Pulse Shaping in Unipolar OFDM-based Modulation Schemes

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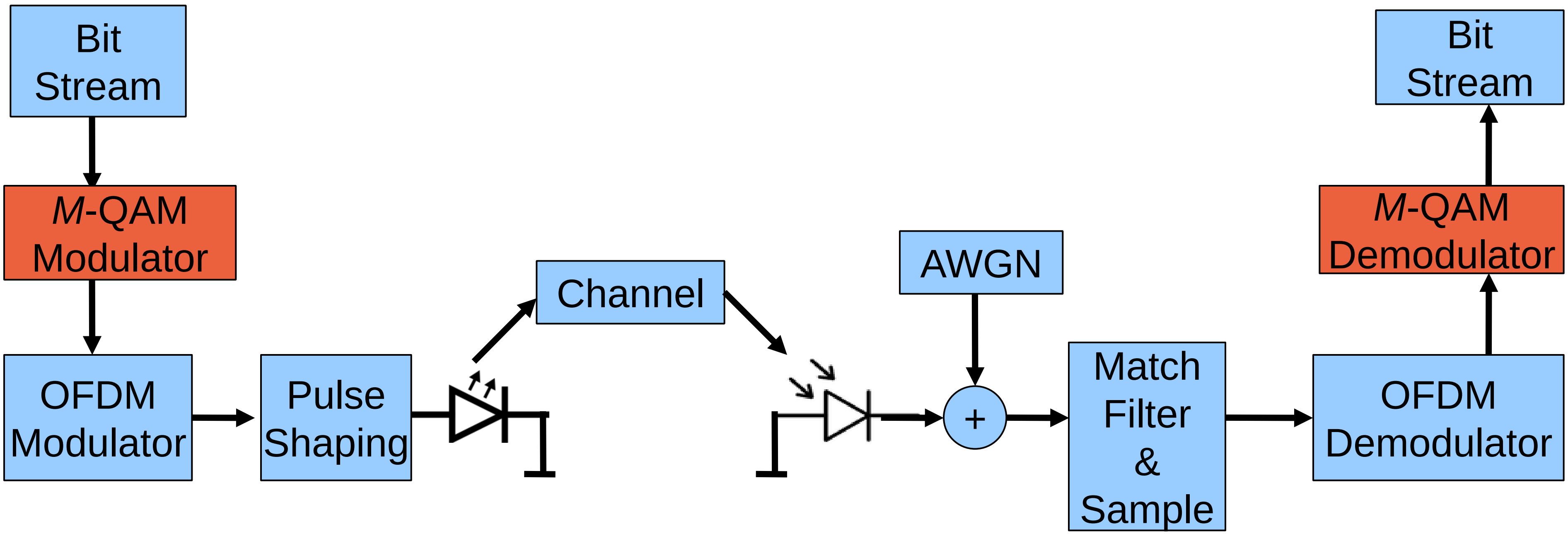
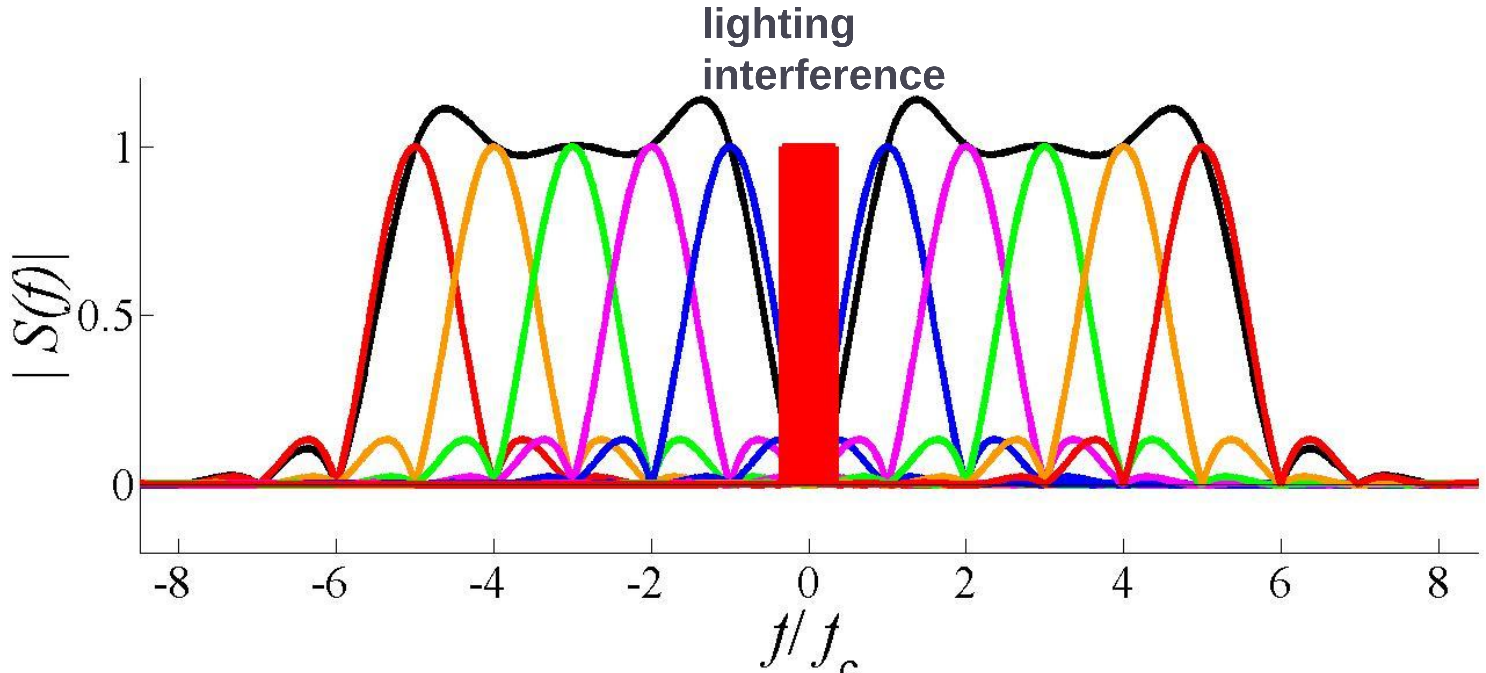
OFDM-based Communication System

- Discrete time-domain samples need to be mapped to continuous time-domain pulse shapes in order to obtain an analog signal suitable for modulation of a device such as a LED.



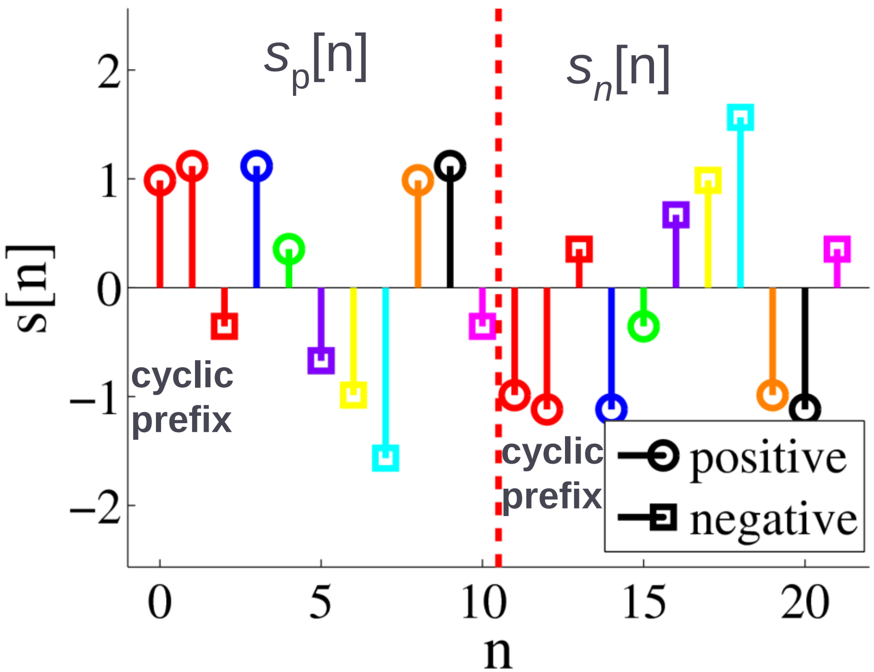
Optical Wireless Communication Based on OFDM

