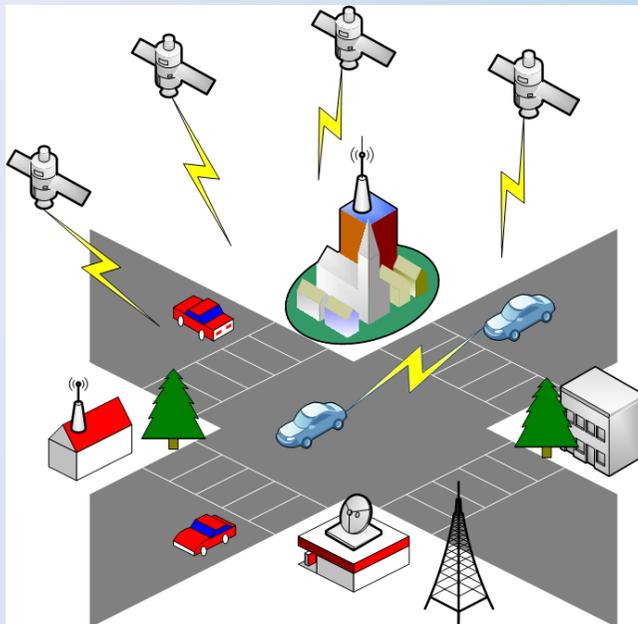


Correlation and Tracking Schemes for the new BOC signals



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Authors: *Aleksandar Jovanovic, Youssef Tawk*

Outline

- CBOC/TMBOC concept (A. Jovanovic)
 - Tracking metrics & Tracking algorithms for MBOC
 - Comparison of MBOC algorithms
 - Results and recommendations for MBOC tracking
- AltBOC concept (Y. Tawk)
 - Tracking metrics & Tracking algorithms for AltBOC
 - Comparison of AltBOC algorithms
 - Results and recommendations for AltBOC tracking

Correlation and Tracking of MBOC

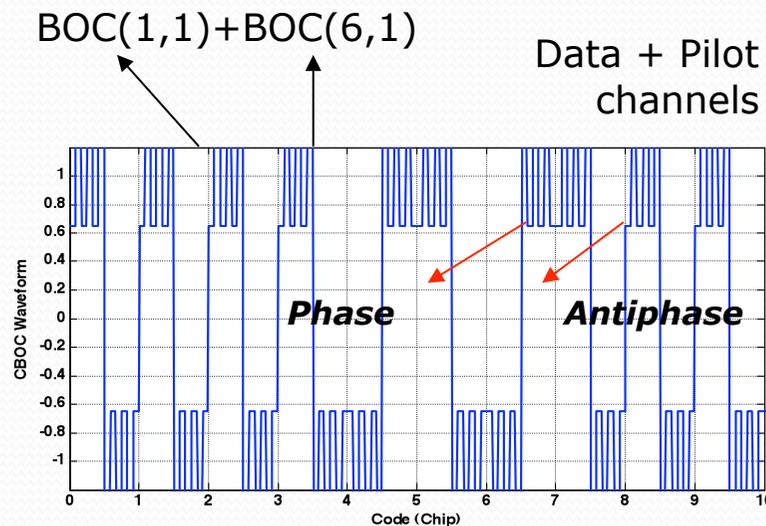
- *Overview of MBOC receiver tracking schemes*
- Perform comparison w.r.t. tracking metrics
 - ACF peak amplitude
 - Multipath error envelope
 - Code tracking error
 - Provide advantages/disadvantages of each algorithm
- Recommendations to reduce receiver complexity

CBOC/TMBOC definition

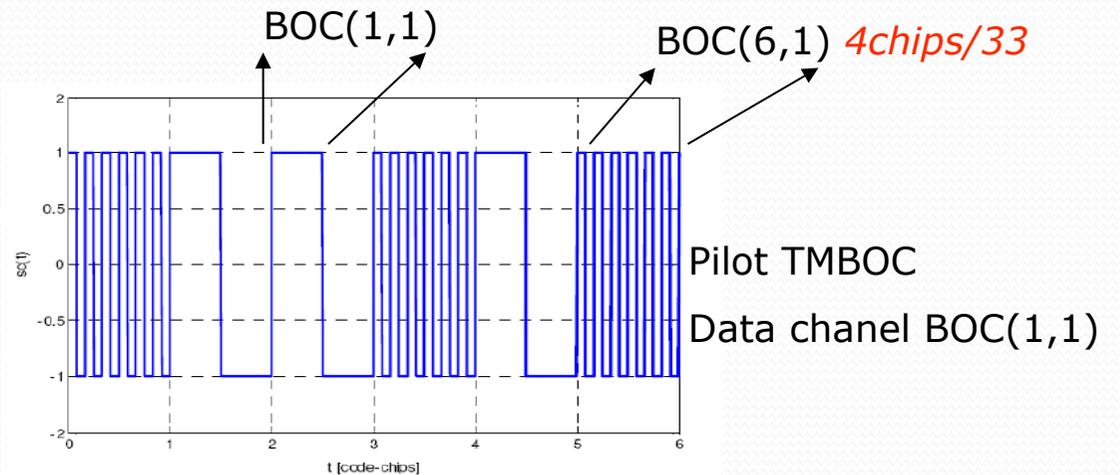
- CBOC vs. TMBOC

- Same power spectral density (PSD) $G_{MBOC} = \frac{10}{11} G_{BOC(1,1)}(f) + \frac{1}{11} G_{BOC(6,1)}(f)$

➤ *Pilot and data channels have different structures*



CBOC structure

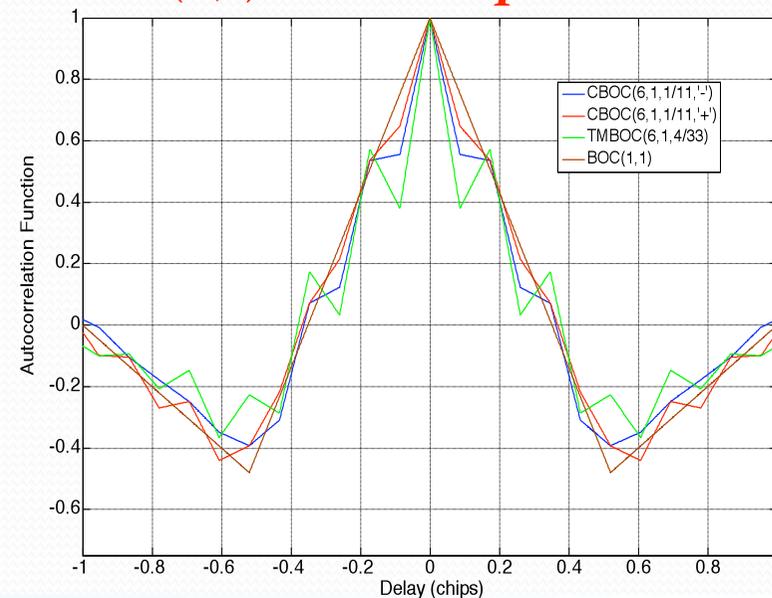
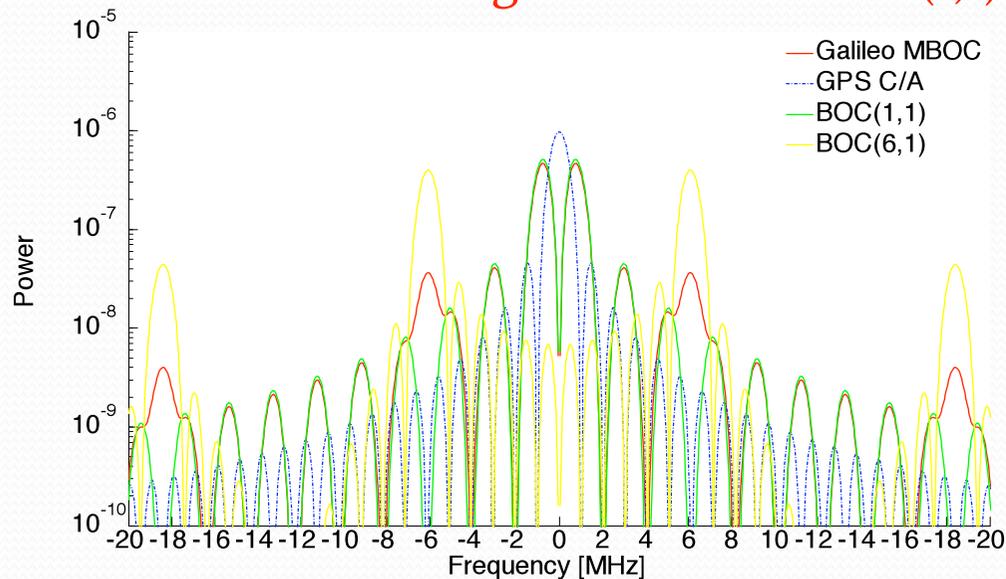


