Technion Israel Institute of Technology
NATIONAL INSTRUMENTS
erc 646804-BNYQ
S_X_MPL Signal Acquisition Modeling and Processing Lab

UWB Communication using Compressed Sensing

Robert Ifraimov, Kfir Cohen, Idan Shmuel, Yair Keller, Yonina C. Eldar

Theoretical Background

Motivation

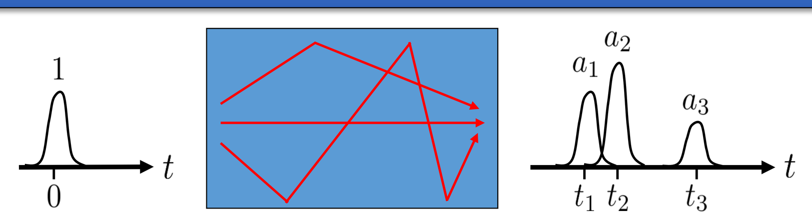
Ultra-wideband (UWB) wireless technology advantages:

- High data rate
- Frequency diversity can be exploited
- FCC Unlicensed commercial deployment due to low transmitted spectral power density [dBm/Hz]

Restrictions: Short range and High rate ADC is needed

We propose sub-Nyquist hardware implementation for channel estimation and data detection, by exploiting the sparse nature of the channel response

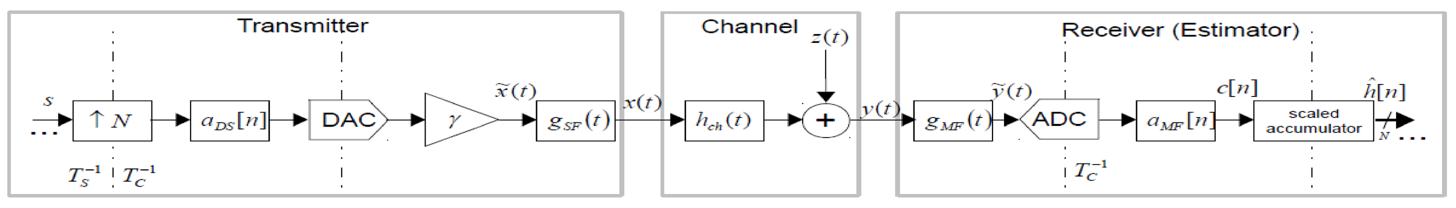
Channel Model



- Packet based wireless communication, during which the channel is linear time invariant
- The channel contains L resolvable echoes of the input with gain a_l. Channel response: $h_{ch}(t) = \sum_{l=1}^{L} a_l \delta(t-\tau_l) + z(t)$
- Zero mean additive white circular symmetric Gaussian noise is added *z(t)*
- The parameters $\{a_l, \tau_l\}$ are unknown to the transmitter and the receiver
- We consider IEEE 802.15.4a channel model, particularly sparse CM1 – Line of Sight Residential
- Our goal is estimating $H_{ch}(f)$ in order to make data detection possible

Nyquist Channel Estimation

- Transmitter uses a trinary {-1, 0, 1} direct sequence (DS) $a_{DS}[n]$ which is N=511 chips length to spread spectrum data symbols ~1Mbps known training sequence (for channel estimation) or data (for data detection) is multiplied by the direct sequence and sent in 500MHz DAC
- Transmitted signal is: $x(t) = \gamma \sum_{i\in Z} s_i \sum_{m=0}^{N-1} g_{SF}(t - mT_c - iNT_c) a_{DS}[m]$



- Complying Nyquist sampling rate requires a high rate ADC
- For channel estimation, an accumulator is used to estimate the channel
- For data detection, rake receiver uses estimated channel

