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Minimum Energy Channel Codes For Nanoscale Wireless Communication With Node Density Limits

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Abstract: ***It is essential to develop energy-efficient communication techniques for nanoscale wireless communications. In this paper, the maximum node density is also considered for minimum energy coding scheme (MEC) for wireless nanosensor networks (WNSNs). The node density of MEC is compared with the node densities of other coding schemes. Discovering the maximum nanonode density is important, since it indicates the communication and computation capability of a nanonetwork within a given amount of area. MEC maintains the desired code distance to provide reliability, while minimizing energy. Performance evaluations show that MEC outperforms popular codes such as Hamming, Reed- Solomon and Golay in the average codeword energy sense.***

Keywords: CNT antennas, minimum energy coding, THz channel, nano sensors, node density.

1. Introduction

Wireless nanosensor networks (WNSNs), which are collections of nanosensors with communication capabilities, are believed to have revolutionary effects in our daily lives. The development of novel communication techniques suitable for nanodevice characteristics is essential for WNSNs. One of the most promising building blocks for future nanodevices are carbon nanotubes (CNT). CNTs are rolled up graphene sheets with nano dimensions that can be used as nanoantennas, nano sensing units and nanobatteries . The resonant frequency of CNT antennas lies in the Terahertz band of the spectrum (0.1-10 THz). This band is not utilized by macro applications and is a candidate for communications between nanodevices . The main challenge of using the THz band is the absorption of EM waves by water vapour molecules, which makes communication impractical by causing severe path loss and molecular noise.

Potential nanosensors have significantly different performance metrics than the macro sensors. Although no complete nanonode has yet been implemented, it is anticipated that power and energy efficiency are of the most critical measures due to their extremely small size. Hence, developing novel energy-efficient communication techniques is essential.

Employing channel coding at the nanoscale is critical to assure reliable communication between nanodevices. The classical channel codes have various design considerations such as the efficient use of code space, as in perfect codes, bounded decoding complexity as the Shannon capacity is approached, as in Turbo or LDPC codes, or low encoding and decoding complexity as in cyclic and convolutional codes. However, the coding scheme for nano wireless communications should consider the energy dissipation at the transmitter as the main metric, since nanonodes run on a strict energy budget. Thus, classical codes are not suitable. Unlike most of the classical codes, minimum energy coding minimizes the average codeword energy, if OOK is the underlying modulation . However, the existing minimum energy codes are unreliable.

To address these needs, a novel minimum energy channel code (MEC), that is reliable and suitable for nano communications is used. Proposed code provides the minimum average codeword energy of all the block codes, given that OOK is used as the modulation scheme. With OOK, average codeword energy is the symbol energy times average codeword weight; therefore, average energy is minimized by minimizing the average code weight. For this, codeword weights and sourceword-codeword mappings are chosen such that the expected code weight is minimized at the cost of increased codeword length, hence increased delay. Lengthy codewords could increase the energy dissipation at the transmitter due to energy dissipation of the nanosensor circuitry. This implies a tradeoff between the transmission and processing energies and a discrete optimization problem could arise. However, such an analysis is not feasible today, since it is inaccurate to estimate the energy dissipation at the nano processing units, as no complete nanonode architecture is yet available.

An OOK-based multi-carrier modulation suitable for WNSNs is proposed. Carriers are chosen to exploit the absorption characteristics of the THz channel. To address the low complexity requirement at the nanosensor nodes, low complexity medium access techniques are investigated. Micro nodes act as central controller units of each cell to enable inter-cell communication and intra-cell coordination.

The objective of this project is to consider the node density limits for the minimum energy channel codes so that we can derive the minimum energy channel codes for an area. The maximum nanonode density is found out so that the maximum number of nanonodes that can be placed in an area so as to cause minimum amount of interference can be calculated. The node density limits of different codes are also compared.

2. Literature Survey

In [1], Kocaoglu et al., provides an in-depth view on minimum energy channel codes for nanoscale wireless networks. An OOK-based multi-carrier modulation suitable for WNSNs is proposed in this paper to reduce the time-delay caused by lengthy codes. Carriers are chosen to exploit the absorption characteristics of the THz channel. To address the low complexity requirement at the nanosensor nodes, low complexity medium access techniques are investigated. Performance evaluations are extended to cover energy per information bit comparisons with popular codes. A cell based architecture is considered here. A micronode is surrounded by many nano nodes in this cell-based architecture. Micro nodes act as central controller units of each cell to enable inter-cell communication and intra-cell coordination.

