Reliability of Wireless On-Chip Interconnects Based on Carbon Nanotube Antennas

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Abstract— **Design technologies for integrated systems beyond the current CMOS era will present unprecedented advantages such as very high device densities and challenges such as soaring power dissipation issues. Most of the research effort in the emerging area of nanoelectronics has revolved around creating novel devices to replace the traditional CMOS transistor. The development of higher-level communication architectures necessary for integrating such devices into high performance systems has not received the same level of attention so far. With the current trend of CMOS scaling, traditional planar metal-based on-chip interconnect schemes are projected to be the principal bottleneck in meeting the performance needs and specifications of Systems on Chip (SoCs). Three-dimensional integration and on-chip optical and RF communication links have been envisioned as promising alternatives. In this paper we explore the possibility of having an on-chip wireless communication infrastructure using carbon nanotube antennas operating in optical frequencies, and the effect of variations in nanotube properties on the communication behavior.**

I. Introduction

With shrinking geometries, global interconnects are becoming the principal performance bottleneck of high-performance Systems-on-Chip (SoCs) [1,2] in terms of communication latency and power. While copper and low-*k* dielectrics have been introduced to decrease the global interconnect delay, they only extend the lifetime of conventional interconnect systems by a few technology generations. According to the International Technology Roadmap for Semiconductors (ITRS) [3], for the long term material innovation with traditional scaling will no longer satisfy the performance requirements and radically new interconnect paradigms are needed. The continued progress of interconnect performance will require approaches beyond the conventional metal/dielectric system, and may require information carriers other than charge. According to the ITRS, multiple options have been considered to provide alternatives to the metal/dielectric system, among which three-dimensional (3-D) integration, optical communication and on-chip RF/wireless are promising alternatives.

The 3-D integrated circuit (IC) consisting of multiple layers of active devices is emerging as a viable alternative to alleviate the delay/power issues of global wires [4]. The layers are separated by a few tens of micrometers. Consequently, the 3-D interconnects allow communication among active devices with very small distances required for signal propagation. Optical communication using waveguides is another promising approach to replace the traditional conductor/dielectric system for signal transmission in a SoC [5]. Low latency communication in a SoC can also be achieved using RF interconnects, where data is transmitted through on-chip transmission lines [6]. In essence these techniques still depend on physical "wired" channels for data transport and hence do not resolve the difficult problem of routing the interconnects. By contrast, employing on-chip wireless communication links can solve the complex interconnect routing problem. Floyd et al. demonstrated this concept for clock distribution using RF signals [7], but their antenna devices consumed a very large area on the chip (a few millimeters in length), limiting the scalability of the technology. Recent research has uncovered interesting optical emission and absorption characteristics and antenna like behavior in carbon nanotubes (CNTs), and we believe these properties could be exploited to create a wireless communication infrastructure using optical wavelengths/frequencies on a chip. In this paper we look at some of the nanotube properties and their variations, which could affect the characteristics and reliability of this wireless technology.

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II. Related work

Current SoCs are implemented predominantly following planar architectures with a single layer of active devices. However, the emergence of 3-D ICs will present a fundamental change. Topol et al., in [4], described in detail the advantages and challenges of manufacturing in a 3-D IC process and show that 3-D ICs are capable of improvements in power, noise, logical span, density, performance, and functionality. One major advantage of the 3-D IC paradigm is that it allows for the integration of "dissimilar technologies", e.g. memory, analog, MEMS, etc. in a single die. On-chip optical communication is another alternative to replace the traditional conductor/dielectric system for signal transmission in a SoC. The design of an optical clock distribution network was demonstrated in [8]. In addition to the clock network, the optical communication medium is useful for constructing the interconnection backbone for multi-core chips. In this regard a photonic network on chip was discussed in [9]. According to Chang et al. intra-chip low latency communication can be achieved through RF interconnects, where the transmission of

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data is guided through transmission lines [6]. The possibility of on-chip wireless interconnects was demonstrated first in [7] for distributing clock signals. With the advent of nanoscale antennas based on carbon nanotubes, we believe that an on-chip wireless communication link using optical frequencies could be built for intra-chip communications. The past few years have seen several interesting works covering theoretical and experimental aspects of CNT antennas [10-13].