TMBOC structure

- Different tracking performance for CBOC/TMBOC

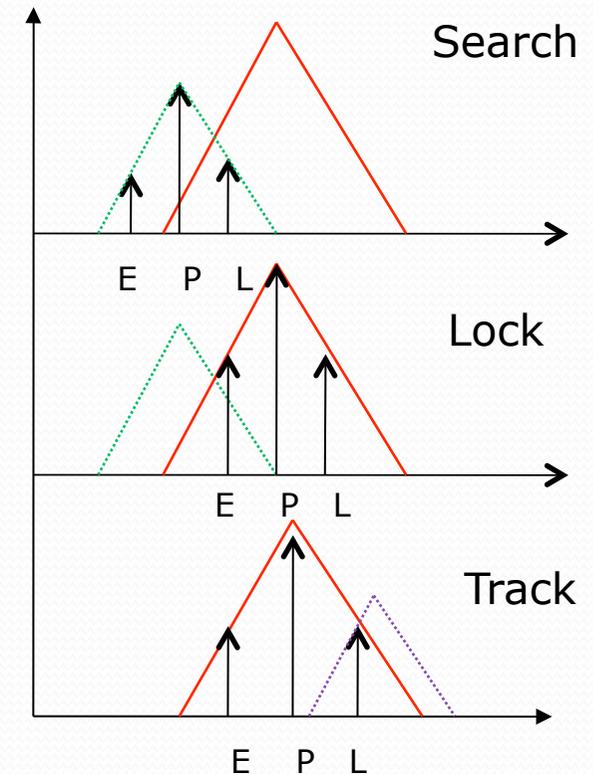
CBOC/TMBOC signals

- **GPS L1C OS TMBOC (6,1,4/33)**
 - BOC(1,1) on data channel (25%), TMBOC on pilot (75%)
 - Multiplex wide-band BOC(6,1) with narrow-band BOC(1,1)
- **Galileo E1 OS CBOC (6,1,1/11,'+/-')**
 - Equally split power (50%), signals in antiphase
 - Weighted sum of BOC(1,1) and BOC(6,1) *on data+pilot*

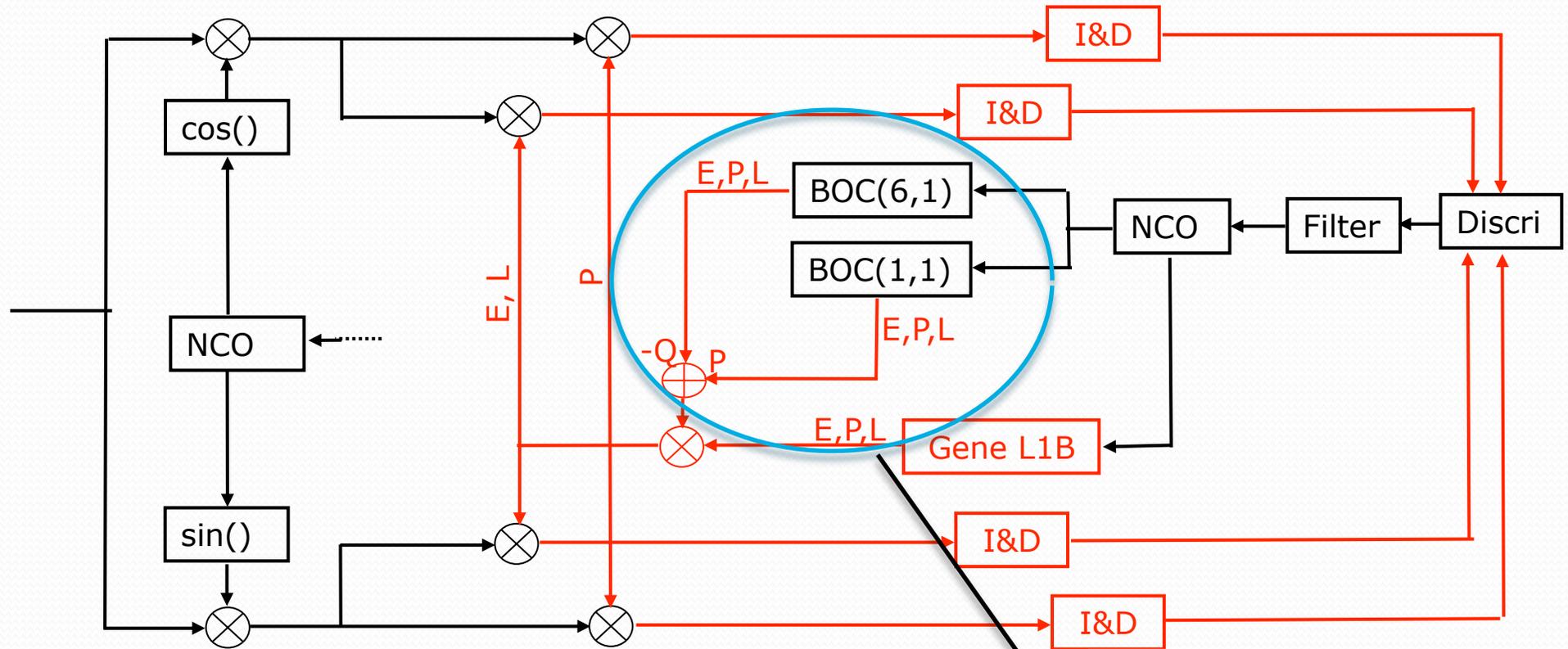


Tracking in general

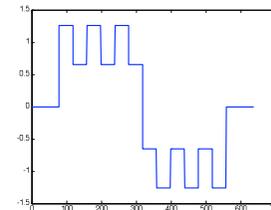
- First step to consider: *Autocorrelation function (ACF)*
- Main tracking parameters:
 - Tracking sensitivity
 - *Minimum SNR to maintain tracking*
 - Tracking robustness
 - *Stability tracking region*
 - Tracking accuracy
 - *Errors: multipath, noise, interference*
 - Multipath main source of error
- Phase tracking (PLL)
- Code delay tracking (DLL)



