Fundamental Issues of Wireless Distributed Computing in SDR Networks

DINESH DATLA
WIRELESS @ VIRGINIA TECH
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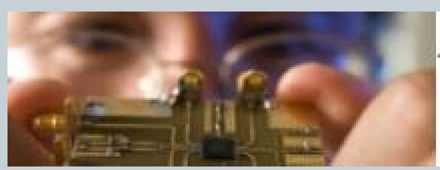


Presentation Outline

- Research motivation
- Fundamental limits on energy savings achieved by wireless distributed computing (WDC)
- Limits on computational capability
- Methodology for cross - layer WDC system design
- Conclusions

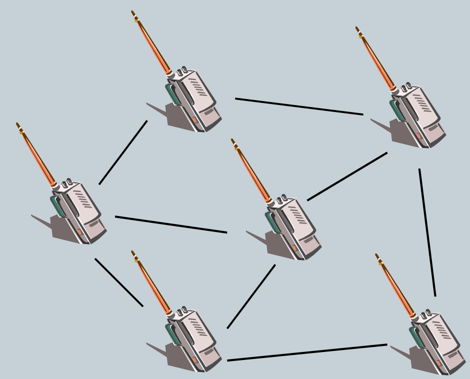
Introduction

- Harness computational capability of SDRs
- Opportunistic usage of computing resources
- Stringent application requirements
- Hard for single radio to fulfill

Computational processing

Local processing

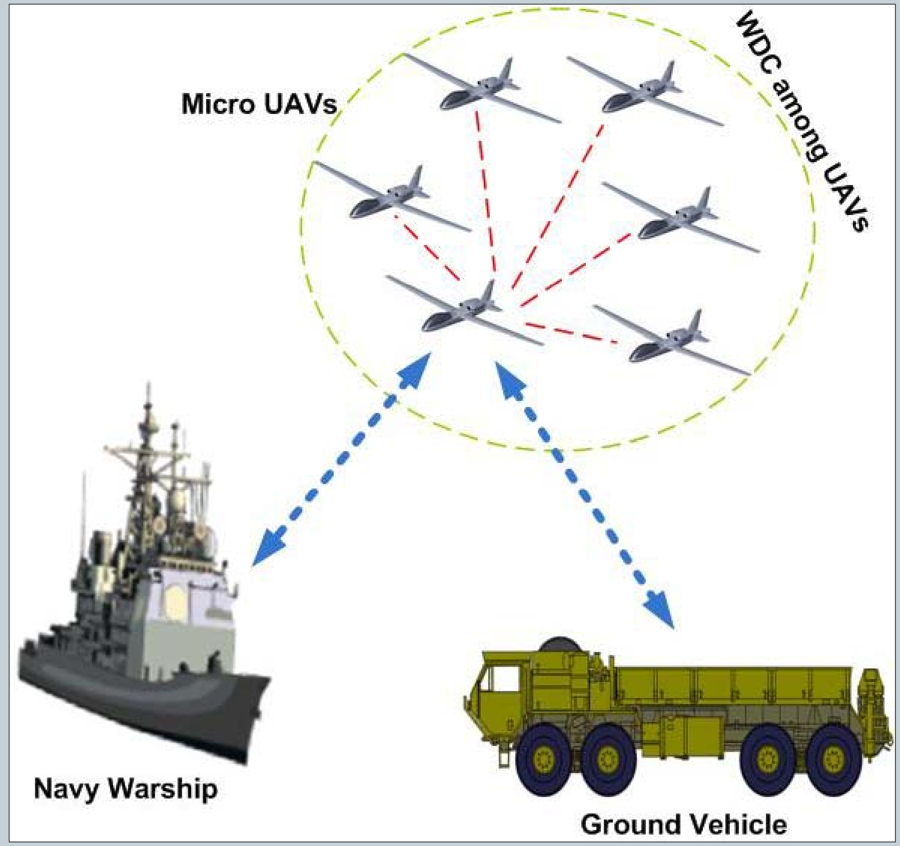
Distributed processing



Collaborative software radio network.