Sub-Nyquist Channel Estimation

- We want to sample less bands (q time slower than Nyquist), yet maintain the frequency selectivity to some degree
- Transmitter uses signal whose frequency support is a subset $\mathcal{L}$ of the full bandwidth
- The transmitter will transmit only on M FFT coefficients that are selected by masking DS
  $b_{DS} = IFFT_N\{FFT_N\{a_{DS}\}[k], k \in \mathcal{L}\}$
- Sampling is performed by a low rate ADC
- Use sparse recovery (e.g. OMP) to reconstruct the sparse signal
- Seeking wide frequency aperture alongside a single analog branch Foldable method was chosen where we aliases through sampling
- The N taps are split into q groups of size M
- Active set is chosen to be self foldable, such that after sampling by 1/q Nyquist rate, all active coefficients are retraceable:
  $\mathcal{L} \cap \{m + M \cdot i\}_{i=0}^{q-1}$ $for\ m = 0, .., M-1$

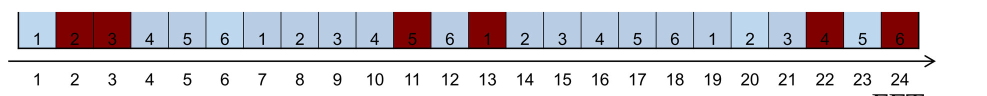
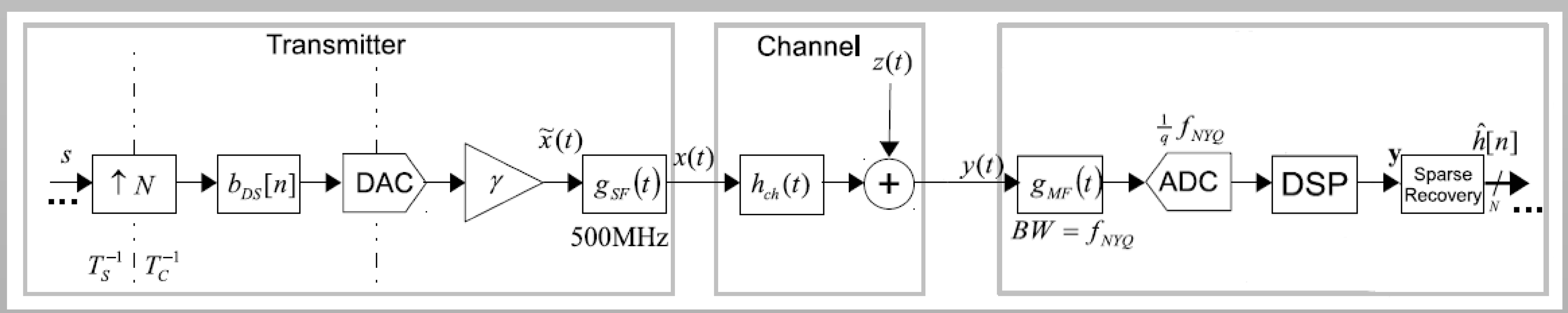
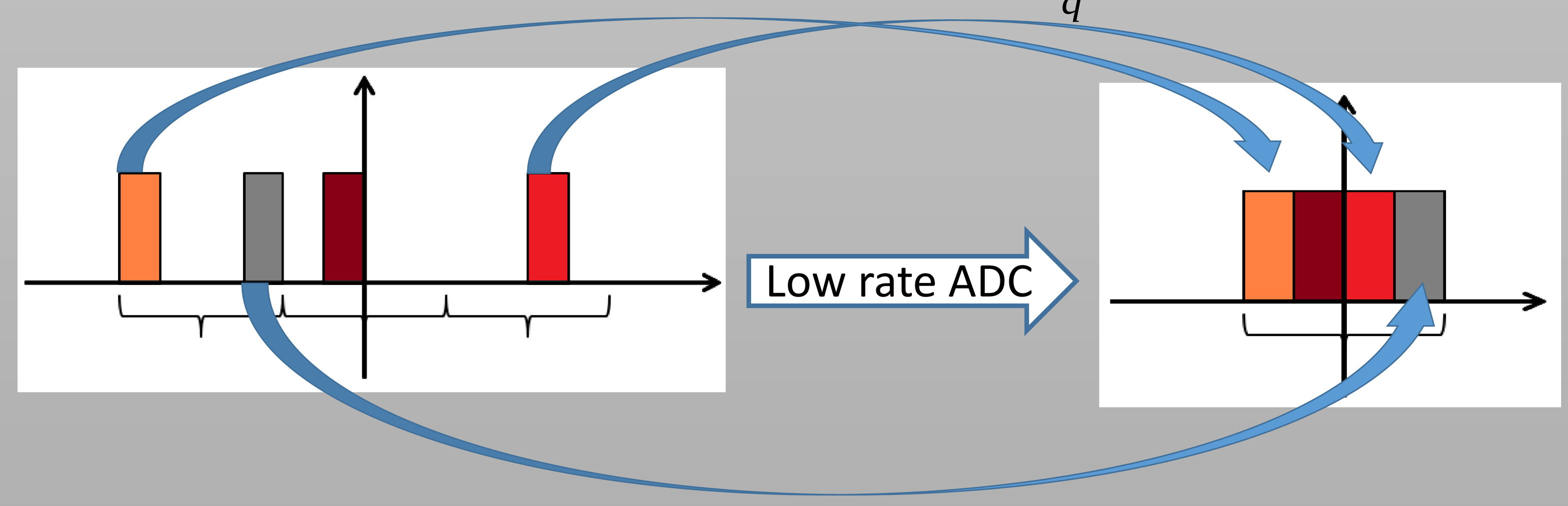