III. Characteristics of the Proposed Devices

A. Why optical frequencies and nanotubes

For on-chip wireless communications, it is important that the transmitter and receiver antennas be as small as possible since area is limited and expensive. Consequently, RF wireless communications using microstrip antennas with millimeter-scale sizes [7] is limited in terms of scalability. However, in order to be able to use smaller antennas (on the order of a few hundred nanometers to a few micrometers in characteristic dimensions), it is necessary to use correspondingly shorter wavelengths, i.e. wavelengths in the optical domain. For fabricating the antennas, highly conductive wires for the submicron scale are needed. Single-walled carbon nanotubes (SWNTs) are the perfect candidates for such structures, which would be extremely hard, if not impossible, to fabricate using metal deposition and traditional patterning techniques. In addition to providing the perfect one-dimensional wires needed, SWNTs have an extremely high conductance approaching the quantum limit, which would minimize resistive losses in the antenna. Moreover, due to their chemically complete and nearly-defect-free structure, nanotube antennas would suffer much less from power loss due to surface and edge roughness, which is present in patterned metals. Another important advantage of nanotubes is their extremely high current carrying capacity of 10^9 A/cm^2, which is orders of magnitude higher than metals. This would potentially allow the radiation of the necessary levels of power to achieve the desired communication range.

B. Transmitter and receiver structures

The structure of the proposed device is remarkably simple compared to a standard RF transmitter. Since optical frequencies cannot be generated using a traditional oscillator circuitry, in our transmitters optical signal generation will also be performed within the nanotube device itself. In other words, the nanotube acts as both the modulation circuit and the antenna. IBM researchers have demonstrated infrared radiation from SWNTs under a DC bias of a few volts, similar to a photodiode [14-16]. Accordingly, here the transmitter consists of a CMOS circuitry that applies a DC voltage to the nanotube whenever the information bit to be transmitted is "1" (Fig. 1). Under this condition, an infrared pulse will be generated by the nanotube. The nanotube length will be chosen so as to optimize the antenna response for the particular frequency of emission in use.

The receiver structure will be just as simple. The signal will be picked up by a nanotube antenna, amplified using a CMOS amplifier circuit, and sent to the rest of the circuit where needed (Fig. 2).

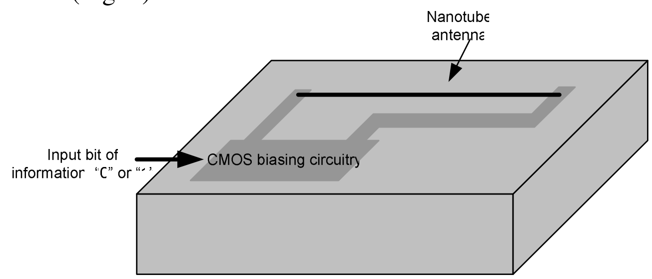

Fig. 1. Schematic representation of the transmitter

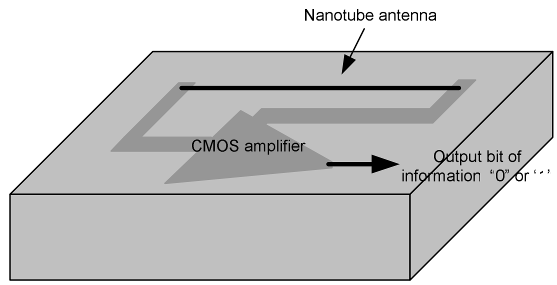

Fig. 2. Schematic representation of the receiver

C. Antenna characteristics

Semiconducting SWNTs come in varieties with energy bandgaps of up to around 1.5 eV, based on their chirality and diameter, corresponding to infrared radiation. Given that the width of the infrared emission and absorption spectra in nanotubes is on the order of 0.15 eV [15, 17], the possibility of creating approximately 10 different frequency channels can be expected. Moreover, the emitted light is polarized, and optical absorption is also polarization dependent (polarization along the nanotube axis is strongly favored). This would enable one to double the number of available communication channels by using parallel and perpendicular nanotubes.

