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Research on Energy Efficiency of Wireless Sensor Networks Based on Network Coding

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Abstract: With butterfly topology, we proposed the wireless sensor networks data transmission model based on network coding, deduced the energy efficiency model with transmission reliability constraints and analyzed NC modes as well as the relationships among the point-to-point transmission energy efficiency and system parameters. The correlative theoretical analysis and simulation indicated that the transmission mode based on NC had higher energy efficiency than the traditional PPT mode.

Key words: Outage probability, energy efficiency, butterfly network, network coding, wireless sensor networks

INTRODUCTION

In Wireless Sensor Networks (WSN), since nodes are unable to get energy supplement, WSN stops working when the energy of nodes runs out. Therefore, how to prolong the lifetime of WSN with energy limitation has become a hotspot in the study of WSN. The lifetime is determined by the energy consumption: the higher the consumption is, the shorter the lifetime is; vice versa. Thus, the above-mentioned problem is equivalent to how to improve energy efficiency. In the long-distance communication, the majority researches focus on how to decrease communication energy consumption, because most of the consumption is at the antenna terminal; while in the short-distance transmission, the consumption mainly comes from the circuit energy consumption of node transceiver modules and antenna consumption. During the long-distance communication, the communication consumption is usually very large, while the circuit consumption of transceiver modules is relatively small; during the short-distance communication, the communication consumption is relatively small because of the short distance, hence the circuit consumption can't be ignored. Therefore, as to WSN, it's necessary to considerate the circuit consumption of transceiver modules.

Ahlswede *et al.* (2000) first proposed the Network Coding (NC), a technology to encode and decode information via intermediate nodes to achieve multicast network capacity. They proved that NC could reach maximum network information flow by utilizing the max flow/min cut theory in graph theory. In the traditional data transmission technologies, intermediate nodes are only responsible for data store-and-forward; while in the network based on NC, besides the function mentioned above, intermediate nodes can forward the information with linear/non-linear processing according to the NC rule. The most visual advantage of doing so is that it reduces the transmission times and energy consumption and that the transmission efficiency increases. As to WSN, which the main consumption is from communication, decrease of transmission times means increase of energy efficiency and lifetime under the condition of the same data quantity. For this reason, the application of NC to WSN can improve energy efficiency and prolong the lifetime of network.

At present, there have been quite a few researches about the application of NC to WSN. Shukui *et al.* (2010) studied the cooperative transmission strategy combined with NC and cooperative communication and analyzed the end-to-end outage probability, but without considering whether the system consumption would increase or not when the transmission reliability increased. By analyzing the proportion of payload information to the packet and its effect on energy efficiency, Sankarasubramaniam *et al.* (2003) developed a method to optimize the packet length of WSN energy and provided the energy efficiency equation combined with transmission reliability, but without considering the consumption problem caused by the application of NC. Based on the energy model of WSN transceiver module, (Hunter *et al.*, 2006) pointed out that the total system energy consumption should include transmission consumption and circuit consumption and provided the energy optimization schemes with different digital modulations, but without considering the effectiveness of node output energy and the reliability of transmission. Woldegebreal and Karl (2010) integrated the analytical method of Sankarasubramamiam *et al.* (2003)

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and Hunter *et al*. (2006) and provided the cooperative NC energy consumption model in WSN. This model took the energy consumption of cooperative nodes and the receiving reliability of destination nodes into account, however, the employed topological structure apparently restricted the application of NC to WSN, since this model laid particular stress on the study of cooperative network.

SYSTEM MODEL

Data transmission model: In the traditional transmission modes, nodes generally employ the Point-to-point Transmission (PPT) mode. As shown in Fig. 1a, when intermediate nodes receive the data derived from source node S1 and S2, data will be transmitted to destination node D1 and D2 in the given route according to the First in First out (FIFO) method. Figure 1b is the butterfly network based on NC. The intermediate nodes calculate the XOR of the received data X_{s1} and X_{s2} and the data will be transmitted to destination node D1 and D2 via intermediate node set $K = \{k_1...k_i...k_n | 0<i\leq n\}$ by means of multicast. The destination nodes can obtain the original data through additional information monitoring. For example, D2 can be acquired by calculating XOR of data X_{s1} gained from extra monitoring and data from node K_n, i.e., $X_{s1}\oplus (X_{s1} \oplus X_{s2}) = X_{s2}$. During this process, X_{s1} and X_{s2} are network coded at intermediate node K_1, then the information is transmitted to Kn via multi-hop relay and then information $(X_{s1}\oplus X_{s2})$ is multicast to destination node D1 and D2 via K_n. Since the nodes utilize the half-duplex communication mode, a node can't be both a destination node itself and an intermediate node for other route, thus the route that avoids from destination nodes is selected within this topology. The route of NC mode nodes employs promiscuous mode, i.e., nodes can both monitor and receive the data which is not from the address of next hop. The security issues under this mode have been studied world widely (Zhixue and Yeung, 2009; Wei *et al*., 2010; Yeung, 2008; Zhengjian *et al*., 2008; Ning and Chan, 2011) which is not within the scope of this study.

