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Performance Analysis of Energy Efficient Asymmetric Coding and Modulation Schemes for Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks generally operate under severe energy constraints. In many cases, the networks are star connected with battery-powered nodes sensing data and sending it to a centrally-powered base station, whose energy constraints are more fore-bearing than that of the nodes. In this paper, an approach for energy efficient communication by using different channel codes on the base-station to node link (downlink) and node to base-station link (uplink) is proposed and analysed for such a network topology. This is in effect shifting complexity from the node to the base station while continuing to have the same BER performance. Also the use of more energy efficient modulation schemes are explored.**

I. Introduction

Wireless Sensor Networks (WSNs) have a wide range of applications in wide range of domains like military, health care, agriculture, consumer electronics etc. However the main function of WSNs generally is data collection. In many such systems the network has nodes which collect data and send it to a base station from which it is sent to an external network as shown in Figure 1. In many of WSNs, the network is configured as a star connected network. Usually the nodes are battery powered and thus energy constrained as changing batteries is cumbersome, whereas the base stations are usually centrally powered thus having more mild energy constraints. Also usually the volume of data transmitted by the nodes (and thus received by the base station) is much greater than that transmitted by the base station (and thus received by some node).

A very good overview of WSNs is provided in [1]. A study of performance and energy consumption of error control codes over WSNs has been performed for various RS, Hamming and convolutional codes in [2] using a design space exploration framework for WSNs. In [3] performance of various modulation schemes with various RS codes on an AWGN channel are evaluated. In [4] the viability of a single hop wireless sensor network (WSN) configuration, utilizing the asymmetry between lightweight sensor nodes and a more powerful base station has been demonstrated. Codes like binary-BCH codes, Reed Solomon (RS) and convolutional codes are studied and analyzed in [5]. Based on their study and comparison of these error control codes, they conclude that binary-BCH codes with ASIC implementation are best suited for wireless sensor networks due to less decoding complexity and hence lesser power consumption. Evaluation of three FEC codes, viz. a single error-correcting code, a double-error-correcting code, and a Reed Solomon code is carried out in [6] and it is concluded that using interleaving improves performance in case of burst errors.

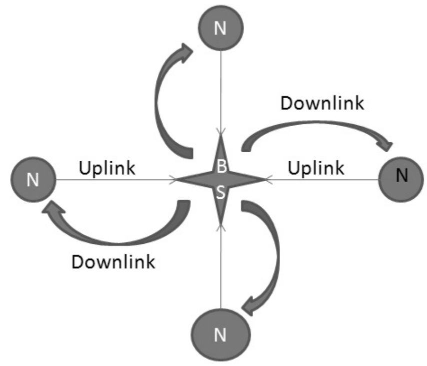

Fig. 1. Assumed Network Topology

The organisation of this paper is as follows: In section II the assumptions of the network are stated. In section III a mathematical analysis of the use of channel codes in WSNs is performed. In section IV the performance of various channel codes with various modulation schemes is presented. In section V the energy consumed by various encoders/decoders are shown and energy consumed by various configurations are presented. In section VI conclusions are elucidated.

II. Network Topology

In the analysis presented, a star connected network (Figure 1) with stringent energy constraints at the nodes but more fore-bearing energy constraints at the base-station is considered. The channel between them is considered to be AWGN in nature. The aim of the work presented is to shift computational effort from the nodes to a base station and also explore more energy efficient modulation schemes such as M-ary FSK (at the cost of larger band-width). The use of channel coding in WSNs decreases the efficiency of communication in the network for small distances. The minimum distance between transmitter and receiver for which the coded and uncoded systems have same energy consumption is called the crossover distance ([7]). In the analysis performed, it is assumed that the operation is at a distance greater than crossover distance and hence the use of channel codes is warranted. An aggressive approach to shift complexity from the nodes to the base-station would be to use no channel code on the downlink while increasing the transmit power at the base station and using a channel code and a powerful soft decoding algorithm on the uplink. However this is eliminated because:

1) increase in transmit power will lead to interference with neighbouring wireless systems.
2) use of computationally expensive decoders will lead to massive power consumption at the base station as it communicates with several nodes, bulk of which is the base station receiving data from the nodes.