D. Power

One SWNT can carry several microamperes of current under an applied voltage of a few volts. This means an emission power maximum of a few microwatts. Depending on the communications range needed, this may or may not be sufficient. However, it is possible to boost the power by using a number of nanotubes in parallel. In addition, this array might enable directionality characteristics. This will be discussed in more detail in the next subsection. Here we focus on the amount of power transfer between one pair of transmitter and receiver nanotubes.

This problem can be broken down into three parts: (a) finding the current distribution in the transmitter antenna; (b) determining the electromagnetic field generated by that current distribution; and (c) finding the power absorbed in the receiver antenna when it is placed in the field generated by the transmitter. Parts (a) and (c) involve quantum mechanical modeling and are presently the subject of more detailed study. Here, we use the current distribution in a nanotube transmitter antenna as predicted in [10] to compute the field generated by solving Maxwell's equations. In order to calculate the absorbed power in the receiver, we also employ a classical model by using effective dielectric constant and conductivity parameters for the nanotube. Experiments are required to confirm the validity of this classical model, and that will be the subject of future work.

Since the processes for fabricating nanotube devices (such as chemical vapor deposition) do not provide full control in terms of the chirality and diameter of the produced nanotubes, there is going to be variations from device to device and, therefore, it is important to analyze the effect of these variations in view of system reliability.

Using the classical model the receiver antenna is assumed to be a distributed resistor, and we calculate the power dissipated in this resistor under electromagnetic irradiation as a measure of the signal absorbed by the receiver. If the nanotube is treated as a metallic cylinder (as it is here), its electrical resistance decreases quadratically with the nanotube diameter, and linearly with the nanotube conductivity. The alternating electromagnetic field produced by the transmitter antenna generates an alternating current in the receiver antenna. One would expect the current density in the receiver and therefore the power absorption to increase as the resistance of the receiver antenna is decreased. Therefore, the power absorption should increase quadratically with nanotube diameter and linearly with conductivity.

In order to further investigate the above, we performed simulations using the software package COMSOL Multiphysics to solve Maxwell's equations. In the simulations presented here, the transmitter antenna is a nanotube with a length of 10 µm, a peak current of 1 µA, and a carrier frequency of 1.5×10^{14} Hz (i.e., wavelength of 2 µm). The receiver antenna is a nanotube with a length of 1 µm, located in parallel with the transmitter antenna at a 15 µm distance from it. In order to see the effect of nanotube diameter, the conductivity of the receiving nanotube is assumed to be 5×10^{7} S/m, which is typical of metals such as copper, and the permittivity of the nanotube is assumed as $5.33\text{-}5.33j$ according to the scheme described in [17]. Power absorption is measured for different diameters of the receiver antenna. Fig. 3 shows the plot of received power as a function of nanotube diameter in a logarithmic scale. It is evident that power absorption increases with the diameter. The slope of the curve is ~2 for diameters smaller than 5 nm (quadratic behavior).

The absorbed power as a function of conductivity of the receiver antenna is depicted in Fig. 4. It is evident that the power absorption increases with conductivity almost linearly.

Power absorption was also measured while the receiver antenna was perpendicular to the direction of the transmitter antenna (investigating the polarization effect). Simulations showed that the power absorption decreases by several orders of magnitude compared to the case where the two nanotubes are in parallel. This confirms that polarization division multiplexing is possible using nanotube antennas.