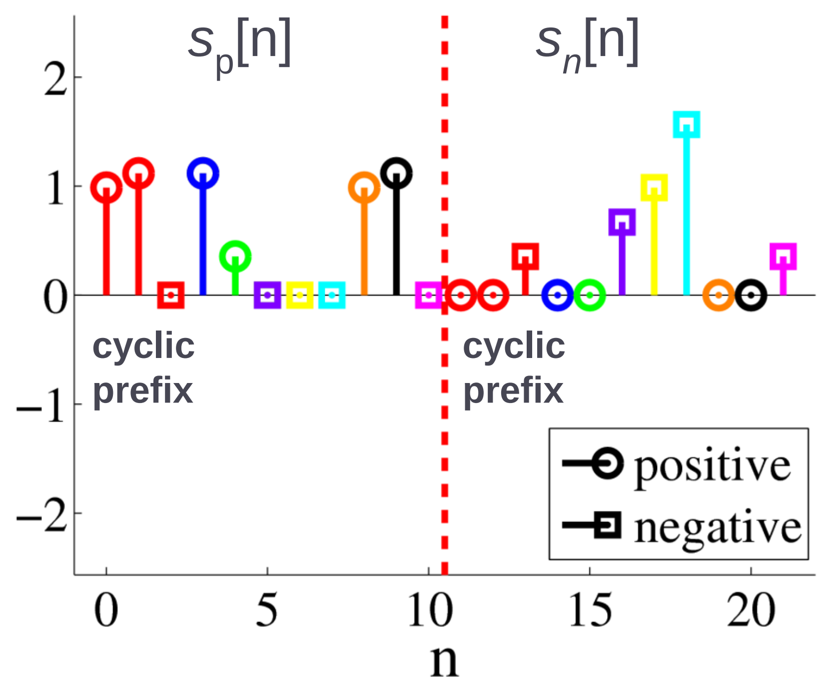
- Real unipolar signals are required for IM/DD systems.
- Real Signals through Hermitian symmetry in frequency: $S(f) = S^*(-f)$
- Unipolar signals are obtained in a variety of ways: DCO-OFDM, ACO-OFDM, PAM-DMT, U-OFDM, Flip OFDM, etc.



Unipolar OFDM (U-OFDM) / Flip OFDM

- Frames are sent in two streams. In the second stream with reversed signs.
- Therefore, $s_p[n] = -s_n[n]$ (Tsonev *et al*., 2012, Fernando *et al*., 2011)
  - $s_p[n]$ = Stream with positive samples
  - $s_n[n]$ = Stream with negative samples



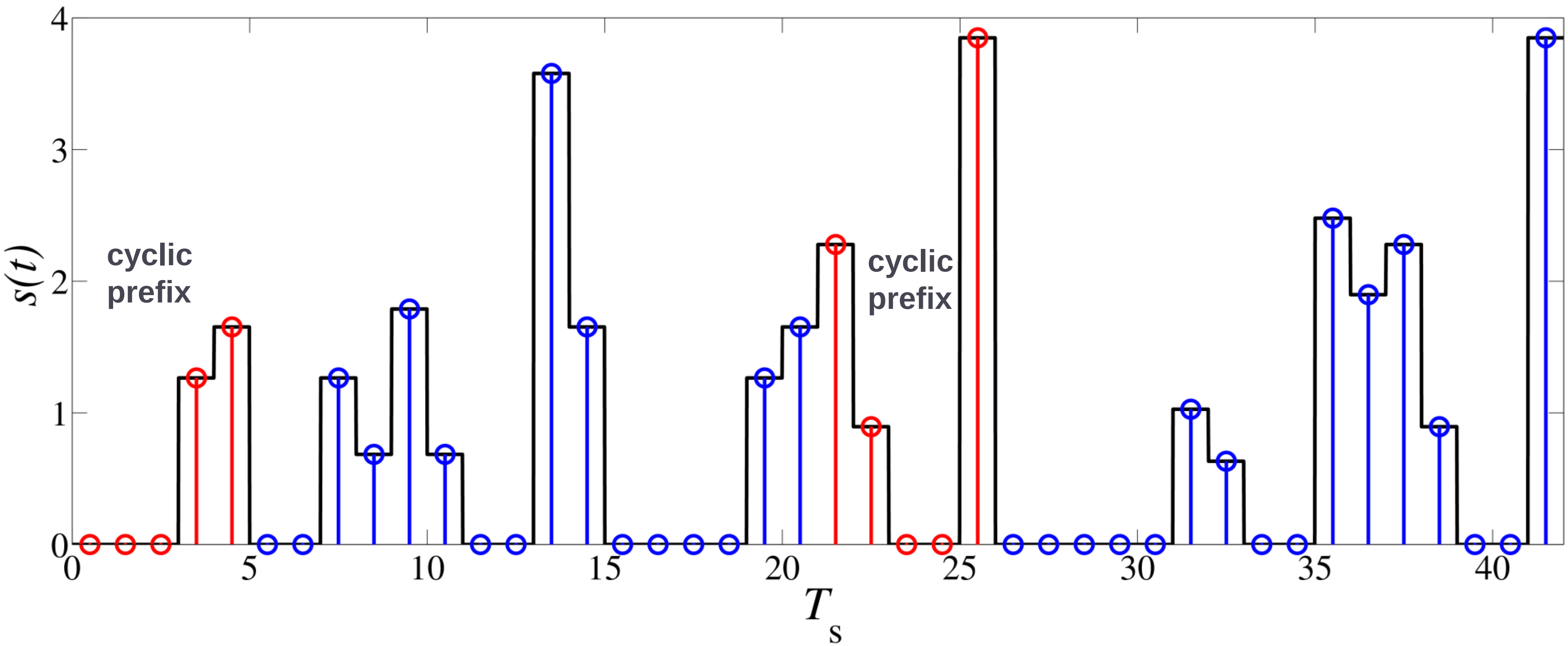


U-OFDM/ Flip OFDM Theory

- In U-OFDM, by design: $s_p[n] = -s_n[n]$
- Original signal is obtained as $s_o[n] = s_p[n] - s_n[n]$
- CLIP($s[n]$) = ($s[n] + |s[n]|$) / 2 !!! This representation is important !!!
- $s_p[n] = - s_n[n]$ => $|s_p[n]| = |s_n[n]|$
- Therefore, distortion from clipping is completely removed by the subtraction operation.