As shown in Fig. 1a and 1b, intermediate node K_i of PPT mode needs to forward the packet twice, which that of NC mode only needs once. In PPT mode, source node S1 and S2 respectively sending a packet to the destination nodes needs to transmit 2(n+1) times; while in NC mode, that only needs n+2 times. The increase of the overhead of destination node D1 and D2 mainly lies in the receiving and coding of the additional information needed in NC, as shown in Table 1. When n is large enough, the transmission times in NC mode are half of those in PPT mode.

Transceiver module model: Figure 2 is a system diagram of a typical WSN transceiver module (Woldegebreal and

Table 1: Comparison between the two transmission modes PPT and NC

Times	NC	PPT
Transmission	n+2	2(n+1)
Receiving	n+5	2(n+1)
Coding	n+2	2(n+1)
Decoding	n+5	2(n+1)
Idle time	1	2
Start-ups	n+4	n+4

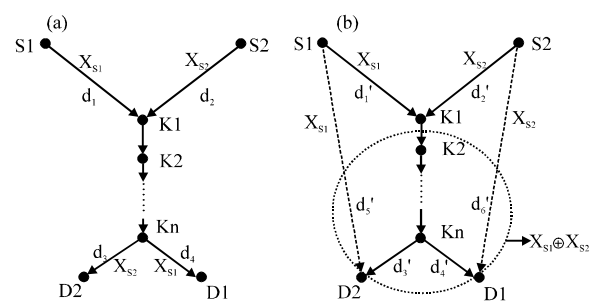

Fig. 1(a-b): Two different transmission modes of WSN (a) PPT and (b) NC

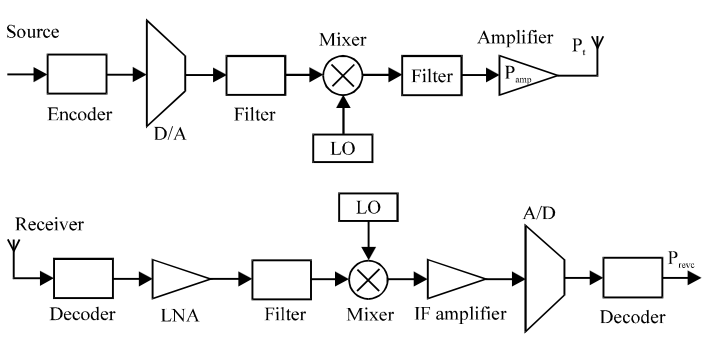

Fig. 2: WSN transceiver module

Karl, 2010; Shuguang *et al*., 2004, 2005). The transmission module consisted of a coder, D/A convertor, filter, local oscillator, mixer, power amplifier and antenna; the receiving module included an antenna, filter, low-noise amplifier, mixer, local oscillator, Intermediate-frequency (IF) amplifier, A/D convertor and decoder. At the transmitting terminal, the D/A converted original signal was processed in a series of analog signal processing (filtering, mixing and amplification), then the analog signal of transmitting antenna terminal was ready for transmission over the wireless channel. The process at the receiving terminal was the inverse process of transmitting terminal. For the convenience of the ensuing analysis and calculation, we define P_{tc} as the power of transmission circuit, P_t the power of transmission, P_{amp} the power of power amplifier, P_{revc} the power of receiving circuit, P_{rev} the average power of receiving.

Energy model: The total energy consumption of WSN transmission module is comprised of P_{amp} and P_t. The relationship between P_t and P_{amp} is as below Shuguang *et al*. (2004):

$$P_{amp} = \frac{\zeta}{\eta} P_t \tag{1}$$

where, ζ is the mean power ratio determined by modulation mode, η is the drain efficiency Lee (1998).