Traditional CBOC receiver architecture



- Same replica for E, P, L correlator



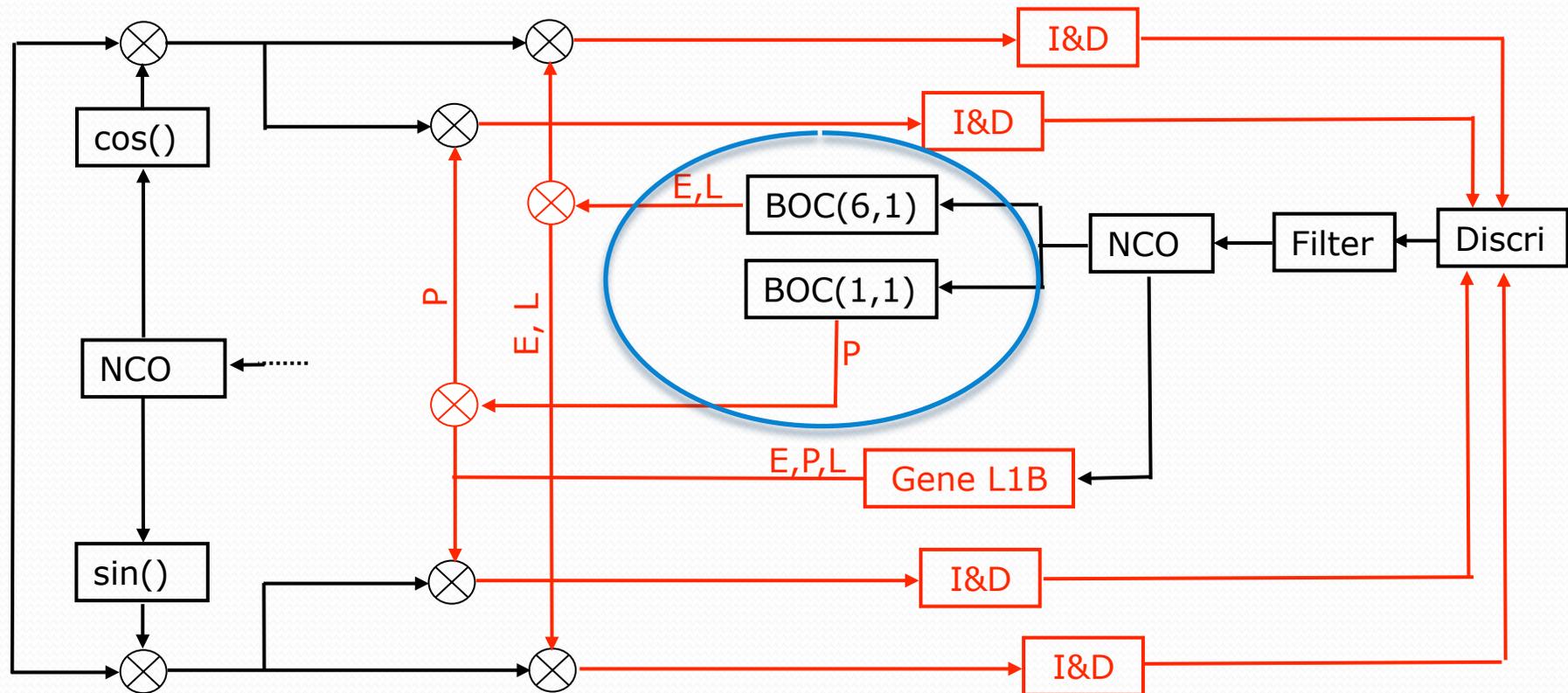
Traditional tracking performance

- Traditional CBOC tracking requires replication of four-level replica
 - *Complicates the receiver architecture*
- Improvement in tracking comparing to BOC(1,1) is different for data and data+pilot channels
 - *=> C/No criterion for comparison*
- CBOC(6,1,1/11,'-') better than TMBOC modulation

Tracking Error Improvement vs BOC(1,1) in Terms of Equivalent C/No (dB) with $BW_2 = 24$ MHz and $E-L = 1/12$ Chips

CBOC(6,1,1/11,'+')	TMBOC(6,1,4/33)	CBOC(6,1,1/11,'-')
1.9	2.4	3.1

TM61 tracking architecture



- Use one-bit replica, using BOC(1,1) and BOC(6,1) *only*

TM61 for TMBOC tracking

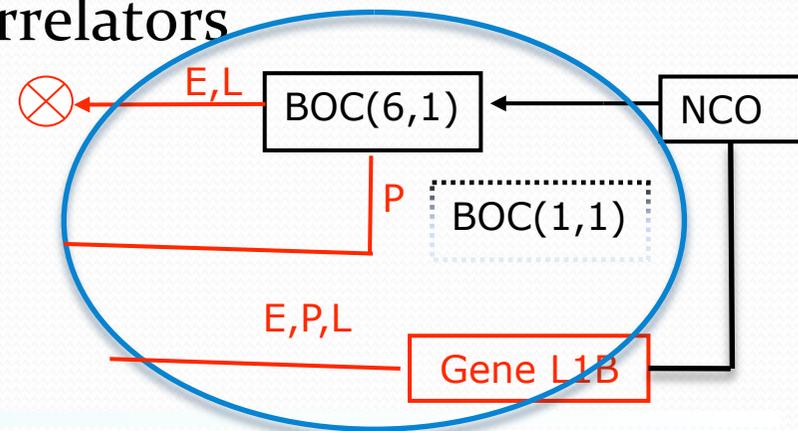
- TMBOC tracking using TM61 is more complicated
 - *Correlation losses high when only BOC(6,1) is used*

Signal vs. Receiver	BOC(1,1)	BOC(6,1)
TMBOC (6,1,4/33)	0.85	0.15
CBOC (6,1,1/11, '-')	0.95	0.3

- This can be avoided using time-multiplex subcarriers
 - *Using zero-padding*
 - When BOC(6,1) is tracked, BOC(1,1) replica contains zeros
 - and vice-versa
- Using this method TMBOC tracking is similar to CBOC tracking
 - *Still 0.2 dB worst in tracking than CBOC*

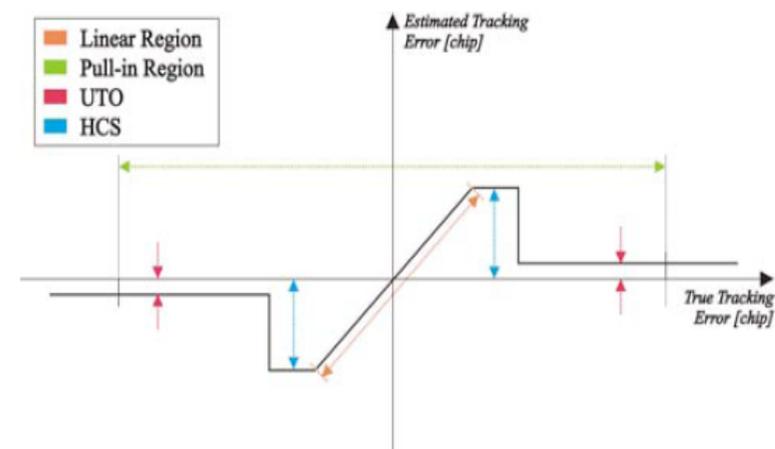
Dual Correlator tracking

- Dual Correlator technique compares two parallel correlations:
 - *Incoming MBOC with BOC(1,1) replica*
 - *Incoming MBOC with BOC(6,1) replica*
- Correlations are weighted, with parameters:
 - β for BOC(1,1) and ρ for BOC(6,1)
- Optimal β/ρ is in the range [1.6,3.2] w.r.t. MEE (Multipath error)
- This method uses twice as many correlators
 - *And binary replicas*
- Good multipath performance
- Easily configurable in the software



S-Curve shaping method

- Method proposed is to find the ideal discriminator
 - Using ideal S-curve
 - Fitting the curve, parameters of the correlator are found
 - Correlator spacing
 - Weight of the correlator
- Great number of correlators needed
 - Multipath reduced strongly
- Uses multicorrelator structure
 - Narrow correlator
 - Double delay correlator

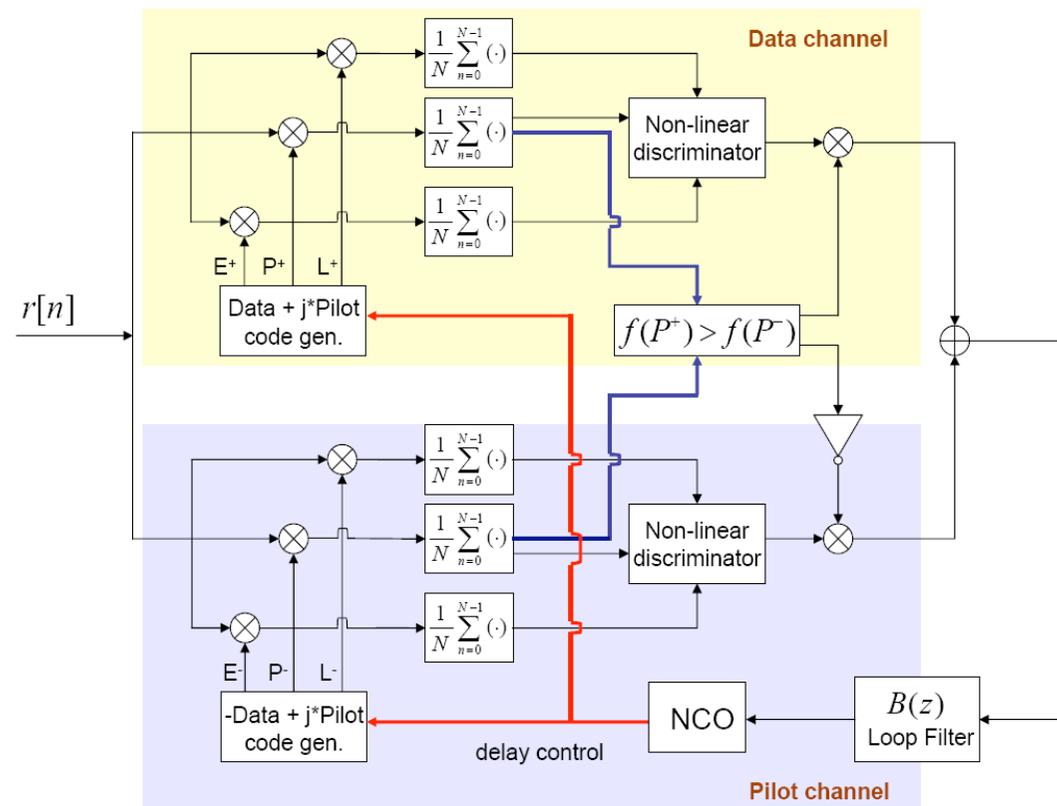


ASPeCT BOC(1,1) algorithm

- ASPeCT has been proposed for BOC(n,n) signals
 - *Unambiguous technique - elimination of the side peaks of ACF*
 - *Limited degradation [0.6-1dB] comparing to traditional*
- ASPeCT can be applied to CBOC(6,1,1/11,'-')
- Price to pay:
 - *Reducing the BOC(6,1) in the local CBOC replica by half*
- This implies:
 - a negligible reduction of resistance to noise
 - a slight degradation of the multipath error envelope

