A Review of DSP Topics in SpeckNet

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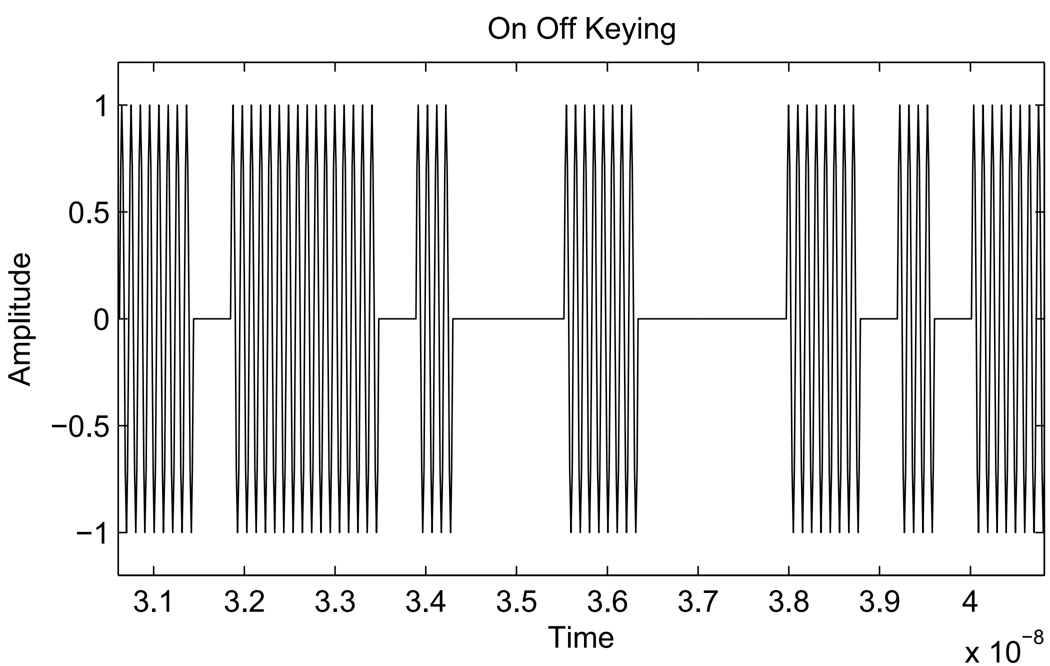
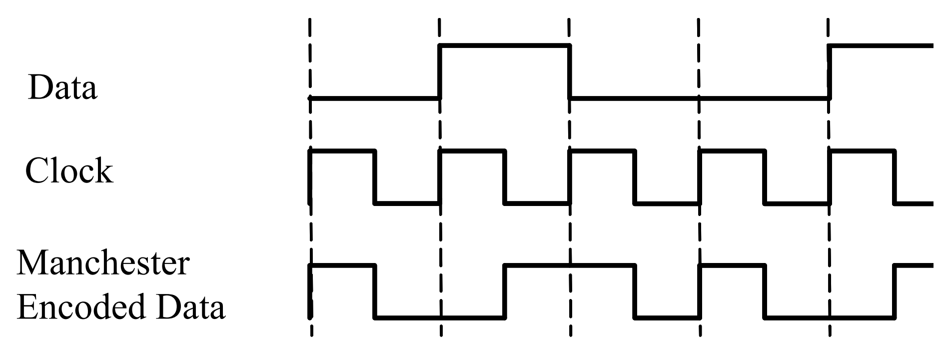
Overview

- Simple Manchester encoded communications for SpeckNets
- BER performance for non-coherent (first generation) and coherently demodulated Speck communications.
- Code Division Multiple Access (CDMA) as the multiple-access protocol
    - Multiple access interference in the system (assumed ad hoc)
    - MAC protocol based on SpeckMAC and CDMA
- Orthogonal Frequency Division Multiple Access (OFDMA) for concurrent communication with a central receiver
- Carrier and timing synchronisation, application to free space optics
- Subsystems for low power radios
    - Carrier generation, filtering, up and down conversion...

First Generation Scheme

- First generation Speck radio communications were simple:
  - 1-bit, ON or OFF data (On-Off Keying Modulation scheme
  - Manchester encoding (XOR of data with the clock)
- Non-coherent (envelope detector / Super-Regenerative Receiver
- Low quality oscillators and timing mismatches

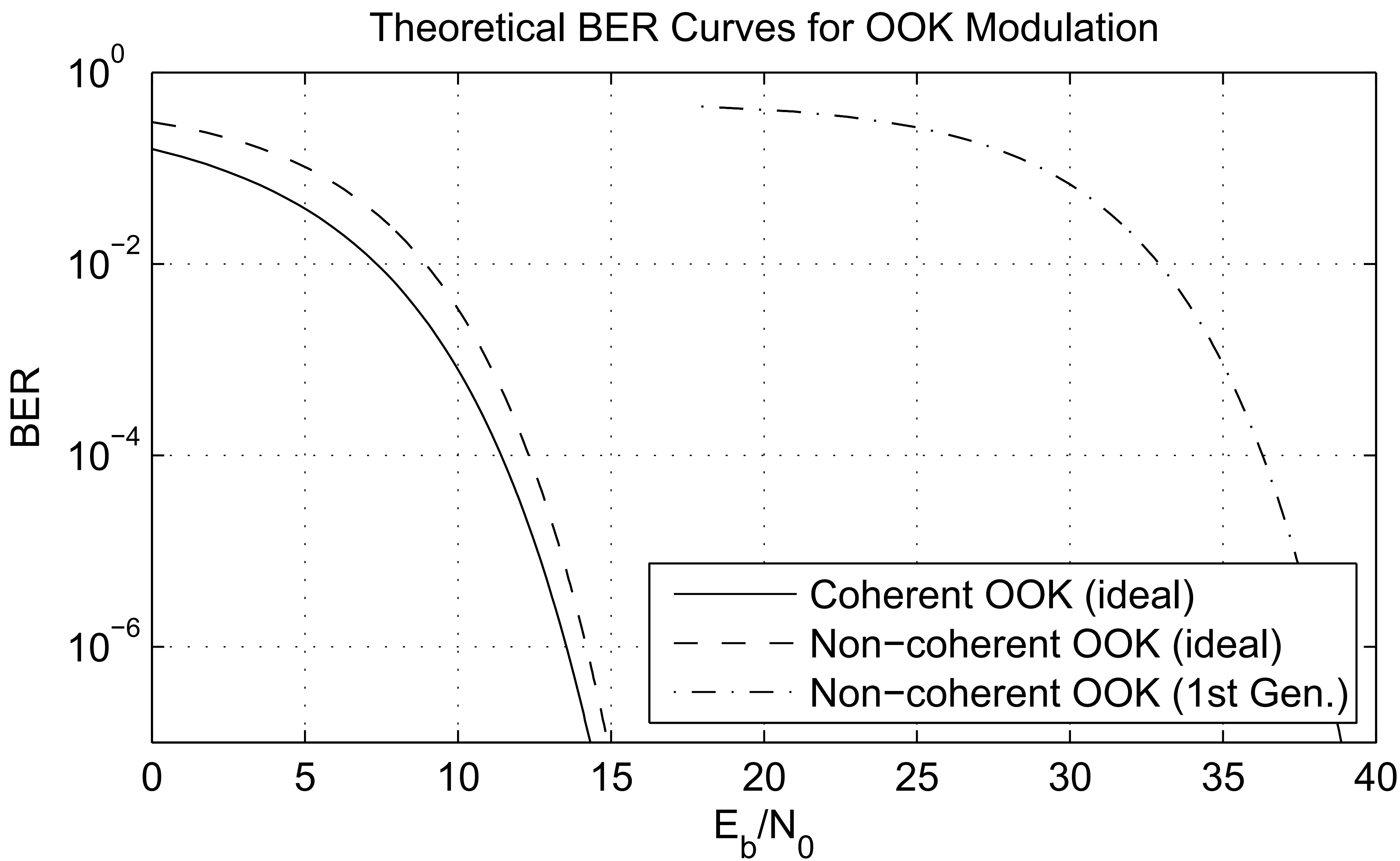




Performance of Non-Coherent Radio Communications

- RF design necessarily (for low power) had little filtering
- A very wide noise bandwidth was accepted into the receiver
- However the performance of the receiver was very sub-optimal as a result... leading to a higher transmit power being required.
- The normal method of measuring the performance of a digital system is in terms of
  - Bits in error per bits sent (Bit Error Ratio, or BER)
  - Energy per bit divided by noise spectral density, or $\frac{E_b}{N_0}$.
- In the case of this design, the noise bandwidth was much greater than the signal bandwidth, so performance was very poor.