Though the base station has more fore-bearing energy constraints, it is assumed that these are stringent enough to prevent it from expending such massive amounts of energy. A moderate strategy would be to use a powerful code with a relatively simple encoder on the uplink and a possibly less powerful code with a simple decoder on the downlink. This essentially brings about an "asymmetric" nature in the WSN. Also on the uplink the use of a more energy efficient modulation scheme would be beneficial.

In most literature the modulation scheme used is usually BPSK. However in a system which is energy constrained, an energy efficient modulation scheme such as M-ary FSK seems to be a viable choice. In this paper, M-ary FSK with M<=32 are considered. Further in this paper, the transmit signal energy and the energy consumed by power amplifier, encoder/decoder have been analysed in terms of energy per information bit.

III. Mathematical Analysis

The total energy per bit consumed by a transmitting node is E_{Radio} when L bits are transmitted is given by equation (1) as in [3]

$$E_{Radio} = \frac{P_{on}T_{on} + P_{tr}T_{tr} + P_{sl}T_{sl}}{L} \tag{1}$$

where P_{on}, P_{tr} and P_{sl} are the power consumed when the node is on, transient and in sleep mode respectively and T_{on}, T_{tr} and T_{sl} are the time for which the node is on, transient and in sleep mode respectively. Assuming that $P_{on}T_{on} \gg P_{tr}T_{tr}$ and $P_{on}T_{on} \gg P_{sl}T_{sl}$ which is reasonable as P_{on} is at least one order of magnitude greater than P_{sl} and $T_{on} \gg T_{tr}$, equation (1) reduces to equation (2) as in [3]

$$E_{Radio} = \frac{P_{on}T_{on}}{L} \tag{2}$$

$$P_{on} = P_{sig} + P_{ckt} + P_{pa} = (1+\alpha)P_{sig} + P_{ckt} \tag{3}$$

where P_{sig} is the transmit power, P_{pa} is the power consumed by power amplifier which is equal to αP_{sig} where $\alpha = \frac{1-\eta}{\eta}$, η being the drain efficiency ratio of the power amplifier, and P_{ckt} is the power consumed by the other circuit elements which include filters, DACs, ADCs etc ([3]).

As shown in [3], equation (2) reduces to

$$E_{Radio} = \frac{((1+\alpha)P_{sig} + P_{ckt})T_{on}}{L} \tag{4}$$

Ignoring noise figure and assuming ideal propagation, the SNR per bit $\left(\frac{E_b}{N_0}\right)_r$ at the receiver when L bits are transmitted in T_{on} seconds is given by

$$\left(\frac{E_b}{N_0}\right)_r = \frac{P_r T_{on}}{L N_0} \tag{5}$$

where N_0 is the noise power spectral density and P_r is the received power which by the Friis Transmission Equation is given by

$$P_r = P_{sig}\left(\frac{\lambda}{4\pi}\right)^2 \frac{G_T G_R}{r^n} \tag{6}$$

where P_{sig} is the transmit power and λ is the wavelength and G_T and G_R are the antenna gains of the transmit and receive antenna, r is the distance between the transmit and receive antennas and n is the path loss exponent whose value is between 2 and 4 [8].

It is assumed that in both the coded and uncoded case K information bits have to be transmitted in T_{on} seconds. For the coded case, using an (N,K) code the energy per information bit used up at the node E_{node_coded} is given by

$$E_{node\_coded} = \frac{(1+\alpha)P_{sig\_coded}T_{on} + P_{ckt}T_{on} + E_{comp}K}{K} \tag{7}$$

Where E_{comp} is the encoder energy per information bit when a (N,K) code is used. However for the coded case the $\left(\frac{E_b}{N_0}\right)_r$=$\left(\frac{E_b}{N_0}\right)_{r\_coded}$ equals

$$\left(\frac{E_b}{N_0}\right)_{r\_coded} = \frac{P_{r\_coded}T_{on}}{N N_0} \tag{8}$$

For the uncoded system, the energy per information bit used up at the node $E_{node\_uncoded}$ is given by

$$E_{node\_uncoded} = \frac{(1+\alpha)P_{sig\_uncoded}T_{on} + P_{ckt}T_{on}}{K} \tag{9}$$

and the $\left(\frac{E_b}{N_0}\right)_r$=$\left(\frac{E_b}{N_0}\right)_{r\_uncoded}$ equals

$$\left(\frac{E_b}{N_0}\right)_{r\_uncoded} = \frac{P_{r\_uncoded}T_{on}}{K N_0} \tag{10}$$

For same BER for coded and uncoded systems, the relation between transmitted energy per bit of the coded and uncoded systems is related as

$$E_{b\_coded} = \frac{E_{b\_uncoded}}{\gamma_C} \tag{11}$$

where γ_C is coding gain obtained by using the code.