In [5], Source coding and channel coding algorithms minimizing the battery power needed for RF transmission are presented. Digital RF transmitters in portable devices using on/off keying modulation consume energy only when high bits are sent and virtually no energy is consumed when low bits are sent. Therefore, energy consumption can be minimized by devising codes that minimize the occurrence of high bits in transmitting information. In this paper, we first formulate the minimum energy coding problem for RF transmission. We then derive the energy optimal source coding algorithm from the source statistics. Finally, we combine this energy optimal source coding algorithm with Hamming codes for energy efficient error recovery. Overall, we take a first step towards a novel energy saving wireless communication protocol.

3. Wireless Nanosensor Network Architecture

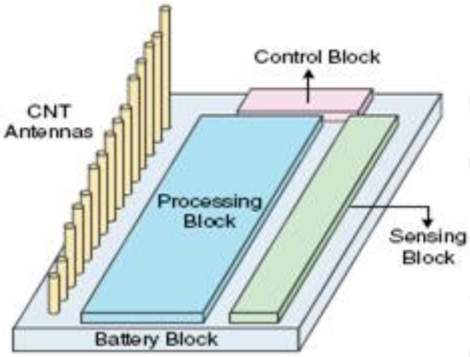

Figure 1: Wireless nanosensor node architecture

Multiple CNT antennas are used to utilize a number of available frequency windows in THz band. Required energy can be provided by the battery via nano energy-harvesting systems. Sensing is also CNT based. Nanosensor readings are quantized to M levels. No source coding is employed so as not to increase complexity. The processing block is also responsible for carrier generation. Control block contains a separate antenna for the control of the nanonode from a central unit. Nanonode activates and transmits only when this antenna is excited. This functionality is required for low complexity multiple access in WNSNs.

Multi-carrier OOK modulation is utilized. Channel codes with minimum average weight are utilized, together with OOK modulation at each carrier to reduce the energy consumption. This coding achieves the minimum codeword energy and guarantees a minimum Hamming distance at the price of lengthy codewords. Multi-carrier modulation mitigates delays due to lengthy codewords of MEC in WNSN node. The number of multi-carrier signals can be chosen to satisfy a certain delay requirement.

Here a cell-based Wireless Nanosensor Network is considered. A cell is composed of a micro node, and nanosensor nodes scattered around it. In order to reduce the interference, nanonodes are deployed within a radius of αR, where R is the cell radius and α is called the coverage ratio satisfying $0 < \alpha \leq 1$. To keep the complexity of the nanonodes low, all the control and scheduling issues are left to the micro node within the cells. A nanonode starts transmission only when an activation signal is sent by the micro node. KHz band can be used for this activation signal, with vibrating CNTs. The central micro node provides not only control, but also synchronization among the nanosensors.

Minimum Energy Channel Codes are equivalent to the codes minimizing average codeword energy for the systems employing OOK modulation. This is because, no energy is dissipated when 0 symbol is transmitted and no ARQ scheme is employed in nano communications for retransmissions.

4. WNSN in an Area

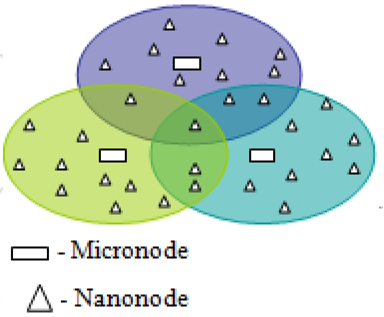

Figure 2: WNSN in an area

The network considered in this work is given in Fig. 2. A source nanonode attempts communication with a nanonode within its range of operation, r. Transmission range is used to obtain the maximum node density in the nanonetwork. Errors are assumed to be due to collisions only, which is justified by keeping symbol error probability below 10^{-9}, by choosing the proper transmission distance for fixed transmission power. A CNT antenna is set to dissipate a power of 5μW, which is currently the largest power level a CNT antenna can support.

In the symbol error probability calculation, only path loss and thermal noise are included as detrimental factors. Molecular absorption and molecular noise is ignored, since the selected modulation scheme uses allowable frequency windows in the THz band, in which molecular effects are negligible. Nanonodes in the interference range are assumed to be distributed within an area of $2\pi(2r)^2$, where r is the maximum distance, at which error probability of OOK modulated symbols does not exceed 10^{-9}. Since the transmission range of a nanonode is r, a destination within range can be compromised by nodes within 2r range. Hence, maximum number of nanonodes supplied by MEC should be distributed within a range of 2r. Choosing the band of operation as 1 THz and bandwidth as 10 GHz, r is easily found to be equal to 10^{-3} meters.

