High-Rate RF Nanoreceivers with CNT Antennas

C. Emre Koksal, Eylem Ekici

***Abstract*—We introduce RF nanoreceivers based on carbon nanotube (CNT) antennas. CNT-based nanoreceivers have been shown to operate in tens to hundreds of MHz range both in theory and practice. We show that a low cost combination of these receivers lead to linear increase in achieved data rate via ON-OFF Keying (OOK). Due to extremely small scale of the CNTs, many hundreds of thousands of these receivers can be packed into very small areas to achieve rates comparable to the commercially available wireless receivers. We show that, with a 1mm^2 forest of CNT antennas, separated by 100nm, our nanoreceiver achieves a rate of 1Mbps at an SNR of 6dB at a bit error rate of 10^{-5}. Hence, a significant spatial miniaturization is achieved by our nanoreceiver compared to a classical RF receiver without a loss in the achievable rate.**

I. Introduction

Nanoscale systems are envisioned for many crucial future applications ranging from targeted medicine and drug delivery to high fidelity sensors [1]. Recently, new EM-based radio receivers have been proposed using *Carbon Nanotubes (CNTs)* [2]. These communication systems are fundamentally different from traditional antenna-based systems in that the EM signals cause vibration of the CNT rather than oscillation of electrons therein. The ground-breaking property of CNT-based communication systems is that it is possible to establish communication in the 100s of MHz range with systems that are 100s of nm in size. Even more recently, we have developed a communication-theoretical analysis of CNT-based receiver systems [3], [4]. Almost concurrently, system and networking aspects of nanoscale devices with CNT-based radios have been discussed in [5].

The main challenge in such systems is to overcome the requirement of high SNR to achieve low error rates. The parallel use of multiple CNTs with similar sizes allows us to tackle this dilemma easily. We show that a cost effective combination of these receivers yield in a rate that increases linearly in the number of CNT antennas used. A 1mm^2 CNT forest with 100nm CNT separation can achieve a data rate of 1Mbps at 6dB SNR for a probability of error of 10^{-5}. This significant reduction in scale without a loss in the achieved rates enables many new applications including miniaturization of existing receiver systems.

II. Physical Model

A single CNT-based nanoreceiver is depicted in Figure 1. CNTs behave like cantilevers with high elastic strength, and an elastic constant in 100 GPa range. A longitudinal electric field applied on a CNT induces a charge density at the tip of the CNT. Under electromagnetic excitation, the oscillating electric field perpendicular to the CNT exerts an oscillating force on it and cause it to move. Near the resonance frequency f_c of the CNT cantilever, EM energy couples most efficiently into the CNT, and the CNT vibrates with a large amplitude. Fundamental properties such as mass, length, and diameter determine the resonance frequency and quality factor (Q) of the cantilever vibration. A simple theoretical model for electromagnetic excitation of CNTs was provided in [2]. The tunneling current varies exponentially with the distance between the tip and the cathode, given by the Fowler Nordheim equation $I = c_1 A(\gamma E_{ext})^2 e^{-\frac{c_2}{\gamma E_{ext}}}$, where c_1 and c_2 are constants that depend on the geometry of the device, A is the area from which the CNT emits electrons, E_{ext} is the external applied electric field, and γ is a "field enhancement factor" that depends linearly on the distance between the tip and the cathode. Since the tunneling current depends exponentially on the inverse of the distance, small deviation of the CNT due to bending can lead to large changes in the tunneling current. The second order term in the Taylor series expansion of I is the dominant term and the amplitude of fluctuations in the current (observed signal) is proportional to vibration amplitude's square $|y|^2$. This leads to a square-law behavior for the observed signal, with respect to the incident radiant electric field strength.

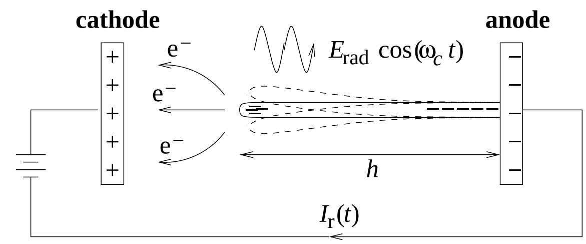


Fig. 1. Single CNT-based nanoreceiver.

