High-rate RF Nanoreceivers with Carbon Nanotube Antennas

C. Emre Koksal and Eylem Ekici

Department of ECE, The Ohio State University

Motivation

Original Motivation:

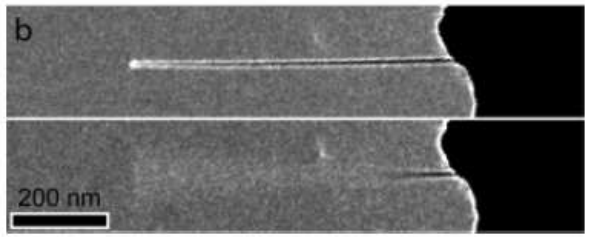
- Nanoscale systems
  - Huge increase in effectiveness & scale of applications with communication capability
  - Mobility $\Rightarrow$ wireless communication
- Nanoscale wireless communication
  - Traditional EM: nanoscale antenna sizes allow for THz range frequencies $\rightarrow$ high attenuation [Jornet and Akyildiz '10], components unavailable
  - Molecular communication [Pierobon and Akyildiz '10]
  - Non-traditional EM $\rightarrow$ carbon nanotube (CNT) antennas enable RF communication at nanoscale [Jensen et.al '07]

Beyond Nanocommunication?

- Antenna forests based on CNTs enable high-performance RF receivers

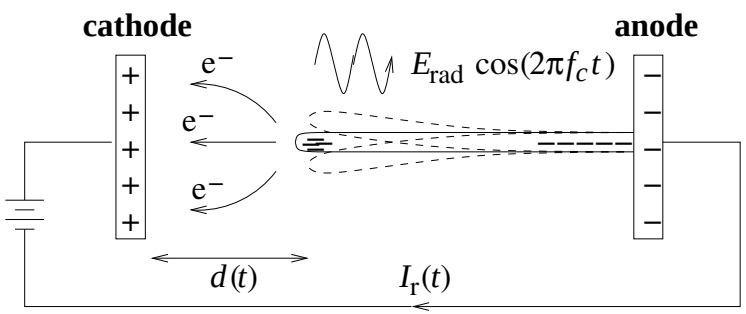
Physics of CNT Antennas - Basic Operation Mechanisms

Mechanism 1:



- Traditional RF receiver utilizes the current caused by oscillation of charges in the antenna
- CNTs are tiny $\Rightarrow$ oscillation of charges causes *physical* vibration of the CNT

Mechanism 2:



- Negatively charged CNT leaks tunnelling current to the cathode from its tip
- Current density reduces with increasing distance $d(t)$

Combine: Incident EM wave $\rightarrow$ CNT oscillations $\rightarrow$ change in observed current

$\Rightarrow$ Exploit this connection for communication of information

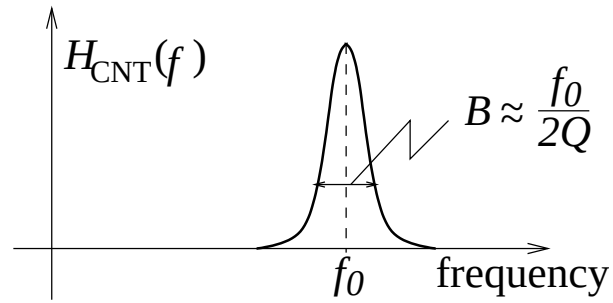
Physics of CNT Antennas - Quantification

Mechanism 1: vibration amplitude

$$\sim \frac{E_{\text{rad}}}{\sqrt{(f_c^2 - f_0^2)^2 + (f_c f_0/Q)^2}}$$

resonance frequency

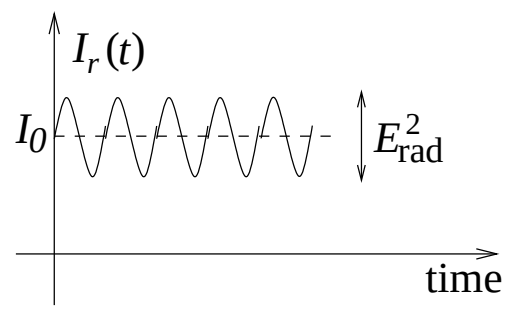
$$f_0 \sim \frac{1}{\text{length}^2 \sqrt{\text{area}}}$$