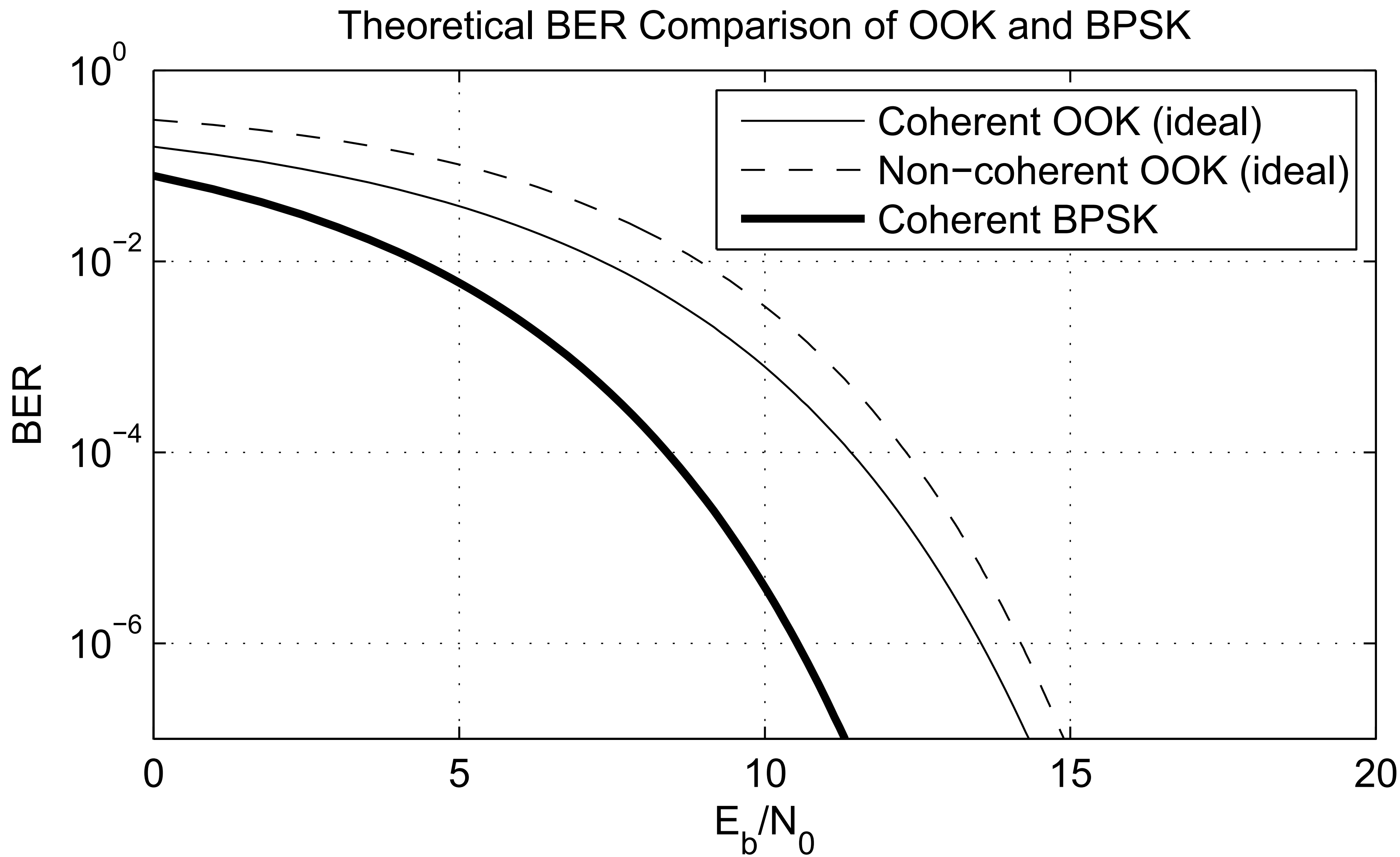
Notes:


Theoretical BER Curves for OOK Modulation
BER
10^0
10^{-2}
10^{-4}
10^{-6}
0
5
10
15
20
25
30
35
40
E_b/N_0
Coherent OOK (ideal)
Non−coherent OOK (ideal)
Non−coherent OOK (1st Gen.)

The Need for Coherent Radio

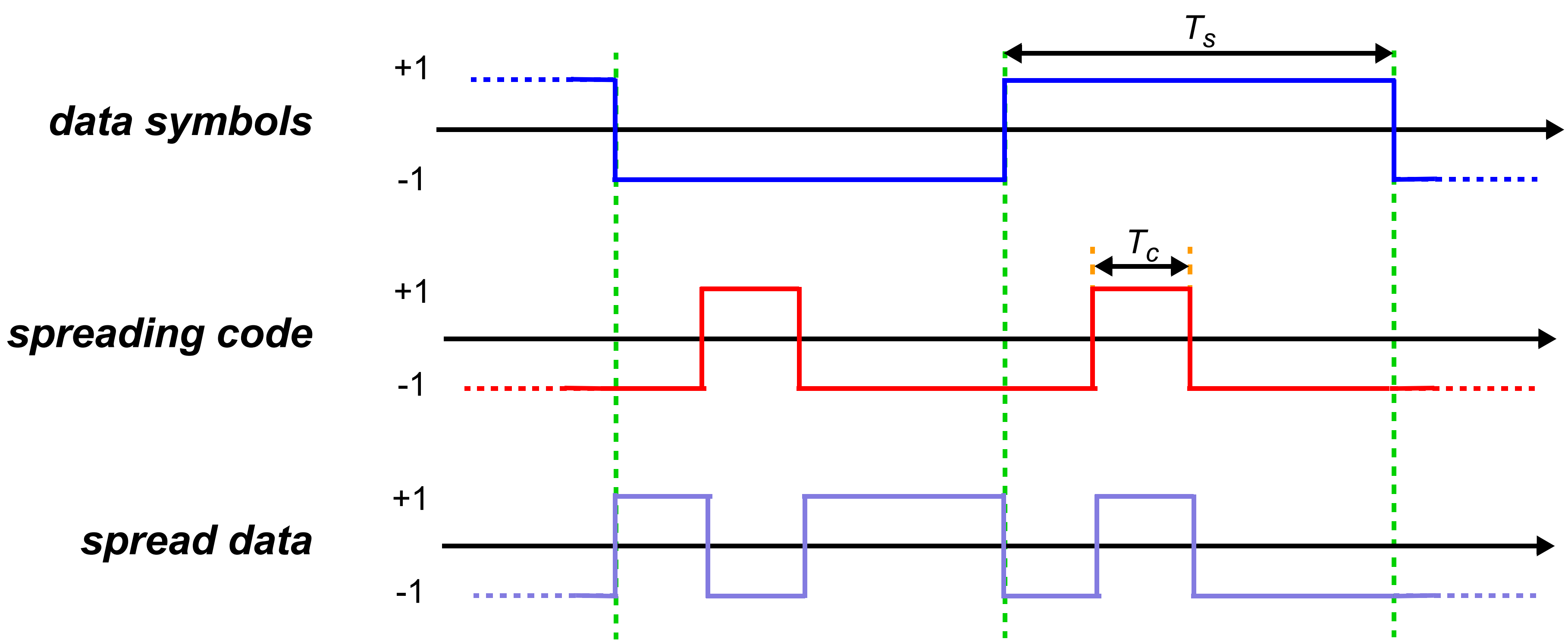
- Better performance in noise can be achieved
- Modulation schemes are very limited if non-coherent detection
- Modulation with a carrier enables phase modulation schemes to be used... which opens up other possibilities...
- The principal difficulty is power - the RF part now requires active components and consumes much more power.

Notes:


Theoretical BER Comparison of OOK and BPSK
Coherent OOK (ideal)
Non−coherent OOK (ideal)
Coherent BPSK
BER
10^{0}
10^{-2}
10^{-4}
10^{-6}
0
5
10
15
20
E_b/N_0