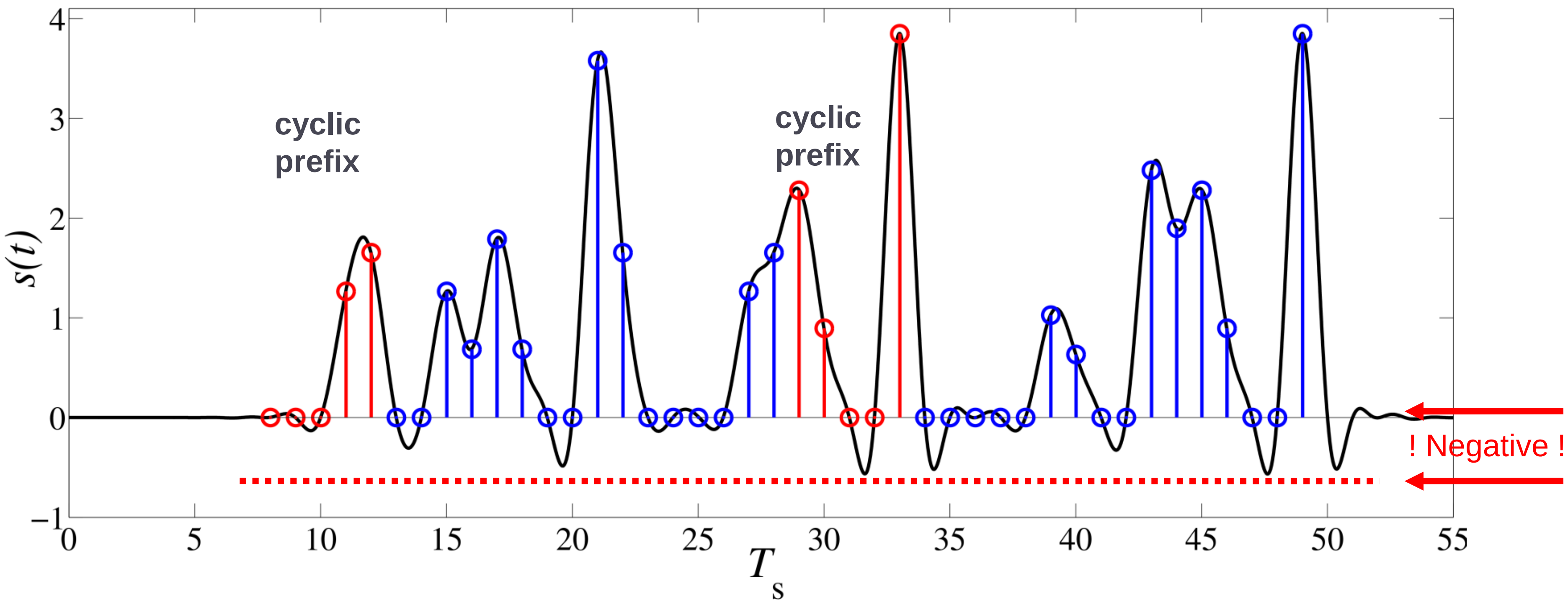
Going from Digital to Analog Domain

- Samples are represented by pulse shapes
- Different pulse shapes have different time and frequency characteristics



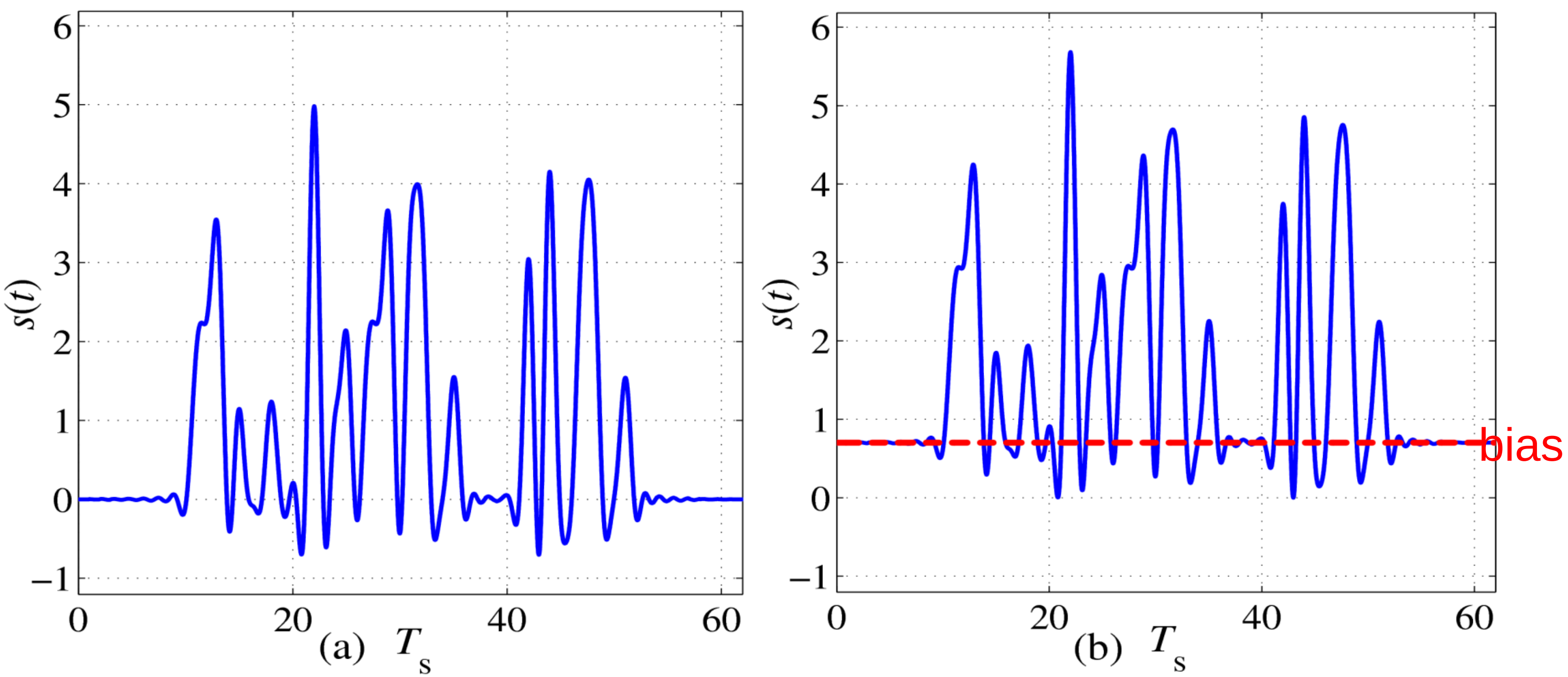
Unipolar vs. Bipolar Pulse Shapes

- **Unipolar** digital signals combined with **unipolar** pulse shapes produce **unipolar** analog signals.
- **Unipolar** digital signals combined with **bipolar** pulse shapes produce **bipolar** analog signals.



