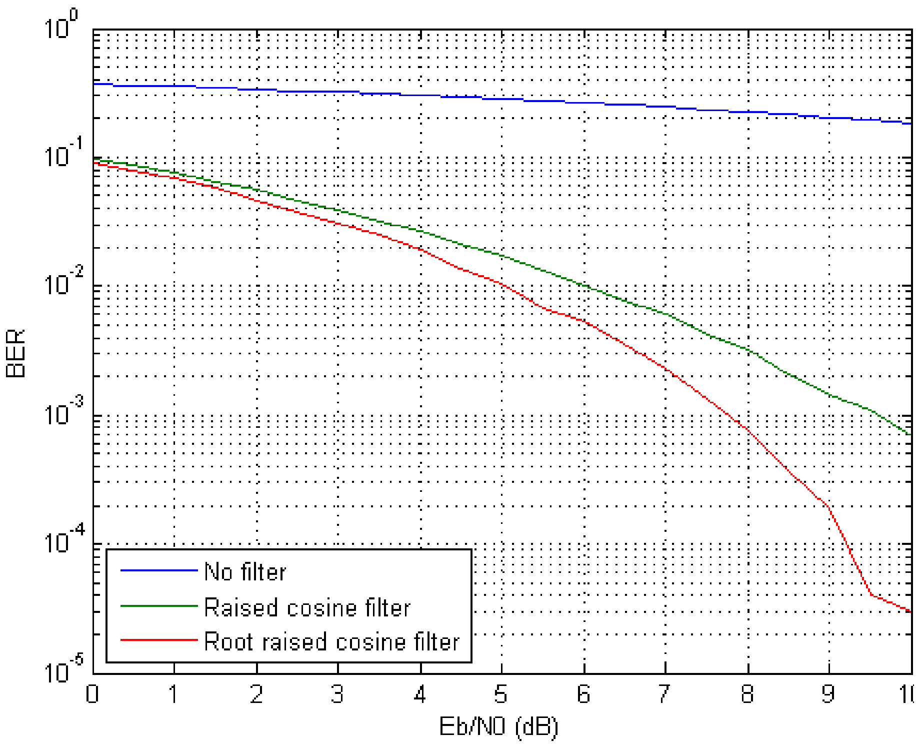
Measured results match the analytical BER for AWGN.

http://www.scribd.com/doc/98611310/BER-performance-for-BPSK

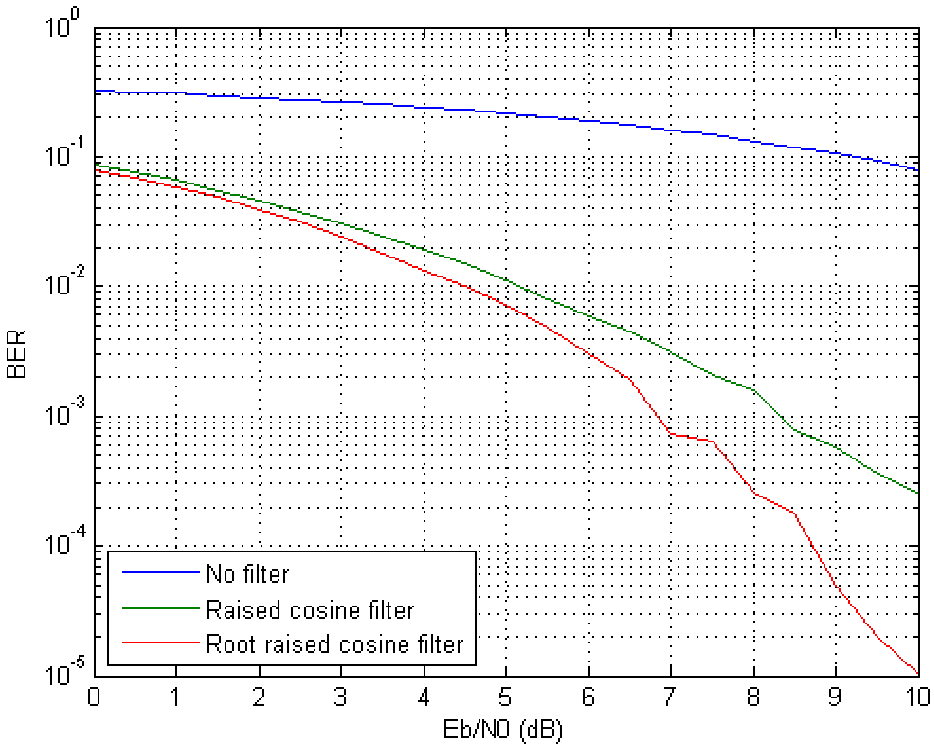
BER PERFORMANCE WITH RCF AND RRCF FOR VARIOUS CHANNEL MODELS (1)

- Roll off factor: 0.5, using BPSK, no. of subcarriers: 128, and Filter order: 128, **no guard intervals**

Indoor multipath channel



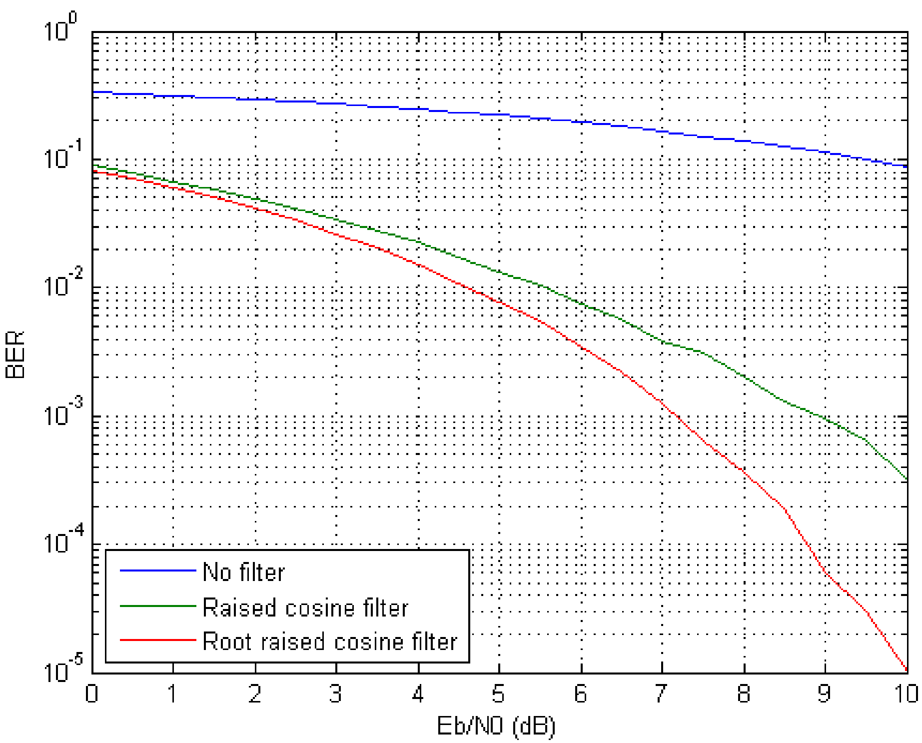
Outdoor multipath channel A



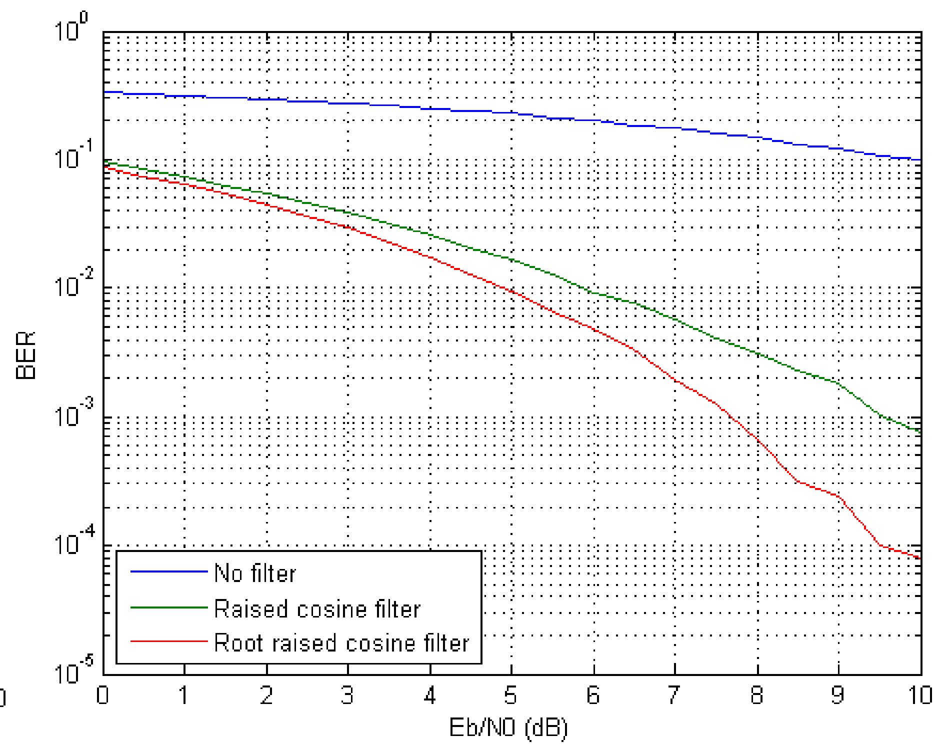
BER PERFORMANCE WITH RCF AND RRCF FOR VARIOUS CHANNEL MODELS (2)

- Roll off factor: 0.5, using BPSK, no. of subcarriers: 128, and Filter order: 128, **no guard intervals**