Introduction: Potential benefits

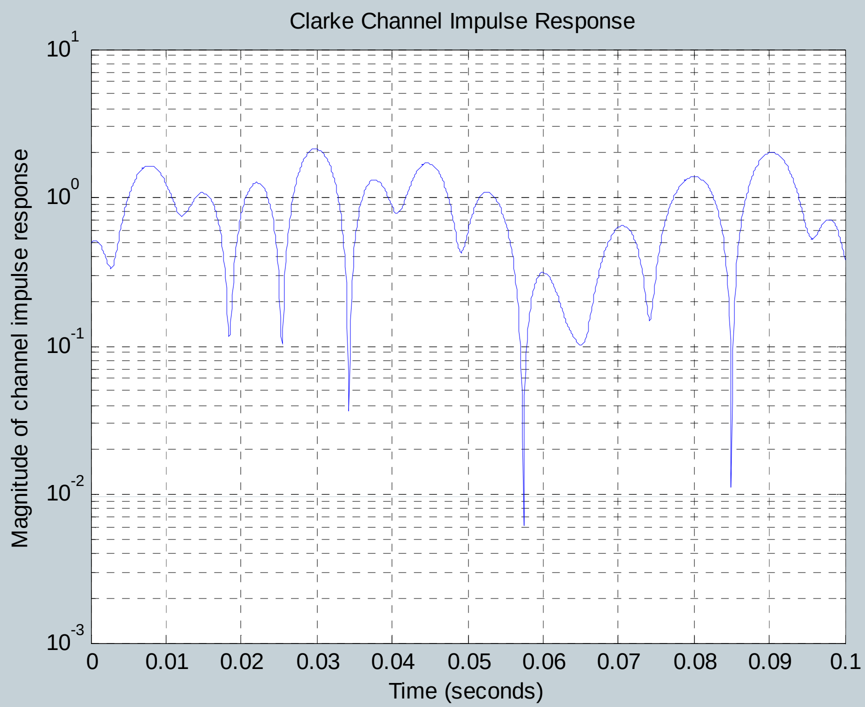
- Energy and power efficiency
- High performance computing capability using network of small form factor radios
- Fault tolerance
- Security



Example application: reducing communication overhead in military backhaul networks

Comparison with Traditional Distributed Computing

- Presence of wireless channel
  - Cross layer design
  - Adaptive workload allocation/ load balancing
- Communication cost negates benefits
- Tradeoffs between local and distributed processing
- Errors imposed by wireless channel
  - Impact on computation error



Channel magnitude with maximum Doppler frequency of 75 Hz.

Paper Contribution

- Conditions under which WDC is energy efficient over local processing
- Fundamental limitation imposed by the underlying communication on computation power
- Cross layer relationships
  - Physical layer parameters (bit-error-rate) Vs application parameters (computational accuracy)

Fundamental Limits on WDC energy savings

SECTION 1

Computation Subsystem Model

- Computational task composed of N_{CU} homogenous sub-tasks or computational units (CUs)
- Computation energy consumption

$$E_{cp} = E_{CU}\, N_{CU} = P_{cp}\, T_{CU}\, N_{CU}$$

E_{cp}	Total energy consumption for computation
$E_{CU}/P_{cp}/T_{CU}$	Energy/power/time consumed to process 1 computational unit (CU)
N_{CU}	Number of CUs per computational task

Communication Subsystem Model

- Communication energy consumption in each node

$$E_{cm} = E_{cm1} + P_{cm2}(D, SNR_{min})\, T_{bit}\, N_{bits}\, N_{CU} \le E_{supply}$$

E_{cm}	Total energy consumption for communication
E_{cm1}	Energy consumed for misc. processes
$P_{cm2}(D, SNR_{min})$	Transmit or receive power consumption (function of distance, min. SNR)
T_{bit}	Time to transmit/receive 1 bit of data
N_{bits}	Number of bits transmitted or received per CU
E_{supply}	Battery capacity