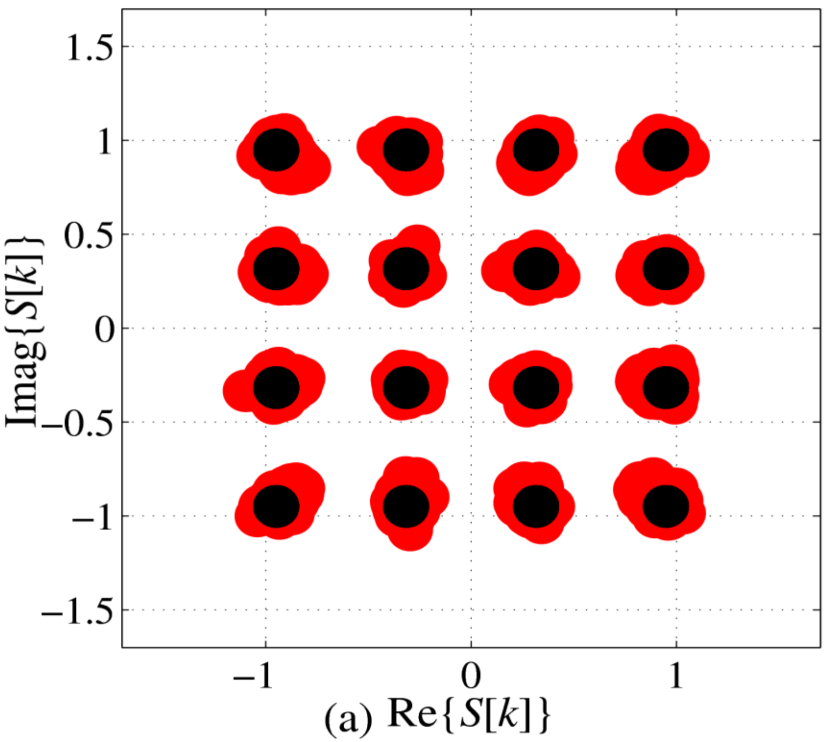
Adding a Bias to a Bipolar Signal

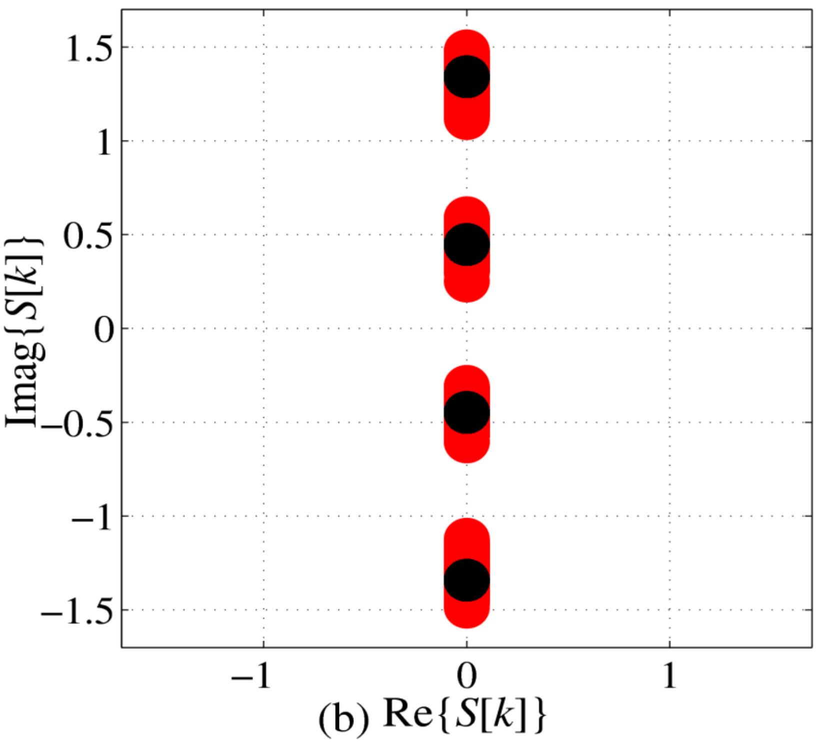
- Bipolar analog signals can be made unipolar by introducing a **bias** as presented below.
- Bias increases power dissipation.



Clipping Negative Values

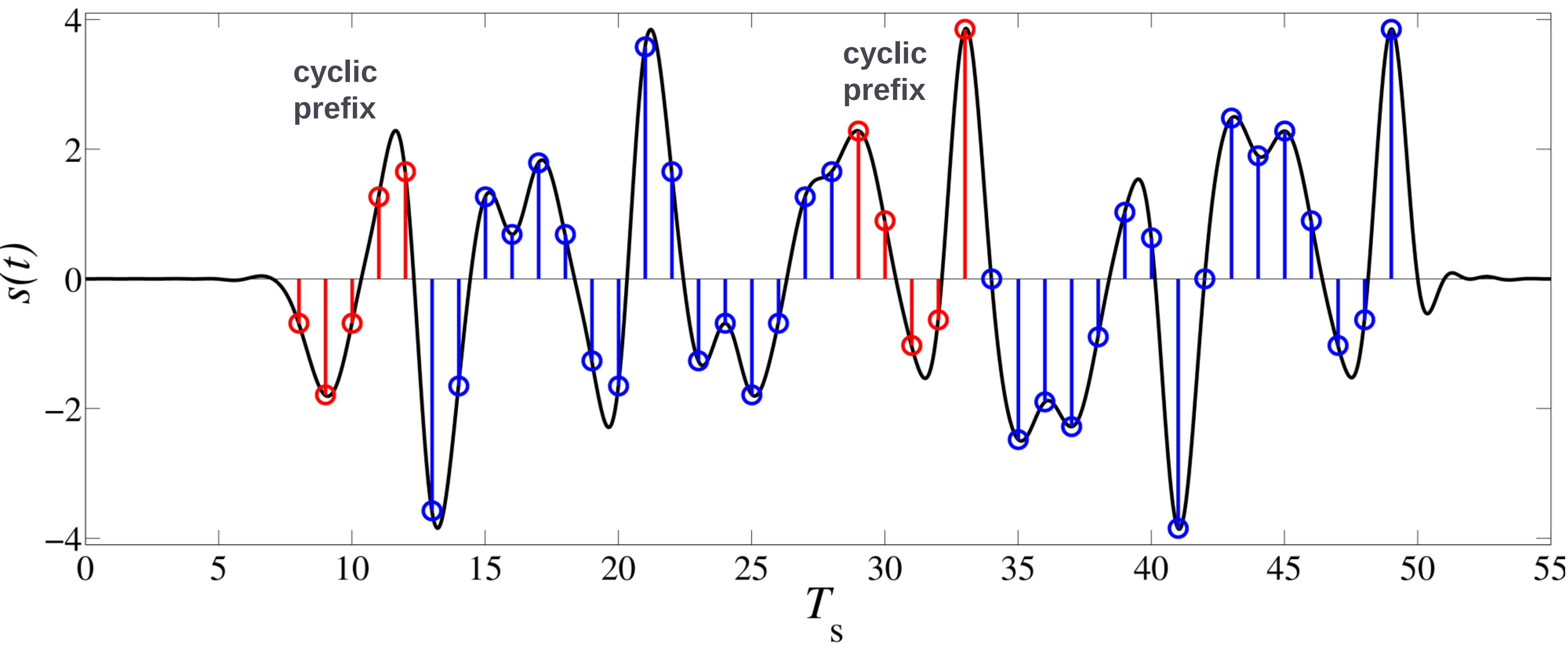
- Most of the analog signal is positive, so the negative values could be ignored (**clipped**).
- This, however, introduces **distortion** and out-of-band **interference**.





What if Pulse Shaping is Done Before Clipping?

- Discrete bipolar signals are shaped with bipolar pulse shapes and clipping is performed afterwards.