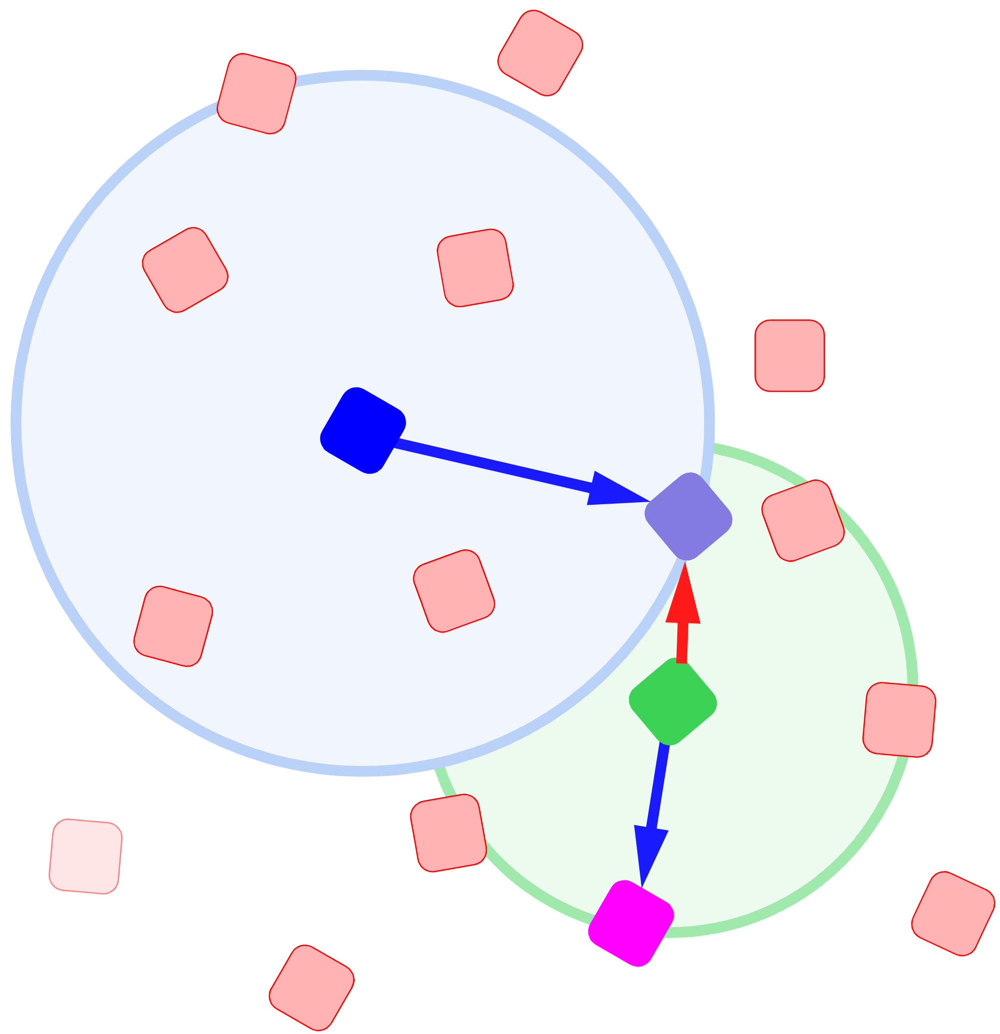
CDMA as the Multiple Access Scheme

- If SpeckNets are entirely ad hoc, frequency or time-division multiple access is difficult to co-ordinate.
- Multiple access can be achieved using codes to differentiate between different sources. These are orthogonal (or nearly orthogonal).
- CDMA codes for ad hoc networks are not absolutely orthogonal and some degree of Multiple Access Interference (MAI) results.



Notes:

- CDMA suffers from the Near Far Problem, where the interference generated by a nearby source causes the greatest interference.

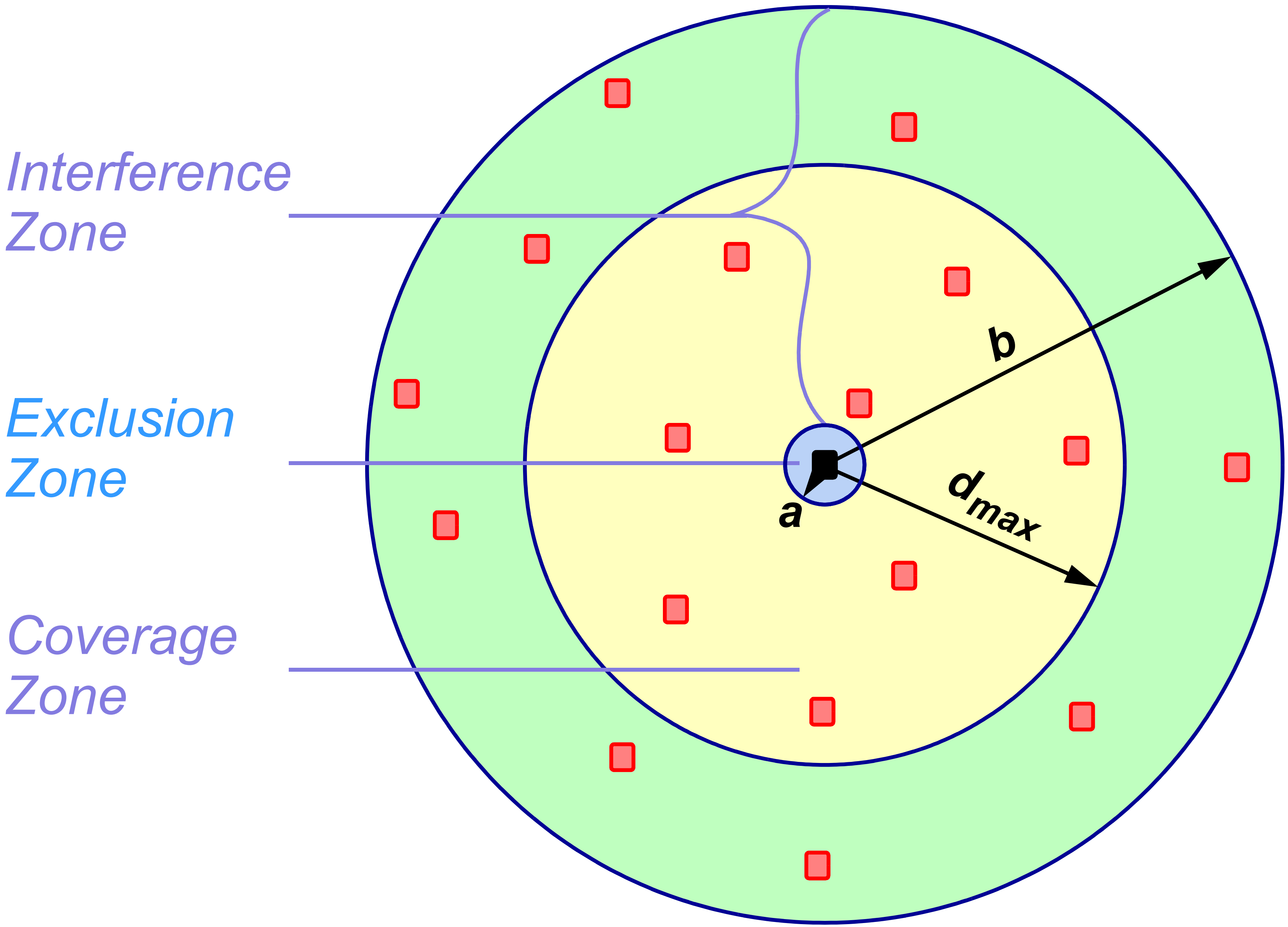


- In fact this occurs in non-CDMA systems too - for example when a single radio channel is shared on a random access basis.

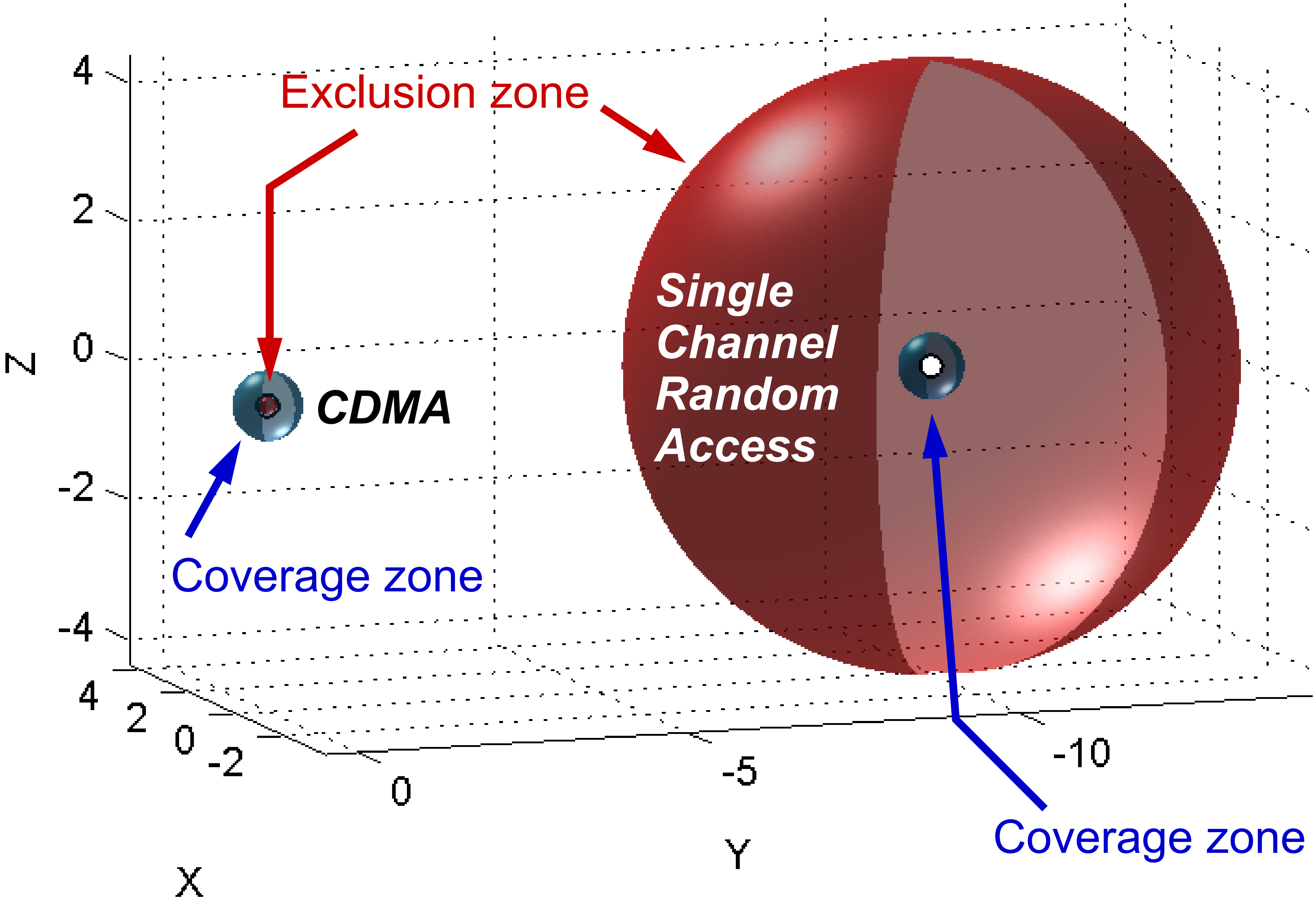
Spatial Reuse of the Radio Channel

- Investigation of whether the Near Far Problem could be overcome in a low cost, low power manner.
- Taking into account the relative signalling rates of the two, how often can CDMA systems reuse the radio channel in a spatial sense, compared to a non-spread, random access system?
- A mathematical model was developed for MAI and used to analyse the impact of CDMA interference on "coverage" and how densely a network could be populated.
- This model included different parameters like path loss index, spreading code length, 2D or 3D deployments, carrier frequency, etc.
- Model can be optimised for coverage area/volume and transmit power.
- The outcome was that the radio channel could be re-used much more often in the CDMA system. This suggests that either the network could achieve higher throughput, or reduced power.