Using complex medium access techniques is not feasible in nanonodes due to the limited complexity. Moreover, popular spread spectrum multiple access techniques such as CDMA cannot be used, since the THz channel shows frequency selective characteristics, which would result in severe distortion of the signal, when passed through the channel. Using low weight channel codes might drop the necessity of a medium access scheme. It is expected that, as more and more nodes communicate with each other within the transmission range of a source node, successful communication probability decreases. For nanonetworks using MEC, the following question is answered: “What is the maximum node density a nanonetwork with MEC can supply without compromising reliability?”. Discovering the maximum nanonode density is important, since it indicates the communication and computation capability of a nanonetwork within a given amount of area. Reliable communication can be achieved in ad-hoc nanonetworks satisfying s<1/p,where p is the transmission probability and s is the number of nanonodes within the interference range of source.

4.1 Maximum Node Density Vs. Reliability

The successful codeword decoding probability at the destination nanonode is analyzed [2]. It is assumed that a nanonode attempts transmission with probability of p. Instead of having nanonodes transmitting continuously, nodes transmitting only when they require, not only reduces interference, but also the energy consumption. ‘s’ is the number of nodes within the interference range of the source nanonode. It is assumed that ‘s’ neighbor nanonodes exist within a distance of 2r, when nanonodes are uniformly distributed with density of

$$\rho = \frac{s+1}{2\pi(2r)^2} \qquad (1)$$

To assure reliability, the correct codeword decoding probability is derived. Probability that the transmitted bit is 1 is

$$\eta_1 = \sum_{i=1}^{M} p(1 \mid c_i)\, p(c_i)$$

$$= \sum_{i=1}^{M} \frac{w_i}{n_{\min}}\, p = \frac{E(w)}{n_{\min}}, \qquad (2)$$

The probability that there is at least single node transmitting bit 1 within the interference range, i.e., p_x is

$$p_x = 1 - \sum_{i=0}^{s} \binom{s}{i} (p\eta_0)^i (1-p)^{(s-i)} \qquad (3)$$

$$= 1 - \left(1 - p(1-\eta_0)\right)^s$$

where $\eta_0 = 1 - \eta_1$, i.e., the transmission probability of bit 0. Collision probability of the nanonode can be calculated as

$$p_c = \eta_1 0 + \eta_0 p_x = \eta_0 - \eta_0\left(1 - p(1-\eta_0)\right)^s \quad (4)$$

Since a maximum of $\left\lfloor \frac{(d-1)}{2} \right\rfloor$ collisions can be corrected, correct decoding probability at the destination, ξ_d, can be written as

$$\xi_{\mathrm{d}} = \sum_{i=0}^{\left\lfloor \frac{d-1}{2} \right\rfloor} \binom{n_{\min}}{i} p_c^i (1-p_c)^{(n_{\min}-i)} \qquad (5)$$

It can be concluded that, ξ_d converges to 1 with increasing Hamming distance, if p < 1/M. In other words, reliable communication can be achieved if collision probability is less than the inverse of source set cardinality.

From [2], we get the condition

$$1 - \left[1 - \frac{p}{M}\right]^s < \frac{1}{M-1}$$

$$p < M\left[1 - \left(\frac{M-2}{M-1}\right)^{\frac{1}{s}}\right] \qquad (6)$$

(6) gives the relation between p, M, and s, i.e. node transmission probability, source set cardinality, and number of neighboring nodes, for which reliable communication is possible with MEC. It is concluded from [2] that p<1/s is the required condition, satisfying (6) for any M. Hence, MEC supplies a nanonetwork having s neighbor nodes, only if nodes transmit with probability less than 1/s. Interpreting the result from the other side leads to the desired bound for maximum node density. Maximum number of nodes within the interference range should be less than 1/p.

5. Simulation Results

An (n, k) code maps $2k$ sourcewords into $length - n$ codewords. For comparison, we use MEC with $M = 2^k$. MEC is compared with the (7,4), (15,11) Hamming, (21,6) binary Reed-Solomon and (23,12) Golay codes. The Hamming codes are distance-3 codes, and can correct 1 bit errors whereas the Golay code is distance-7 and can correct 3 bit errors. The minimum distance of (21,6) binary Reed-Solomon code is known to be 6.