WDC System Model

- Computation performed on-board locally

$$E_s = E_{CU}\, N_{CU} = P_{cp}\, T_{CU}\, N_{CU}$$

- Computation performed in a distributed manner

$$E_{node} = P_{cp}\, T_{CU}\, N_{CU1} + E_{cm1} + P_{cm2}\, T_{bit}\, N_{bits}\, N_{CU2} \leq E_{supply}$$

E_{node}	Energy consumption at master node or slave node
N_{CU1}	Number of CUs processed by master node
N_{CU2}	Number of CUs processed by slave nodes

WDC Energy Savings Metric

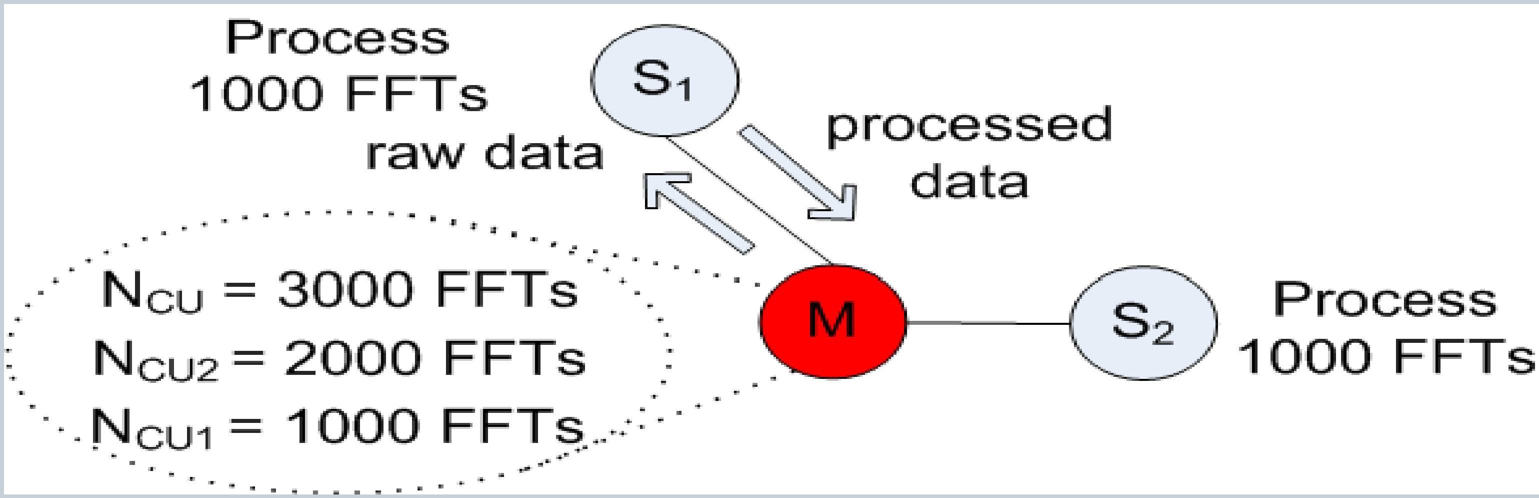
- Energy savings achieved in master node by executing task in a distributed manner in comparison to local processing

$$E_{savings}^{node} = E_s - E_{node}$$

$$= P_{cp}\, T_{CU}\, N_{CU} - (P_{cp}\, T_{CU}\, N_{CU1} + E_{cm1} + P_{cm2}\, T_{bit}\, N_{bits}\, N_{CU2})$$

  - Decide between local and distributed processing
- Impacted by channel conditions, radio platform and network topology
- Negative savings => local processing is more energy efficient

Simulation Scenario & Assumptions



- Uniform workload allocation
- Homogenous computational energy consumption
- Time-division multiplexed communication with master node
- N_{nodes} = Number of participating nodes

Simulation Parameters

- Target $BER = 10^{-3}$
- $SNR_{min} = 10$ dB
- BPSK with no coding
- Medium harsh channel
- Data rate = 32 kbps