Outdoor multipath channel B



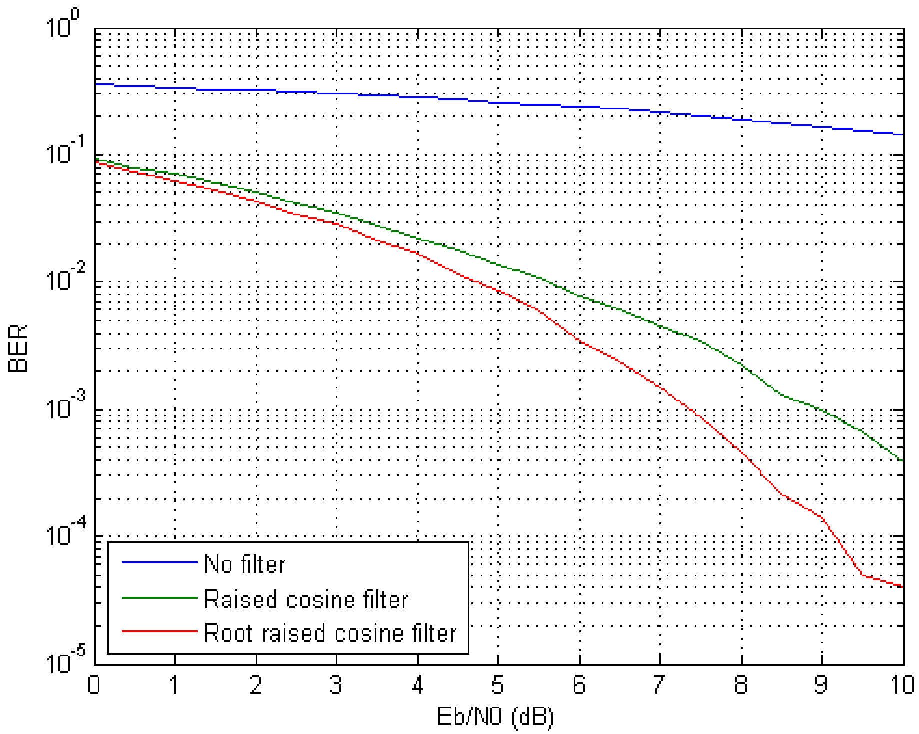
Outdoor multipath channel C



BER PERFORMANCE WITH RCF AND RRCF FOR VARIOUS CHANNEL MODELS (3)

- Roll off factor: 0.5, using BPSK, no. of subcarriers: 128, and Filter order: 128, **no guard intervals**

Outdoor multipath channel D

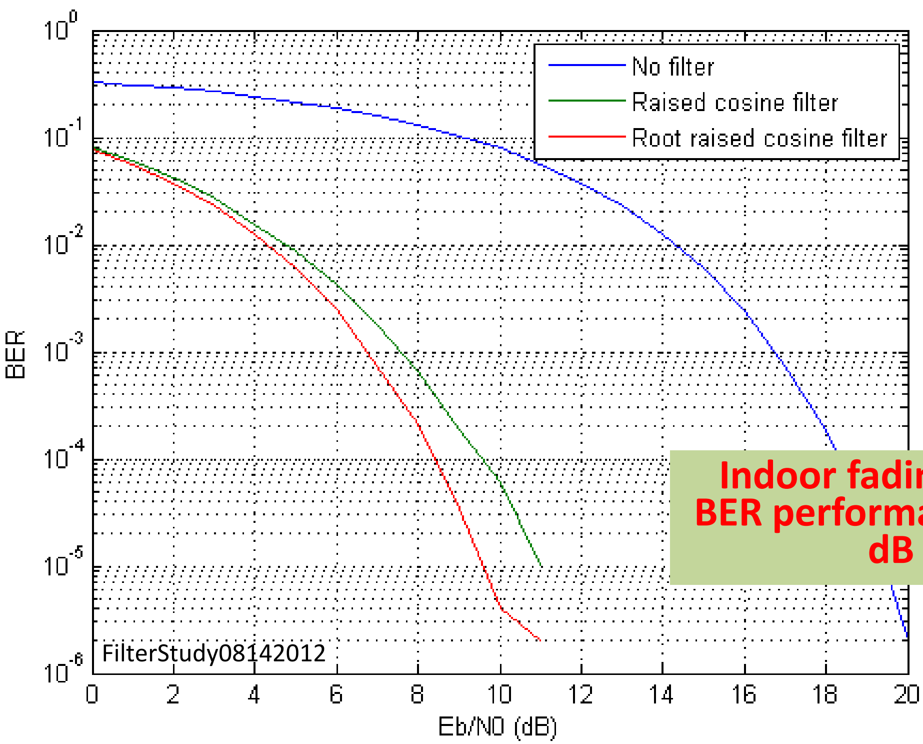


Raised cosine filtering used for pulse shaping improves BER performance.
Root raised cosine filters have better BER performance than raised cosine filters.

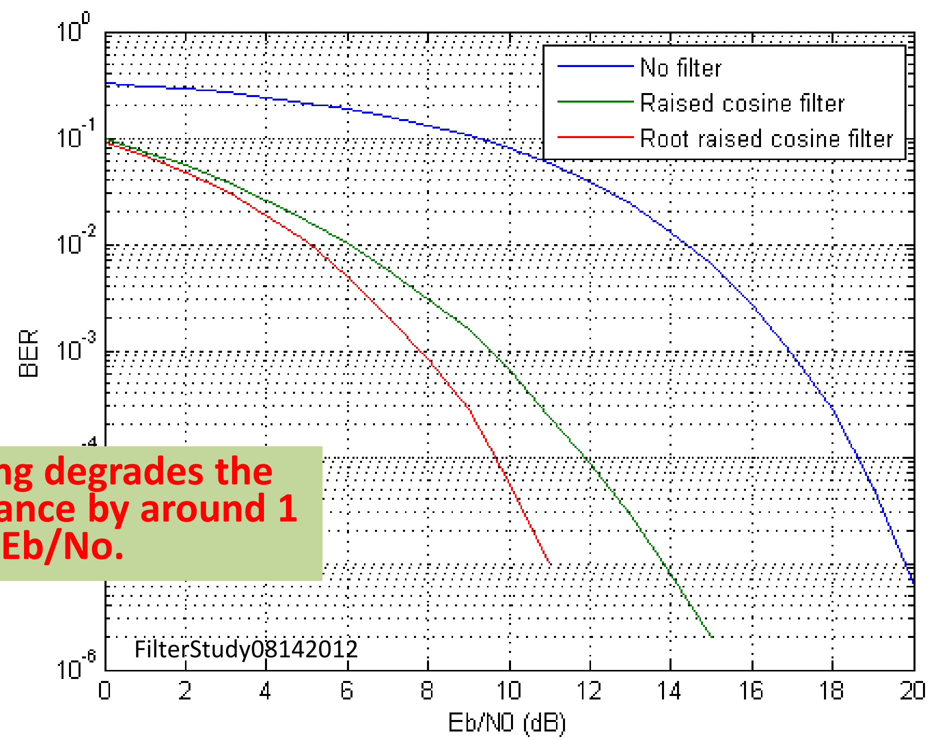
BER PERFORMANCE WITH RCF AND RRCF FOR BPSK AND QPSK (1)

- Roll off factor: 0.5, using **BPSK**, no. of subcarriers: 128, and Filter order: 128, **no guard intervals**

No fading



Indoor multipath channel

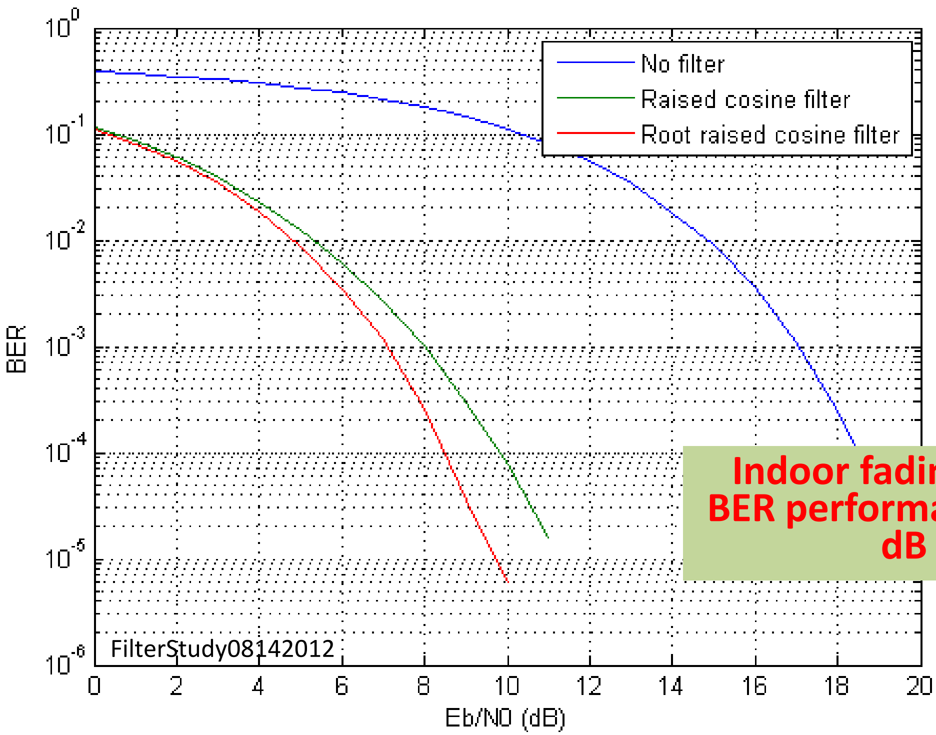


Indoor fading degrades the BER performance by around 1 dB Eb/No.