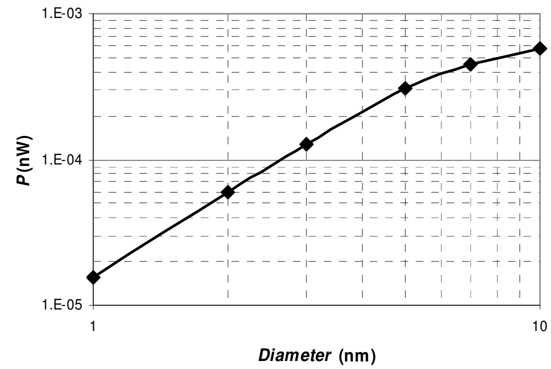

Fig. 3. Effect of diameter on the power absorption in the receiver antenna

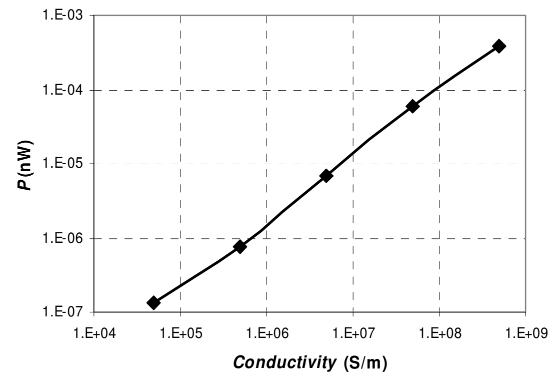

Fig. 4. Effect of conductivity on the power absorption in the receiver antenna

E. Nanotube antenna arrays

In addition to boosting the power, an antenna array could also lead to directional properties, which would in turn lead to less power waste when point-to-point communications is needed. One important factor is that although the input voltage applied to all the nanotubes in the array is the same (all connected to the same electrode), due to the spontaneous nature of light emission, the optical signals generated in the nanotubes can have complicated phase relations. Nevertheless, amongst the photons emitted during each bit of information (when the input signal to all the nanotubes is "1"), there might be specific phase relations, which would have major implications on the possibilities offered by nanotubes (in terms of directionality and, ultimately, range) for the design of the wireless infrastructure. We analyze this case here using both analytical formulation and simulations. A SWNT can be considered a virtually one-dimensional antenna as it can be as long as several micrometers while being in the order of 1 nm in diameter. Consequently it can be treated as a linear array of several Hertzian Dipoles (Fig. 5) [18]. Considering a single SWNT to be such an array of dipoles its directional properties in both θ- and φ-planes can be computed. Here θ and φ are the angles between the line joining the point of observation to the centre of the array and the nanotube and the plane containing the nanotube bundle, respectively.

For a Hertzian dipole the magnetic and electric fields are given by [18]

$$H_{\phi s} = \frac{jI_0 \beta d \sin\theta e^{-j\beta r}}{4\pi r}; E_{\theta s} = \eta H_{\phi s}, \tag{1}$$

where I_0 is the current through the dipole centered at the origin with the axis along the z dimension and $\beta=2\pi/\lambda$, with λ the wavelength of the emitted signal. The length of the dipole, d, is considered small enough to assume a constant current through each element. The point of observation is a far-field point located at polar coordinates (r, θ) and $\eta=120\pi$ for free space.

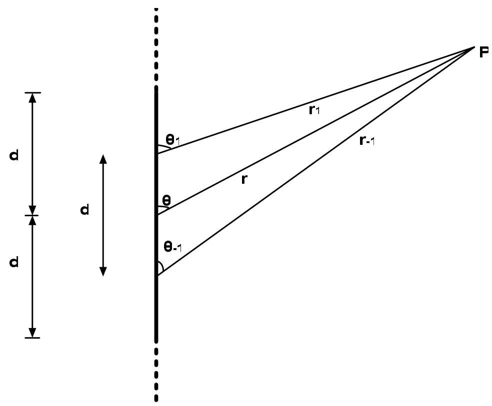

Fig. 5. Array of dipoles making up the entire nanotube

Considering the far-field point P (r,θ,φ) the following approximations can be made:

$$\begin{aligned} r_1 &= r - \frac{d}{2}\cos\theta, \\ r_{-1} &= r + \frac{d}{2}\cos\theta ... \end{aligned} \tag{2}$$