Illustration: N=24, q=4, M=6

Sub-Nyquist Model



Foldable Sampling - One sampler $\frac{1}{q} f_{NYQ}$



Data Detection

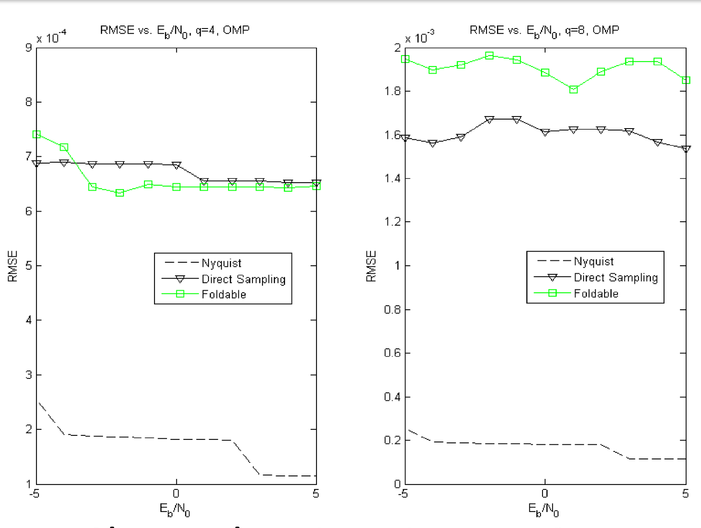
- Data detection uses the same front end as the channel estimation phase
  $Y[k] = sH[k]A_{DS}[k] + Z[k], k \in \mathcal{L}$
- To detect the symbol we use the A_{DS} and H_{ch} matching filter that was found in channel estimation stage
  $$R[k] = s + \frac{A_{DS}^*[k]H^*[k]}{||H[k]||^2||A_{DS}[k]||^2} Z[k], k \in \mathcal{L}$$
- The maximum likelihood estimator under additive Gaussian noise is given by the frequency domain
  $$\hat{s}_{soft} = \frac{1}{M}\sum_{k\in\mathcal{L}} R[k]$$
- Hard decoding is applied on $\hat{s}_{soft}$ by finding the nearest QPSK symbol

Simulation Results

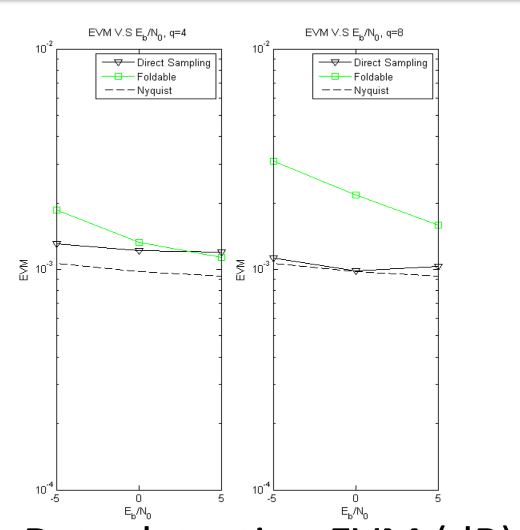
- Matlab simulation compare results for Nyquist, Foldable and *Direct sample methods