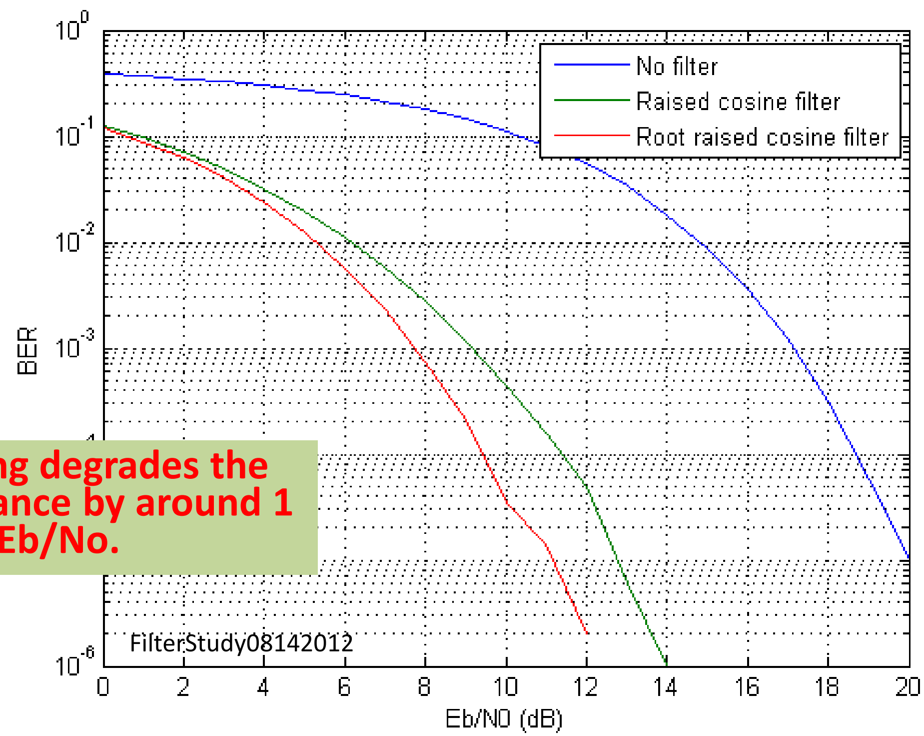
BER PERFORMANCE WITH RCF AND RRCF FOR BPSK AND QPSK (2)

- Roll off factor: 0.5, using **QPSK**, no. of subcarriers: 128, and Filter order: 128, **no guard intervals**

No fading



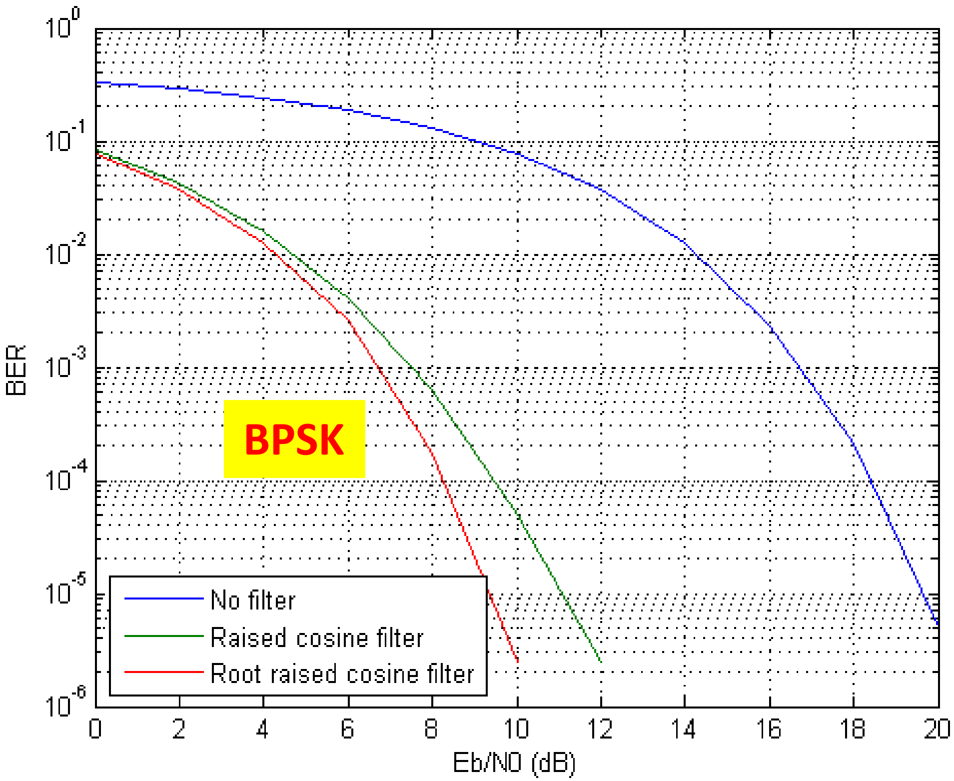
Indoor multipath channel

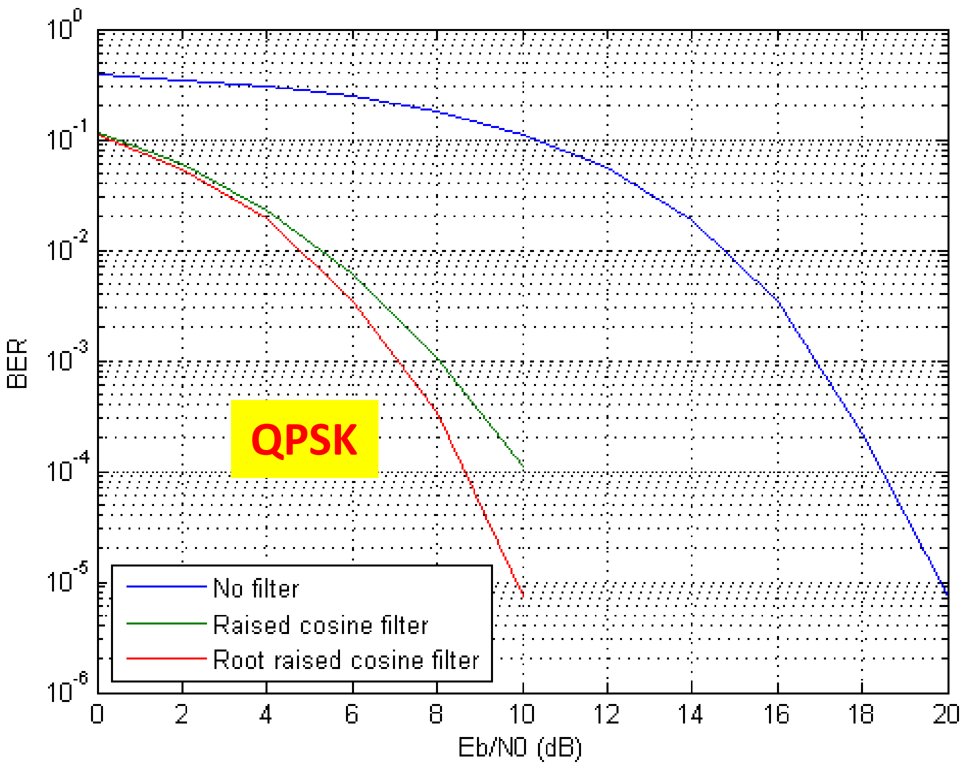


Indoor fading degrades the BER performance by around 1 dB Eb/No.

BER PERFORMANCE WITH RCF AND RRCF FOR BPSK AND QPSK (3)