Here, the length of each dipole, d is also the distance between two subsequent elements. The distances of the point P from the antenna elements can all be approximated as r. However the phase terms of the electric and magnetic fields from (1) involving those distances can not be approximated in a similar fashion and hence (2) is used to evaluate the phase terms. Although the current through each dipole can be considered a constant for very small d, the current elements in the individual dipoles are considered to be at a phase difference of α progressively. In [10] the current distribution along the axis of an infinitely long SWNT is shown as a result of numerical analysis. Using this distribution and approximating it as a near full-cycle sinusoid across the length of the nanotube the phase difference between successive elements can be obtained as $\alpha=2\pi d/l$. Thus for a SWNT with N individual dipoles the electric field at point P is given by the following sum:

$$\begin{aligned} E_{\theta s} = \frac{j\eta I_0 \beta d \sin\theta}{4\pi r} [& e^{-j\beta\{r-(N-1)\frac{d}{2}\cos\theta\}} e^{j(N-1)\frac{\alpha}{2}} + ... + e^{-j\beta(r-\frac{d}{2}\cos\theta)} e^{j\frac{\alpha}{2}} \\ & + e^{-j\beta(r+\frac{d}{2}\cos\theta)} e^{-j\frac{\alpha}{2}} + ... + e^{-j\beta\{r+(N-1)\frac{d}{2}\cos\theta)} e^{-j(N-1)\frac{\alpha}{2}}] \end{aligned} \tag{3}$$

This sum can be simplified to:

$$E_{\theta s} = \frac{j\eta I_0 \beta d \sin\theta}{4\pi r} \frac{\sin N\gamma}{\sin\gamma} e^{-j\beta r}, \tag{4}$$

where $\gamma = \frac{1}{2}(\beta d \cos\theta + \alpha)$. The θ-plane directional characteristics can be obtained from (4) for a nanotube of length l with N individual dipoles in the linear array. Using this as the characteristics of a unit antenna the directional properties of a bundle of M antennas shown in Fig. 6 can be computed as outlined below.

As can be observed from (4) the fields are omni directional in the φ-plane and hence their effects from multiple antennas will just add up. Each nanotube is separated by a distance d_t. At the far-field point, P, the effective field is the sum from all the individual nanotube elements:

$$E_\theta(\theta,\varphi) = \frac{j\eta I_0 \beta d \sin\theta}{4\pi r} \frac{\sin N\gamma}{\sin\gamma} [e^{-j\beta\{r-(M-1)\frac{d_t}{2}\cos\phi\}} + ... + e^{-j\beta\{r+(M-1)\frac{d_t}{2}\cos\phi\}}] \tag{5}$$

This can be simplified to

$$E_\theta(\theta,\varphi) = \frac{j\eta I_0 \beta d \sin\theta}{4\pi r} \frac{\sin N\gamma}{\sin\gamma} \frac{\sin M\psi}{\sin\psi} e^{-j\beta r}, \tag{6}$$

where $\psi = \frac{1}{2}\beta d_t \cos\varphi$. The above expression gives the combined 3-D directionality of a bundle of nanotube antennas. It can be predicted from (6) that maximum power is obtained in the direction of $\theta=\varphi=90^o$. The above directionality characteristics of the antenna array were also verified by simulations using COMSOL Multiphysics. A bundle of 200 nanotube dipole antennas was considered, with a length of 10 μm each. The space between the nanotubes was chosen as 10 nm, which leads to the maximum directionality for a wavelength of 2 μm. The peak current in each nanotube was assumed to be 1 μA. The profile of the electric field strength generated by the antenna array as a function of the distance and the observation angle are shown in Fig. 7. In this figure, $10\cdot\log_{10}(E)$ is plotted, where E is the electric field (gray scale limited between 22 and 42 to obtain a good quality image). As shown, the radiated power is maximum at $\varphi=90°$, and almost no power is radiated in the direction of $\varphi=0$. A directionality