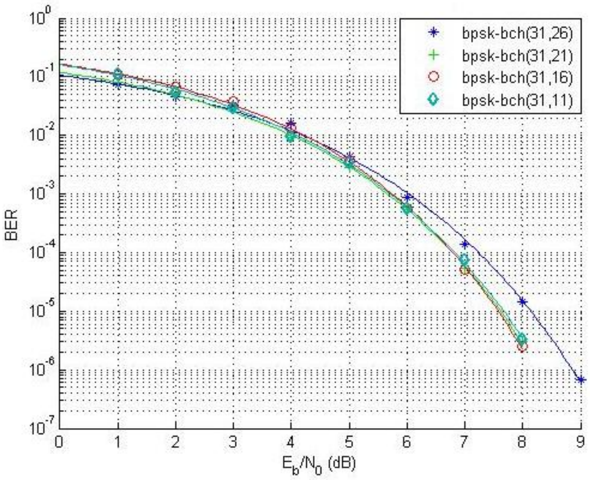

Fig. 2. Performance of BCH(31,k) with BPSK

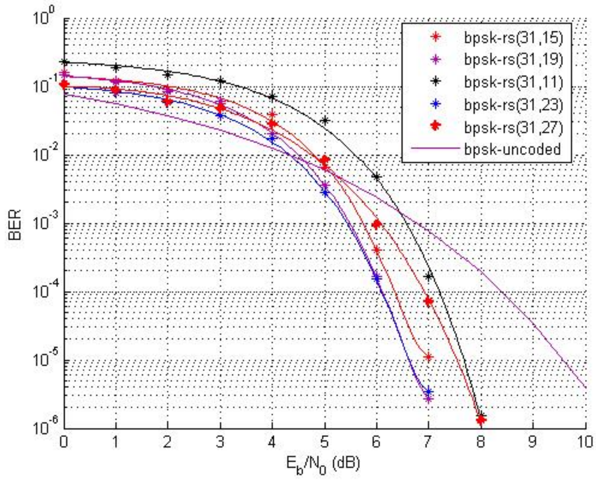

Fig. 3. Performance of various (31,k) RS codes with BPSK

$$P_{sig\_coded} = \frac{P_{sig\_uncoded} N}{K \gamma_C} \tag{12}$$

The energy savings per information bit for a given BER is given by ΔE_s is

$$\Delta E_s = E_{node\_uncoded} - E_{node\_coded} \tag{13}$$

Thus

$$\Delta E_s = \frac{1+\alpha}{K} P_{sig\_uncoded} \left(1 - \frac{N}{K\gamma_C}\right) T_{on} - E_{comp} \tag{14}$$

The cross over distance r_{xover} obtained by equating ΔE_s to 0 and solving for r is given by

$$r_{xover} = \left(\frac{E_{comp} K}{(1+\alpha)\left(1 - \frac{N}{K\gamma_C}\right)\left(\frac{4\pi}{\lambda}\right)^2 \frac{\left(\frac{E_b}{N_0}\right)_{r\_uncoded} N_0 K}{G_T G_R}} \right)^{\frac{1}{n}} \tag{15}$$

where $\left(\frac{E_b}{N_0}\right)_{r\_uncoded}$ is $\left(\frac{E_b}{N_0}\right)$ needed at receive antenna to obtain required BER in uncoded case.

IV. Performance of Channel Codes with Modulation Schemes

Performance of BCH codes with length 31 and various dimensions with BPSK is shown in Figure 2. Here the performance is best when code rate is between 0.6 and 0.7 [8]. BCH(31,16) is observed to perform best among BCH codes simulated.

Performance of RS codes of length 31 and various dimensions with BPSK is presented in Figure 3 and the performance is found to be best when code rate is in the range 0.6 to 0.7 [8]. RS(31,23) is observed to perform the best among RS codes simulated.