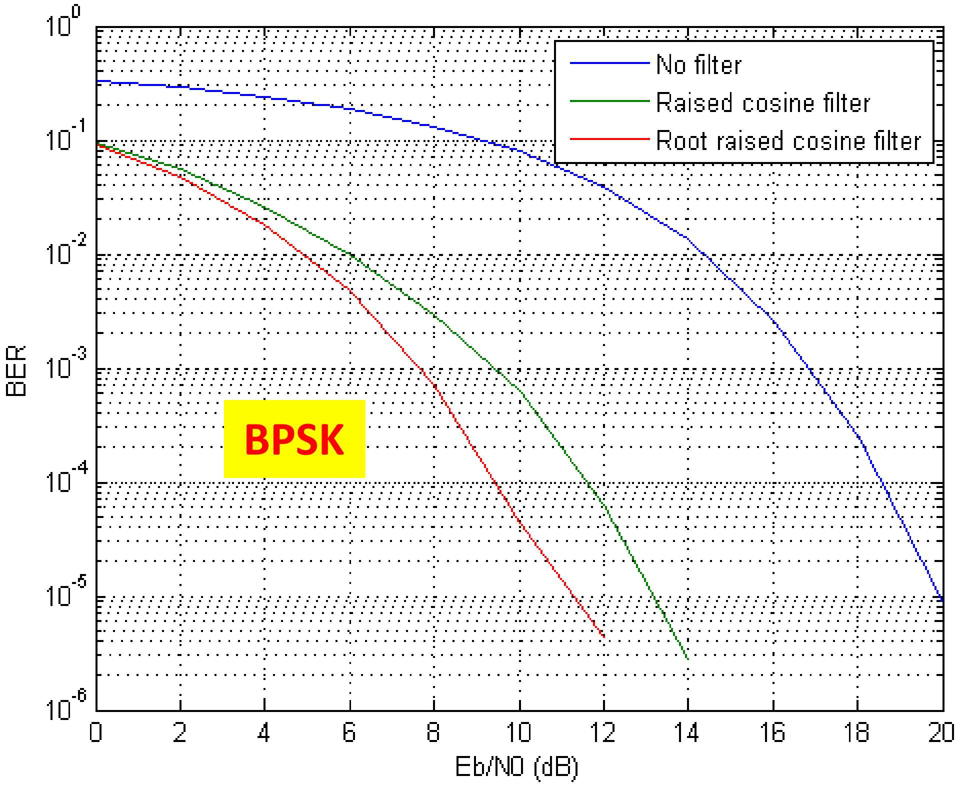
No fading

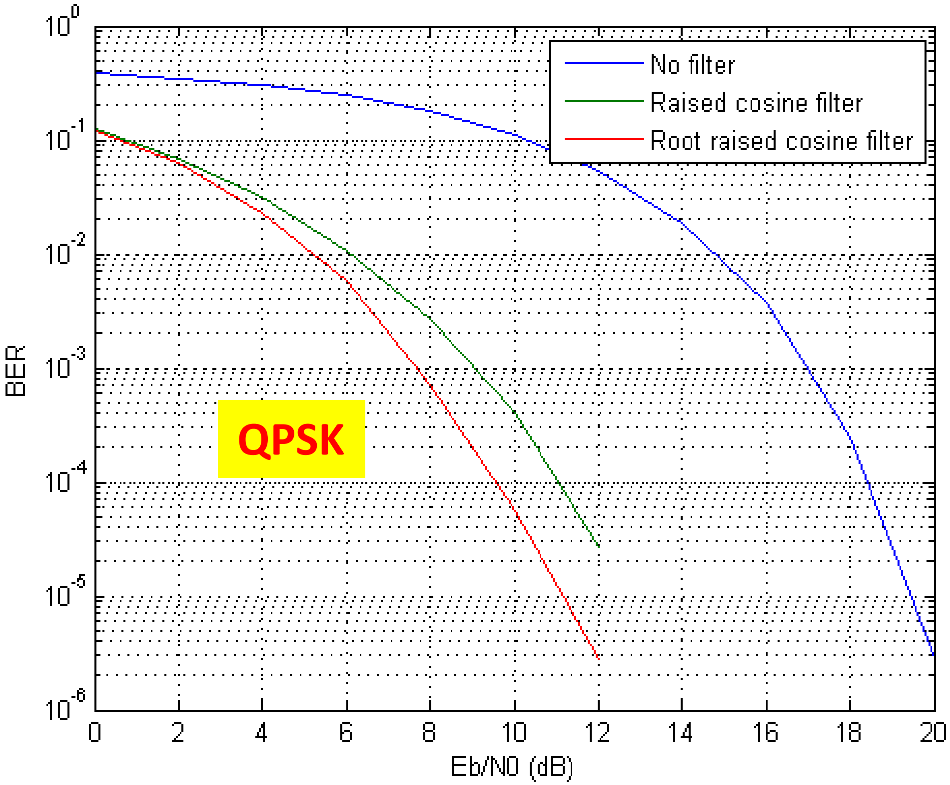




BER PERFORMANCE WITH RCF AND RRCF FOR BPSK AND QPSK (4)

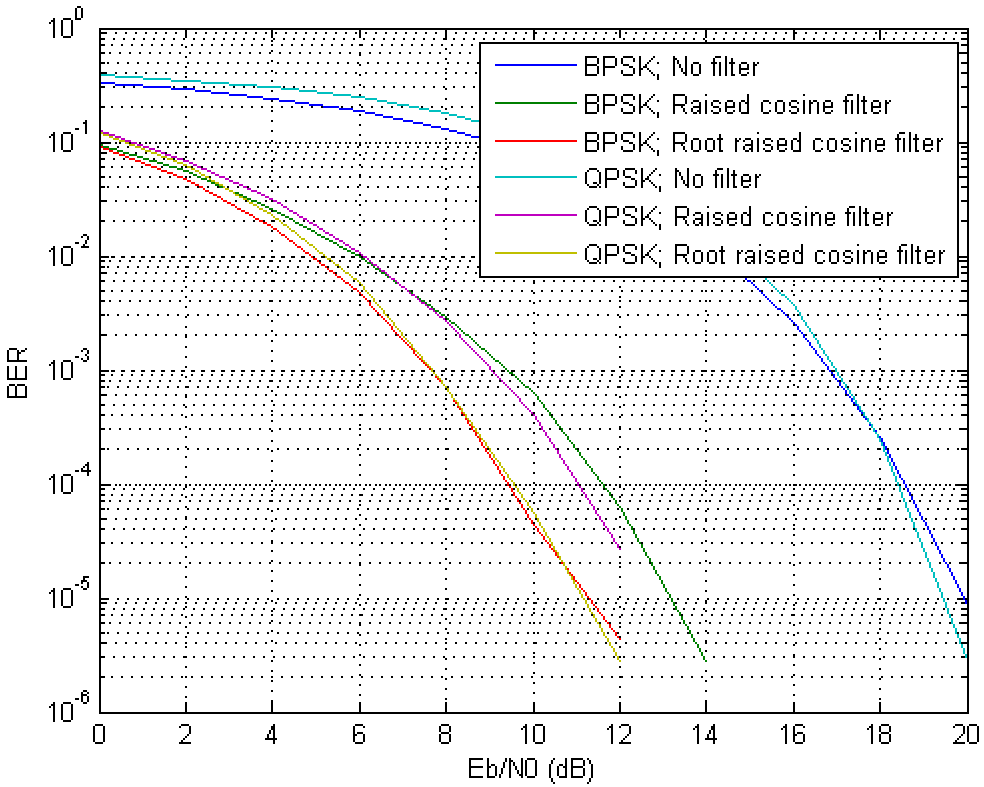
Indoor multipath channel





BER PERFORMANCE WITH RCF AND RRCF FOR BPSK AND QPSK (5)

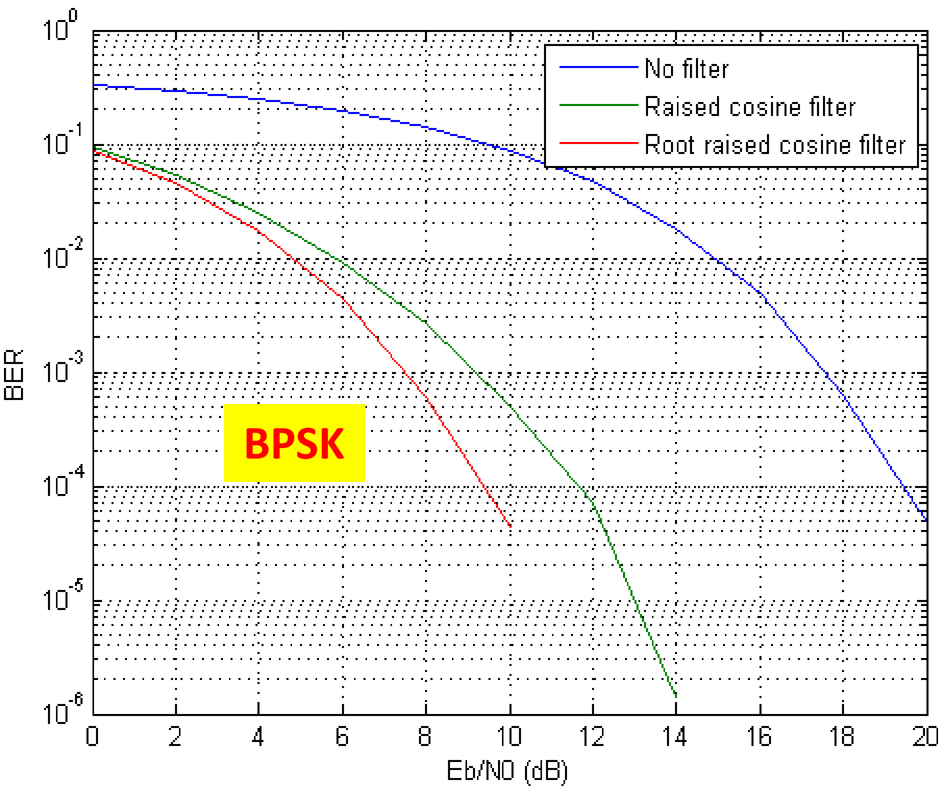
Indoor multipath channel

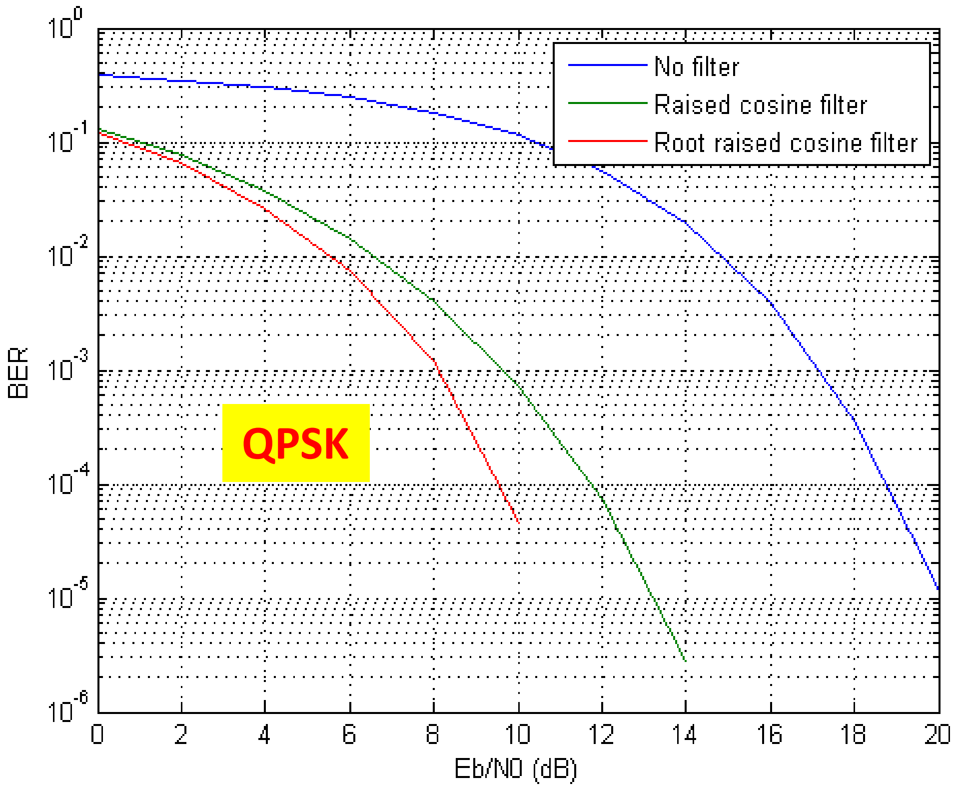


Rolloff=0.5;
Filter order=256;
No. samples per symbol=10

BER PERFORMANCE WITH RCF AND RRCF FOR BPSK AND QPSK (6)