***Direct FFT Sampling**: Randomly select M coefficients to sample from full rate (not feasible)

- Measuring performance using energy capture and RMS error: $\mathrm{RMSE}(h, \hat{h}) = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1} |h_{\mathcal{T},n} - \hat{h}_{\mathcal{T},n}|^2}$
- Performance of data detection through Error Vector Magnitude (EVM): $EVM(s, \hat{s}) = \frac{1}{J}\sqrt{\sum_{i=1}^{J} \|s_i - \hat{s}_i\|^2}$



Channel estimation RMSE



Data detection EVM (dB)

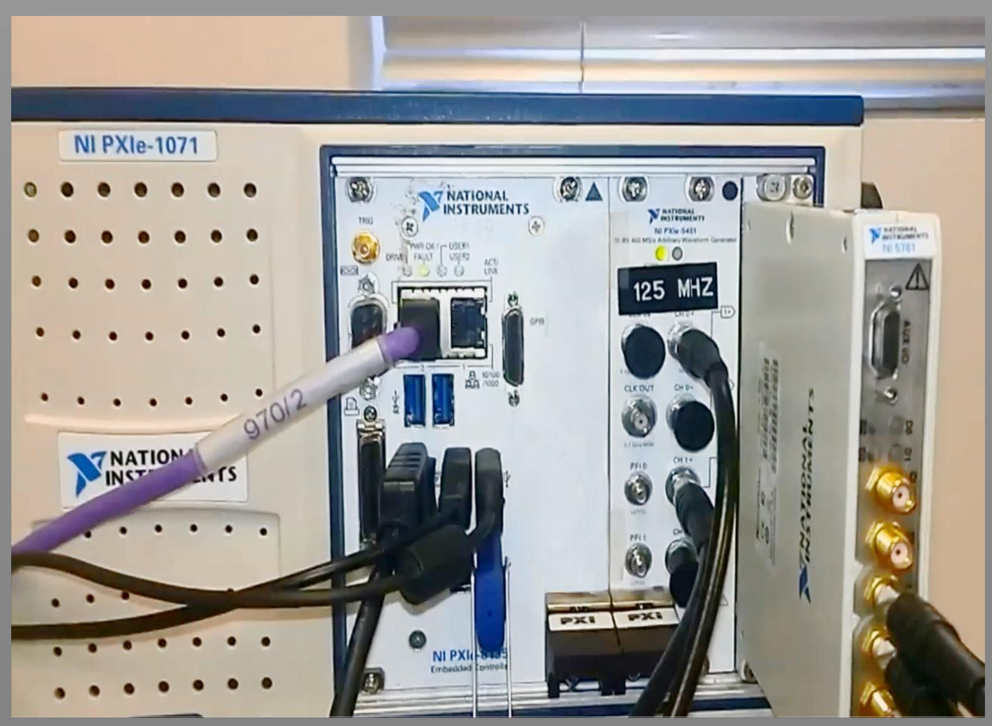
Conclusions:

Analog acquisition using a low rate ADC and standard front-end can be performed to detect data in multipath channels
For q=8, only 12% of the energy is dropped at estimation and EVM raised by factor 2 only at EbN0 of 0dB at data detection stage

System Implementation

- The demo system illustrates the application of sub-Nyquist sampling to QPSK UWB signals
- In the system ~250Kbps data rate is applied, which spreads to 125 MHz bandwidth
- 2 channels are active for I and Q in both AWG and sampler
- The channel response and noise are modeled before the packet transmitted through AWG
- The system implemented on NI PXIe chassis with signal generator – NI PXIe-5451 AWG and receiver – NI 5761 digitizer samples the signals directly at 125/64/32 MSps to achieve down to 1/8 of the signal's Nyquist rate