Composite tracking algorithm

- Composite tracking
 - Data and pilot together
- Convex combination of discriminator outputs
- *Non-coherent + coherent channel combining*
- Tracking jitter reduced
- SER (Sign Error Rate)
 - *New tracking metrics*



Tracking CBOC/TMBOC with BOC(1,1)

- Narrowband receivers ($BW \ll 12$ MHz) do not have access to *full* range of MBOC characteristics

Transmission	Receiver reference	Delta Losses [dB]	Relative Noise Jitter	RAME error
Baseline	BOC(1,1)	0.0	1.00	1.00
CBOC	BOC(1,1)	+0.3	0.94	0.97
TMBOC	BOC(1,1)	+1.7	1.31	1.03
CBOC	CBOC	0.0	0.76	0.84
TMBOC	CBOC	+0.3	0.71	0.84

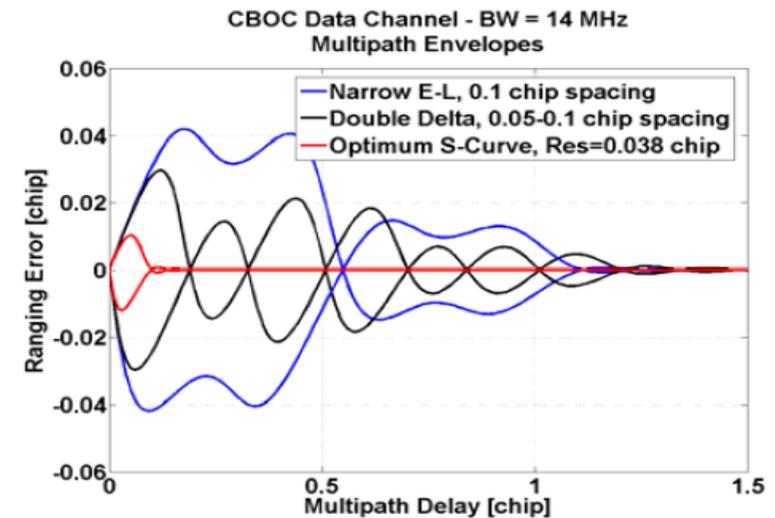
- Optimal tracking performance is reached with the matching channel
- Reference: [Dr. Massimo Crisci, ESTEC, GIOVE

Tracking algorithms comparison

Tracking scheme	Tracking complexity	Tracking robustness	Tracking accuracy	Applicability to mass-market receiver
TM61	+	+	-	+
Dual Correlator	+/-	-	+/-	+/-
S-Curve shaping	+	-	+	+
ASPeCT	+	+/-	-	+/-
Composite tracking	-	+/-	+	+/-

Multipath performance

- Multipath error envelopes:
- TM61 provides *better results* than pure CBOC tracking
 - If DP discriminator used
- HRC not good solution
 - for CBOC tracking
- S-curve shaping
 - *Provides the best results*
- Use of advanced correlators:
 - Strobe
 - Narrow, Double Delta



[M.Fantino, L.Presti]

Conclusions and outlook MBOC

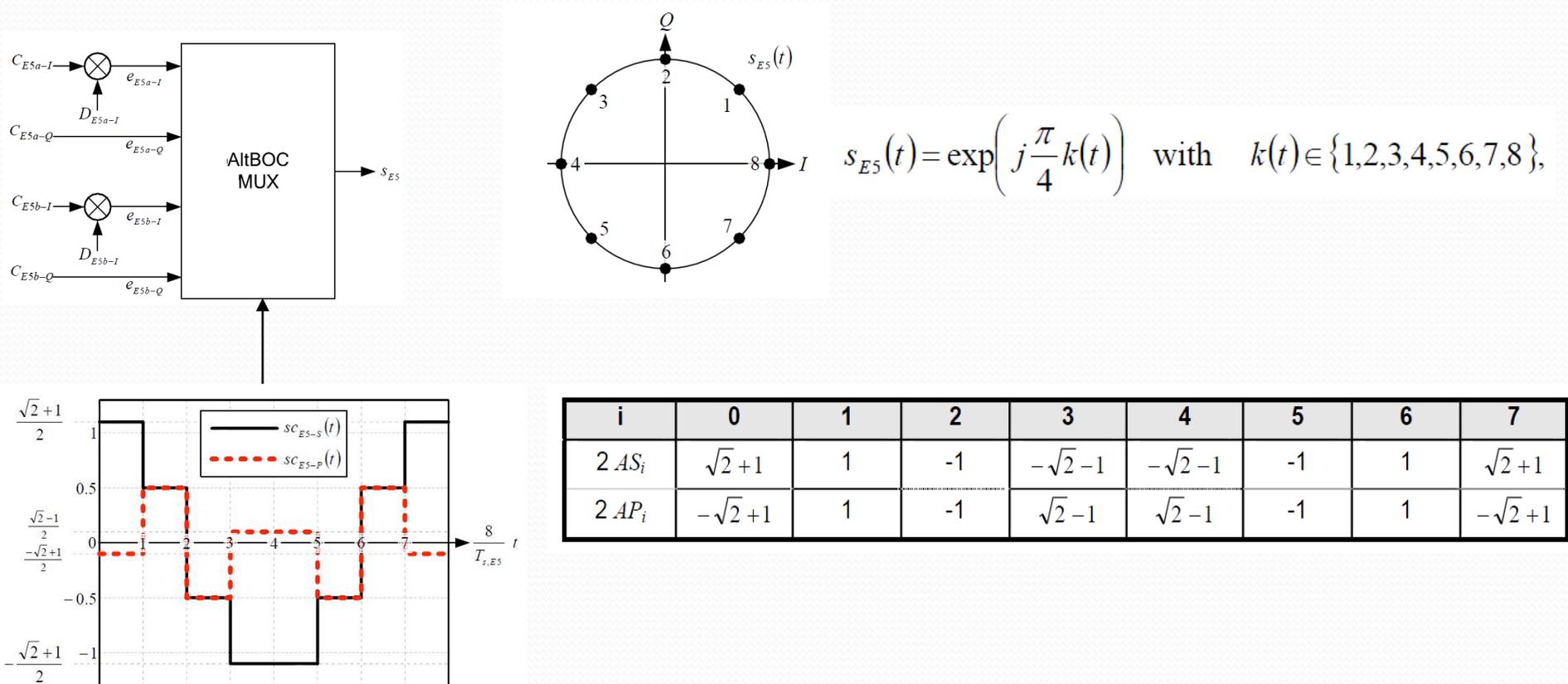
- BOC(1,1) receivers receiving CBOC/TMBOC
 - *Losses too high*
- New specific tracking algorithms proposed:
 - *TM61 and Dual Correlator outperform* BOC(1,1)
- Future work :
 - *Composite tracking*
 - *To be further investigated*
 - Common tracking CBOC/TMBOC architecture
 - *Real challenge*
 - Separate algorithm for CBOC and TMBOC?
 - *Need for advanced multipath mitigation algorithms*
 - *Use of new correlator types*

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 - Tracking metrics & Tracking algorithms for AltBOC
 - Comparison of AltBOC algorithms
 - Results and recommendations for AltBOC tracking

Galileo E5 Signal

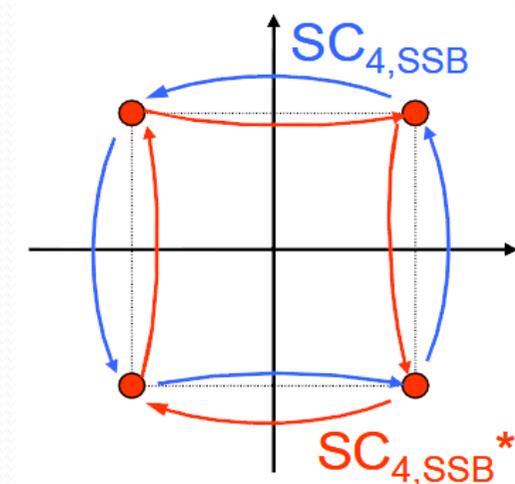
- AltBOC(15,10) is the new modulation on the Galileo E5 Band.