Mechanism 2: observed current

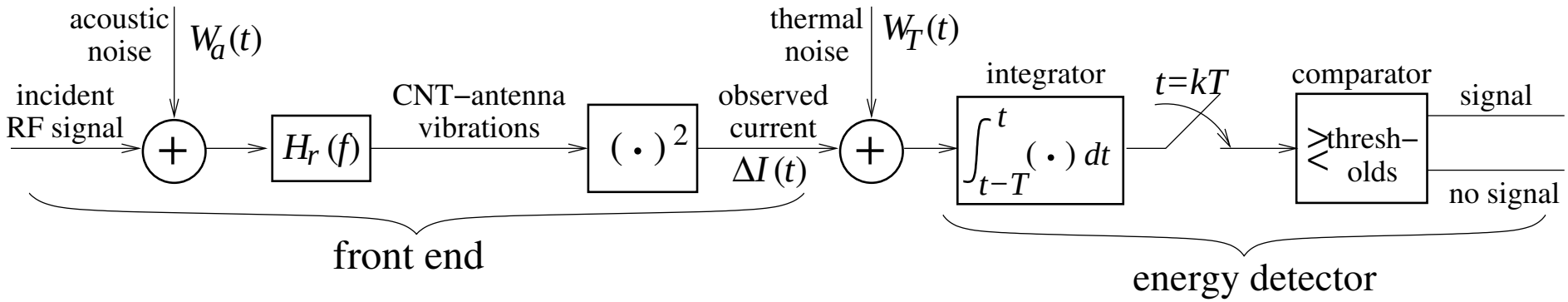
$$I_r(t) \sim I_0 - \underbrace{\text{constant} \times d^2(t)}_{\Delta I}$$

$$\Rightarrow \Delta I \sim \text{constant} \times E_{\text{rad}}^2$$



$\Rightarrow$ System acts as a square-law detector for signals at f_0

Nanoreceiver Model - Front End

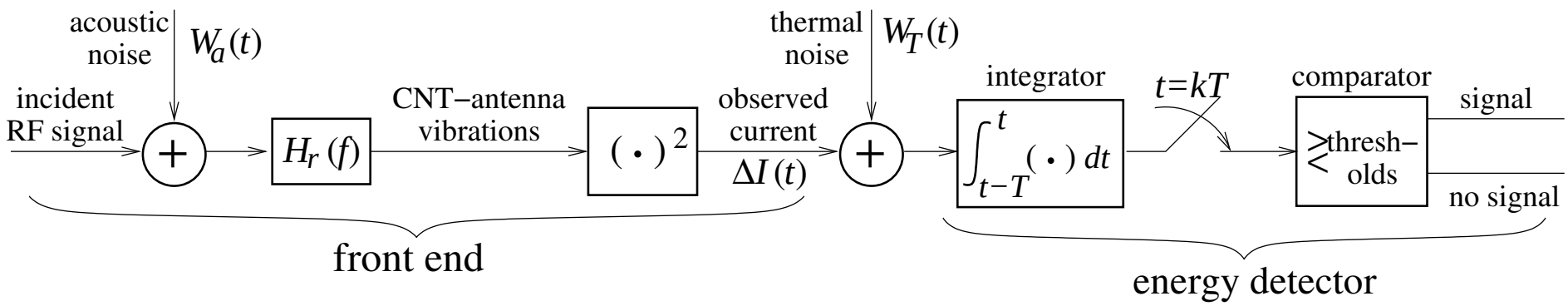


- Sources of noise:
  - *Acoustic noise* $W_a(t)$ - caused by radio static, AWGN
  - *Thermal noise* $W_T(t)$ - caused by electronic components, AWGN
- CNT response: $H_r(f) = \frac{\text{constant}}{\sqrt{(f_c^2 - f_0^2)^2 + (f_c f_0/Q)^2}}$
- Signaling: On Off Keying (OOK) - incident signal (coherent) =

$$\begin{cases} a\cos(2\pi f_0 t + \phi), & \text{signal present} \\ 0, & \text{otherwise} \end{cases}$$

  - *Advantages:* (1) demodulation comes for free via square-law device; (2) detector is simple, since its input is DC+noise if a signal is present
  - *Disadvantages:* does not exploit the full bandwidth of the CNT