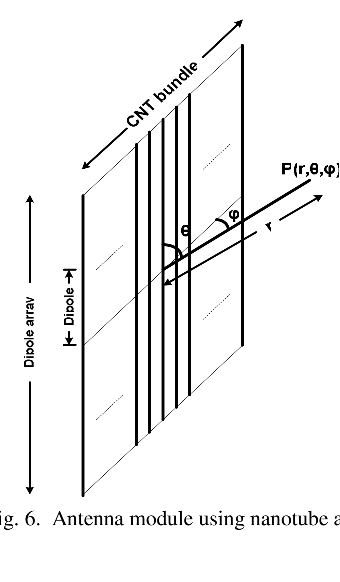

Fig. 6. Antenna module using nanotube array.

of several tens of dB is obtained in this manner.

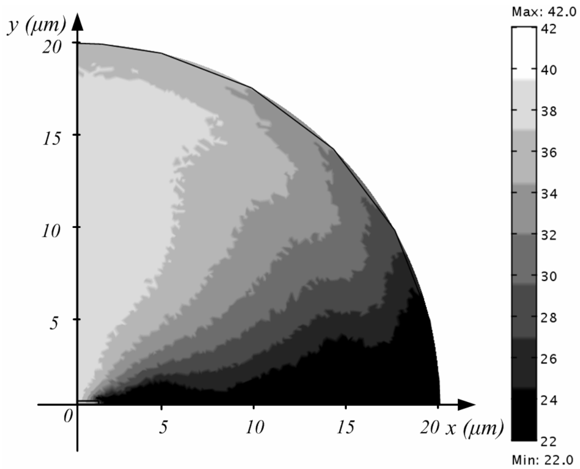

Fig. 7: Electric field around a bundle of CNT dipole antennas

IV. DESIGNING ON-CHIP WIRELESS LINKS

Nanotubes by themselves can act as high frequency signal generators when excited with a voltage. Therefore a simple On-Off Keying (OOK) scheme can be used to transmit logic levels. The receiving CNTs produce current upon being excited by photons of a particular frequency and effectively perform non-coherent envelope detection. This obviates the use of separate oscillators and filters for modulation and demodulation. In the case of inter-subnet data transmission multiple channels are required to achieve acceptable throughput.

As explained earlier each CNT-based antenna can emit and absorb electromagnetic radiation of a particular frequency determined by its band-gap energy, E_g. Using band-gap engineering, one can create CNT antennas operating at multiple different frequencies. This provides a natural candidate for a simple FDM-based scheme. As mentioned previously, by modifying the band gaps, up to 10 frequency channels could be created. This enables the transmission of 10 bit streams simultaneously on 10 sub-carrier frequencies. To further increase the bandwidth of the wireless link the sensitivity of the CNTs to polarization of incident radiation can be utilized. We can arrange CNTs with same frequencies perpendicular to each other. This results in doubling the link width. Thus a combination of FDM and Polarization Division Multiplexing (PDM) can make the link width 20. To further scale up the communication bandwidth a simple Time Division Multiplexing (TDM) scheme with N time-slots can be used where each separate frequency/polarization channel is responsible for the transmission of N bits. Thus a hybrid scheme using FDM, PDM and TDM can result in a high bandwidth communication infrastructure.

V. RELIABILITY OF THE WIRELESS CHANNEL

Reliability issues in the proposed on-chip wireless communication link may arise due to channel non-uniformity and variations/failure of the nanodevices.

The TDM technique mentioned above is easy to implement with low hardware overhead. However TDM does not adapt well if the channel has a colored frequency response, which is different at different frequencies. To enhance the reliability of the link more sophisticated multi-carrier modulation schemes like orthogonal FDM (OFDM) can be used. OFDM can easily adapt to severe channel conditions without complex equalization. It is robust against narrow-band co-channel interference and intersymbol interference (ISI), and there is no cross-channel interference if cyclic prefixes are used [19]. Though OFDM can be efficiently implemented using Fast Fourier Transform (FFT), it has significantly more overhead.