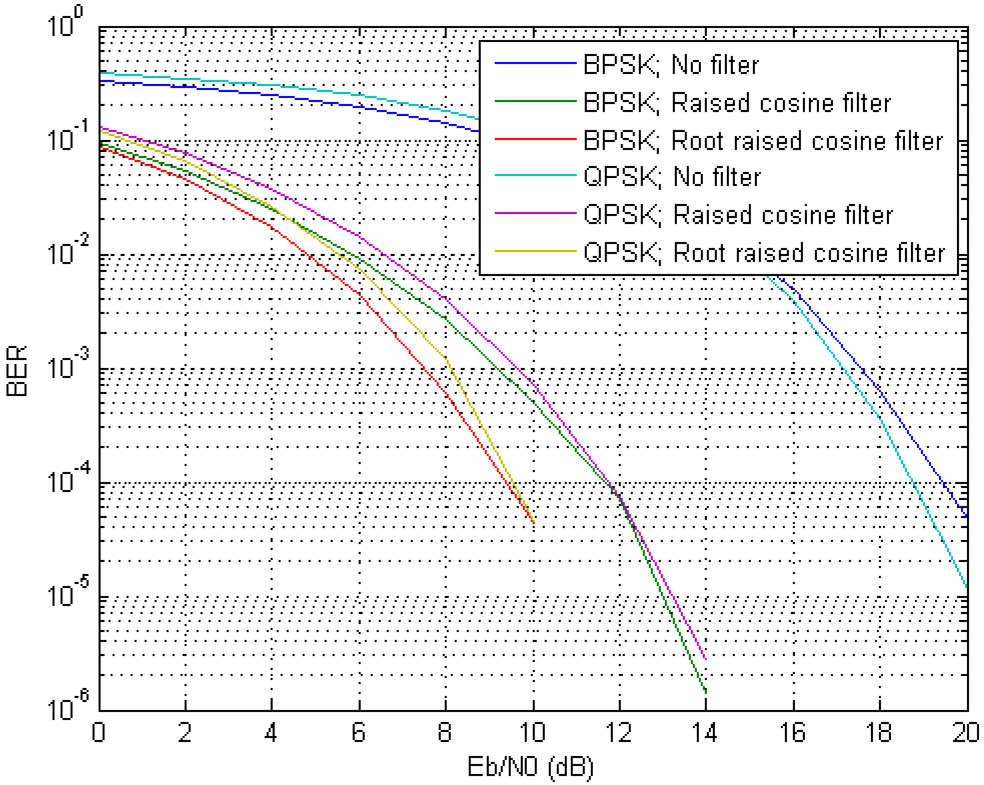
Outdoor multipath channel C





BER PERFORMANCE WITH RCF AND RRCF FOR BPSK AND QPSK (7)

Outdoor multipath channel C

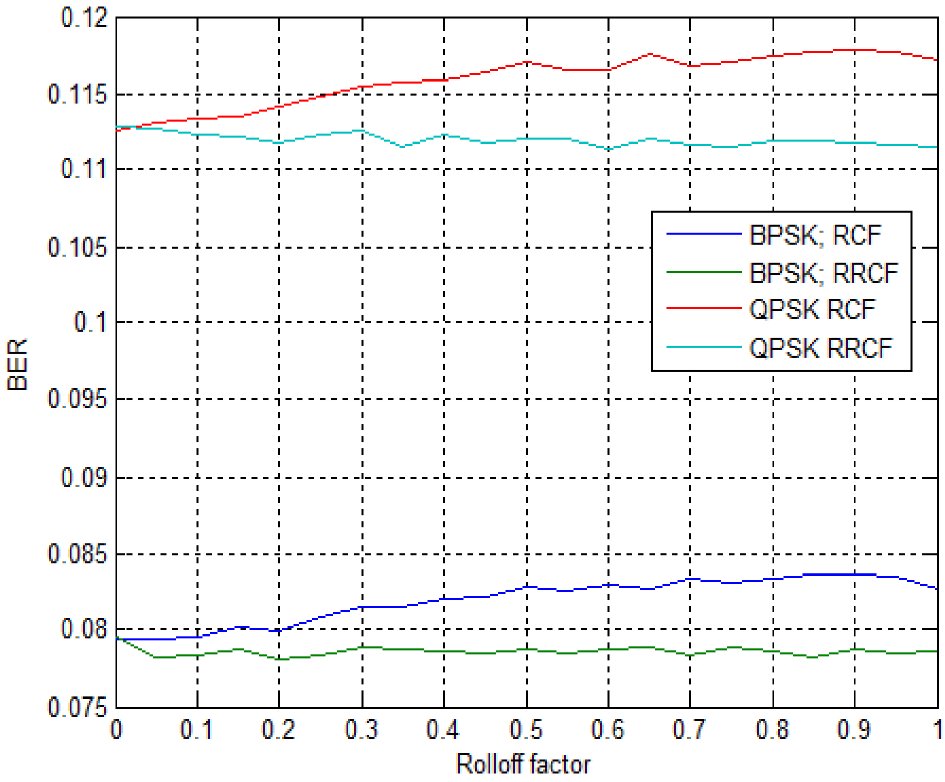


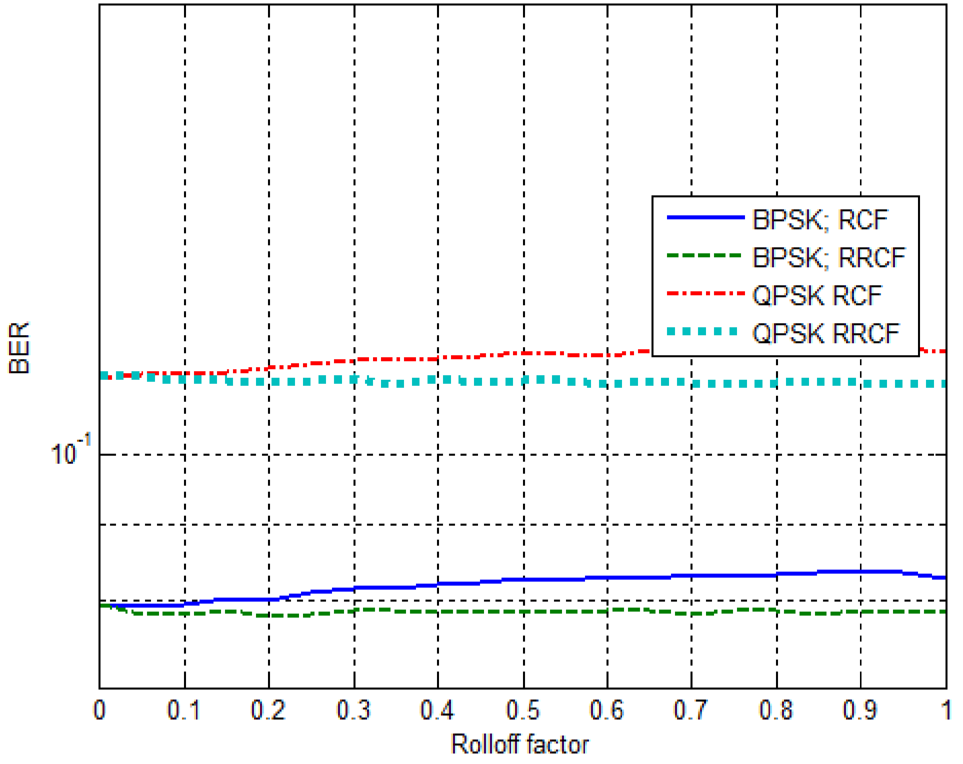
Rolloff=0.5;
Filter order=256;
No. samples per symbol=10

OFDM BER PERFORMANCE FOR VARIOUS ROLL-OFF FACTORS AND FILTER ORDERS

BER PERFORMANCE WITH RAISED COSINE FILTERING, VARIOUS ROLL-OFF FACTORS (1)