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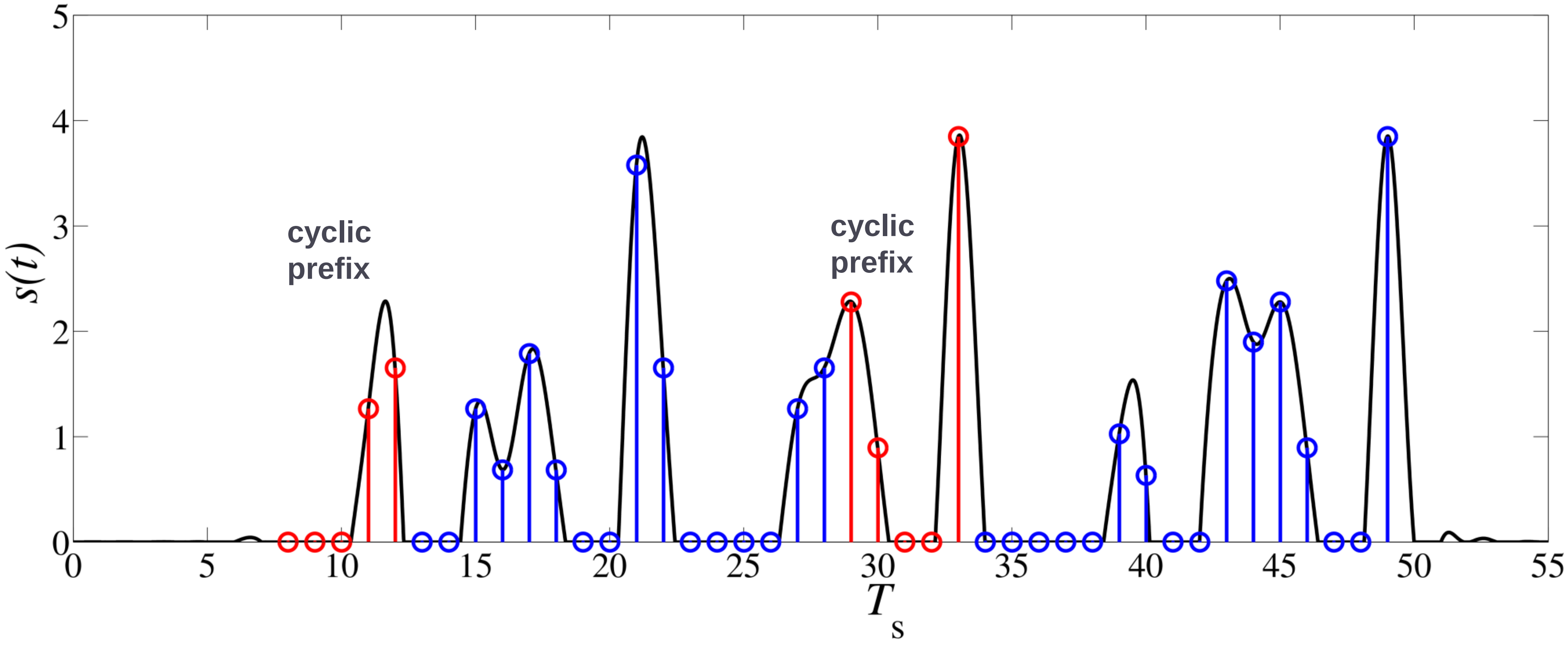
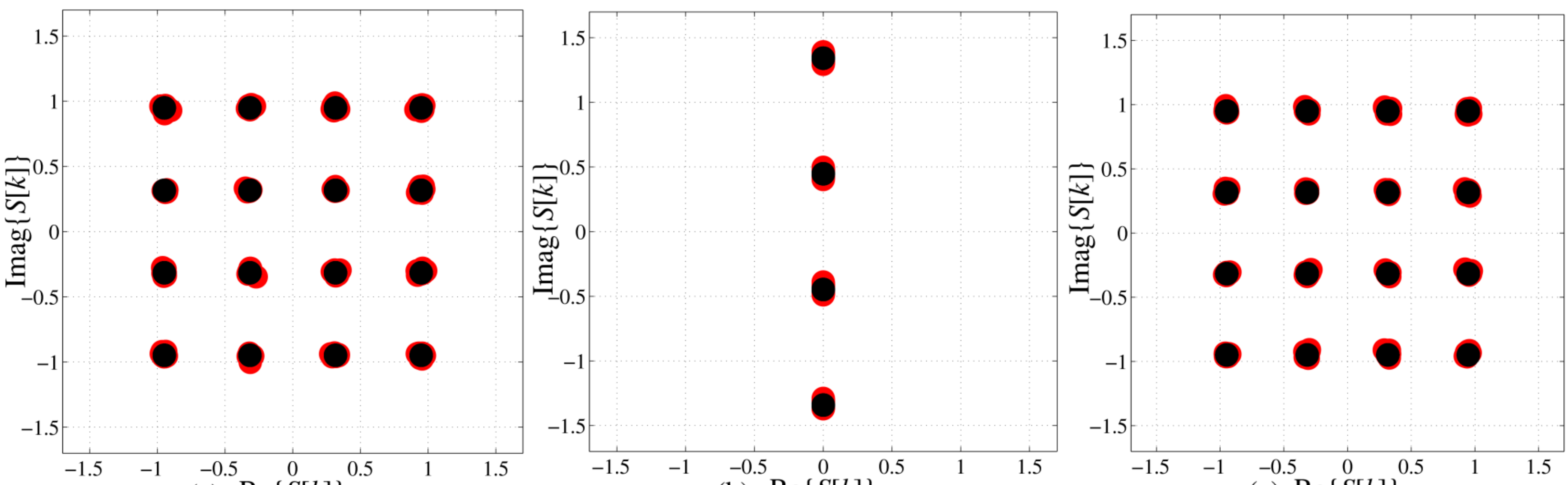


Clipping the Negative Values

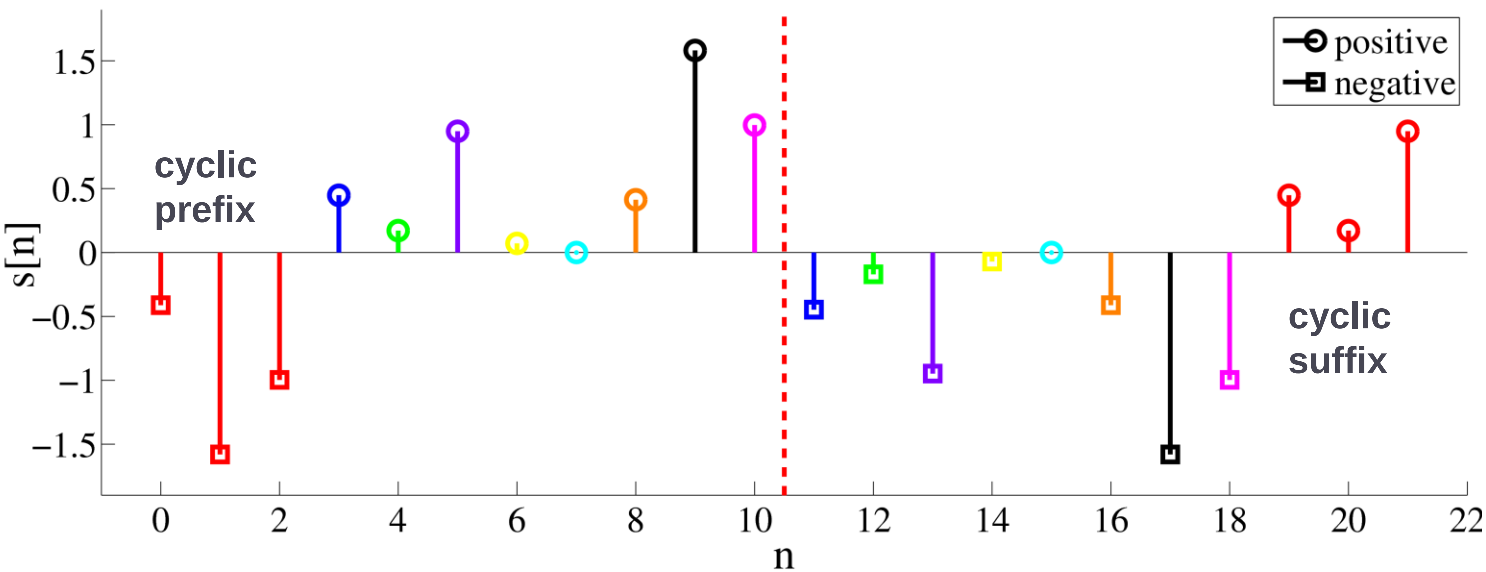
- The useful signal is kept in the required band.
- Only the distortion term is attenuated by limited channel response.
- The necessary symmetry of the distortion term is kept after pulse shaping and after the channel effects for all three modulations.
- Some distortion is still present. The non-causal response of the pulse-shaping filter disrupts the noise symmetry.