Constant Envelope

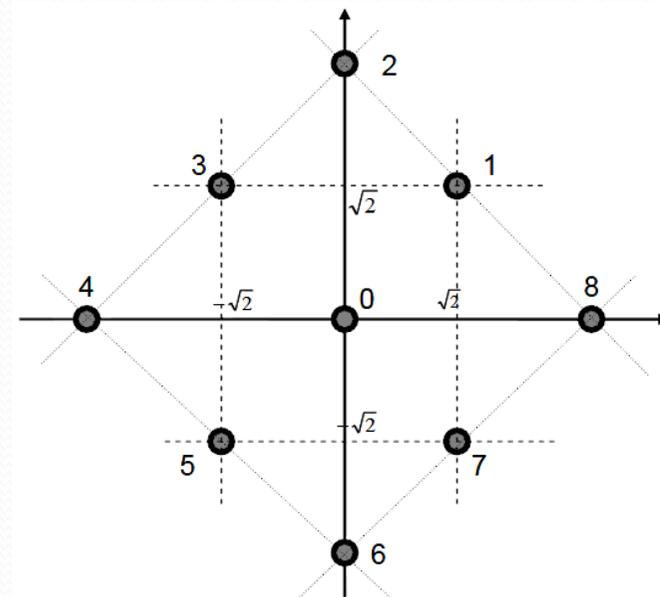
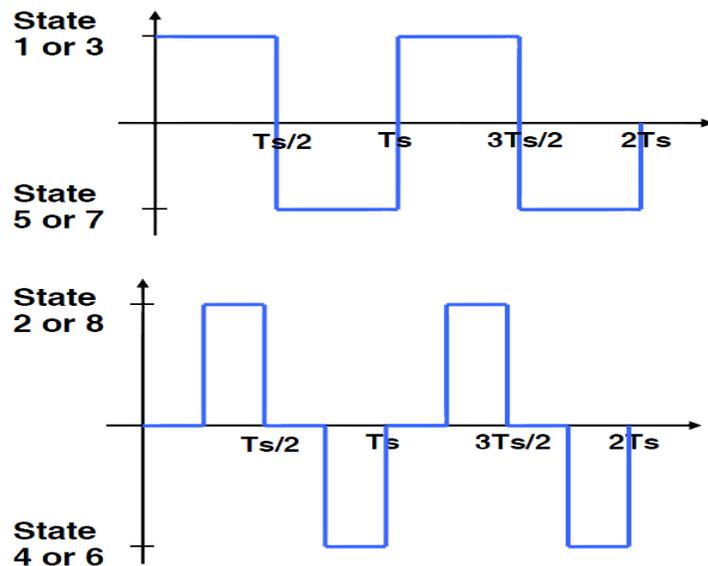
$$s(t) = \underbrace{c_A(t) \cdot SC_{B,SSB}^*(t)}_{E5a} + \underbrace{c_B(t) \cdot SC_{B,SSB}(t)}_{E5b}$$

C_A	C_B	$C_A + C_B$	$C_A - C_B$	Fresnel plot	Phasing
1	1	2	0		
-1	-1	-2	0		
1	-1	0	2		
-1	1	0	-2		



Constant Envelope (cont')

$$s(t) = [c_A(t) + j.c'_A(t)] \cdot SC_{4,SSB}^*(t) + [c_B(t) + j.c'_B(t)] \cdot SC_{4,SSB}(t)$$



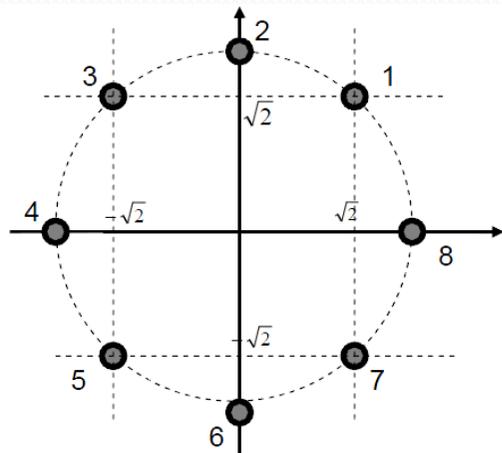
Constant Envelope (cont')

$$s_{E5}(t) = \frac{1}{2\sqrt{2}} (e_{E5a-I}(t) + j e_{E5a-Q}(t)) [s_{C_{E5-S}}(t) - j s_{C_{E5-S}}(t - T_{s,E5}/4)] +$$

$$\frac{1}{2\sqrt{2}} (e_{E5b-I}(t) + j e_{E5b-Q}(t)) [s_{C_{E5-S}}(t) + j s_{C_{E5-S}}(t - T_{s,E5}/4)] +$$

$$\frac{1}{2\sqrt{2}} (\bar{e}_{E5a-I}(t) + j \bar{e}_{E5a-Q}(t)) [s_{C_{E5-P}}(t) - j s_{C_{E5-P}}(t - T_{s,E5}/4)] +$$

$$\frac{1}{2\sqrt{2}} (\bar{e}_{E5b-I}(t) + j \bar{e}_{E5b-Q}(t)) [s_{C_{E5-P}}(t) + j s_{C_{E5-P}}(t - T_{s,E5}/4)]$$



C _A	C _B	C' _A	C' _B	Fresnel Plot	Phasing													
					0	T _s /8	T _s /4	3T _s /8	T _s /2	5T _s /8	3T _s /4	T _s						
1	1	1	1		↑													
-1	-1	-1	-1		↓													
-1	1	1	-1		↑													
1	-1	-1	1		↓													
-1	1	1	1		↑													
1	-1	-1	-1		↓													
1	1	-1	-1		↑													
-1	-1	1	1		↓													
-1	1	-1	1		↑													
1	-1	1	-1		↓													
1	1	-1	1		↑													
-1	-1	1	-1		↓													
1	1	1	-1		↑													
-1	-1	-1	1		↓													

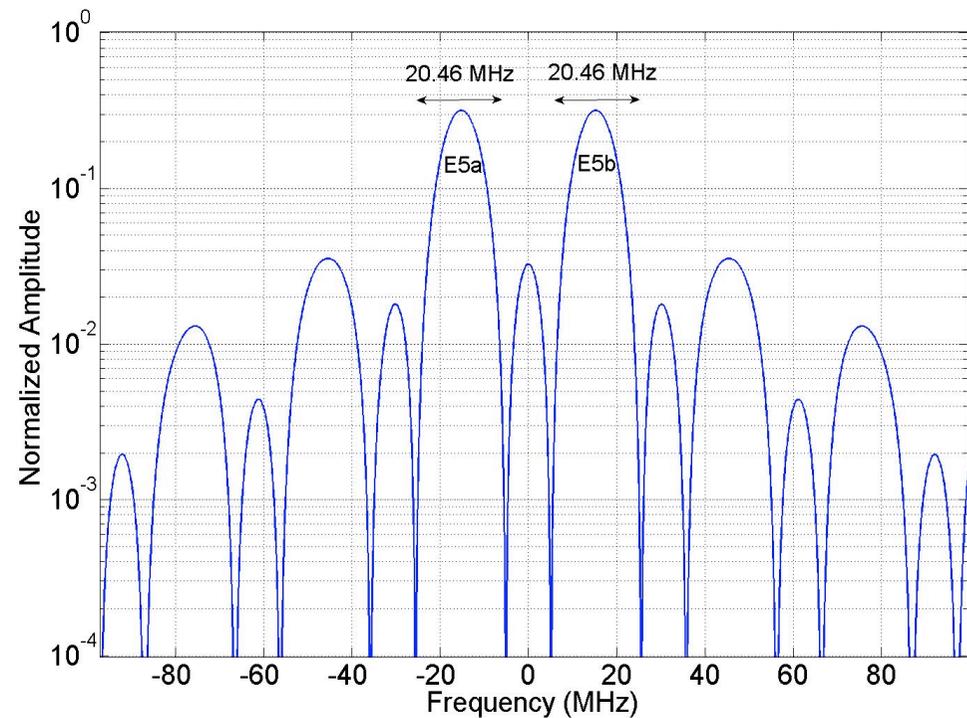
AltBOC Characteristics

Channel	Code Rate [Mchip/s]	Subcarrier Freq.[MHz]	Symbol Rate [symbols/s]	Service
<i>E5a-I</i>	10.23	15.345	50	F/NAV
<i>E5a-Q</i>	10.23	15.345	No data	Pilot
<i>E5b-I</i>	10.23	15.345	250	I/NAV
<i>E5b-Q</i>	10.23	15.345	No data	Pilot

E5 Signal Parameter

Channel	Code length [chips]		Code length [ms]
	Primary	Secondary	
<i>E5a-I</i>	10230	20	20
<i>E5a-Q</i>	10230	100	100
<i>E5b-I</i>	10230	4	4
<i>E5b-Q</i>	10230	100	100