Notes:



Spatial Reuse Example

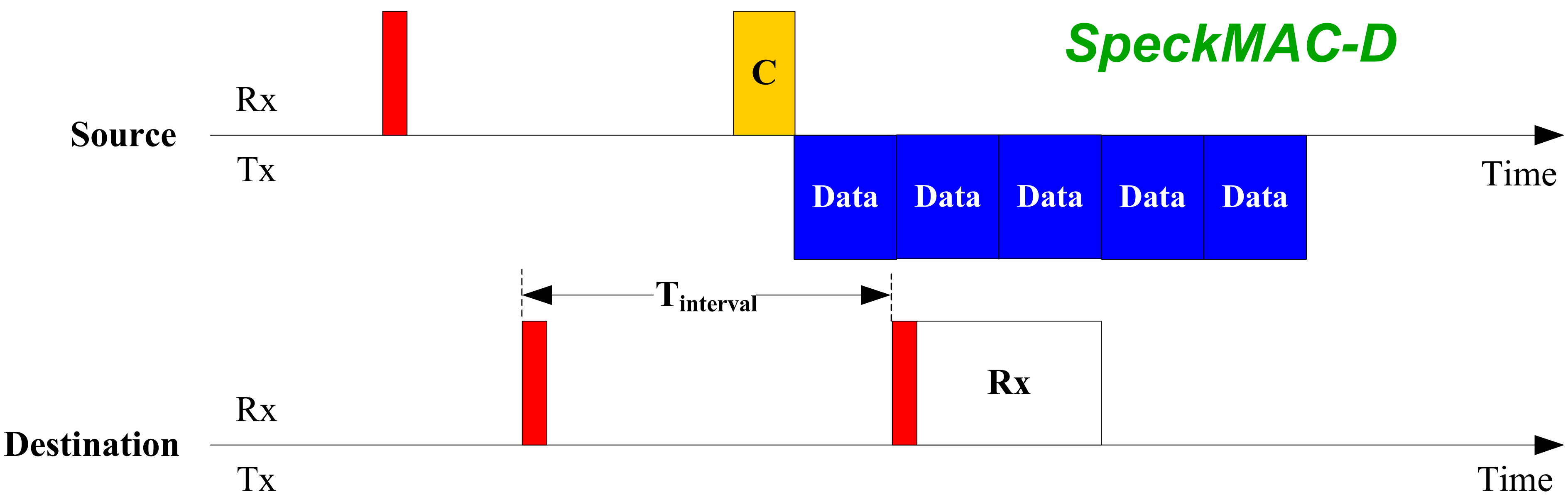


Notes:

- The transmission can be said to "occupy" the volume of the outer sphere.
- In this example, the CDMA transmission occupies $0.0085m^3$, whereas the non-spread, single channel random access system occupies $352.39m^3$ - a factor of 41,457!
- Therefore more concurrent communications can take place without collisions, retransmissions etc. Less power wasted!
- SpeckNets are intended to be redundant networks.
- Exclusion zones could be set up around active Specks in a network to ensure the Near Far Problem is controlled.

CDMA-based SpeckMAC Protocols

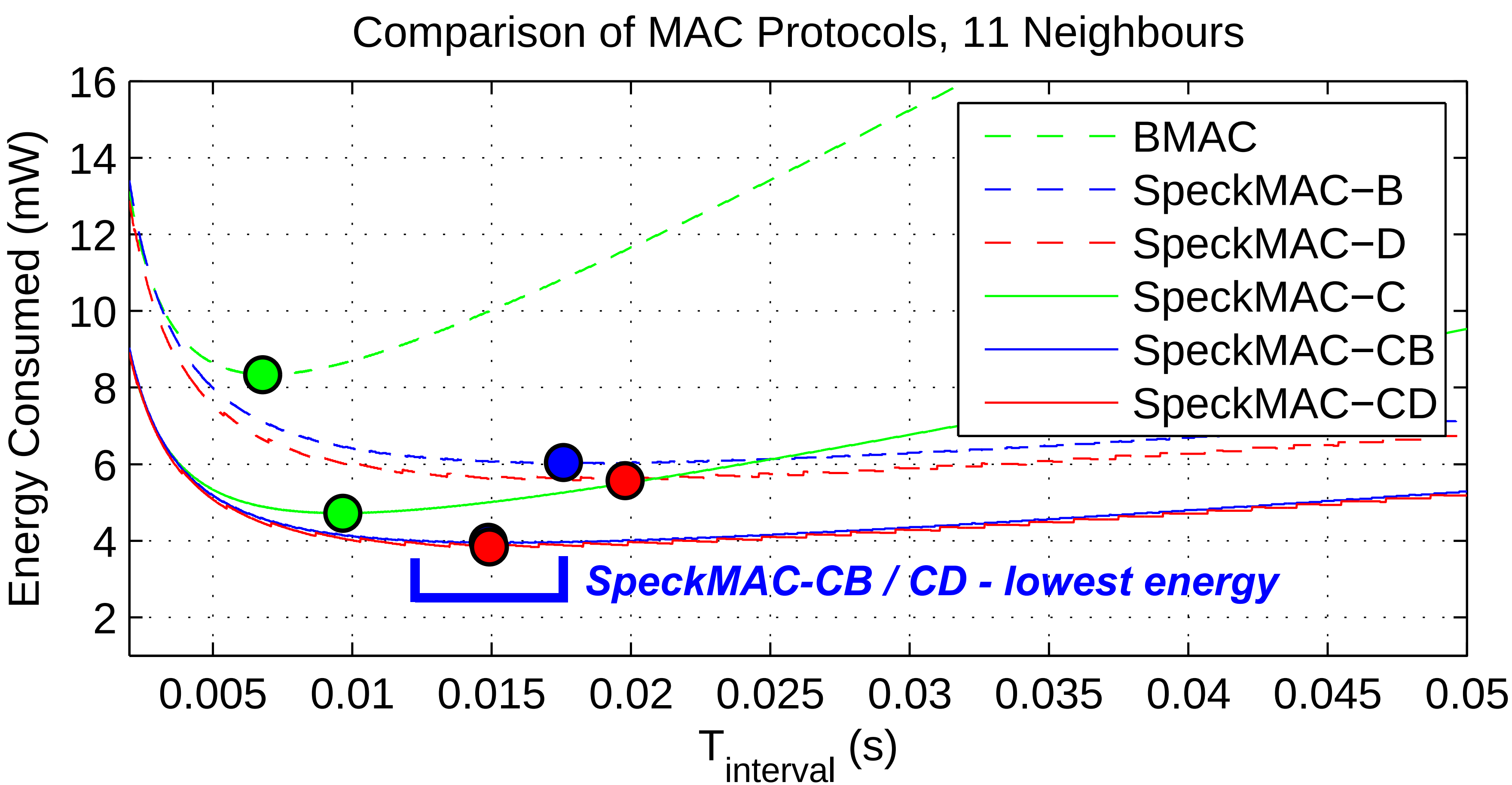
- SpeckMAC protocols had been developed within the consortium for single channel random access.
- Three variations: SpeckMAC, SpeckMAC-Backoff, SpeckMAC-Data.
- Rate of channel sampling tuned to minimise overall energy consumed.



- Assumes that all nodes receive all transmissions - much overhearing!