Nanoreceiver Model - Detector



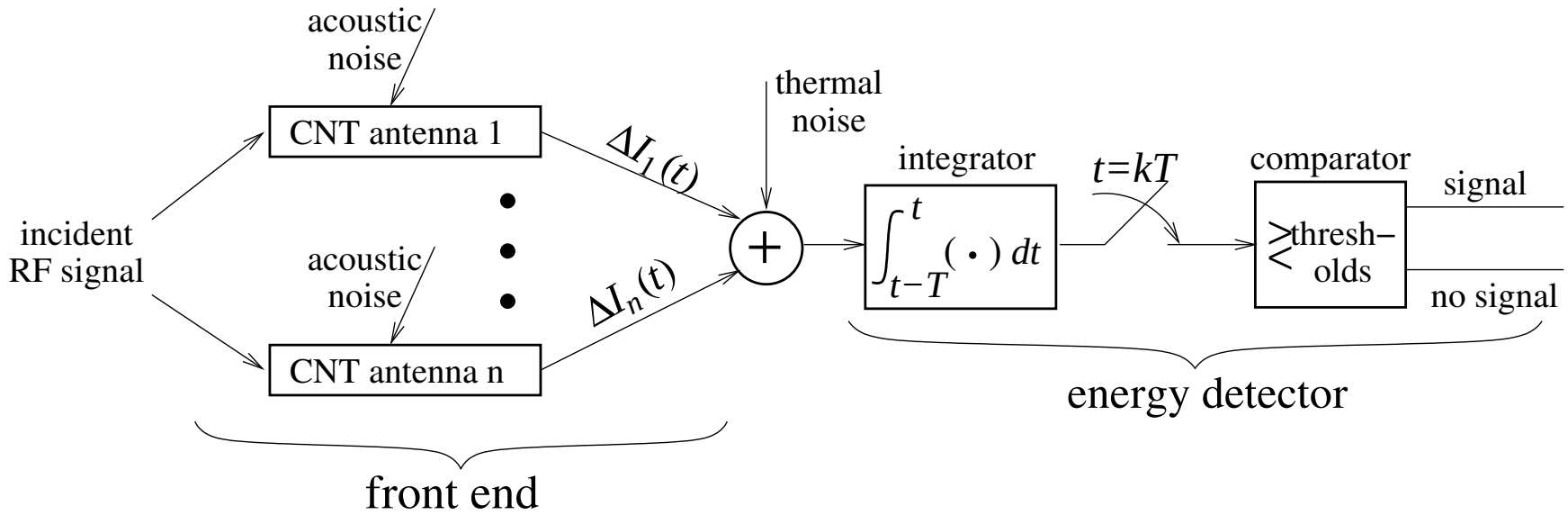
$$\text{detector input} = [a\cos(2\pi f_0 t + \phi)H(f_0) + (W_a * h_r)(t)]^2 + W_T(t)$$

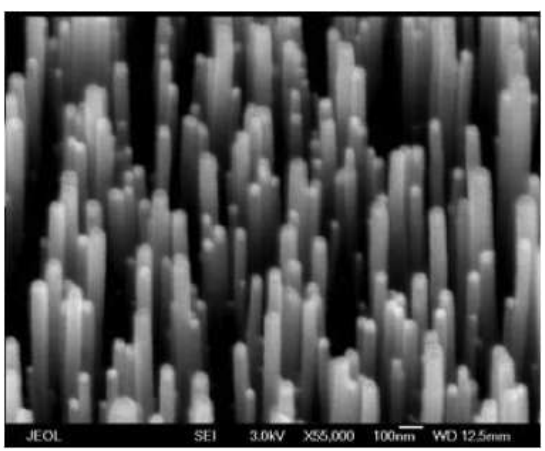
$$\text{(ignoring components at } 2f_0) = \underbrace{\frac{a^2}{2}H^2(f_0)}_{\text{signal}} + \underbrace{2a(W_a * h_r)(t)}_{\text{signal-noise beat}}\cos(2\pi f_0 t + \phi)H(f_0)$$

$$+ \underbrace{(W_a * h_r)^2(t)}_{\text{noise-noise beat}} + W_T(t)$$

- *signal-noise beat*: amplifying signal improves the SNR minimally
- *noise-noise beat*: gets worse with larger antenna BWs (smaller Q)