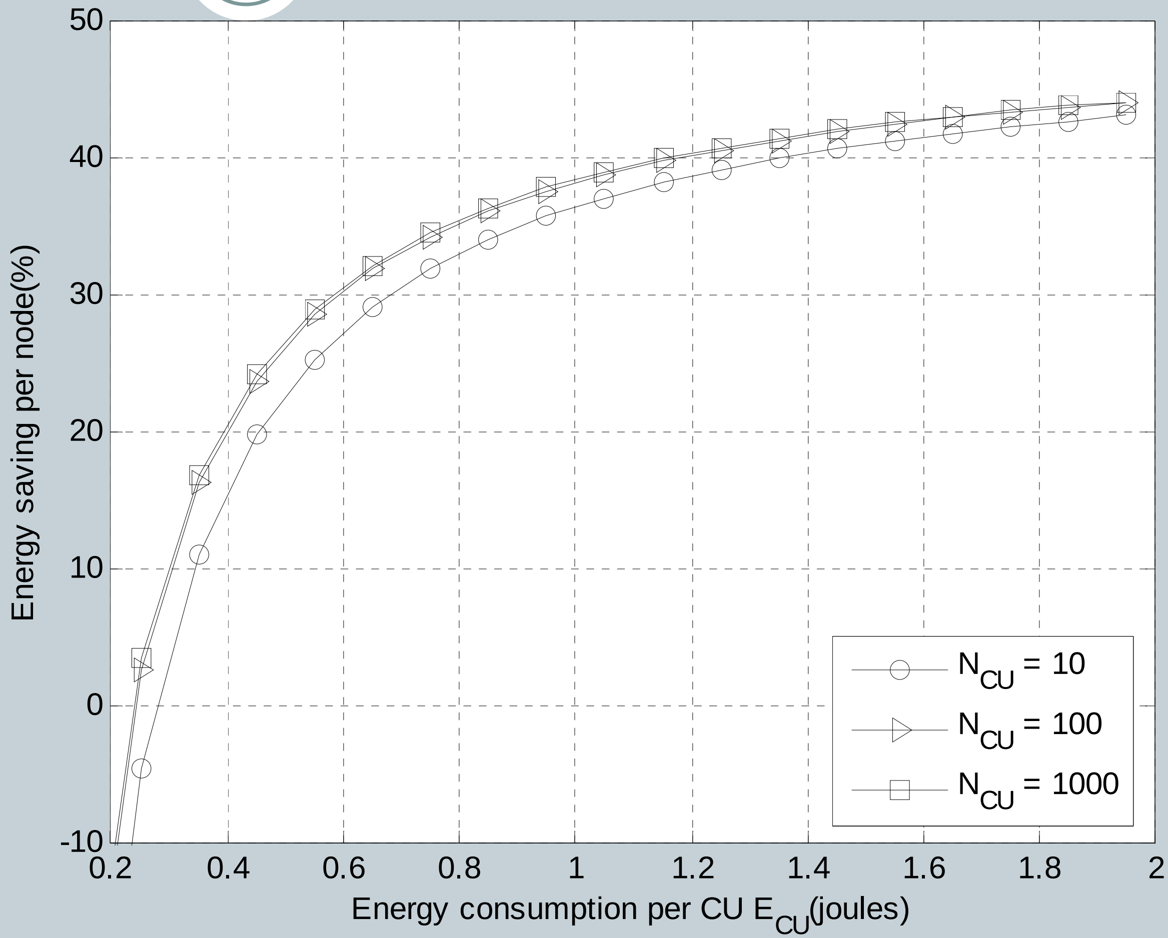
Parameter	Value	Parameter	Value
n	3	SNR_{min}	10 dB
η	5	P_{txelec}	82.8 mW
NF	10 dB	β	174 mW
p	99 %	P_{trs}	58.7 mW
G_t, G_r	2 dBi	P_{DAC}	15.4 mW
f	450 MHz	P_{stat}	0.25 mW
σ_s	8 dB	LM	15 dB
d_o	10 m	B	30 KHz
P_{rxelec}	102.8 mW	P_{ADC}	4.6 mW
E_{spr}	0.2 joules	T_{trs}	470 μ secs