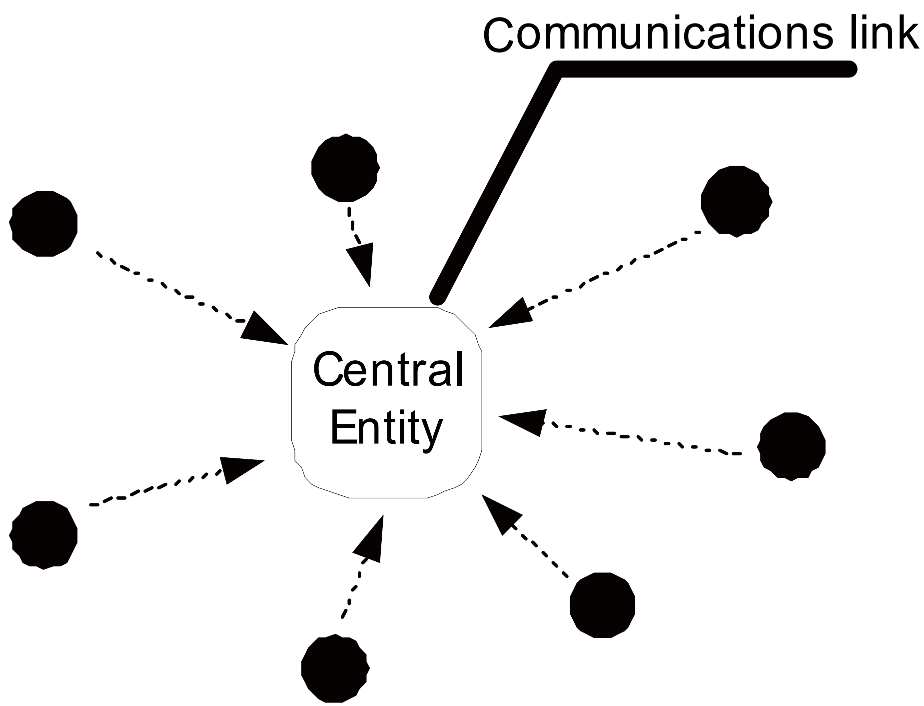
Notes:

- CDMA versions of these three protocols were developed.
- Assumes that multicast and unicast traffic is separated -
  - Unicasts spread with the code of the destination Speck
  - There is also a single, shared multicast code

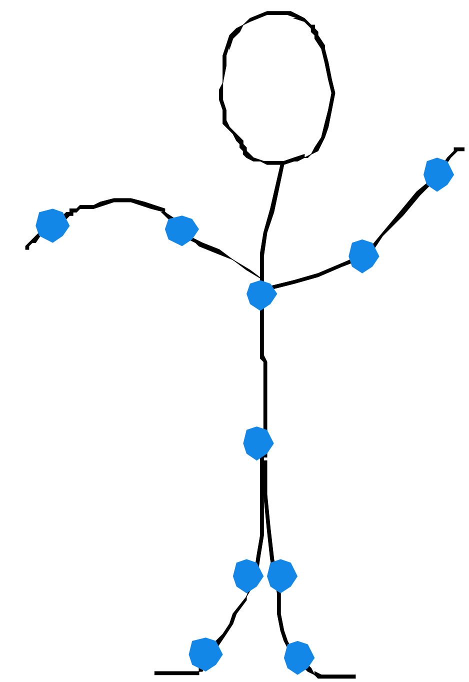


Data Sinking Applications

- For some applications, such as wireless motion tracking, a SpeckNet would require to collect multiple channels of data at a single receiver.



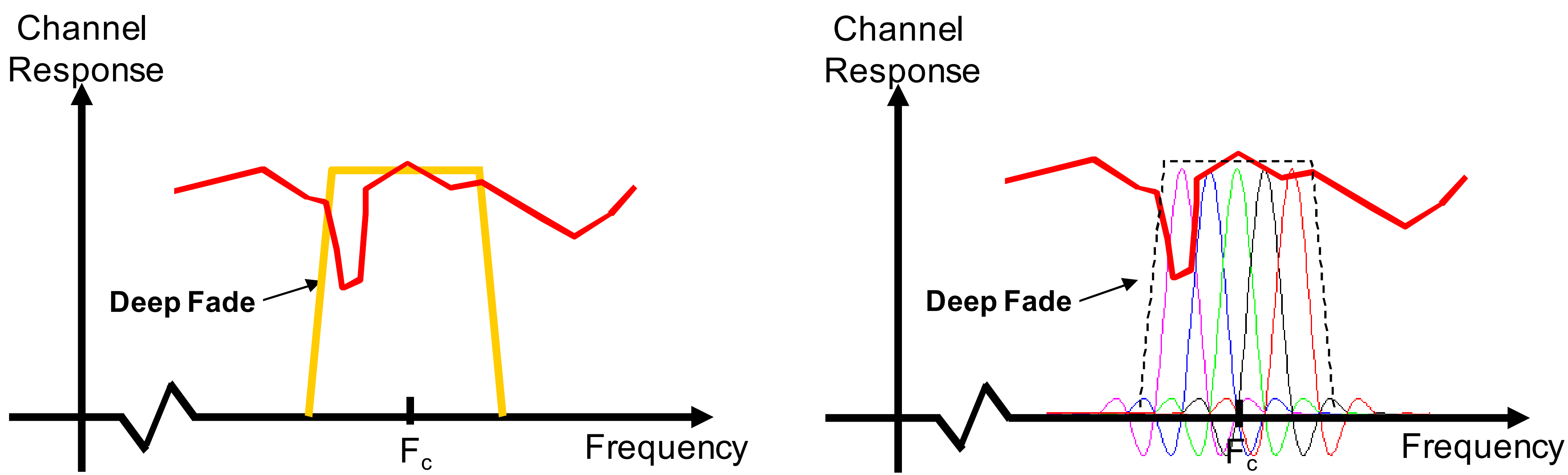
Orient-series application



- The latency and update rate are important to the performance of this type of system.
- OFDMA is a candidate solution because its subcarriers can deliver multiple channels in a very spectrally efficient and low cost manner.