Nanoreceiver Model - Multiple CNT Antennas

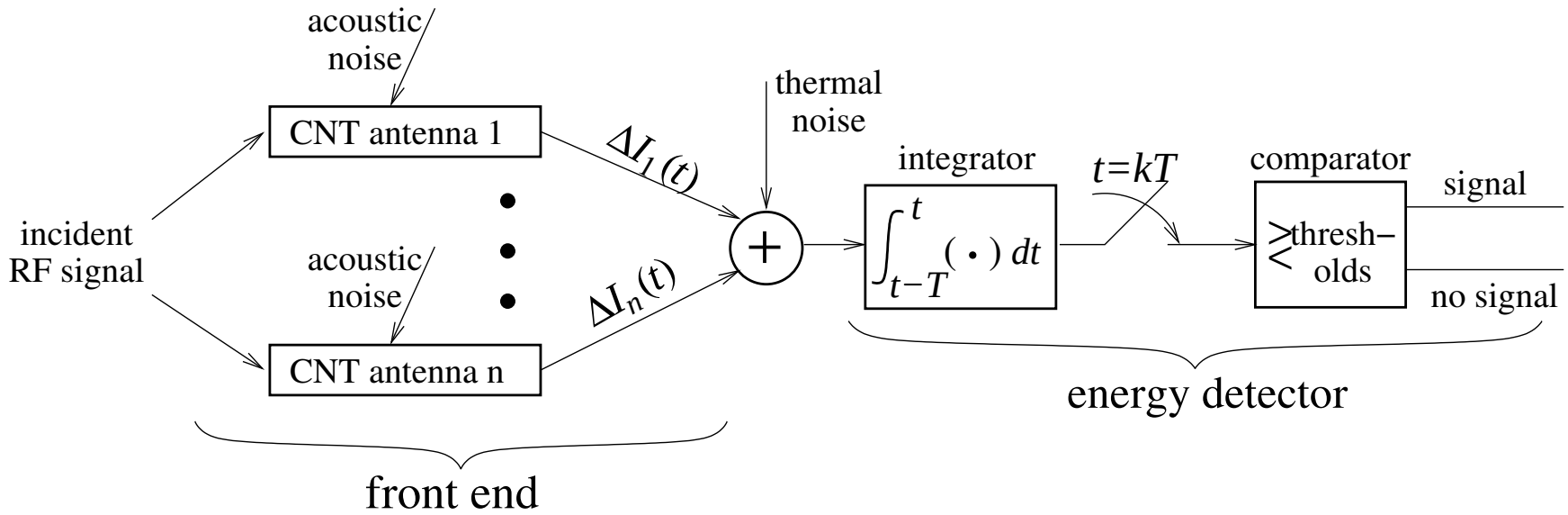


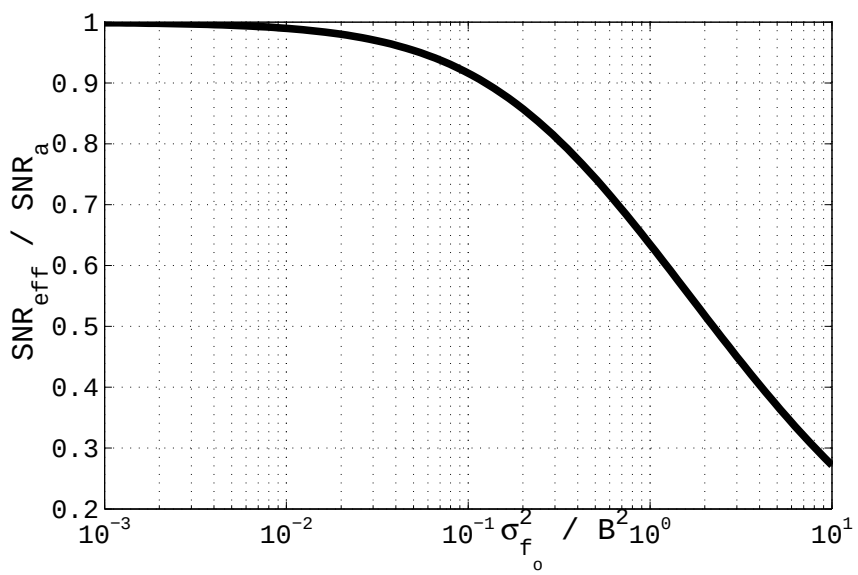


Assumptions:

- $n \gg 1 \Rightarrow$ acoustic noise dominant
- acoustic noise is spatially white
- non-uniform CNT-lengths: $f_{c,j} \sim \mathcal{N}(f_0, \sigma_{f_0}^2)$

Nanoreceiver Model - Multiple CNT Antennas

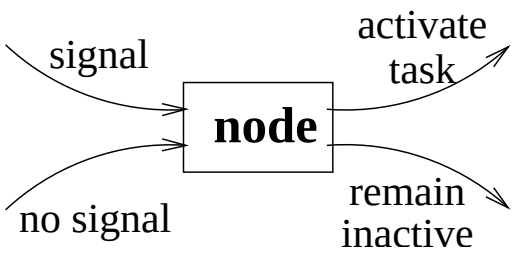




$SNR_{\text{eff}} \leq SNR_a$ due to non-uniformity of CNT lengths

Performance of Our Nanoreceiver

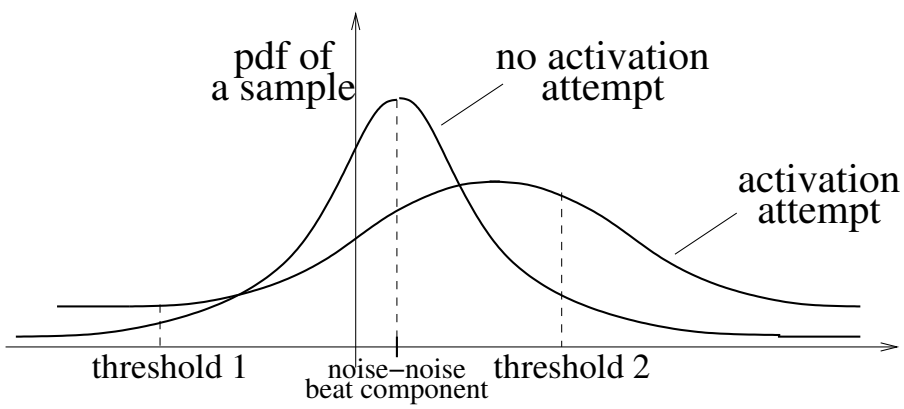
Activation of nanosystems:



- tasks activated by activation signals
- time slotted - activation slot size T
- activation probability in a slot is p_a
- activation signal narrowband wrt.