Demo system

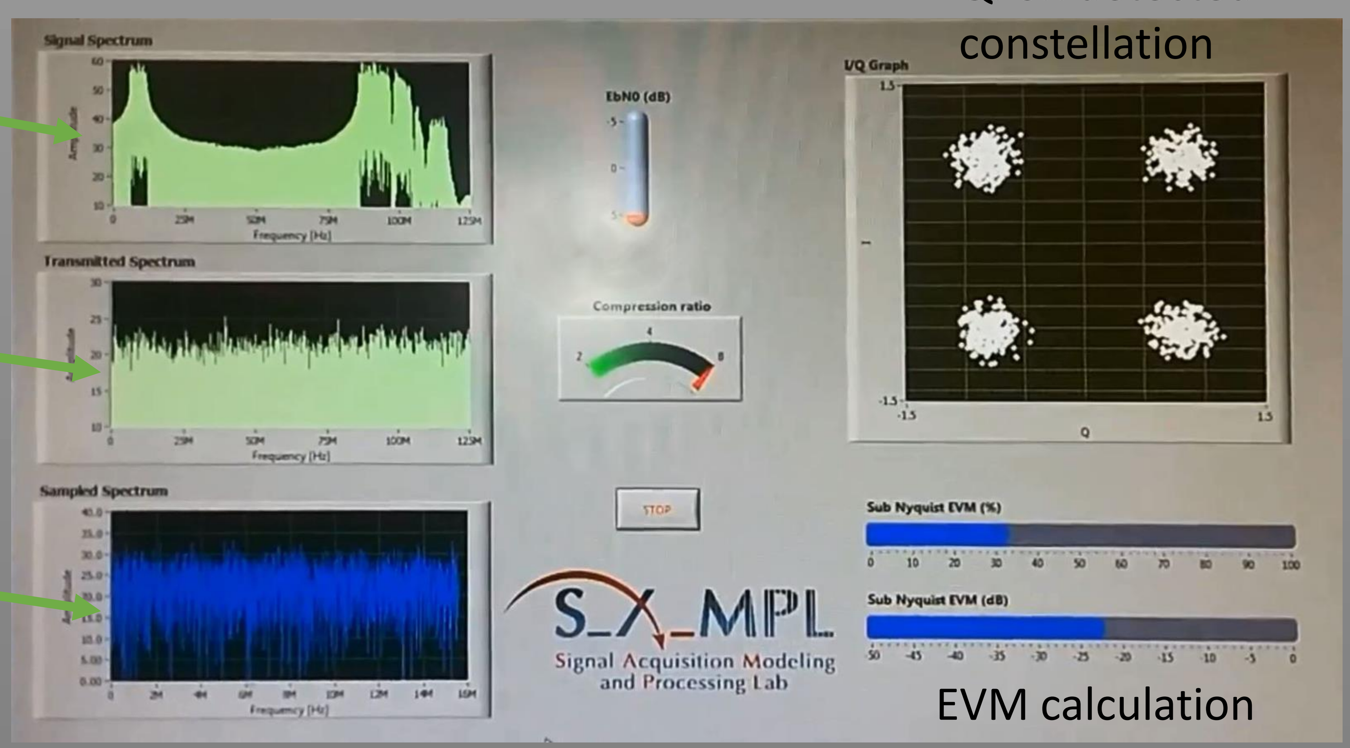


Foldable generated signal

Transmitted signal with channel response and noise

Aliased signal as sampled by 1/q Nyquist rate

QPSK detected constellation



EVM calculation

References

1. K. M. Cohen, C. Attias, B. Farbman, I. Tselniker, and Y. C. Eldar, "Channel estimation in uwb channels using compressed sensing," in Proc. IEEE ICASSP-14, Florence, Italy, May 2014
2. M. Win and R. Scholtz, "Ultra-wide bandwidth time-hopping spreadspectrum impulse radio for wireless multiple-access communications," Communications, IEEE Transactions on, vol. 48, no. 4, pp. 679–689, Apr 2000
3. J. Paredes, G. Arce, and Z. Wang, "Ultra-wideband compressed sensing: Channel estimation," Selected Topics in Signal Processing, IEEE Journal of, vol. 1, no. 3, pp. 383–395, Oct 2007

Contact Us

Robert Ifraimov rifraimov@tx.technion.ac.il (Technion)
Yonina Eldar yonina@ee.technion.ac.il (Technion)
SAMPL LAB http://sampl.technion.ac.il