(a) (b) (c)

Guard Interval at the End

- A physical communication channel has a **causal** impulse response, which makes a **cyclic prefix** sufficient to maintain orthogonality.
- A band-limited **pulse shape** like the raised cosine filter has a **non-causal** impulse response.
- **Non-causal** pulse shapes **disrupt** the symmetry of the distortion terms. A second guard interval (cyclic suffix) can mitigate this.

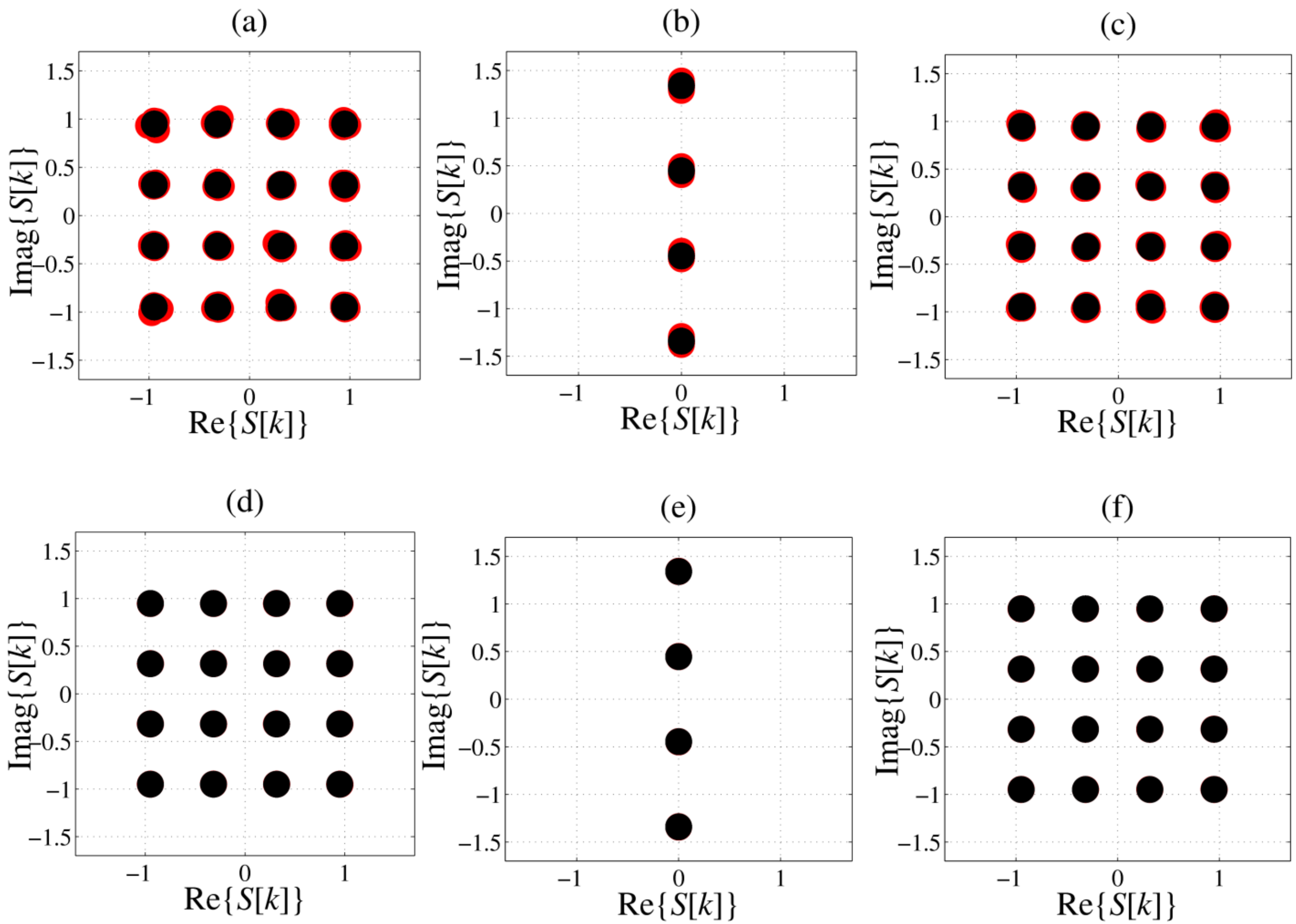


Effect of the Cyclic Suffix

- Root-raised cosine filter with rolloff factor of 0.5, 16-QAM, N_{fft}=16

No suffix

With suffix

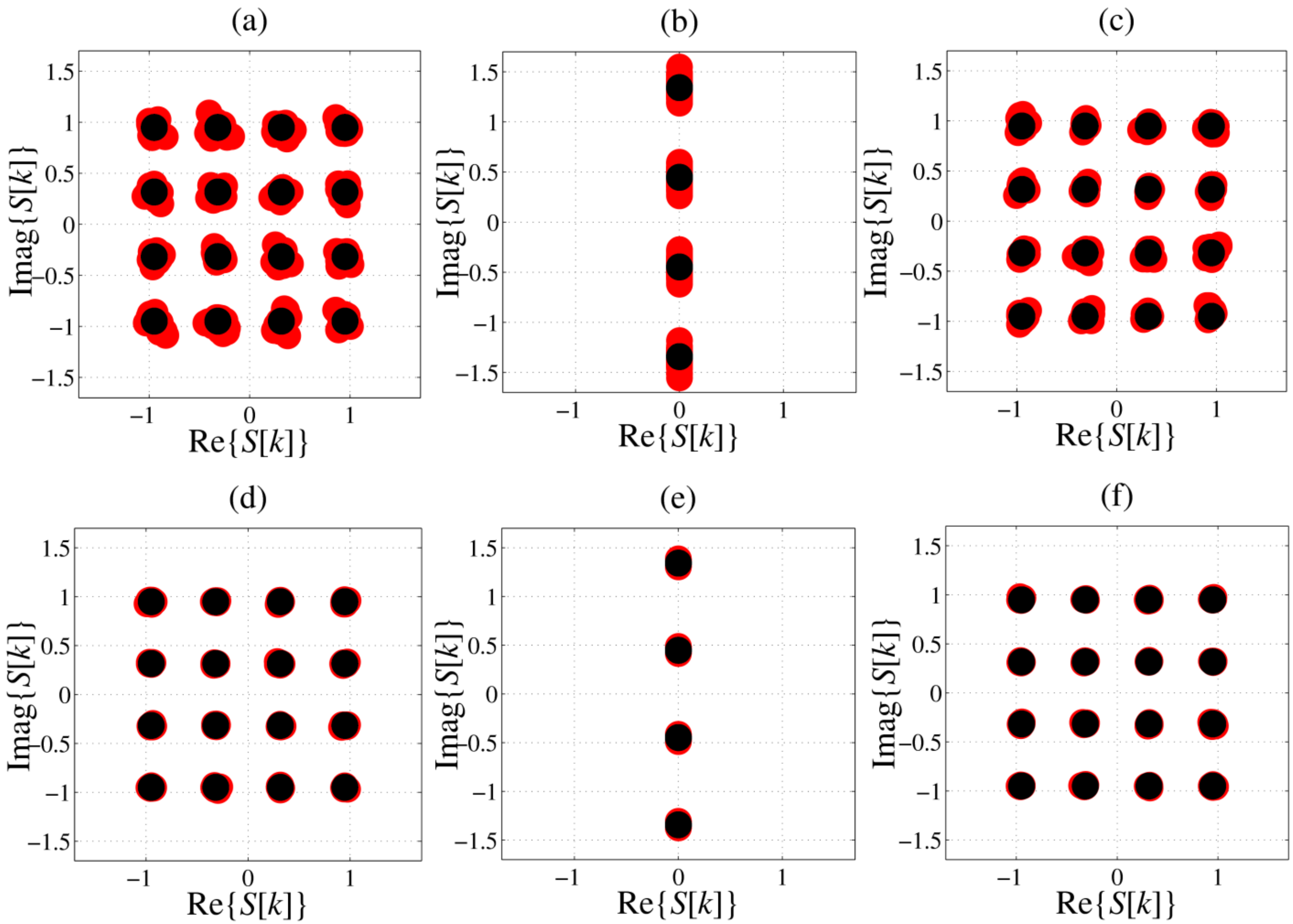


Effect of the Cyclic Suffix

- Root-raised cosine filter with rolloff factor of 0.1, 16-QAM, N_{fft}=16

No suffix

With suffix



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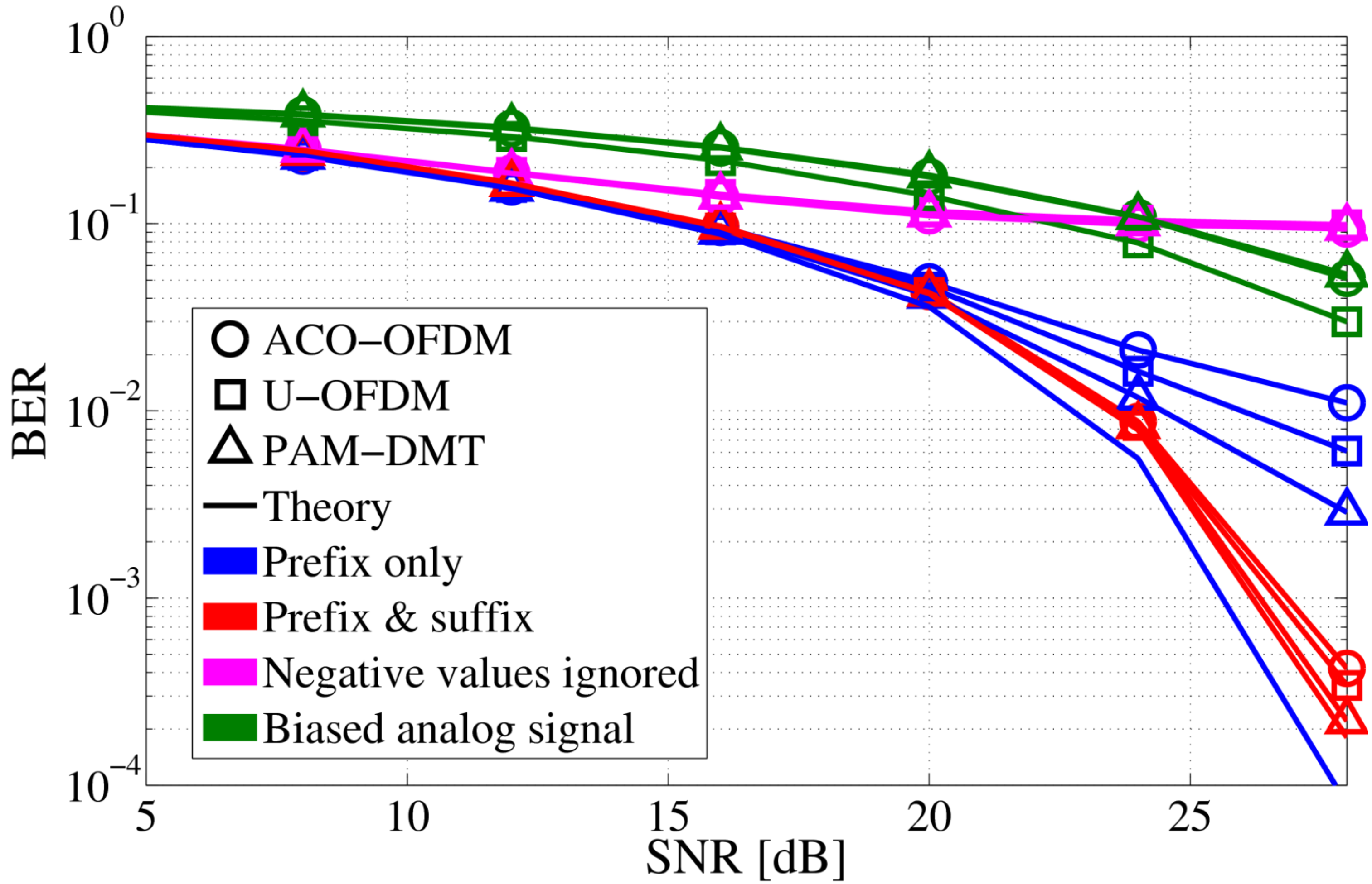
Effect of the Cyclic Suffix

- Root-raised cosine filter with rolloff of 0.1, N_{fft}=32, 256-QAM



Effect of the Cyclic Suffix in Numbers

- $S[k]$ = signal in frequency domain
- $\bar{S}[k]$ = distorted signal in frequency domain