CNT bandwidth: $T \gg \frac{1}{B}$

Sampler output:



- MAP decision rule involves two thresholds
- two *types* of error:

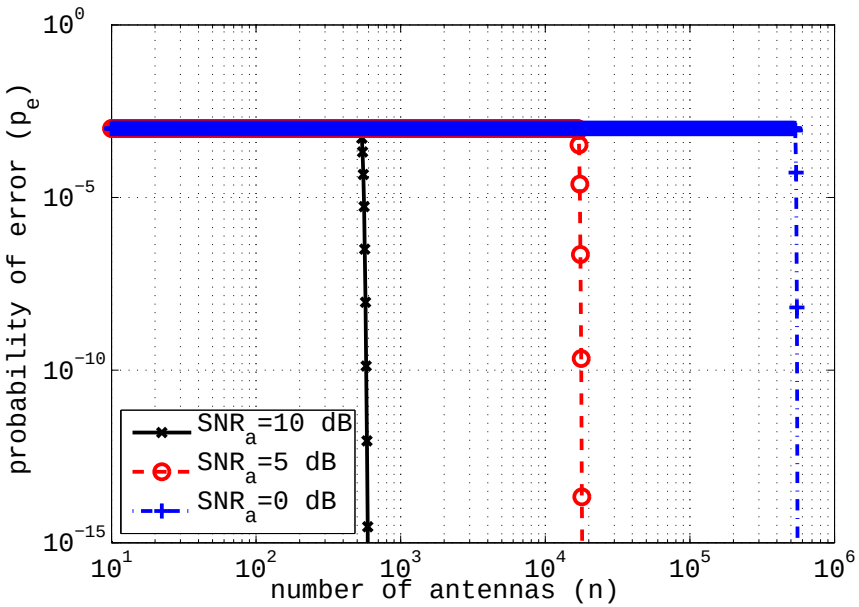
(1) probability of false activation p_{fa};

(2) probability of unsuccessful activation p_{ua}

Performance of Our Nanoreceiver - Probability of Error

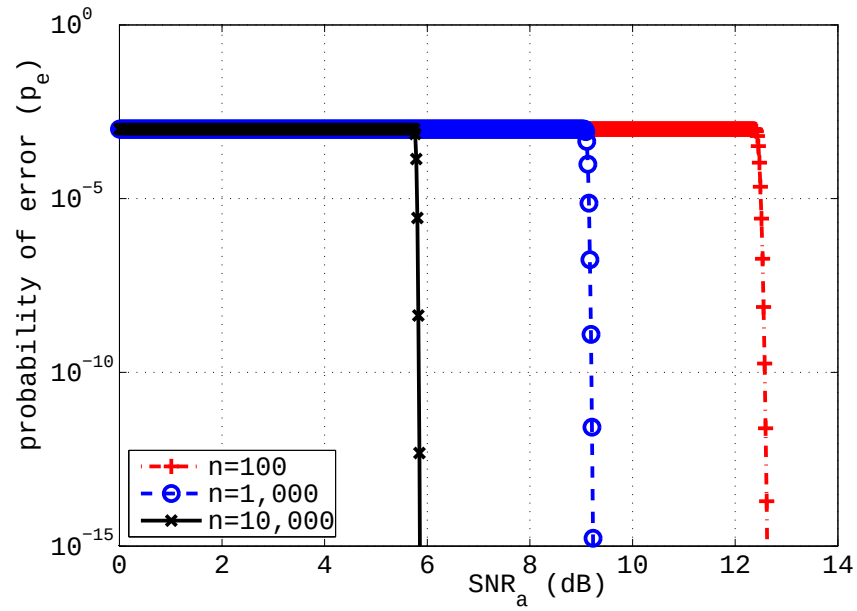
- Parameters: $f_0 = 15$ MHz, $Q = 500 \Rightarrow B = 15$ kHz, $p_a = 10^{-3}$, and $\frac{\sigma_{f_0}}{B} = \frac{1}{3}$
- MAP decision rule (minimize overall probability of error)