In Figure 4, the performance of BCH(31,26) with various modulation schemes is shown. It is observed that the performance of 32-FSK is better than that of BPSK for BERs less than 10^{-4}.

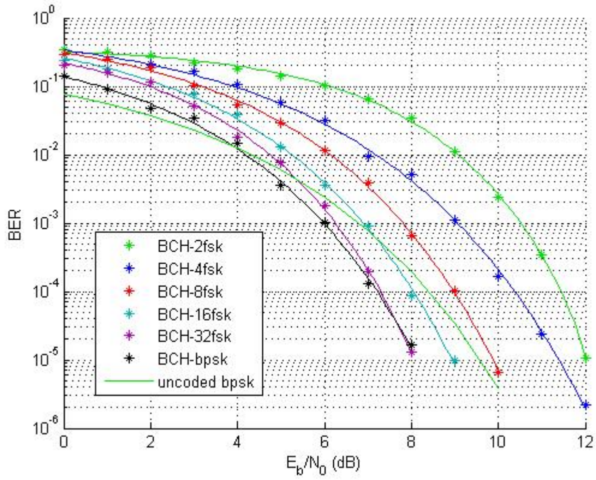

Fig. 4. Performance of BCH(31,26) with MFSK and BPSK

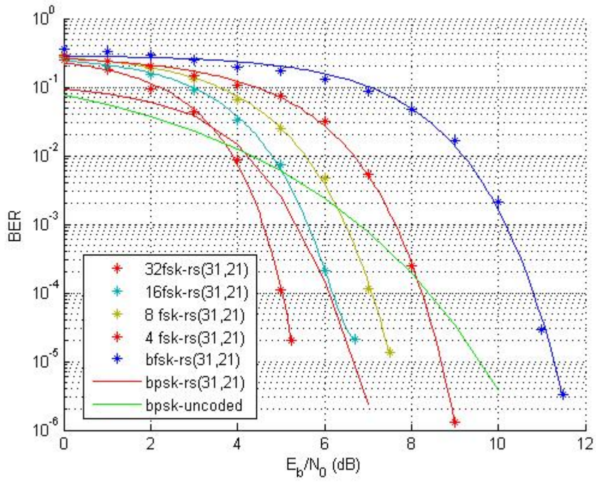

Fig. 5. Performance of various (31,21) RS codes with various modulation schemes

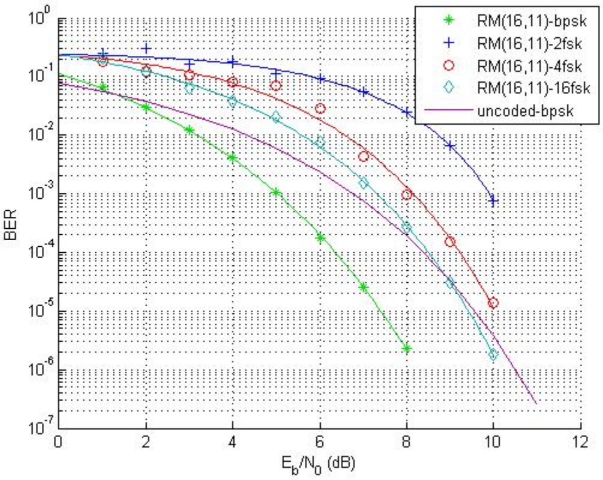

Fig. 6. Performance of $\Re(2,4)$ with MFSK and BPSK

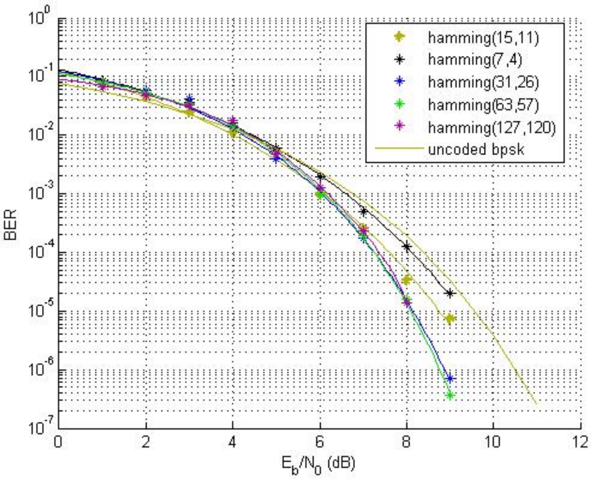

Fig. 7. Performance of Hamming codes with BPSK

In Figure 5, the performance of RS(31,21) with various modulation schemes is presented. It is observed that the performance of 32-FSK is better than that of BPSK for BERs less than 10^{-2}.