Simulation Result 1
Energy Savings Vs Computational Complexity

- Plotted for different workloads (N_{CU})
- Inferences

(Discussion on next slide)

- *Breakpoint*
- *Lower workloads benefit more*
- *Curve flattens for higher complexity*



$N_{nodes} = 2$, $D = 200$ m

Discussion of Simulation Results 1

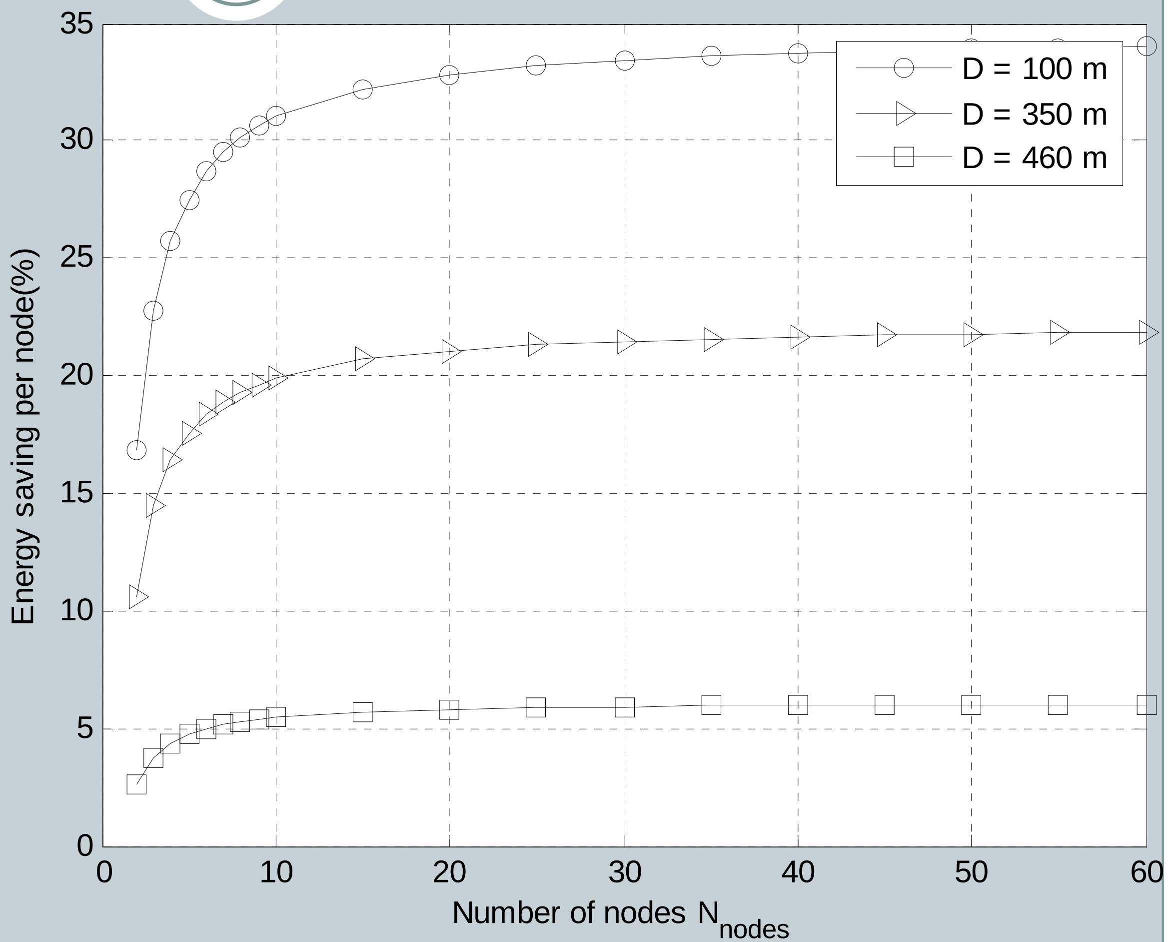
- Tasks with E_{CU} > 0.25 joules benefit from WDC
  - Similar breakpoint for all computational workloads
  - Result valid for given channel conditions
- Non- linear scaling with workload
  - Result valid for uniform load balancing scheme
  - Higher workloads => increase in workload allocated to slave nodes
  - Increasing communication overhead for master node
- Savings do not scale linearly with computational complexity