$T = 1$ sec



$\text{SNR}_a = 0$ dB $\Rightarrow p_e < 10^{-15}$ for $n = 10^6$

$T = 1$ sec

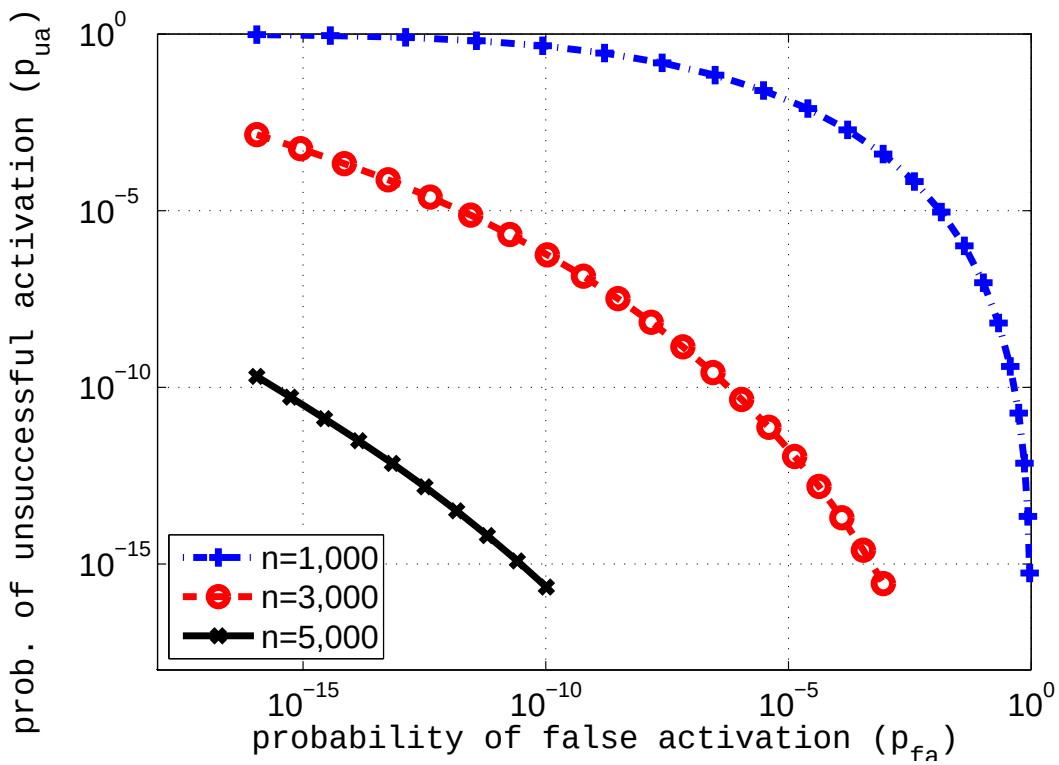


$\times 10$ increase in $n \Rightarrow 3.5$ dB gain

Performance of Our Nanoreceiver - ROC

- Parameters: $f_0 = 15$ MHz, $Q = 500 \Rightarrow B = 15$ kHz, $p_a = 10^{-3}$, and $\frac{\sigma_{f_0}}{B} = \frac{1}{3}$
- MAP decision rule (minimize overall probability of error)

$$SNR_a = 0 \text{ dB}$$



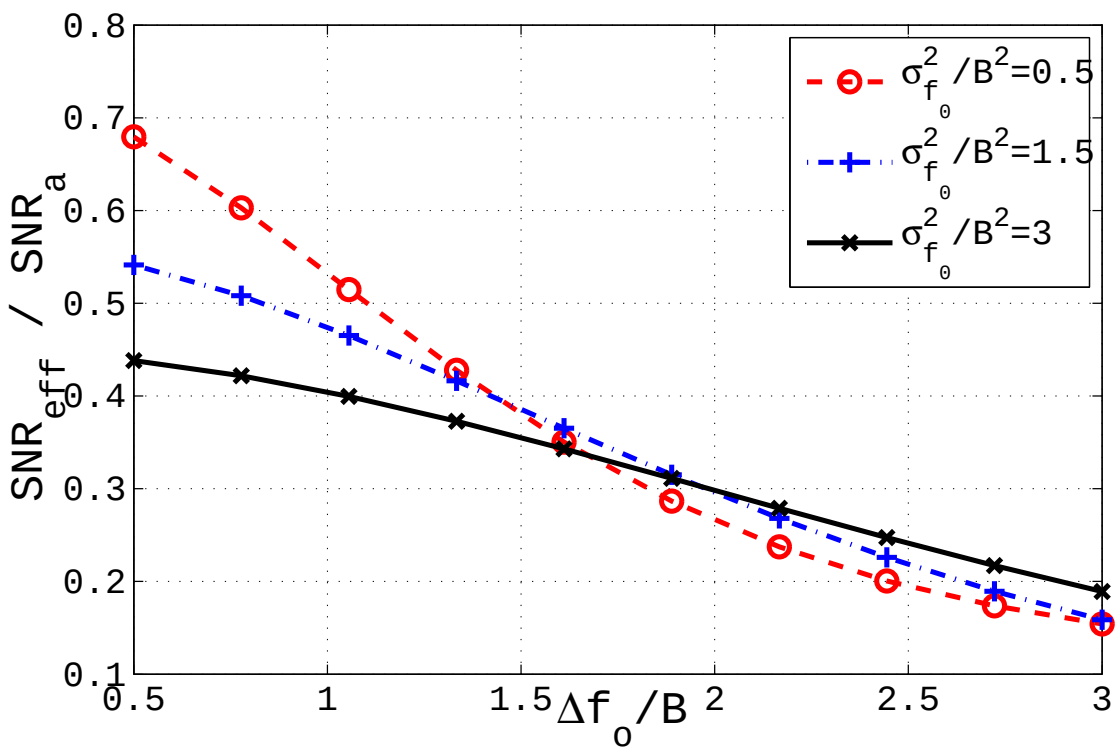
$\Rightarrow SNR_a = 0$ dB and $n = 3000$ are sufficient for **1 month** of continual operation with $p_{ua} = 10^{-7}$ at a cumulative $p_{fa} < 10^{-2}$