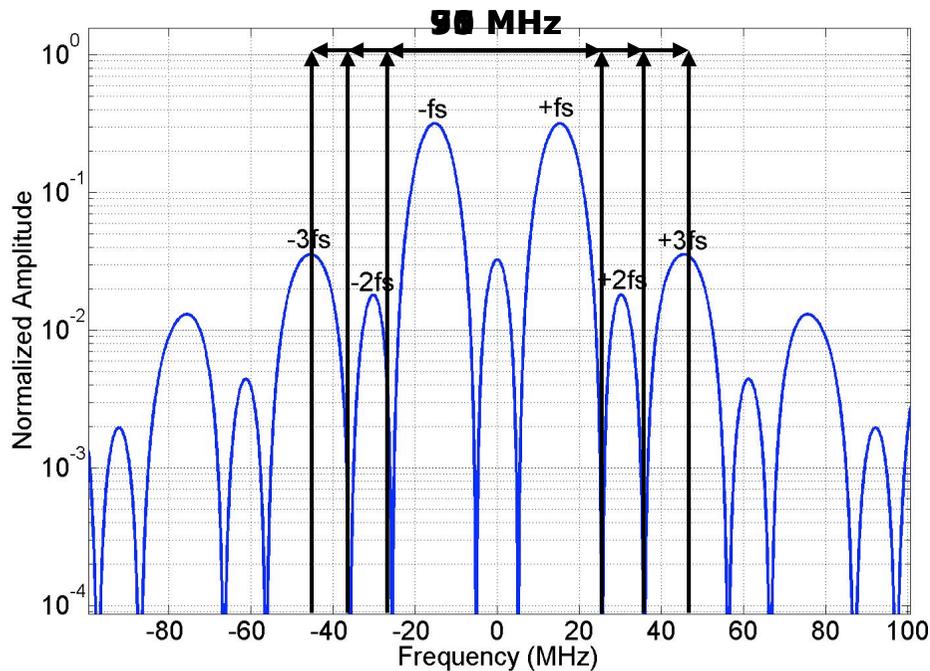
E5 Spreading Code Lengths



E5 Signal Spectrum

Power Distribution

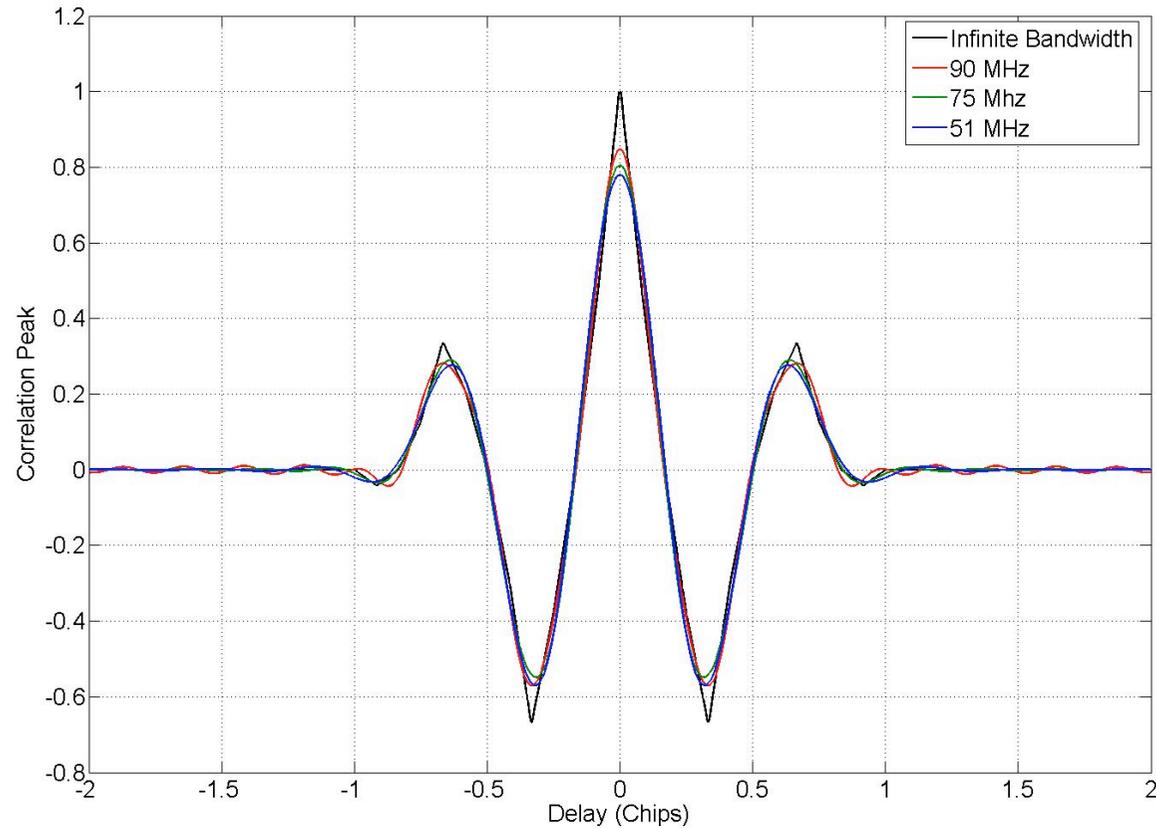
	Power	1 st Harmonic (Power Distribution)	2nd Harmonic (Power Distribution)
SSC	85.36%	+fs/-fs (94.36%)	+7fs/-7fs (1.36%)
PSC	14.64%	+3fs/-3fs (61.5%)	+5fs/-5fs (22.2%)



Bandwidth	Theoretical Power	Power Transmitted
90 MHz	85.34%	100%
75 MHz	80.54%	94.37%
51 MHz	77.88%	91.25%

