HIGH-RATE RF NANORECEIVERS WITH CARBON NANOTUBE ANTENNAS

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Original Motivation:

- Nanoscale systems
  - Huge increase in effectiveness & scale of applications with communication capability
  - Mobility ⇒ wireless communication

- Nanoscale wireless communication
  - Traditional EM: nanoscale antenna sizes allow for THz range frequencies → high attenuation [Jornet and Akyildiz ’10], components unavailable
  - Molecular communication [Pierobon and Akyildiz ’10]
  - Non-traditional EM → 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 ⇒ 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 → CNT oscillations → change in observed current

⇒ Exploit this connection for communication of information
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

\[ I_r(t) \sim I_0 - \text{constant} \times d^2(t) \]

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

⇒ System acts as a square-law detector for signals at \( f_0 \)
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

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

(ignoring components at \(2f_0\)) = \[ \frac{a^2}{2}H^2(f_0) + 2a(W_a * h_r)(t)\cos(2\pi f_0 + \phi)H(f_0) \]

\[ + (W_a * h_r)^2(t) + W_T(t) \]

- **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

\[
\begin{aligned}
&\text{incident RF signal} \\
&\text{CNT antenna 1} \quad \Delta I_1(t) \\
&\text{CNT antenna n} \quad \Delta I_n(t) \\
\end{aligned}
\]

\[
\int_{t-T}^{t} (\cdot) \, dt
\]

integrator

\[
t = kT
\]

t = kT

\[
\text{comparator}
\]

\[
\text{thresholds}
\]

\[
\text{energy detector}
\]

\[
\text{SNR}_{\text{eff}} \leq \text{SNR}_a \quad \text{due to non-uniformity of CNT lengths}
\]
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 $\frac{\sigma_f}{B} = \frac{1}{3}$

- MAP decision rule (minimize overall probability of error)

$$T = 1 \text{ sec}$$

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

$\times 10$ increase in $n \Rightarrow 3.5$ dB gain
Performance of Our Nanoreceiver - ROC

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

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

$\Rightarrow SNR_a = 0 \text{ dB}$ 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 $\Delta f_0$ be the carrier frequency mismatch
- Recall $\sigma_{f_0}^2$ is the length variation and $\sigma_{f_0}^2 \not\Rightarrow \text{SNR}_{\text{eff}} \downarrow$

Q: Do we still want a small length variation if $\Delta f_0$ is high?
A: No. Large $\sigma_{f_0}^2$ is diversification wrt. $\Delta f_0$
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

\[ E_{\text{rad}} \cos (\omega_c t) \]
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:
    * bandwidth-noise tradeoff, spatially colored noise, variable length CNT receivers, distributed antenna placement
  - Develop applications
  - Implementation?