5.1 Node Density Vs. Detection

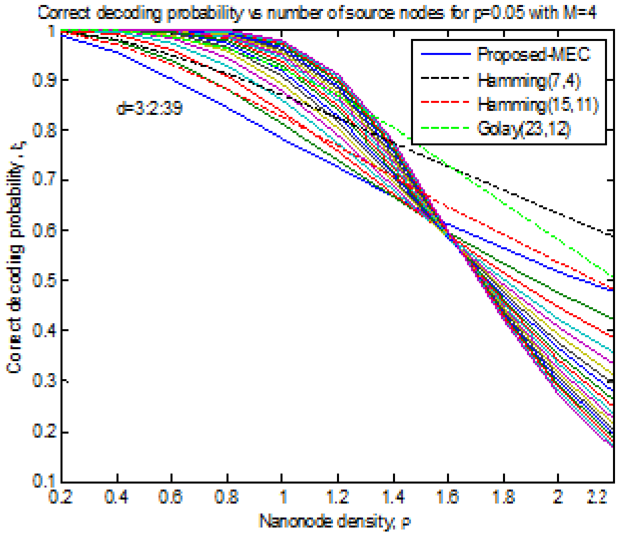

Figure 3: Correct decoding probability vs. number of source nodes for p=0.05 with M=4

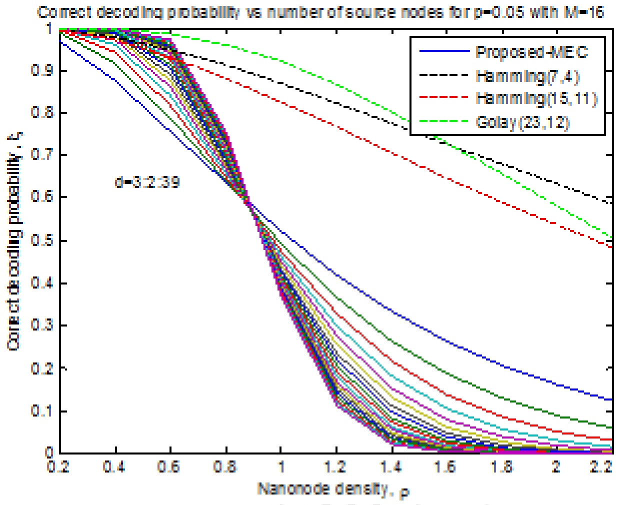

Figure 4: Correct decoding probability vs. number of source nodes for p=0.05 with M=16

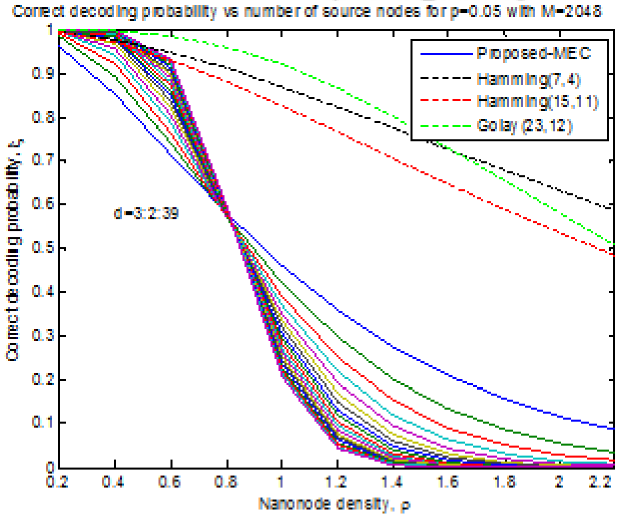

Figure 5: Correct decoding probability vs. number of source nodes for p=0.05 with M=2048

Variation of reliability with respect to node density is shown in the figures. Reliability can be increased by increasing Hamming distance of the channel code if node density is below a threshold, corresponding to 1/p number of neighboring nodes. This shows that, MEC with large delays can compensate the absence of a medium access control scheme up to nanonode density of ρ_{max}.

6. Conclusions

In this project, the maximum nanonode density of WNSN is found out inorder to cause only minimum interference. A multi-carrier OOK modulation is used, motivated with the THz channel characteristics. MEC satisfies a minimum Hamming distance to guarantee reliability. Codewords can be decoded perfectly using MEC with large code distance, if the number of quantization levels is less than the inverse of symbol error probability. MEC is superior to popular block codes such as Hamming, Reed-Solomon and Golay.

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Author Profile

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