Performance of Our Nanoreceiver - Carrier Mismatch

- Let Δf_0 be the carrier frequency mismatch
- Recall $\sigma^2_{f_0}$ is the length variation and $\sigma^2_{f_0} \nearrow \Rightarrow \mathrm{SNR}_{\mathrm{eff}} \searrow$

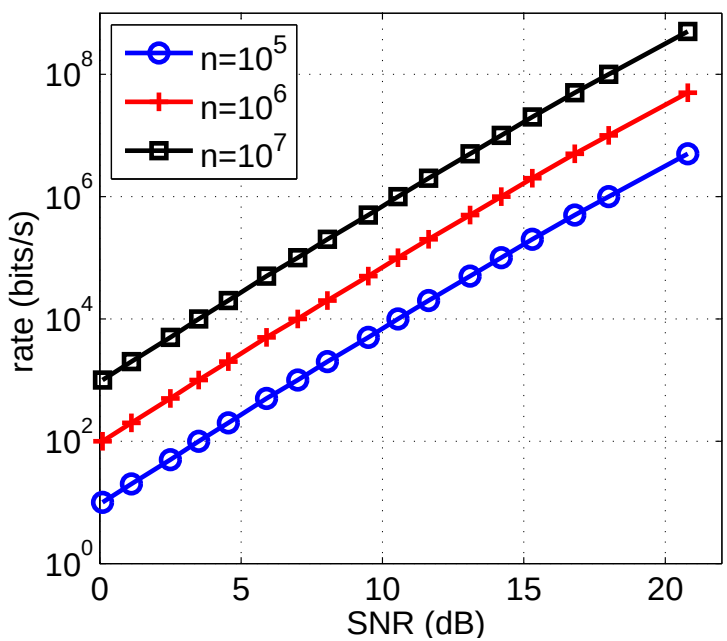
Q: Do we still want a small length variation if Δf_0 is high?

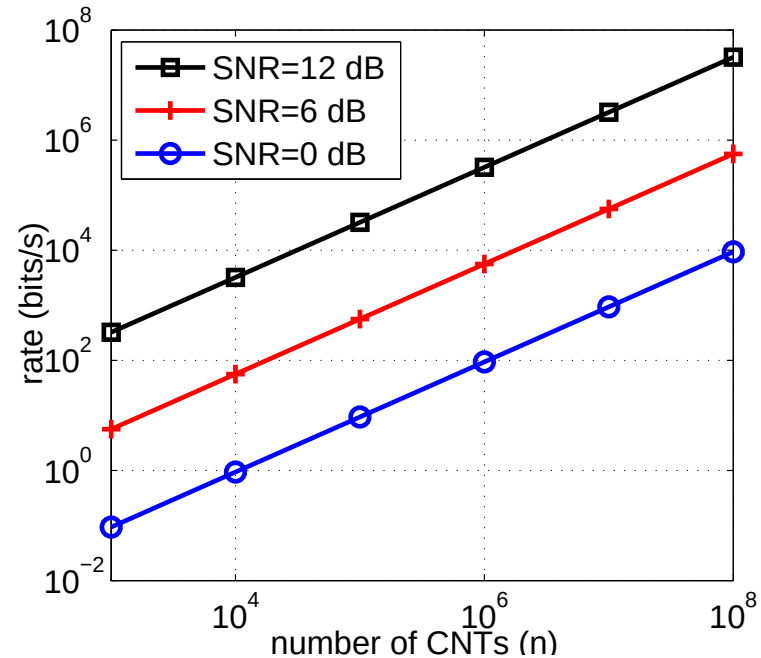
A: No. Large $\sigma^2_{f_0}$ is diversification wrt. Δf_0



From Node Activation to Data Communication

- Above results are not close to satisfactory rates: activation time $0.1 - 1$ sec $\Rightarrow$ data rates $\sim$ few bits/sec
- However, the performance improves drastically with # antennas
- Performance with CNT forests for $f_0 = 15$ MHz, $Q = 500$ and $\frac{\sigma_{f_0}}{B} = 0.1$