- Signal-to-Distortion Ratio (SDR) = $\dfrac{\mathrm{E}\left[S^2[k]\right]}{\mathrm{E}\left[\left(S[k]-\bar{S}[k]\right)^2\right]}$

<u>SDR in Different Scenarios</u> *

N_{fft}	ACO-OFDM SDR [dB]		PAM-DMT SDR [dB]		U-OFDM SDR [dB]	
	Prefix Only	Prefix & Suffix	Prefix Only	Prefix & Suffix	Prefix Only	Prefix & suffix
32	27.33	39.19	29.15	41.61	28.7	40.69
64	30.5	42.26	32.46	44.76	31.01	43
256	36.6	48.33	38.2	50.19	36.72	48.38

! Cyclic suffix provides 12 dB improvement in SDR !

*Root-raised cosine filter with rolloff factor of 0.1 has been used in these calculations. The QAM constellation size is 256.

Conclusions

- **Discrete unipolar** signals require **unipolar** pulse shapes
- **Bipolar** pulse shaping can be applied as long as pulse shaping is applied **before** clipping the negative values.
- After pulse shaping, **distortion** terms still retain required **symmetry** to stay **orthogonal** to the useful information.
- **Non-causal** pulse shapes **disrupt** the symmetry of the distortion terms. A second guard interval (cyclic suffix) can mitigate this.

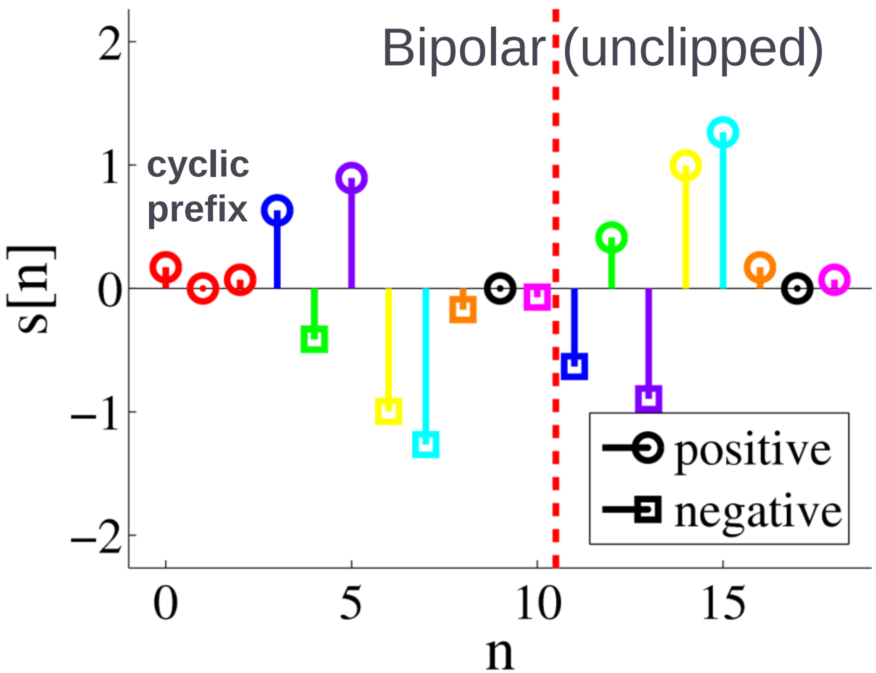
Thank you very much for the attention !