III. Receiver Model

Our multi-CNT nanoreceiver was introduced in [4], with the abstract model shown Fig. 2. The basic components of the *front end* include n nanoantennas and n associated square-law devices. Here, $h_{r,j}(t)$ is the impulse response of the linear filter that captures the input-output behavior of the jth nanoantenna, where the input $Y_{i,j}(t)$ is the incoming electromagnetic field and the output $Y_{o,j}(t)$ is the amplitude of the associated vibrations. The frequency response of the jth nanoantenna is:

$$H_{r,j}(f) = \frac{|Y_{o,j}(f)|}{E_{\text{rad}}(f)} = \frac{q/m_{\text{eff}}}{4\pi^2\sqrt{(f^2 - f_{c,j}^2)^2 + (ff_{c,j}/Q)^2}},$$

where $f_{c,j}$ is the resonance frequency of the jth nanoantenna. We assume the length of each nanoantenna to be random. We

C. Emre Koksal and Eylem Ekici are with the Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH (E-mail: {koksal, ekici}@ece.osu.edu).

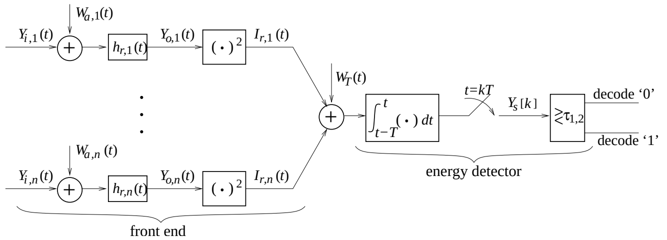
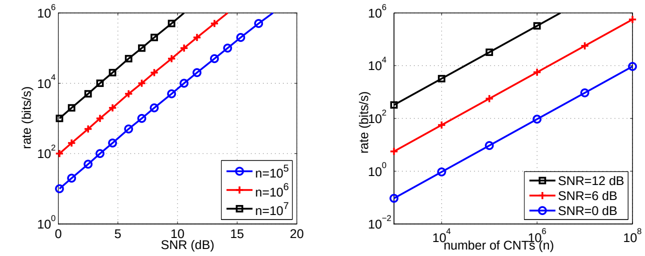


Fig. 2. System model of our nanoreceiver.



(a) Rate vs. SNR (b) Rate vs. n

Fig. 3. Rate of multi-CNT nanoreceivers.

model this randomness using a normal distribution, i.e., $f_{c,j} \sim \mathcal{N}(f_0, \sigma_{f_0}^2)$, independently of $f_{c,j'}$ for all $j' \neq j$. We assume that $H_{r,j}(f_{c,j}) \approx \frac{q/m_{\text{eff}}}{4\pi^2 f_0^2/Q} \triangleq H_{\text{res}}$ for all $j \in \{1, \ldots, n\}$. The 3-dB bandwidth is approximated as $B \approx \frac{f_0}{2Q}$ for all antennas.

The signal is corrupted by AWGN at two levels: The **acoustic noise**, $W_{a,j}(t)$, is the mechanical component that affects the amplitude of the vibrations $Y_{o,j}(t)$, whereas the **thermal noise**, $W_T(t)$ is added to the total detected current. We denote the two sided power spectral densities of acoustic and thermal noises by $N_a/2$ and $N_T/2$ respectively. Note that, as the number of CNTs increases, acoustic noise becomes the dominant noise source, since it scales with the number of antennas, as it is observed in each CNT antenna independently.

To decode each bit, we use a simple energy detector as shown in Fig. 2. Since the signal $\sum_{j=1}^{n} I_{r,j}(t)$ is the current at the output of the front-end of the receiver, the integrator can be realized by a mere *capacitor*. The integrator is followed by the sampler, sampling the output of the integrator once every T seconds (**symbol period**), i.e., the data rate is $1/T$ bits/sec. Each sample $Y_s[k]$ is compared with a pair of predetermined thresholds τ_1 and τ_2 and a '0' or a '1' bit is decoded depending on these comparisons.