With no multipath fading: for Eb/N0 = 0dB

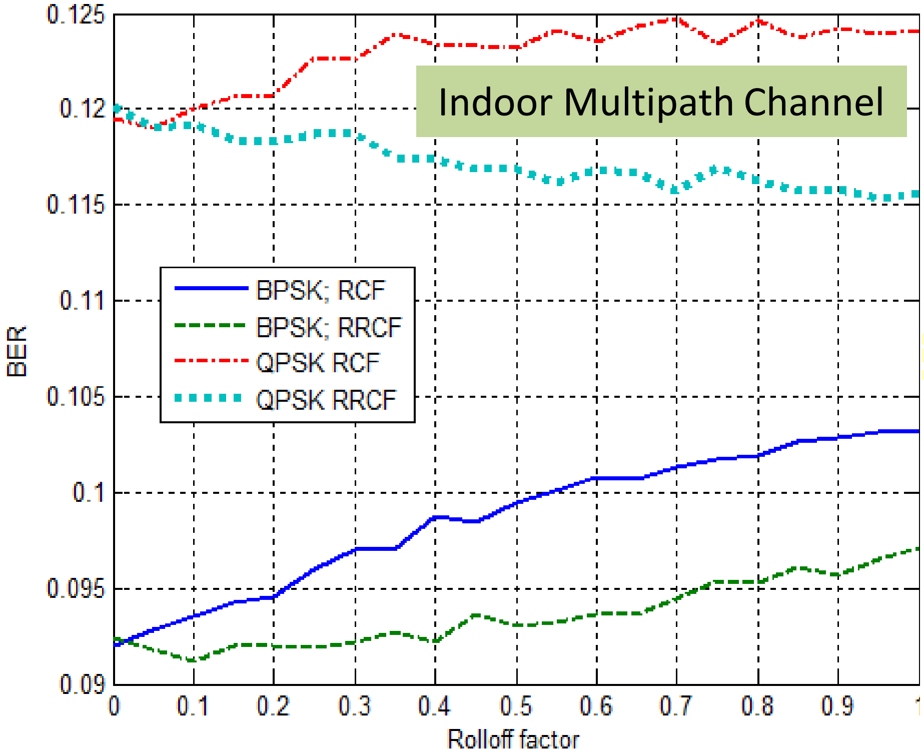


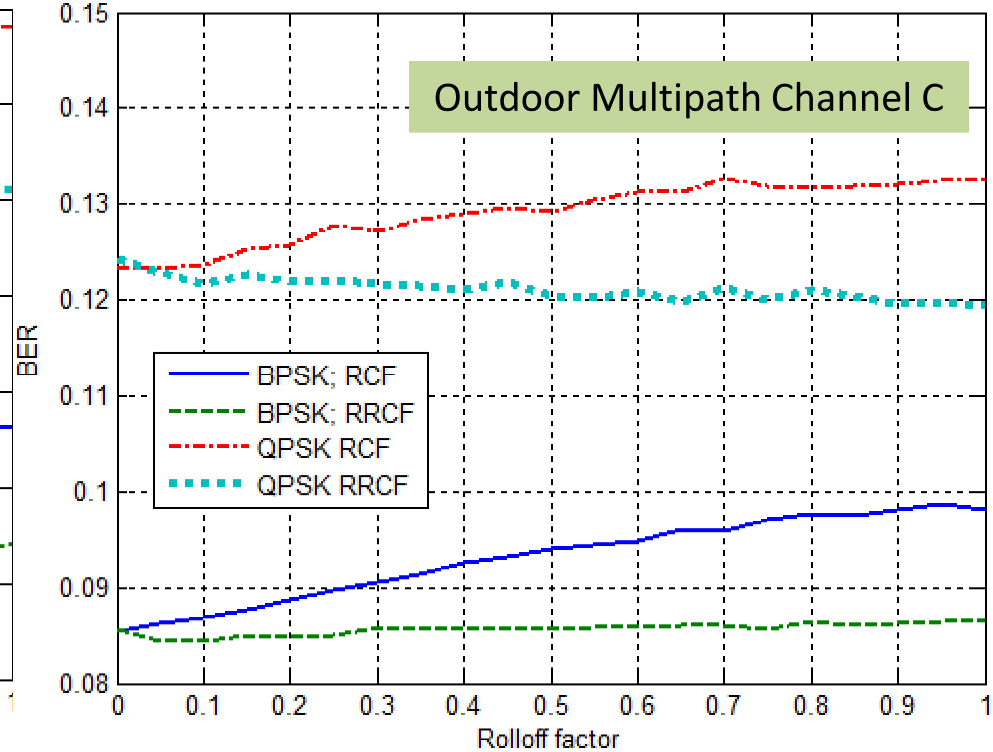


Increasing roll-off factors does not improve BER performance: BER with RRCF is not affected by roll-off factors while BER with RCF increases as its roll-off factor increases.

BER PERFORMANCE WITH RAISED COSINE FILTERING, VARIOUS ROLL-OFF FACTORS (2)