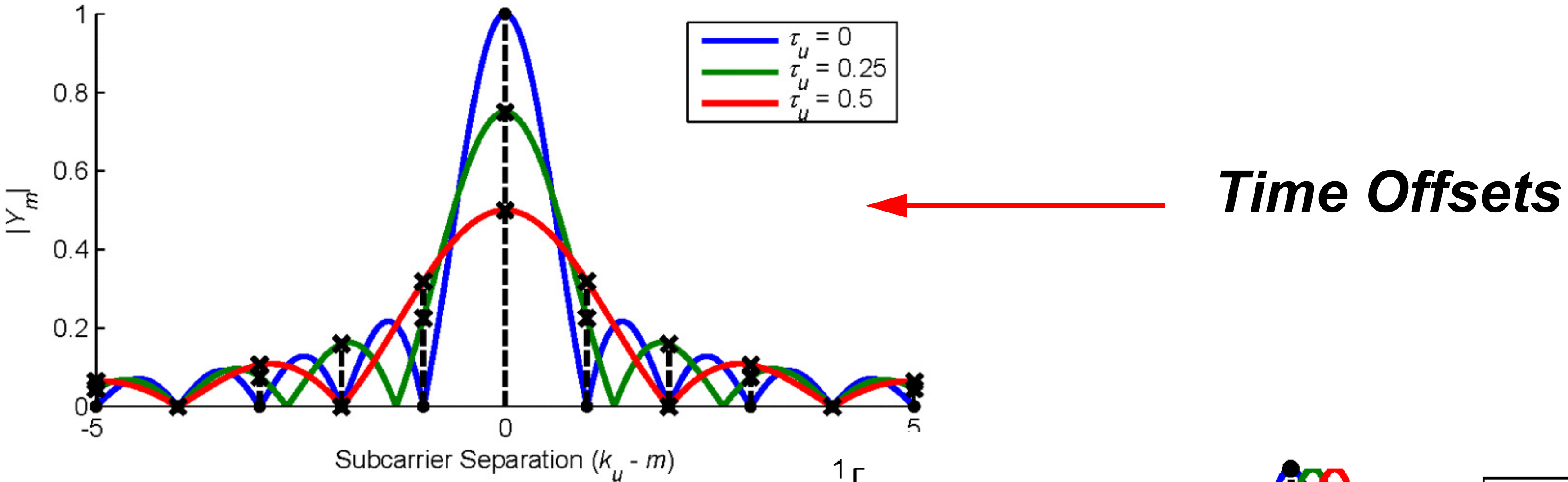
OFDM and OFDMA

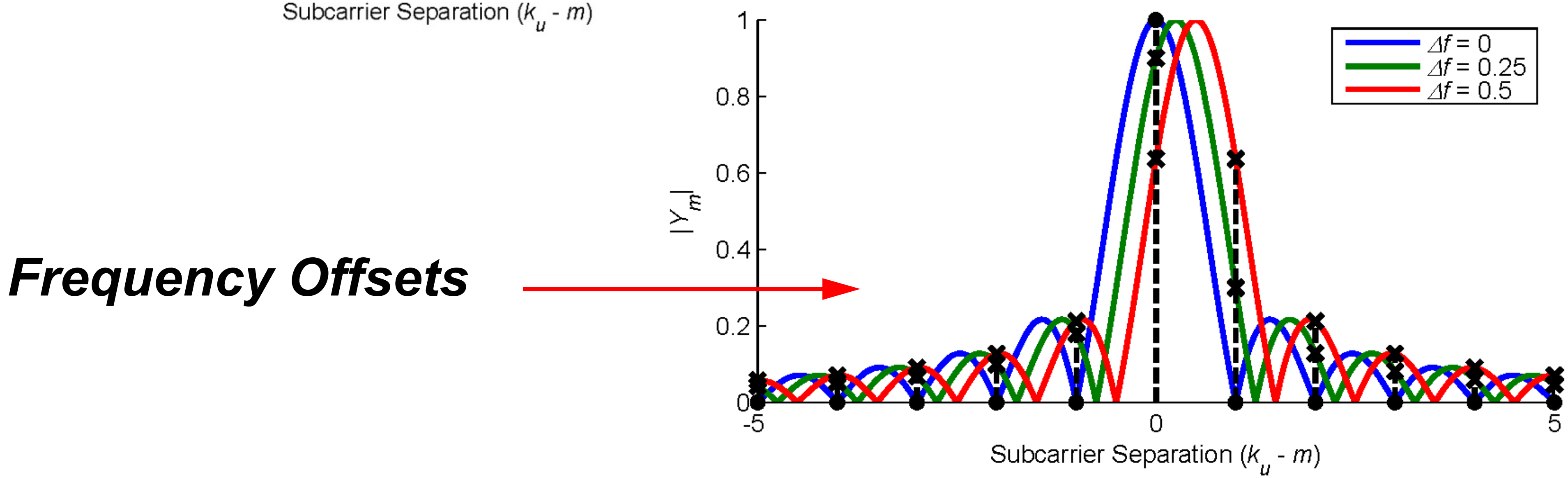
- OFDM involves transmitting on orthogonal subcarriers.
- Modulation and demodulation accomplished with simple DSP.
- Deep fades affect only one or two subcarriers - mitigated by coding.
- OFDMA delivered by assigning different “users” with one or more subcarriers each.



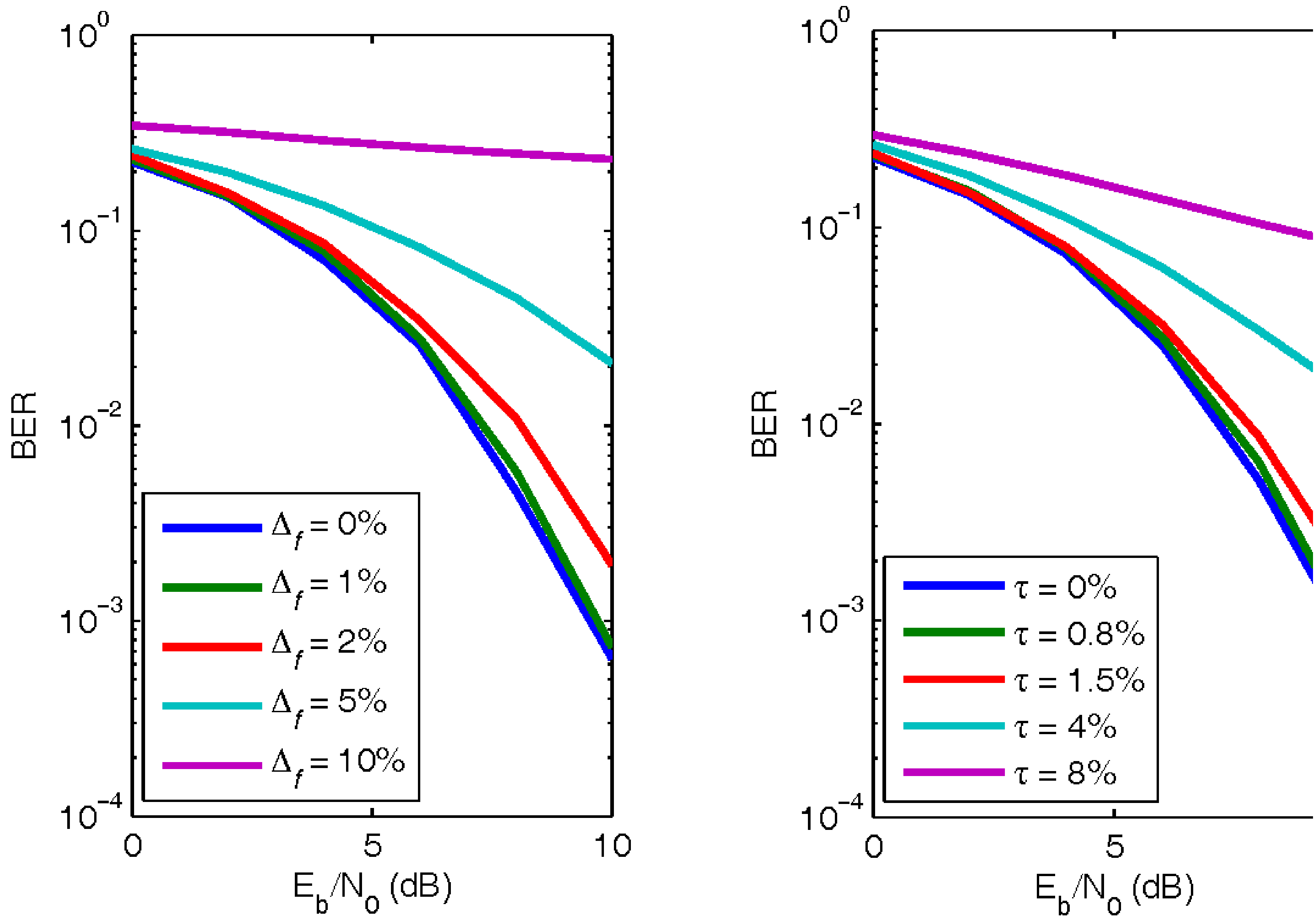
Frequency and Timing Offset Correction

- OFDM/A systems require tight time and frequency synchronisation to work optimally - orthogonality is important.





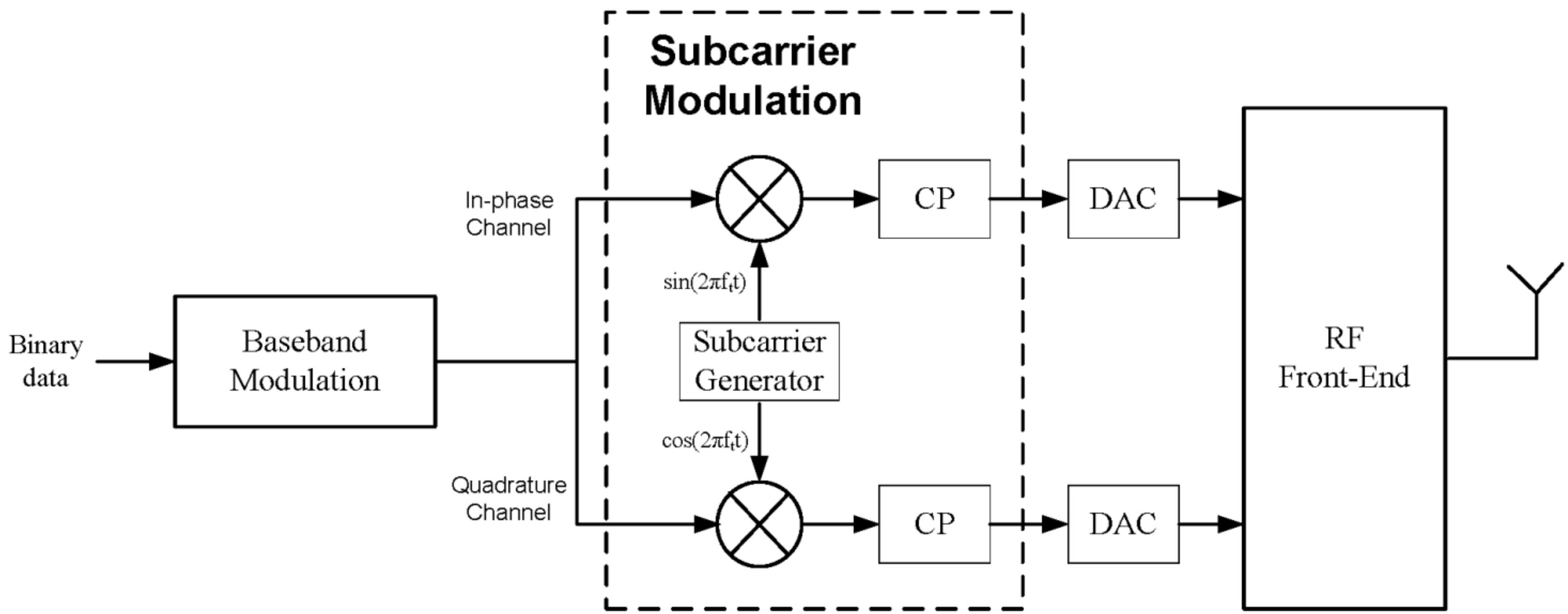
Notes:



BER
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
5
10
E_b/N_o (dB)
$\Delta_f = 0\%$
$\Delta_f = 1\%$
$\Delta_f = 2\%$
$\Delta_f = 5\%$
$\Delta_f = 10\%$
BER
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
5
E_b/N_o (dB)
$\tau = 0\%$
$\tau = 0.8\%$
$\tau = 1.5\%$
$\tau = 4\%$
$\tau = 8\%$