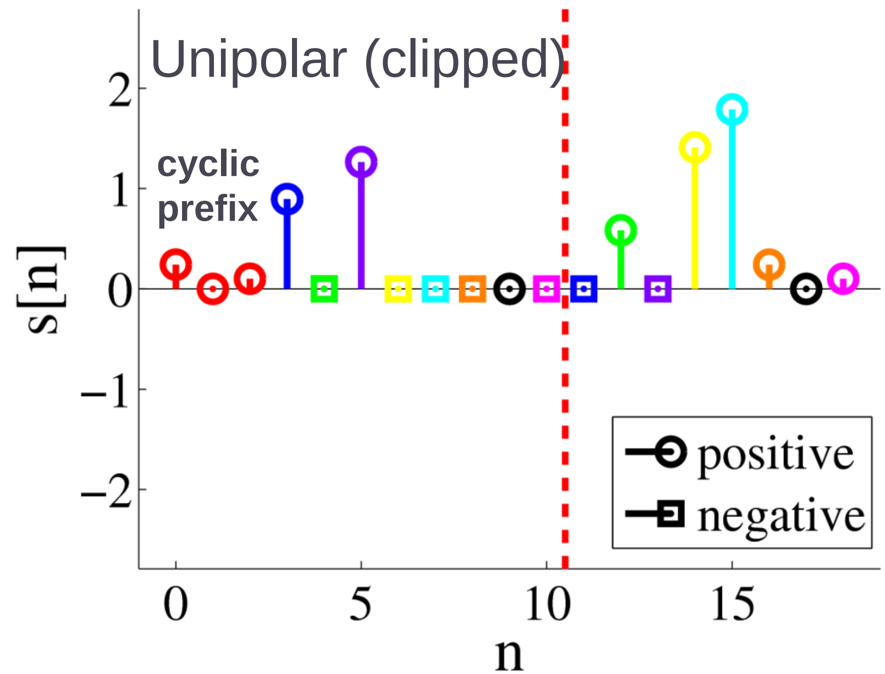
Motivation

- Demands for wireless data rates are growing exponentially. In 2015, more than 6 Exabytes of data are expected to be sent globally.
- RF spectrum is insufficient for growing demands. New physical domains for Wireless Communications are desirable.
- Optical wireless communication is a potential solution to the emerging spectrum problem.

Asymmetrically Clipped Optical OFDM (ACO-OFDM)

- Only odd carriers are modulated. This leads to a symmetry in time domain: $s[n] = -s[n+N/2]$ (Armstrong et al., 2006)
  - N = number of carriers/number of FFT points
  - $s[n]$ = time domain signal





ACO-OFDM Theory

- **Odd carriers only contain information <=> $s[n] = -s[n+N/2]$**
- **Even carriers only contain information <=> $s[n] = s[n+N/2]$**

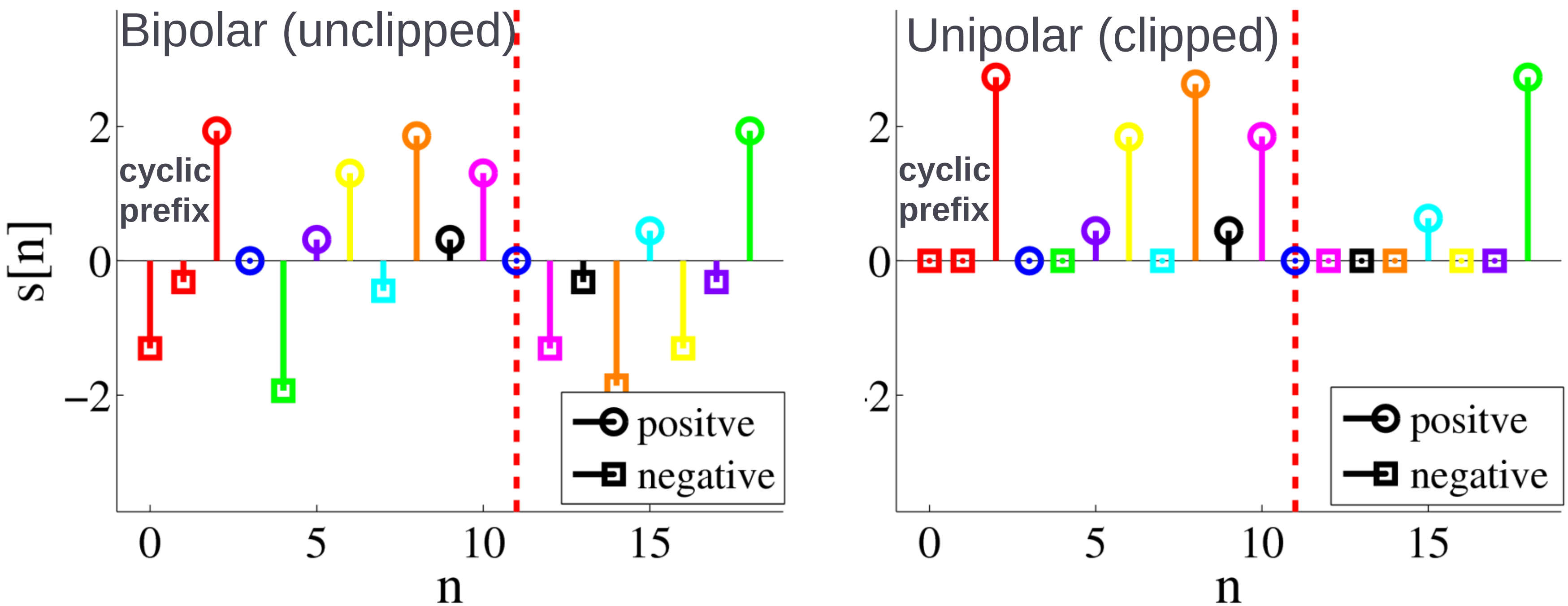
- CLIP($s[n]$) = ($s[n] + |s[n]|$) / 2 !!! This representation is important !!!

- In ACO-OFDM, $s[n] = -s[n+N/2] \Rightarrow |s[n]| = |s[n+N/2]|$

- Therefore, distortion from clipping falls only on the even subcarriers.

Pulse-amplitude-modulated Discrete Multitone Modulation (PAM-DMT)

- Carriers are modulate with imaginary symbols only. This leads to a symmetry in time domain: $s[n] = -s[N-n]$ (Lee et al., 2009)
  - N = number of carriers/number of FFT points
  - $s[n]$ = time domain signal



PAM-DMT Theory

- **Carriers are modulated with imaginary symbols <=> $s[n] = -s[N-n]$**
- **Carriers are modulated with real symbols <=> $s[n] = s[N-n]$**

- CLIP($s[n]$) = ($s[n] + |s[n]|$) / 2 !!! This representation is important !!!

- In PAM-DMT, $s[n] = - s[N-n] \Rightarrow |s[n]| = |s[N-n]|$

- Therefore, distortion from clipping falls only on the real values in frequency domain.