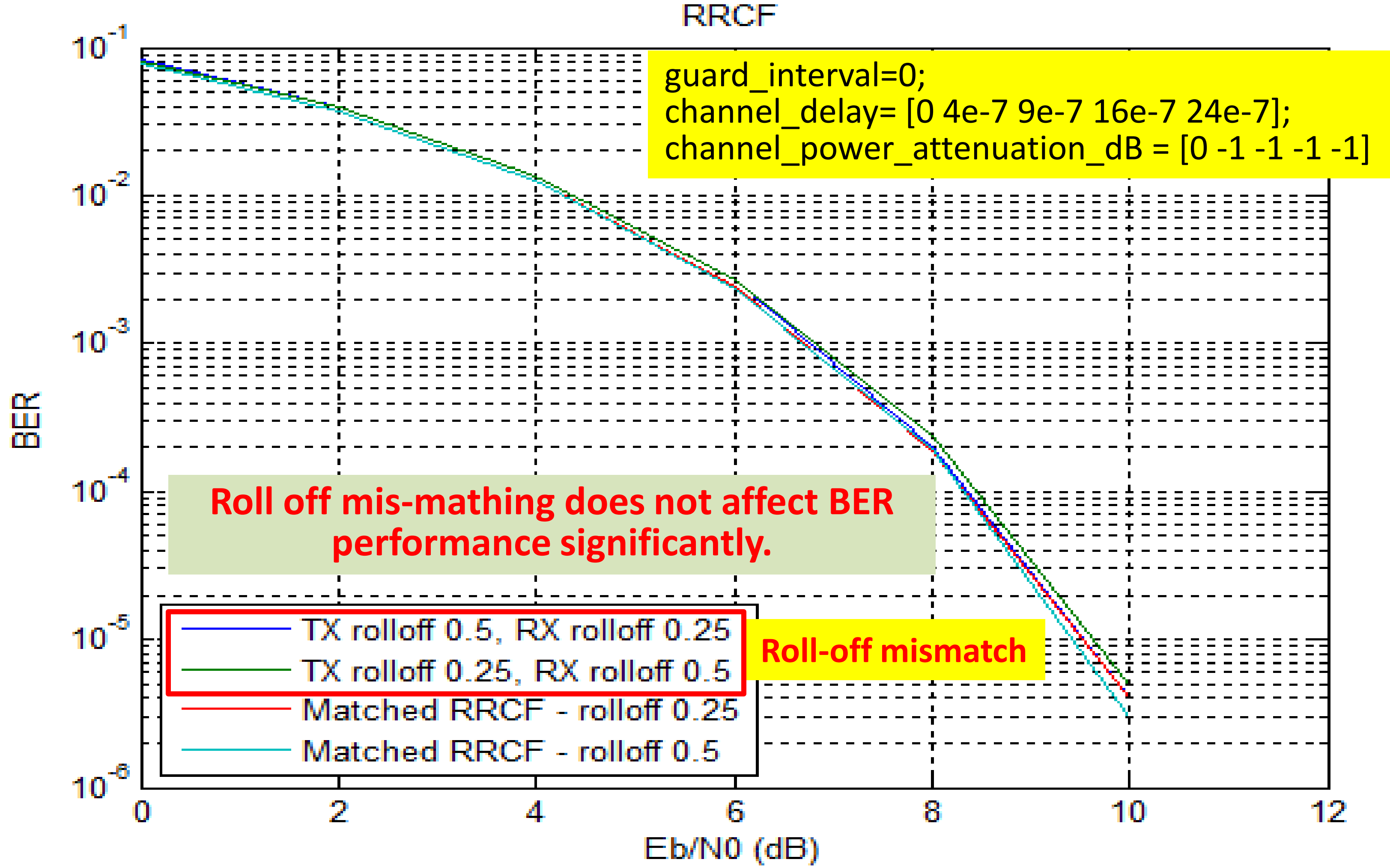
With multipath fading: for Eb/N0 = 0dB



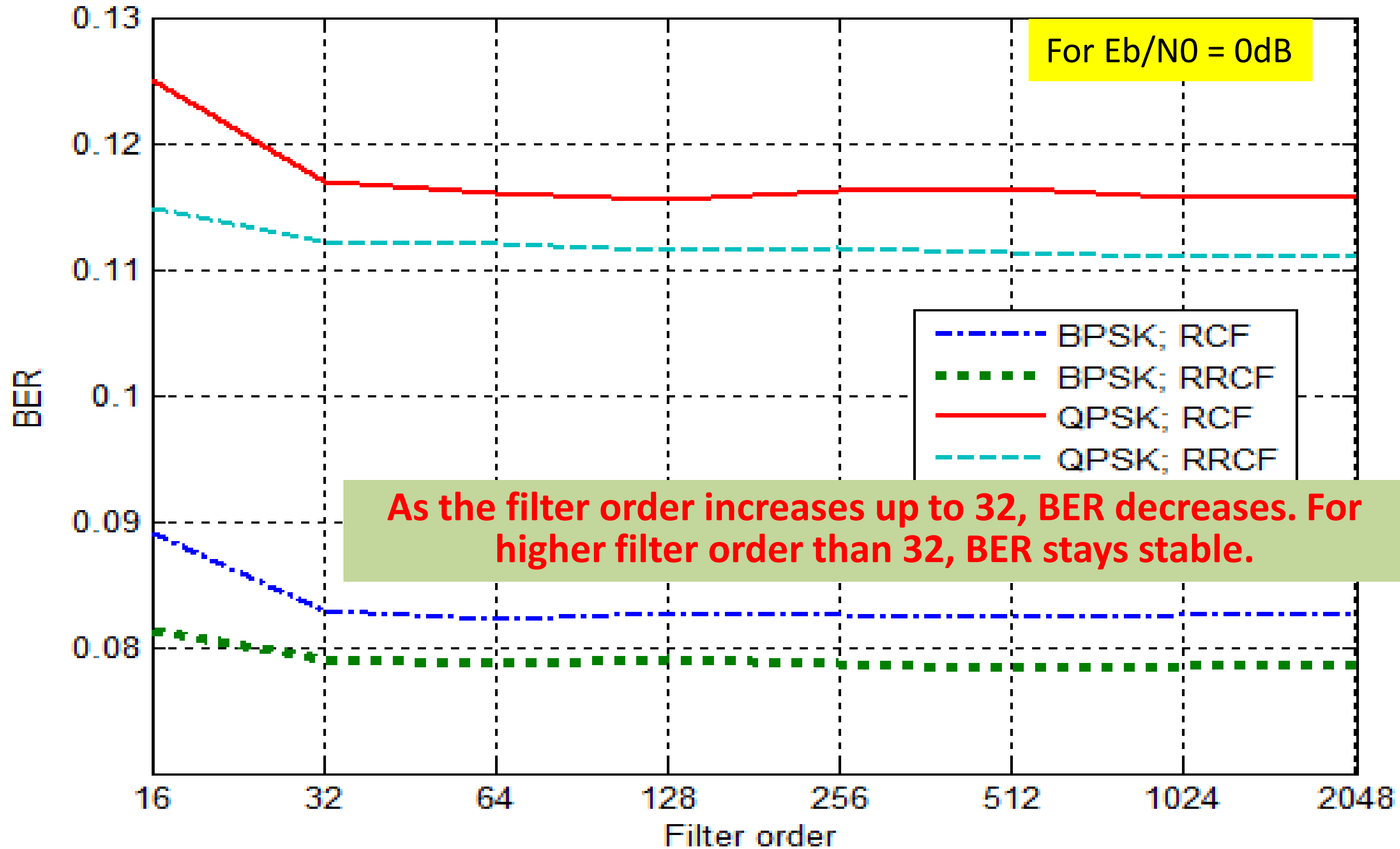


Multipath fading results in more BER difference between with RCF and with RRCF.

BER PERFORMANCE WITH RAISED COSINE FILTERING, ROLL-OFF MISMATCH



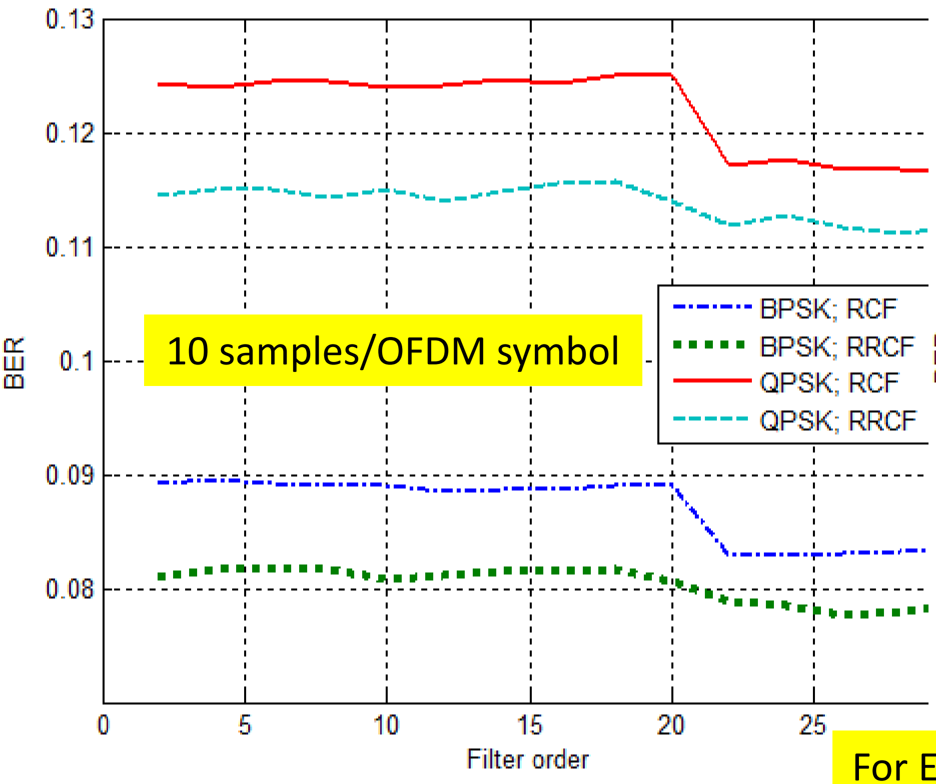
BER PERFORMANCE WITH RAISED COSINE FILTERING, VARIOUS FILTER ORDERS (1)

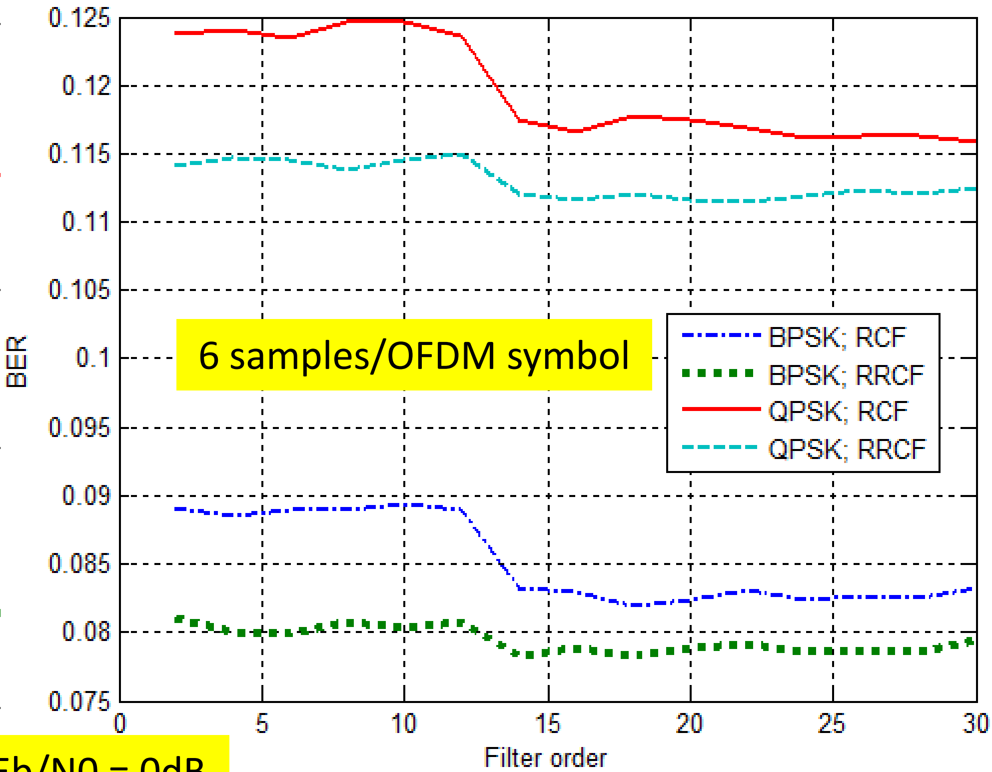


As the filter order increases up to 32, BER decreases. For higher filter order than 32, BER stays stable.

BER PERFORMANCE WITH RAISED COSINE FILTERING, VARIOUS FILTER ORDERS (2)

- There seems to be two levels of BER performances and the break-point happens when filter order = (no. Samples)*2.
- Filter order seems to have a more dynamic impact when we want to control the transmission (e.g., spectral over-spill) than when we study the reliability performance.