N.B: Power is shared equally between the four components of the E5 signal

Autocorrelation Function



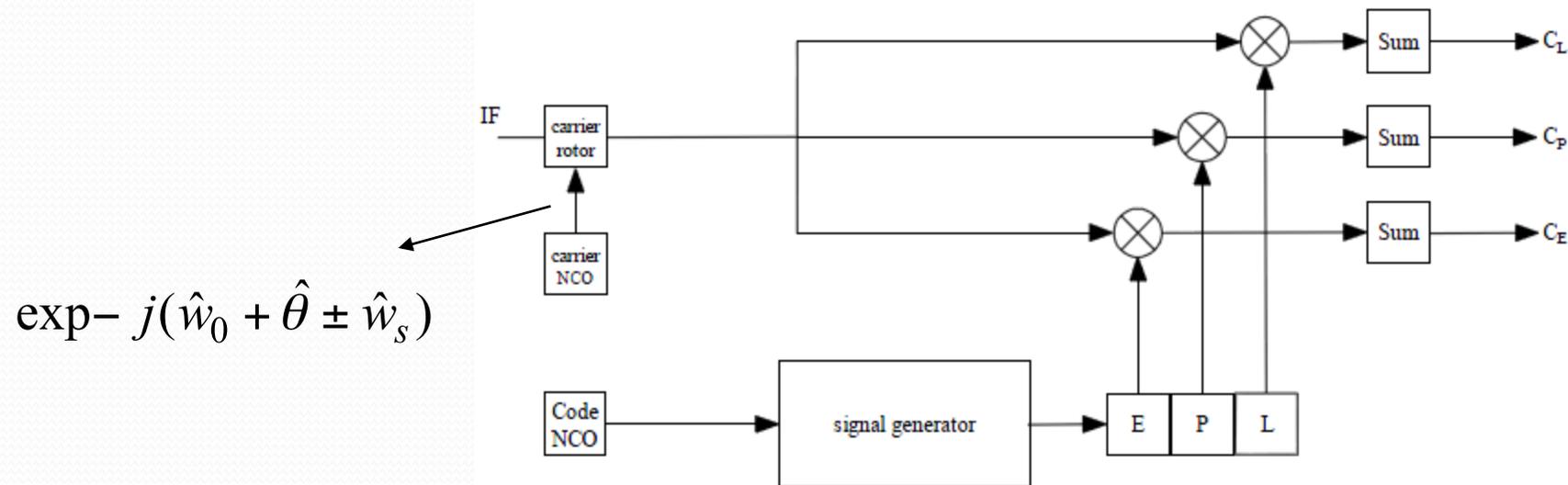
Autocorrelation vs. Bandwidth

Tracking Possibilities

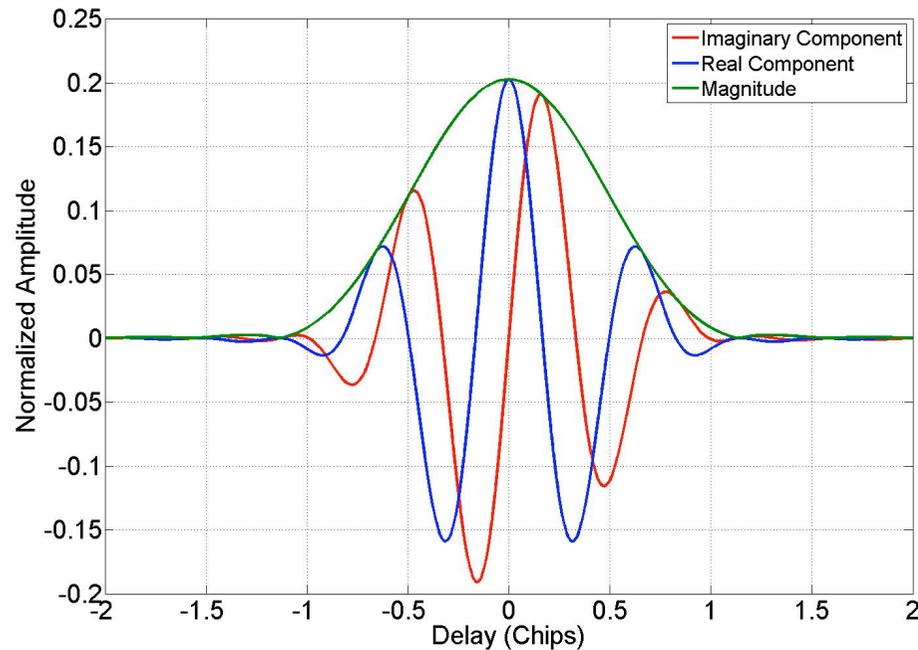
- The presence of 4 components on the E5 signal allow the receiver designers to have different possibilities in tracking this signal:
 - Free subcarriers Local generated signal
 - Full Band Correlation
 - 8-PSK like processing
- Several combination of signal components are possible:
 - E5a-I, E5a-Q, E5b-I or E5a-Q
 - Data or pilot
 - E5

Free Subcarriers

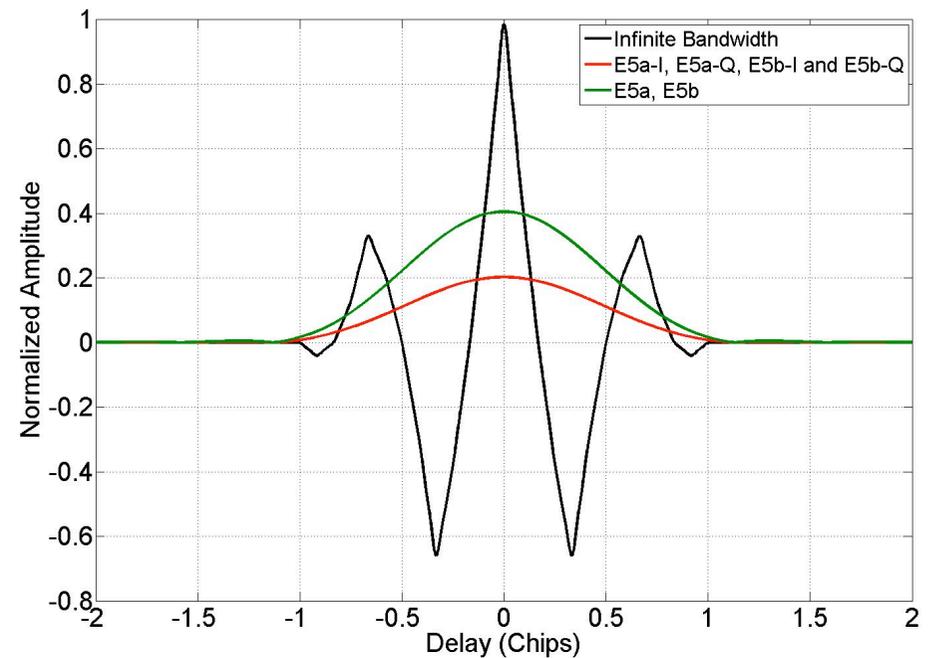
- The local signal is generated free of subcarriers
- The E5 signal components are translated to base band from their center frequencies
- E5a-I, E5a-Q, E5b-I, E5b-Q, E5a and E5b can be tracked individually resulting in a BPSK(10) correlation



Free Subcarriers (cont')



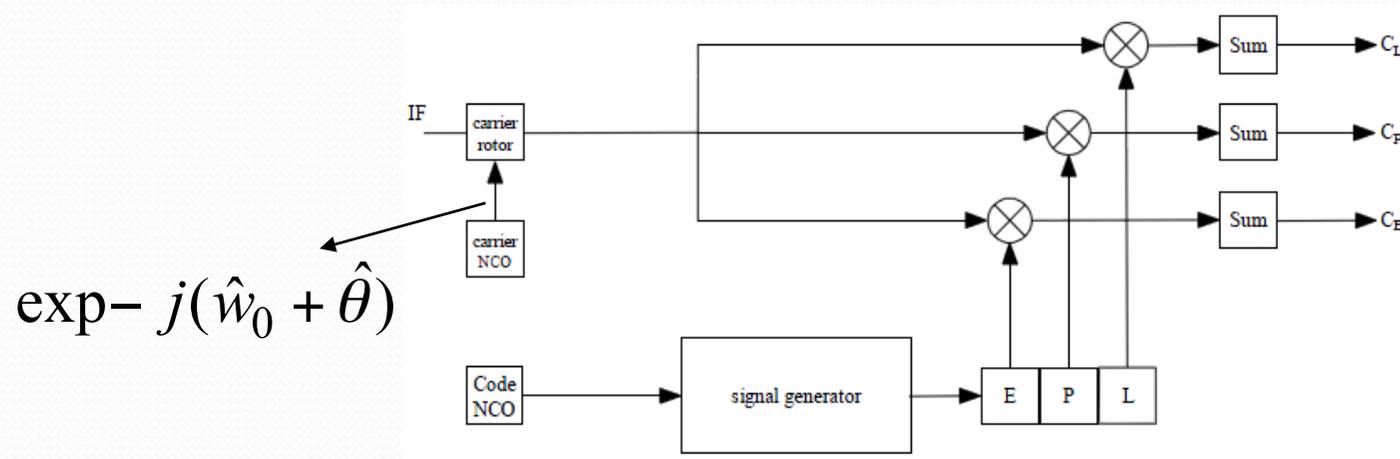
Autocorrelation Function for a single E5 component with a 20 MHz Bandwidth



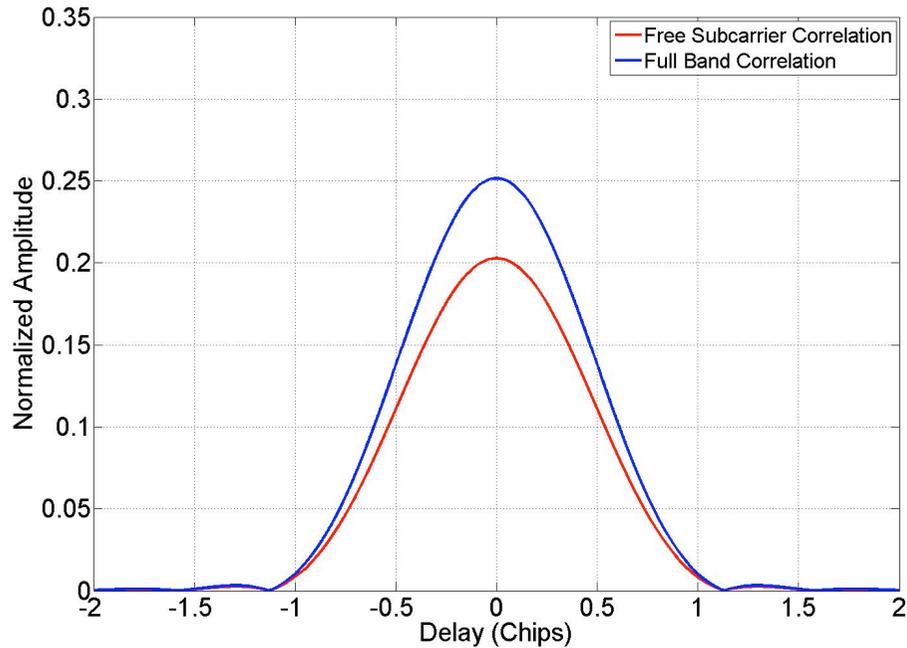
Comparison between an infinite bandwidth and a 20 MHz AltBOC receiver