The performance of Reed Muller Code $\Re(2,4)$ with Reed Decoding algorithm with M-ary FSK and BPSK is shown in Figure 6. It is seen that BPSK is the best modulation scheme among those considered. In Figure 7, performance of various hamming codes with BPSK is presented.

It is expected that as M increases the performance of codes with M-ary FSK will improve in all cases. However increase in M of M-ary FSK is expected to be accompanied by a sizeable increase in the modulator energy consumption.

V. Energy Performance

The energy consumed by encoder and decoder for different codes is measured using Sim-Panalyzer([9]) by running the corresponding C-codes on StrongArm 1100 processor. The

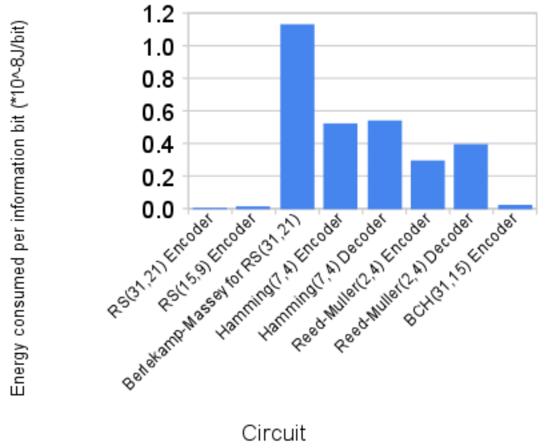

Fig. 8. Energy per Information bit Consumed by various Circuits on SA1100

TABLE I
System Assumptions

Antenna Gains G_T,G_R	1	BER	10^{-5}
Distance r	50m	Noise PSD N_0	4×10^{-21} W/Hz
α	1.9	Frequency f	2.4GHz
Path Loss Exponent n	4	Bandwidth B	1MHz

values obtained were an average for 5 different input vectors.

The encoder and decoder energy per information bit consumptions of various channel codes are shown in Figure 8. Here only energy consumed for implementing the logic is considered. This is justified as energy consumed by processes like leakage will occur irrespective of if the channel code is implemented or not as the processor has to be in ON state when data is received. It is observed that for codes of longer code lengths, generally encoder energy per information bit is marginally lower. As in the analysis presented, the concern is only towards nodes. In a star connected network, none of the bits encoded at a node will be decoded at a node. Hence for a fair comparison between the energy expended per information bit sent at the node for decoding and encoding, a network level parameter μ, the *Node Downlink-Uplink Ratio*, is defined as the number of information bits received per information bit sent at the node, $i.e.$

$$\mu = \frac{Number\ of\ Information\ bits\ Decoded\ at\ the\ Node}{Number\ of\ Information\ bits\ Encoded\ at\ the\ Node} \quad (16)$$

It can be observed that the range of μ is $[0, \infty)$.

The assumptions made in the simulations are tabulated in Table I.

The energy per information bit consumed by the node E_{tot} is estimated by

$$E_{tot} = E_{Sig} + E_{PA} + E_{Enc} + \mu E_{Dec} = (1+\alpha)E_{Sig} + E_{Enc} + \mu E_{Dec} \quad (17)$$

where E_{Enc}, E_{Dec} are energy per information bit consumed by the encoder and decoder respectively, E_{Sig} is the transmit signal energy per information bit for the required SNR per bit $\left(\frac{E_b}{N_0}\right)$ at the receiver, and $E_{PA} = \alpha E_{Sig}$ is the energy