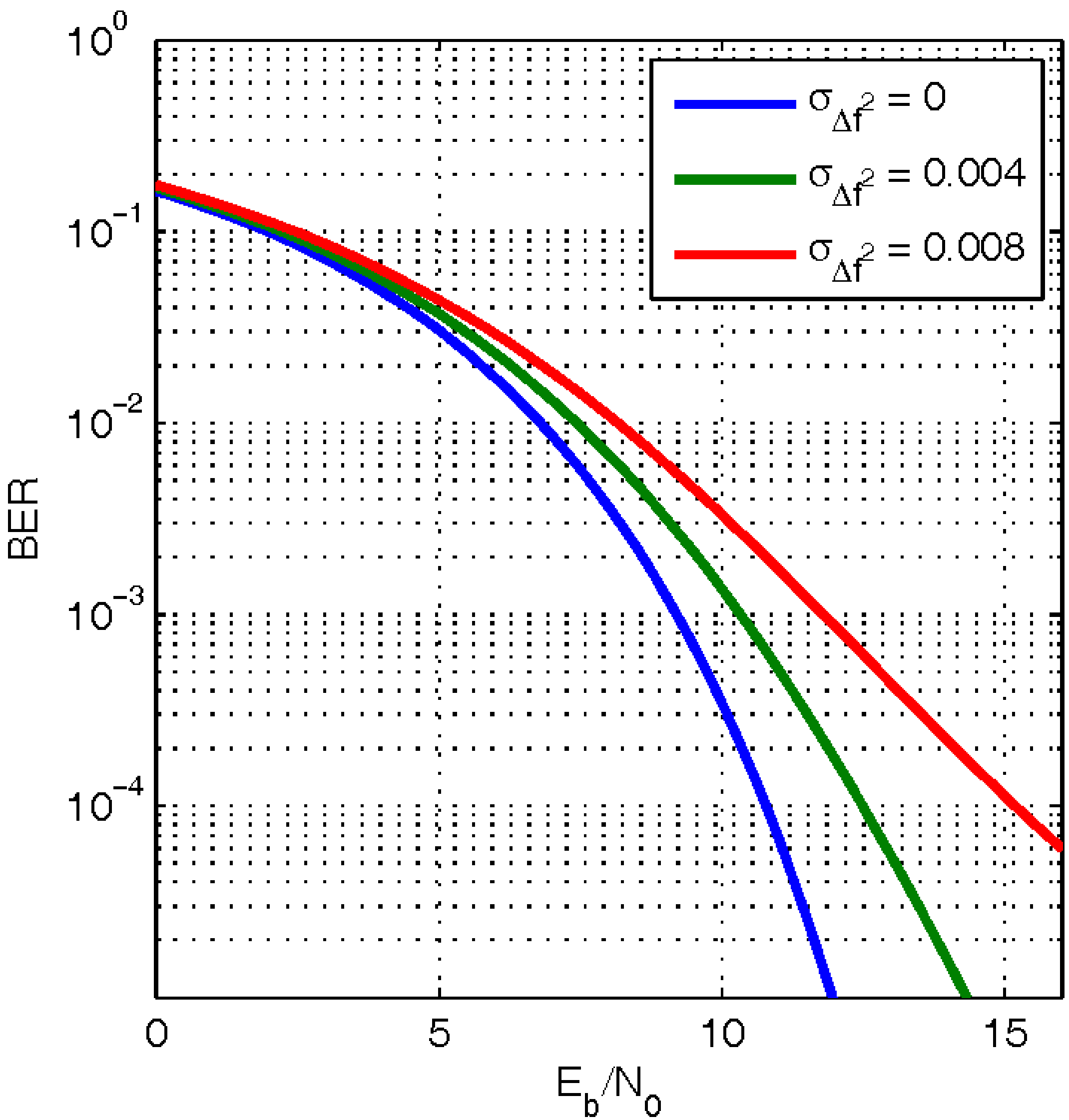
Low Cost Frequency Offset Correction

- Of the two effects, frequency offsets are the more significant.
- Need a low cost method of compensating for offsets...
    - Receiver sends a reference signal
    - Transmitter (Speck) computes an estimate of the frequency offset and compensates for it.



Notes:

- Analysis of different estimation algorithms and implementations.
- Minimal cost subcarrier synthesis through minimum wordlength analysis for target offset variance (offset variance linked to BER).

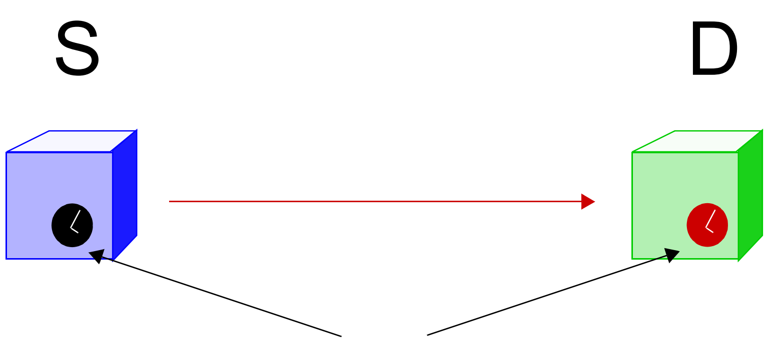


$$\frac{\overline{E_b}(\Delta f)}{N_0 + I_0(\Delta f)}$$

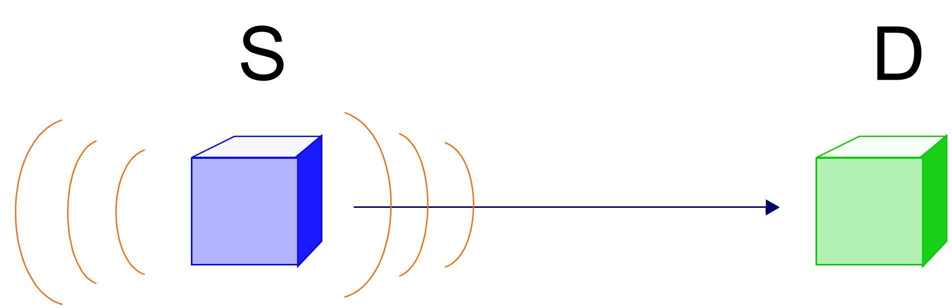
Offset Variance $\sigma^2_{\Delta f}$	E_b/N_0 Degradation (dB)
0.001	0.37
0.0025	0.99
0.005	2.24
0.0075	3.95

Synchronisation in SpeckNets

- As with any practical communications system, synchronisation is required in the receiver.
- Coherent radio reception - carrier and timing synchronisation
- Non-coherent radio / optical - timing synchronisation only
- Two examples of why timing synchronisation is needed...

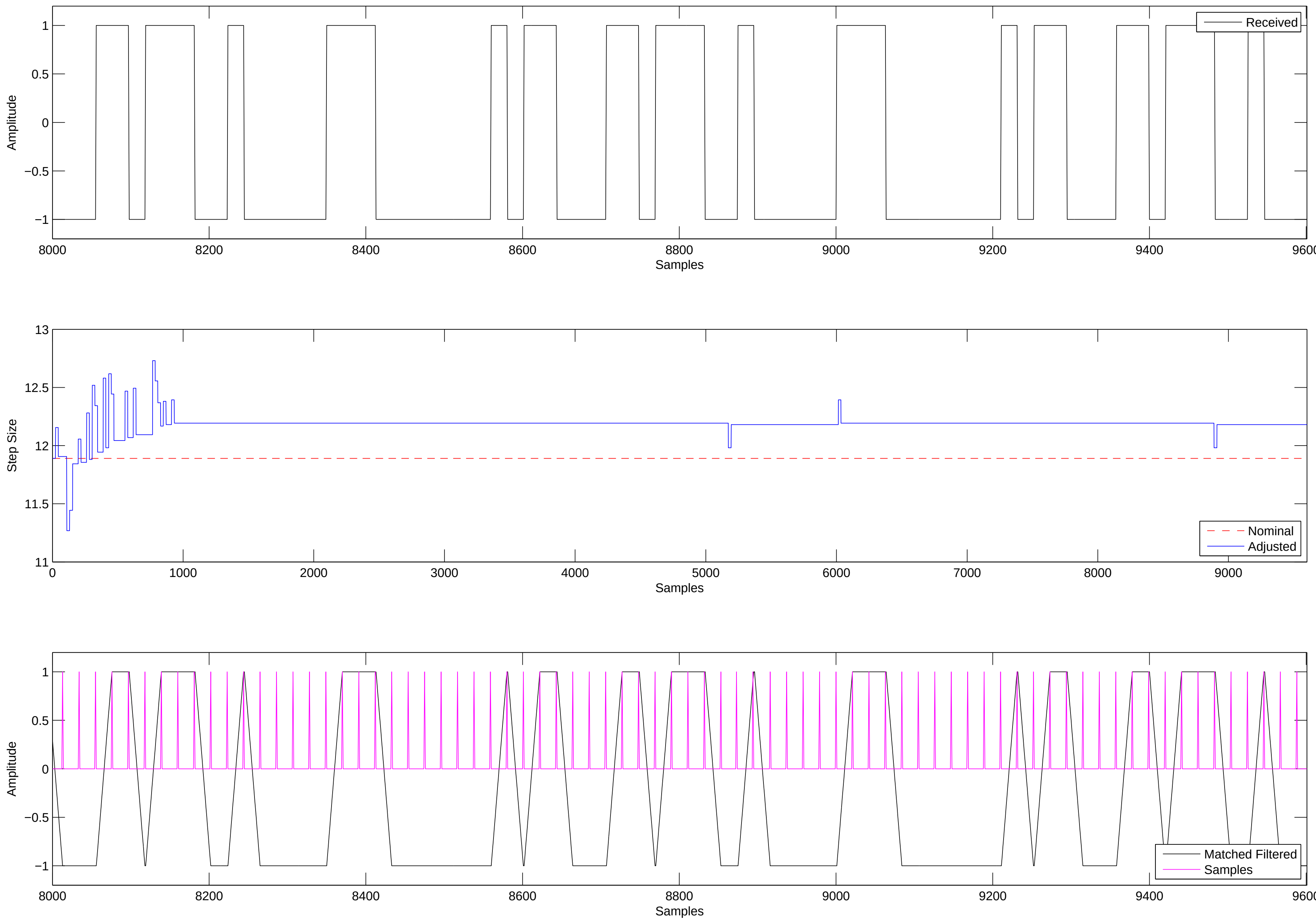


The Source (S) and Destination (D) have clock oscillators with DIFFERENT frequencies.