The combination of the square-law devices at each branch and the integrator acts as a *demodulator* for each waveform $Y_{o,j}(t)$ separately, which also includes the noise component $W_{a,j}(t)$, filtered by the antenna response $h_{r,j}(t)$. With no front-end filter to remove the out-of-band noise components, the performance of the system degrades. For information transmission, an ON-OFF Keying (OOK) scheme is used. During the ON period, the transmitter transmits pure sinusoids of duration T, i.e., for each antenna j, we have $Y_{i,j}(t) = Y_i(t) = a\cos(2\pi f_0 t + \phi)$, where ϕ is the random phase. The energy detector integrates $\sum_{j=1}^{n}(I_{r,j}(t)) + W_T(t)$ over T and a sampler samples the output of the integrator every T. There are three components of $I_{r,j}(t)$ under the activation attempt: *signal component*; *signal-noise cross component*, which is a Gaussian process; and *noise-noise cross component*, which has Chi-squared samples.

The performance analysis of the energy detector with a maximum a posteriori decision rule is given in [4]. There, the nanoreceiver is used to activate tasks and the activation signal (ON) is transmitted for an activation event, which occurs with probability p_a and no signal is transmitted (OFF) otherwise. Here, we use the maximum likelihood (ML) detector. The ML detector involves two thresholds, which can be found using Eqs. (28,29) of [4], by plugging $p_a = 1/2$. Eqs. (30,31) of [4] give the probability of unsuccessful activation and the probability of false activation respectively. With p_a chosen as 1/2, the two are identical and they give the associated bit error probability of the ML detector.

IV. Rate of CNT-Based Nanoreceivers

Here, we analyze the achieved data rate of our nanoreceiver. In our study, we assume $\sigma_{f_0}^2/B^2 = 0.1$, $f_0 = 15MHz$, and $Q = 500$. For each studied case, we use a symbol period T that corresponds to a probability of error of $p_e = 10^{-5}$. In our evaluations, the number of CNTs is large and consequently the dominant noise source is the acoustic noise. Hence the signal to noise ratio (SNR) is roughly identical to the signal to acoustic noise ratio. The rate is computed as the reciprocal of T. Fig. 3(a) depicts the rate of transmission as a function of SNR for nanoreceivers with 10^5, 10^6, and 10^7 antennas. We observe that, the achieved rate increases by a factor of 10 for every 7 dB increase in the SNR.

From Fig. 3(b), one can observe the linear relationship between the achieved rate and the number of antennas. This is really key to the success of our nanoreceivers, since, considering that many hundreds of thousands or millions of CNTs can be fabricated on a substrate, it is possible to achieve very high rates with very small devices: According to our analysis, a rate of approximately 1Mbps can be achieved at 6dB SNR with $p_e = 10^{-5}$ with a receiver with 10^8 CNTs, which would cover only 1mm^2 substrate with 100nm CNT separation. Noting that CNTs can be placed much closer than this, the achievable miniaturization is very significant.

V. Conclusions

We proposed a high-rate multi-CNT nanoreceiver and analyzed its performance. Our results show that it is possible to achieve high reception rates at very small scales, paving the road towards a multitude of applications benefiting from the resulting miniaturization.

References

[1] I. Akyildiz and C. B. F. Brunetti, "Nanonetworks: A new communication paradigm," *Computer Networks*, vol. 52, pp. 2260–2279, 2008.

[2] K. Jensen, J. Weldon, H. Garcia, and A. Zettl, "Nanotube Radio," *Nano Letters*, vol. 7, pp. 3508–3511, November 2007.

[3] C. E. Koksal and E. Ekici, "A Nanoradio Architecture for Interacting Nanonetworking Tasks," *Elsevier Nano Communication Networks Journal*, vol. 1, pp. 63–75, March 2010.

[4] C. E. Koksal, E. Ekici, S. Rajan, "Design and Analysis of Systems Based on RF Receivers with Multiple Carbon Nanotube Antennas," *Elsevier Nano Communication Networks Journal*, vol. 1, pp. 160–172, September 2010.

[5] B. Atakan and O. B. Akan, "Carbon Nanotube-Based Nanoscale Ad Hoc Networks," *IEEE Communications Magazine*, pp. 129–135, June 2010.