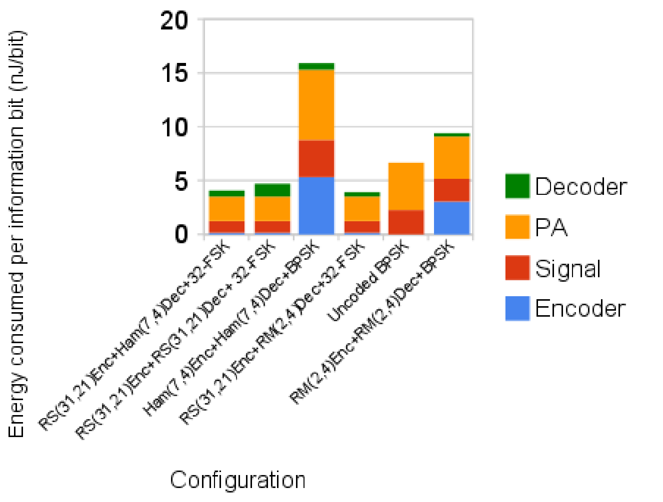

Fig. 9. Energy per Information bit consumed at node for encoder, decoder, modulation configurations with μ=.1

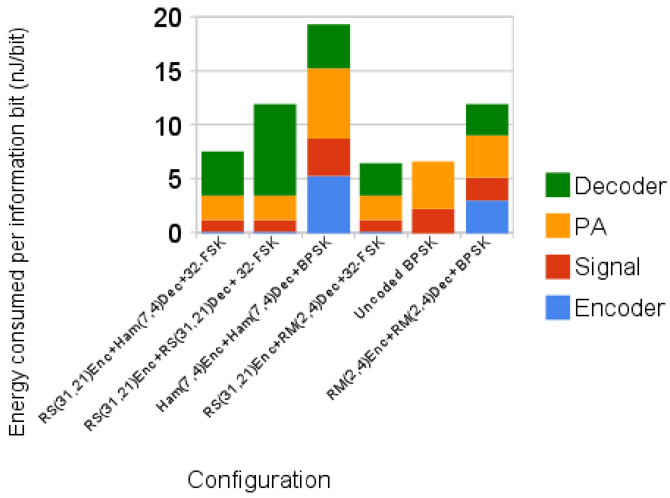

Fig. 10. Energy per Information bit consumed at node for encoder, decoder, modulation configurations with μ=.75

per information bit consumed by the power amplifier.Energy consumed by the modulator and demodulator circuits has been assumed to be negligible.

Assuming ideal propagation for an (N,K) channel code, E_{Sig} is given by

$$E_{sig} = \left(\frac{E_b}{N_0}\right)(N_0)\left(\frac{4\pi}{\lambda}\right)^2 \frac{r^n}{G_T G_R}\frac{N}{K} \quad (18)$$

when a wavelength λ is used to communicate between transmit and receive antennas of gains G_T,G_R respectively placed a distance r apart so that SNR per bit at receiver is $\left(\frac{E_b}{N_0}\right)$, the path loss factor being n which is assumed to be 4 in simulations performed.

The energy per information bit consumed for different coding schemes with various modulation schemes at the node is shown in Figure 9 for μ=0.1. It is observed that, RS(31,21) with 32-FSK on the uplink with $\Re(2,4)$ on downlink is the most efficient among the configurations simulated. In Figure 10, the energy per information bit consumed by different configurations with μ=0.75 is shown. It is observed that for a BER of 10^{-5} the $\left(\frac{E_b}{N_0}\right)$and thus transmit power required for 32 FSK with RS(31,21) is less than that for BPSK with RS(31,21) on the uplink (Fig.5). It must be noted that the energy consumed at the base station has not been taken into account in both cases shown in Figures 9 and 10. Also as the energy consumed by modulator/demodulator circuits are ignored, the modulation used on the downlink is immaterial in the analysis presented.

VI. Conclusions

In this paper, a new scheme of using two different channel codes along the uplink and downlink, such that energy consumption at the node is minimised is proposed and explored. It is observed that with increase in the Node Downlink-Uplink Ratio μ, decoder energy becomes more significant $i.e.$ all other parameters remaining same, increase in μ leads to increase in the crossover distance. It is also seen that the use of M-ary FSK provides an advantage over BPSK only for higher values of M. If for each information bit, the transmit energy is much greater than the encoder/decoder energy, using more powerful channel codes would be advantageous. However in configurations where for each information bit, the transmit energy is small compared to the encoder/decoder energy, uncoded communication or using simpler channel codes would be more efficient. Thus careful consideration of codes used on the uplink and downlink link can minimize the energy per information bit consumed at the node.

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