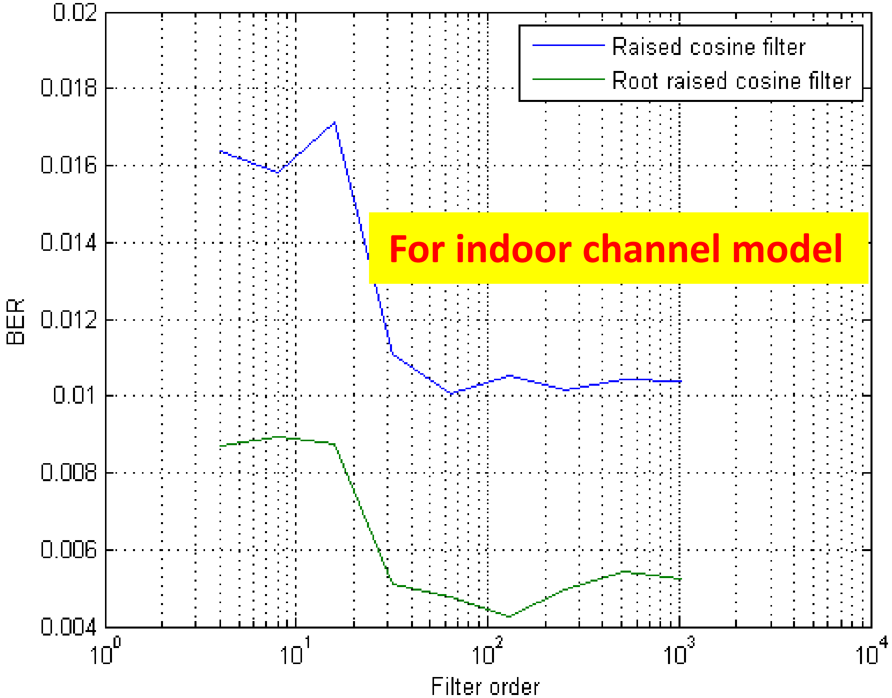


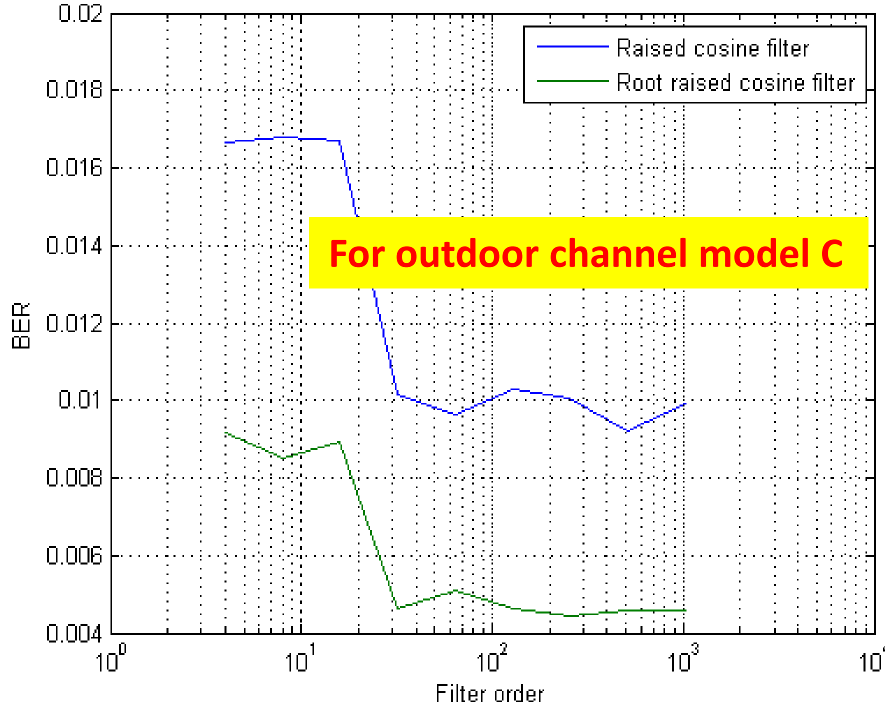
For Eb/N0 = 0dB

BER PERFORMANCE WITH RAISED COSINE FILTERING, VARIOUS FILTER ORDERS (3)

BER performance for various filter orders

- Roll off factor: 0.5, using BPSK, Eb/No: 6dB, **no. of subcarriers: 128** and no guard intervals



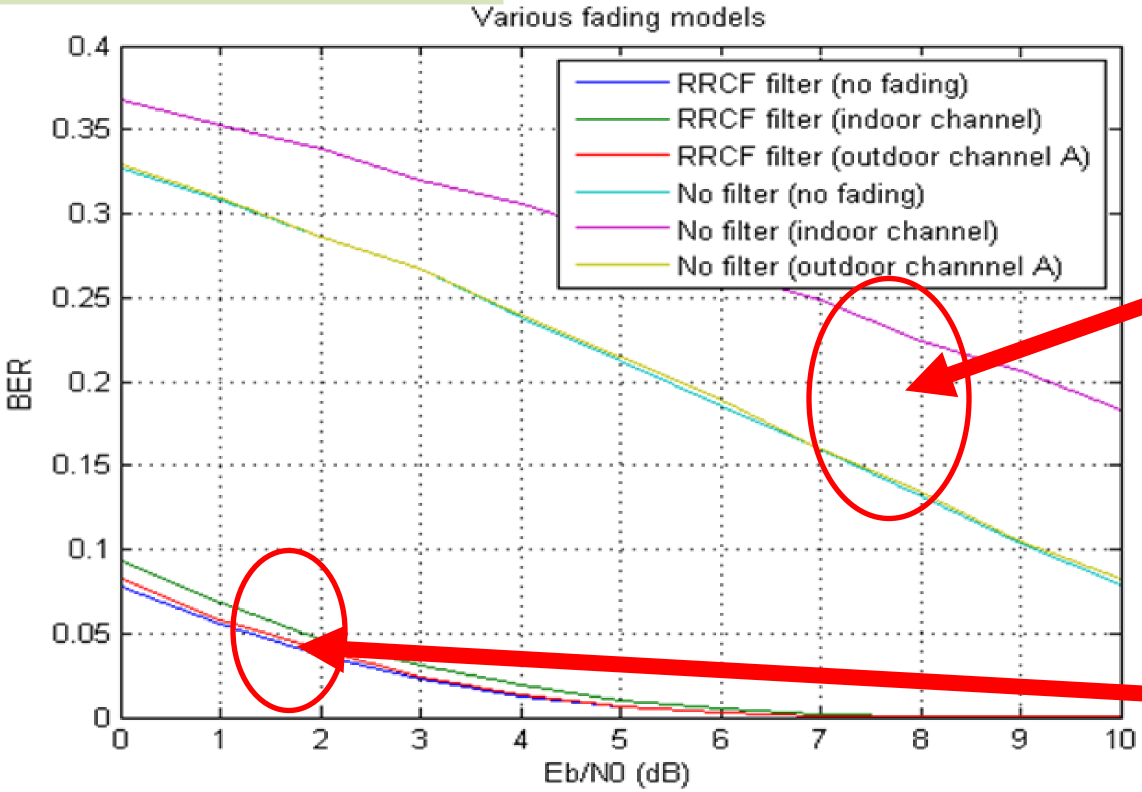


As the filter order increases up to 32, BER decreases. For higher filter order of 32, BER stays stable.

OBSERVATIONS AND CONCLUSIONS

COMPARISON OF BER PERFORMANCE WITH AND WITHOUT FILTERING

With no guard intervals



- **Without filtering**
  - **Indoor model fading causes BER performance degradation while outdoor model A has negligible impact on BER performance.**

- **With filtering**
  - **Indoor channel and outdoor channel A do not make significant difference in BER performance.**
  - **Fading effects on BER are mitigated by filtering.**

Observations from these results

1. **RCF filtering improves BER performance.**
2. **RCF filtering mitigates fading effects on BER for all channel models in TGD.**

OBSERVATIONS

- **Spectral shaping with raised cosine filtering**
  - As the roll-off factor increases, distance between -55dBr point and the in-band edge decreases.
  - As the filter order increases, distance between -55dBr point and the in-band edge decreases.
- **BER performance with raised cosine filtering**
  - With and without fading, around 10 dB performance improvement is made by using raised cosine filtering both at transmitter and receiver.
  - Root raised cosine filters have better BER performance than raised cosine filters by around 1 dB.
  - BPSK cases have better BER performance than QPSK cases by around 1.5 dB for a fixed symbol rate.
  - Multipath fading degrades BER performance by 1-2 dB comparing to no fading cases.
  - Increasing roll-off factors does not improve BER performance:
    - BER with RRCF is not affected by roll-off factors while BER with RCF increases as its roll-off factor increases.
  - As the filter order increases up to around 30, BER decreases. For filter orders of higher than 30, BER stays stable.
    - There seems to be two levels of BER performances and the break-point happens when filter order = (no. of samples)*2.
  - Roll off mis-mathing does not affect BER performance significantly.

CONCLUSIONS (1)

BER performance is improved with raised cosine filtering due to reduction in ISI while its adoption can satisfy strict white space out-of-band emission requirements.

- The case of raised cosine filtering at transmitter and no filtering at receiver has the worst BER performance.
  - For this case, the receiver does not need to know transmitted signal profile. It means that the standard will not specify receiver filtering.
- The case of root raised cosine filtering has the best BER performance while the case of raised cosine filtering both at transmitter and receiver (that is, matched filtering) has almost the same performance as the case of root raised cosine filtering.
  - For these cases, the receiver should know transmitter filter parameters. It means that the standard should specify receiver filtering.
  - Roll-off mismatch does not affect BER performance significantly.

CONCLUSIONS (2)

The best filter parameters for TG4m

- Comparison/analysis of filter parameters which affect performance

	Raised cosine filtering		Root raised cosine filtering	
	Spectral shaping	BER performance	Spectral shaping	BER performance
Roll-off factor	Should be larger than 0.5	0.5 difference in roll-off factor→ 0.2 dB Eb/N0 difference	Should be larger than 0.25	0.5 difference in roll-off factor→ 0.2 dB Eb/N0 difference
Filter order	Higher filter order → less out-of band BW required	should be higher than 30 for stable BER	Higher filter order → less out-of band BW required	should be higher than 30 for stable BER

- The best choice for TG4m pulse shaping filter parameters from the above analysis
  - Raised cosine filtering: with roll-off factor of 0.5 and filter order of 128
  - Root raised cosine filtering: with roll-off factor of 0.5 and filter order of 128

CONCLUSIONS (3)

Proposed change to the draft

- Change sub-clause 20.2.3.11 to add the following sentence to the end of the paragraph:
  - "In addition to pulse shaping at the transmitter, filtering at the receiver may be used for improved performance."

- With the proposed change, the sub-clause looks as follows:

20.2.3.11 Pulse Shaping

Pulse shaping is applied at the transmitter. The pulse shaping method is as needed to meet regulatory requirements in the band of operation. **In addition to pulse shaping at the transmitter, filtering at the receiver may be used for improved performance.**