Full band Correlation

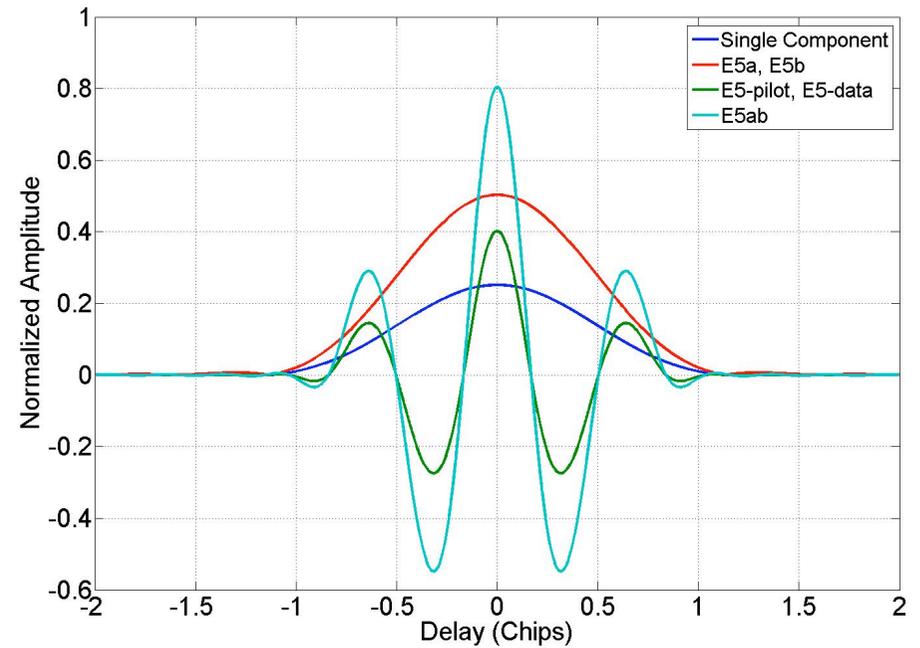
- The local signal is generated with subcarrier for the required signal component
- Additional power is gained comparing to the free subcarrier method
- E5ab, E5-pilot and E5-data can be tracked in addition to the other signal components



Full Band Correlation



Comparison between autocorrelation function for a single E5 component with a 75 MHz Full Band correlation and a 20 MHz Free Subcarrier correlation



Full Band Correlation for different signal components with a 75 MHz bandwidth receiver

8-PSK Like Processing

- Only the complete E5 signal is tracked
- Correlation is done using a look up table (LUT) of 8 values

		Input Quadruples															
e_{E5a-I}		-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1
e_{E5b-I}		-1	-1	-1	-1	1	1	1	1	-1	-1	-1	-1	1	1	1	1
e_{E5a-Q}		-1	-1	1	1	-1	-1	1	1	-1	-1	1	1	-1	-1	1	1
e_{E5b-Q}		-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1	-1	1
$t' = t \text{ modulo } T_{s,E5}$		k according to $s_{E5}(t) = \exp(jk\pi/4)$															
i_{Ts}	t'																
0	$[0, T_{s,E5}/8[$	5	4	4	3	6	3	1	2	6	5	7	2	7	8	8	1
1	$[T_{s,E5}/8, 2 T_{s,E5}/8[$	5	4	8	3	2	3	1	2	6	5	7	6	7	4	8	1
2	$[2 T_{s,E5}/8, 3 T_{s,E5}/8[$	1	4	8	7	2	3	1	2	6	5	7	6	3	4	8	5
3	$[3 T_{s,E5}/8, 4 T_{s,E5}/8[$	1	8	8	7	2	3	1	6	2	5	7	6	3	4	4	5
4	$[4 T_{s,E5}/8, 5 T_{s,E5}/8[$	1	8	8	7	2	7	5	6	2	1	3	6	3	4	4	5
5	$[5 T_{s,E5}/8, 6 T_{s,E5}/8[$	1	8	4	7	6	7	5	6	2	1	3	2	3	8	4	5
6	$[6 T_{s,E5}/8, 7 T_{s,E5}/8[$	5	8	4	3	6	7	5	6	2	1	3	2	7	8	4	1
7	$[7 T_{s,E5}/8, T_{s,E5}[$	5	4	4	3	6	7	5	2	6	1	3	2	7	8	8	1

Look up table for AltBOC phase states

AltBOC Summary

	Power Sharing	Code Phase Jitter	Receiver Complexity	Multipath Mitigation
Free Subcarrier	-	-	+	-
Full Band	-/+	-/+	-/+	+
8-PSK	+	+	-	+

Performance of the different tracking architectures

Conclusions

- Good tracking performance of new BOC signals
 - Better multipath mitigation
 - Improved code tracking performance
 - New tracking strategies requirements
- More complex receiver architecture
 - More processing power, higher f_s , more correlators
 - High cost– need simplifications

- Thank You for the attention
 - Q&A?

- Contacts:

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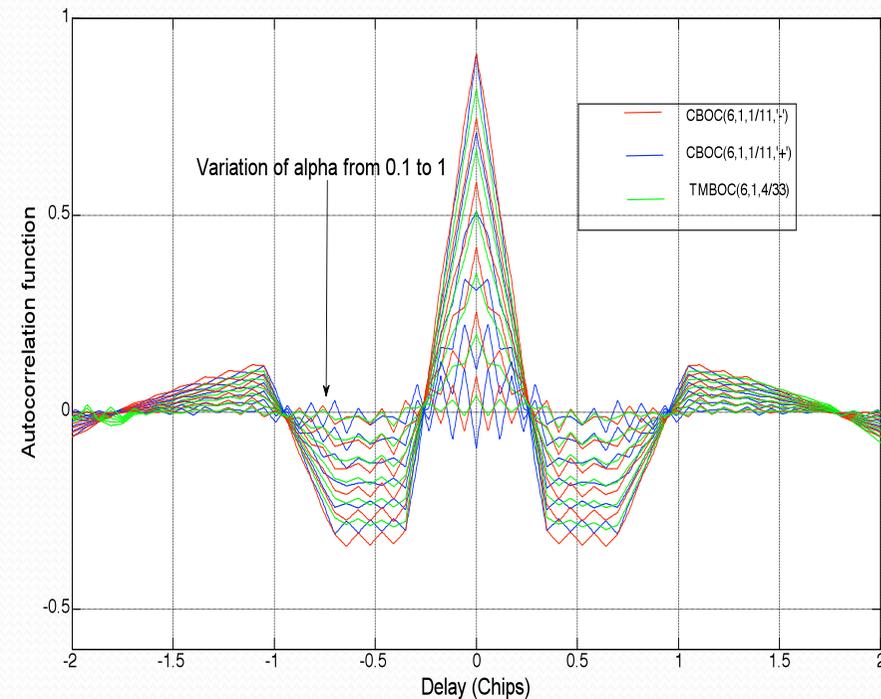
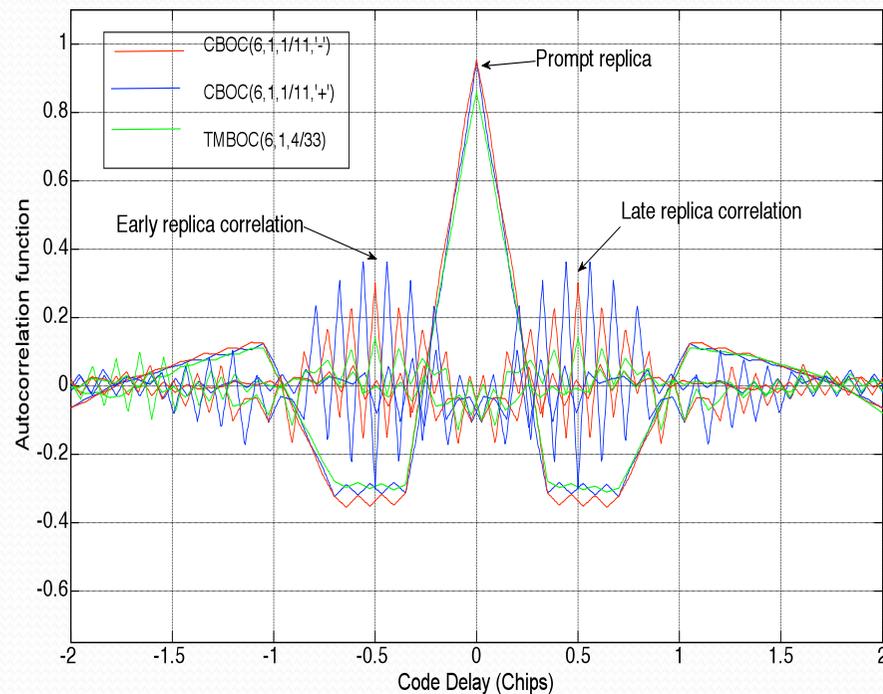
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Back – up slides

Algorithm comparison

- False correlation peaks at 0.6 chips



- Correlation losses TM61

ACF peak variation $\alpha = [0.1, 1]$