It is well known that with shrinking geometries, SoCs will be increasingly exposed to different sources of transient noise affecting signal integrity and system reliability. There are multiple sources of transient errors in traditional CMOS-based ICs such as ground bounce, supply voltage scaling, electromagnetic radiation and alpha particle hits. Moreover, the functionality of the proposed wireless interconnect infrastructure depends on the performance of the CNT-based devices. It is an accepted fact that these nano devices will have high manufacturing defect rates, more operational uncertainties and process variability [20]. As explained above diameter and conductivity of the nanotubes significantly influence the absorbed power at the receivers. If the receiver power falls below a certain threshold due to variation in these parameters then correct data can not be received and it will give rise to erroneous transmission. In particular, in a SWNT fabrication process such as chemical vapor deposition, the obtained nanotubes have a diameter distribution in the 0.7 nm – 5 nm range, with a peak around 1.3 nm. This means, according to Fig. 3 that one can expect to see variations from device to device of up to an order of magnitude in terms of the amount of absorbed power at the receiver. A similar situation exists with respect to conductivity. Consequently the wireless interconnect infrastructure needs to be guarded against different sources of possible errors. Instead of building hardware-level redundancy it will be more economical to apply well-established error control coding (ECC) techniques [20]. In the proposed on-chip wireless link, for both TDM and OFDM schemes, one antenna element is responsible for the transmission of multiple bits. Consequently, malfunctioning of one antenna element will affect multiple contiguous bits. As a result the coding scheme should be capable of handling both random and burst errors. Using simple product codes simultaneous random and burst error corrections can be achieved.

VI. COMPARISON WITH A WIRED CHANNEL

Here the power dissipation of the wireless link is compared with the wireline counterpart. Here we vary the length of the communication link and compute the power dissipation for different bit rates. Fig. 8 shows the power dissipation of the wireline and wireless links at the 65 nm technology node. The wireline link consists of a copper wire transmitting data between two nodes. In presence of data transmission the wire dissipates power due to charging and discharging of capacitances. For simplicity we have considered the dynamic power dissipation only and it was obtained through CADENCE simulations. On the other hand the power dissipation in the wireless link comes principally from the transceivers. It is clear that the wireless link dissipates less power. The power dissipation of the wireline link increases with increasing bandwidth, but that of the wireless link remains unchanged.

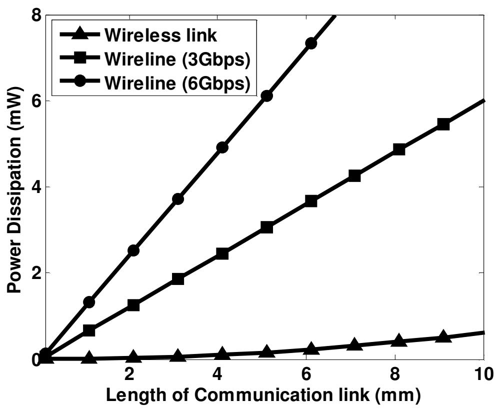

Fig. 8. Power dissipation of wireless and wireline links

As mentioned in section V, by incorporating error control coding, the reliability of the wireless link can be enhanced. This reduces the signal to noise requirements at the receiver. Consequently the power level of the transmitting antennas can be reduced in the presence of coding. Alternatively, keeping the transmitted power unchanged the range of communication between the receiver and transmitter can be increased.

VII. Summary

The optical antenna properties of carbon nanotubes could be used to create a wireless communication infrastructure at the scale of an IC. Given the relative sizes of the microstructures in a typical IC, the wavelengths in question (optical) and the nanotube antennas, this infrastructure can be thought of as a miniaturized version of the more familiar world of radio communications at the scale of a city. Various communication system schemes can be employed, such as having a cellular arrangement, a combination of wireless and wired links, etc. Due to the inherent lack of control in the fabrication technologies of nanodevices, device-to-device variations become very important. In this paper we looked at the effect of nanotube diameter and conductivity on the amount of power transmitted between a pair of nanotube transmitter and receiver. It was observed that variations of more than an order of magnitude can be expected. Accordingly, appropriate communication and error correction schemes need to be used to reduce the sensitivity to these variations.

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