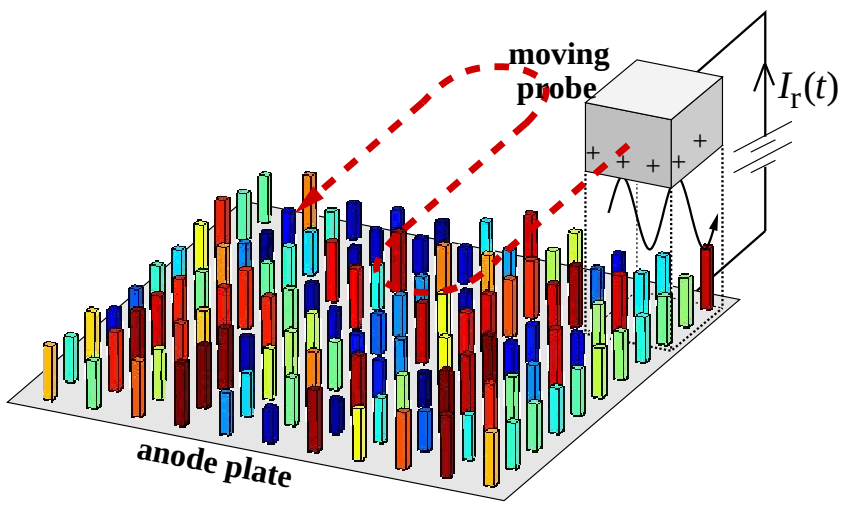




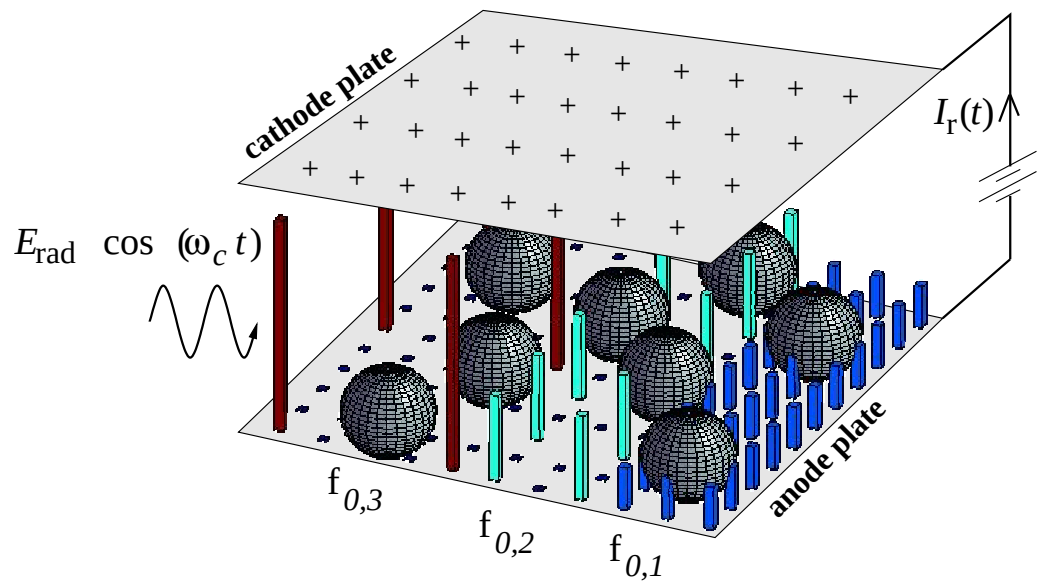
- Further analysis is necessary: (1) small $Q \rightarrow$ larger bandwidth $\rightarrow$ stronger noise; (2) relax the spatially white noise assumption; (3) distributed antennas

Further Applications

- Variations of our setup enable many nanoscale applications:



CNT length distribution measurement



Particle detection

Summary and Future Work

- A nanoreceiver architecture based on CNT forests
  - simple, robust
  - facilitates nano scale process control
  - potential for high-rate RF receivers
- We will
  - Extend our analysis incorporating further practical concerns:
    - badwidth-noise tradeoff, spatially colored noise, variable length CNT receivers, distributed antenna placement
  - Develop applications
  - Implementation?

(1) Koksal C. E. and Ekici E., "A Nanoradio Architecture for Interacting Nanonetworking Tasks," *Nano Communication Networks, Volume 1, Issue 1, Mar. 2010, Page: 63-75*

(2) Koksal C. E., Ekici E., and Rajan S., "Design and Analysis of Systems Based on RF Receivers with Multiple Carbon Nanotube Antennas," *Nano Communication Networks, Volume 1, Issue 3, September 2010, Page: 160-172*