Relative acceleration or deceleration of the Source (S) and Destination (D) (dynamic Doppler Effect).

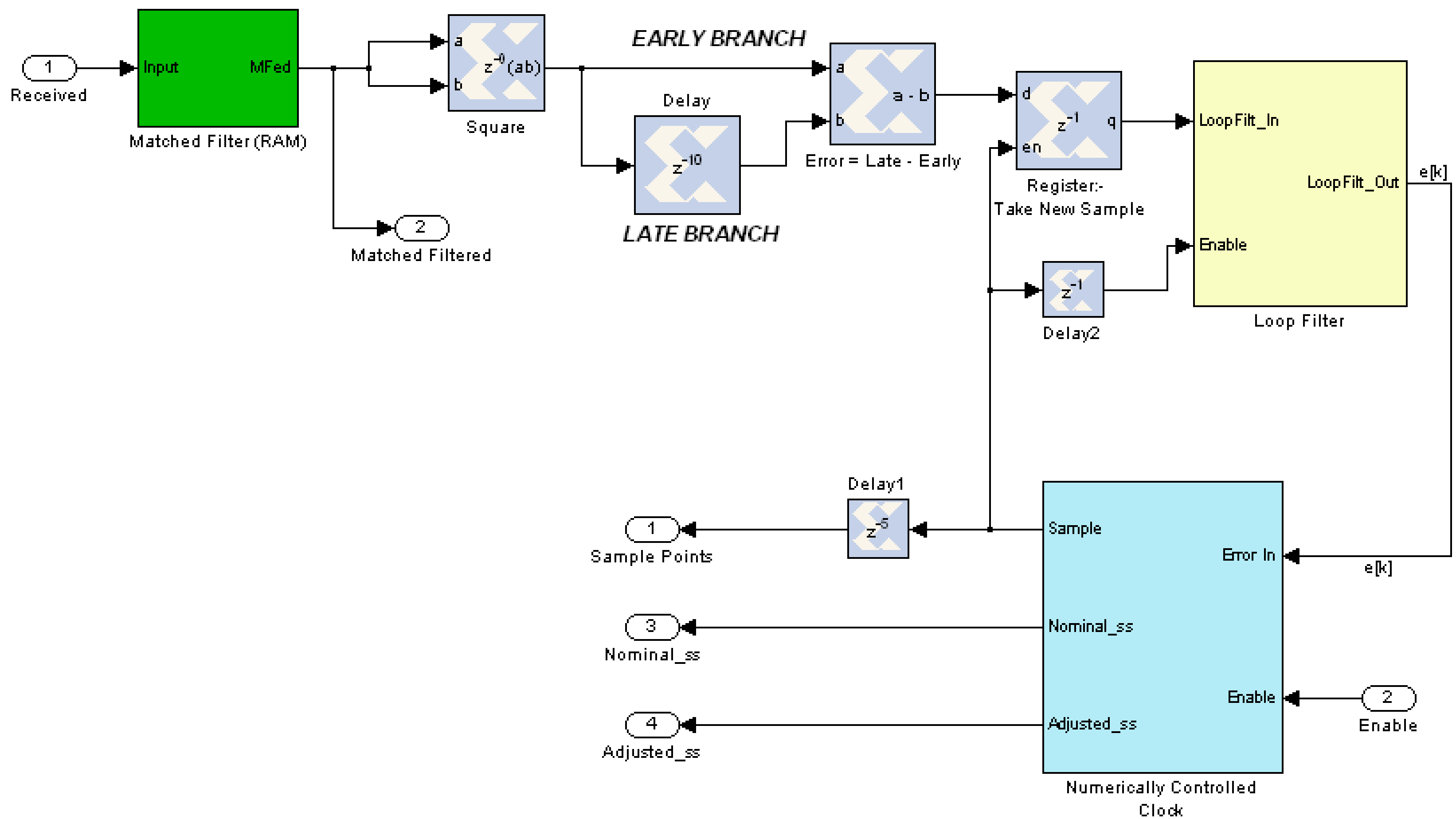
Notes:



Received
Amplitude
Samples
Step Size
Nominal
Adjusted
Matched Filtered
Samples

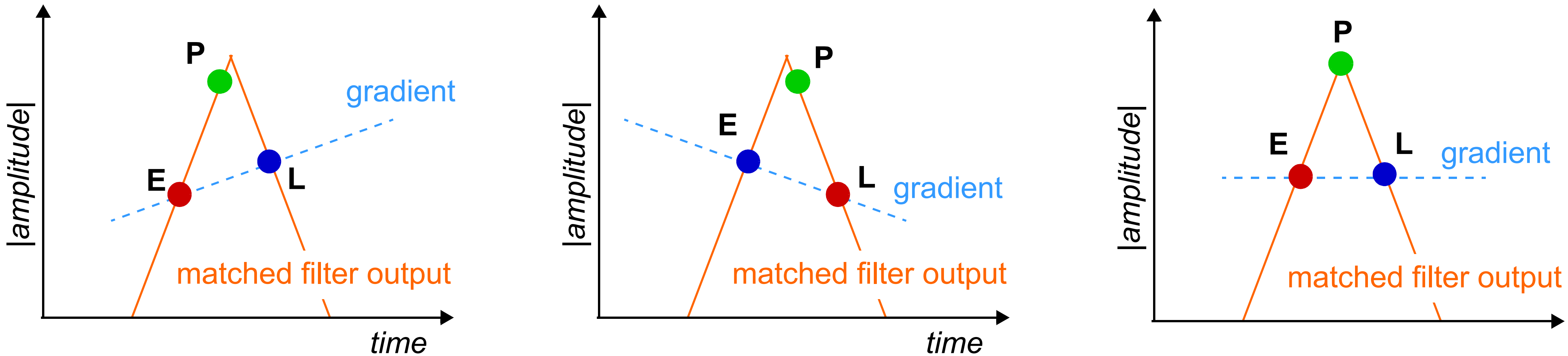
Synchroniser Implementation

- One candidate method of timing synchroniser implementation is the Early Late Gate synchroniser
- Fixed point model developed and tested in AWGN.



Notes:

- 11 - 12 bits for most of the circuit shown to provide adequate performance.



(a)
negative timing error

(b)
positive timing error

(c)
zero timing error

Notes:

Review

- First generation Specks the and limitations of passive, non-coherent radio communications
- Multiple access of the radio channel
    - Potential of CDMA to enhance spatial reuse of the channel
    - An extension to the SpeckMAC protocols based on CDMA
- OFDMA for parallel, low latency data sinking in applications like wireless motion capture
- Protocol developed for frequency offset estimation and correction in the transmitter
- The importance of synchronisation and some low cost synchroniser implementations

Notes:

Papers

- L. H. Crockett, N. C. MacEwen, E. Pfann and R. W. Stewart, "A Low Power, Digital Transceiver for Wireless Sensor Networks," Proceedings of the 2nd IEE/Eurasip Conference on DSP Enabled Radio, pp 18/1 - 18/6, Southampton, UK, September 2005.

- N. C. MacEwen, L. H. Crockett, E. Pfann and R. W. Stewart, "Symbol Synchronisation Implementation for Low-Power RF Communication in Wireless Sensor Networks", Proceedings of the 39th IEEE Asilomar Conference on Signals, Systems and Computers, Asilomar, CA, USA, October/November 2005.

- L. H. Crockett, N. C. MacEwen, E. Pfann and R. W. Stewart, "Pulse Shaping for RF Communications in Wireless Sensor Networks," Proceedings of the 39th IEEE Asilomar Conference on Signals, Systems and Computers, Asilomar, CA, USA, October/November 2005.

- L. H. Crockett, E. Pfann and R. W. Stewart, "Coverage and Density of a Low Power, Low Data Rate, Spread Spectrum Wireless Sensor Network for Agricultural Monitoring", Proceedings of the 15th European Signal

Processing Conference (EUSIPCO), Poznan, Poland, September 2007.

- L. H. Crockett and R. W. Stewart, "Spatial Reuse of the Radio Channel in CDMA-Enabled, Ad-hoc Wireless Sensor Networks", Proceedings of the 17th European Signal Processing Conference (EUSIPCO), Glasgow, UK, August 2009.