Simulation Result 2: Energy Savings Vs Number of Nodes

- Plotted for different distances (D)
- Inferences

(Detailed discussion on next slide)

- *Breakpoint*
- *Short range networks benefit more*
- *Curve flattens for higher number of nodes*



$N_{CU} = 60$, $E_{CU} = 0.35$ joules

Simulation Results 2 - Discussion

- Breakpoint varies with distance
- Energy savings degrade with distance
  - Increasing transmitter power consumption at master node
  - No energy benefits for network with range D > 500 m
- Non-linear scalability with N_{nodes}

Curve Region	Trend	Reason
Small N_{nodes}	Savings improve with N_{nodes}	Reduced computational workload of master node
Large N_{nodes}	Savings do not improve significantly	Increase in communication overhead

Conclusions

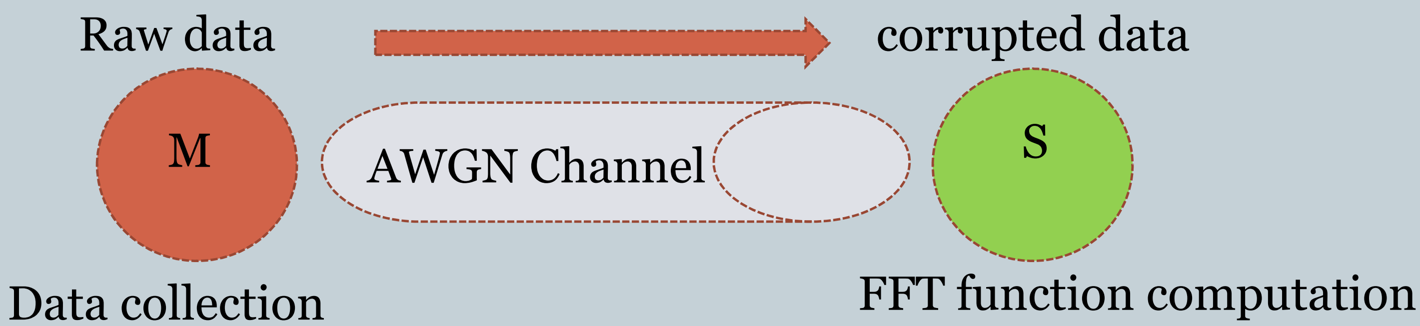
- Determined *breakpoint* when WDC is energy efficient
- Conditions under which WDC is beneficial: *When communication overhead does not dominate over computational energy consumption*
  - Lighter workloads
  - Small sized networks
  - Short range networks
- *Non-linear scaling* with network size and computational complexity

CROSS LAYER DESIGN: Impact of wireless channel on computational accuracy

SECTION 2

Introduction

- Scenario



- Cross layer design methodology
  - Design based on function computation accuracy (application layer) rather than BER (link layer)
- Computation reliability
  - Impact of link on computation accuracy
  - Communication overhead versus computation accuracy

Simulation Setup and Methodology

- Function error:

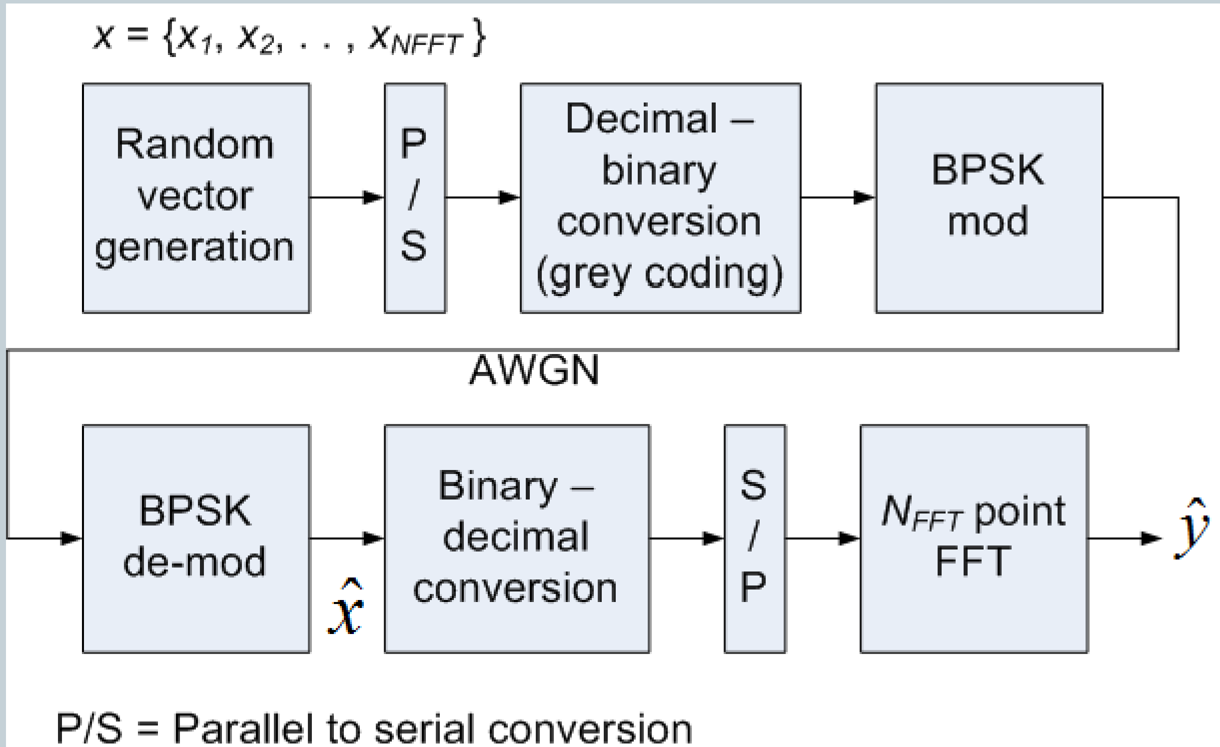
$$F_e = \sum_{i=1}^{N_{FFT}} |y_i - \hat{y}_i|$$

- y_i and $\hat{y}_i$ are i^{th} elements of vectors:

$$\overline{y} = FFT\left(\overline{x}\right)$$

$$\hat{\overline{y}} = FFT\left(\hat{\overline{x}}\right)$$

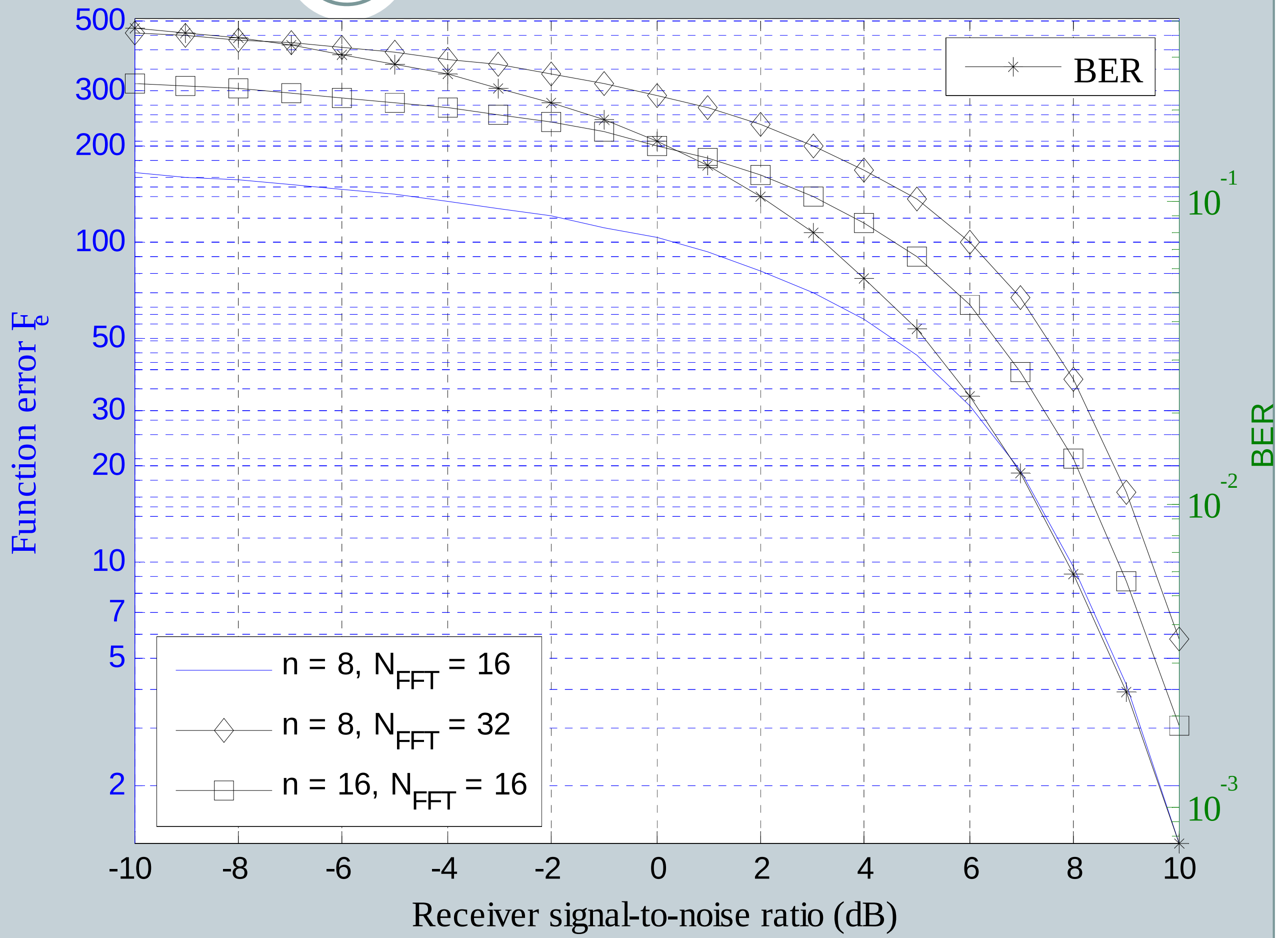
- n = function domain (or quantization levels)
- N_{FFT} = FFT size



Function error rate (FER) averaged over 10000 instances of FFT input vector and channel noise

Simulation Results: Relating BER to Function Error Rate

- *BER Vs FER*
  - FER < 2 => BER < 10^{-3}
- *BER/FER Vs algorithm parameters*
- *Better FER performance for*:
  - Lower quantization levels
  - Lower FFT resolution



Relationship between function error and BER for various values of SNRs, n and NFFT for FFT computation scenario.

Conclusions

- Cross layer approach to WDC system design
  - Computational reliability taken into consideration
- Demonstrated relationship between:
  - FER and BER
  - FER/BER and algorithmic parameters (quantization levels and FFT size)
- Methodology can be applied for any computational task

Summary

- What is WDC?
- Example application discussed
- How is WDC different from traditional distributed computing?
- Scalability of WDC benefits with range, computational workload and network size
  - Non-linear scalability – Law of Diminishing Returns!!!
- Cross layer methodology to relate application layer parameters with physical layer parameters

Questions

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