Through the wireless link budget analysis, we could obtain the path loss model of the additive Gaussian white noise channel which is in slow fading and Rayleigh distribution (Hunter *et al*., 2006):

$$P_t = \frac{\xi}{d^{\alpha}} P_{rev} \tag{2}$$

d is the distance between the transmission node and the receiving node, $2 \le \alpha < 5$ is the channel attenuation coefficient, ξ is:

$$\xi = G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{N_f}\right) E\{|h|^2\} \tag{3}$$

G_r and G_t are the receiving antenna gain and transmission antenna gain, respectively, λ is the wavelength of the carrier wave, N_f is the receiver noise figure, $E\{|h|^2\}$ is the mean fading coefficient Hunter *et al*. (2006). From Eq. 1 and 2, we can acquire :

$$P_{amp} = N_0 W \left(\frac{\zeta}{\xi\eta}\right) \cdot \Gamma_{SNR} \cdot d^{\alpha} \tag{4}$$

$N_0 = k_B T_0$ is noise power spectrum density, k_8 is Boltzmann's constant (1.38×10-23 J/K), T_0 is in Kelvin temperature, W is the signal bandwidth, Γ_{SNR} is the mean receiving Signal Noise Ratio (SNR). Equation 4 provides the relationship among power amplifier consumption, mean receiving SNR and distance between receiving node and transmission node.

ENERGY EFFICIENCY

Whether the energy is efficiently utilized or not should be evaluated from the following two aspects:

- During one transmission, the ratio of the energy that is needed when sending the payload bit to the total energy
- Outage probability. Assume that a packet was successfully sent out and that the receiving terminal didn't successfully receive it, thus although the transmission terminal consumed energy, yet the payload information was failed to successfully transmitted. The more this case happened, the lower the energy efficiency was. Therefore when considering sending out a packet at the transmission terminal, we should also give consideration to the reliability, i.e., the discussion will be meaningless unless outage probability is considered

This study utilizes energy efficiency to evaluate and analyze the consumption of PPT and NC. The energy efficiency is defined as below:

$$\eta_e = \frac{E_{payload}}{E_{total}} \left(1 - P_{outage}\right) \tag{5}$$

$E_{payload}$ is the consumption of payload, E_{total} the total consumption, P_{outage} the outage probability. Define outage event as $\{C(\gamma)<R\}$, i.e., if the normalized channel capacity $C(\gamma)$ (bit/s/Hz) can't reach the given bandwidth efficiency R, then an outage event occurs (Hunter *et al*., 2006). $C(\gamma)$ is a transformation of Shannon equation, i.e.:

$$C(\gamma) = \frac{C}{W} = \log_2(1+\gamma) \text{ (bits/s/Hz)} \tag{6}$$

C is channel capacity, γ is real-time SNR.

Outage probability is:

$$P_{outage} = P_r\{\gamma < 2^R - 1\} = \int_0^{2^R-1} p_\gamma(\gamma) d\gamma \tag{7}$$

$p_\gamma(\gamma)$ is the probability density function of γ. As to Rayleigh fading channel, γ has the exponential distribution character with the parameter of $1/\Gamma_{SNR}$, where

Γ_{SNR} is the expectation of , γ i.e., the SNR after fading, which is affected by the transmission power, large-scale path loss and shadow effect, etc. Hunter *et al.* (2006) Therefore, we can acquire:

$$P_{outage} = 1 - \exp\left(\frac{1-2^R}{\Gamma_{SNR}}\right) \tag{8}$$

When Γ_{SNR} is large enough, the above equation can be transformed into Woldegebreal and Karl (2008):

$$P_{outage} \approx \frac{2^R - 1}{\Gamma_{SNR}} \tag{9}$$

Equation 9 provides the relationship among outage probability, mean SNR and band efficiency. As shown in Eq. 9, the decrease of band efficiency or the increase of transmission power will lead to outage probability decrease.

Energy analysis of two transmission modes: The energy efficiency calculation in this study is based on the packet structure model given in literature Sankarasubramaniam *et al.* (2003), as shown in Fig. 3.

A packet consists of head information φ, payload information l and redundant information τ. As to NC mode, the additional NC controlling information in φ is relatively small compared with the total packet bit, thus it is ignored here. Payload information l contains payload information as well as cyclic redundancy check (CRC) bit. Redundant information τ is the error control to packet head and payload.

According to Table 1, we obtain the consumed energy of transmitting 1 bit information in PPT mode:

$$\begin{aligned} E_p &= \frac{n+1}{2l}\left(P_{tc} + P_{amp} + P_{revc}\right)T_p \\ &+ \frac{1}{4l}\left[2P_{id}T_{id} + (n+4)P_{st}T_{st} + 2(n+1)E_{enc} + 2(n+1)E_{dec}\right] \end{aligned} \tag{10}$$

$T_p = (\varphi + l + \tau)/R$ is the time of transmitting a packet, R_s is the symbol rate; $P_{id}T_{id}$ is the consumption when nodes are in idle state; $P_{st}T_{st}$ is the consumption when nodes are in start-up state; E_{enc} and E_{dec} are, respectively the consumed energy of one coding and one decoding, which is determined by the coding type and the coding algorithm. According to Eq. 5, we can calculate the energy efficiency η_p in PPT mode:

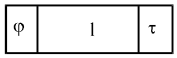

Fig. 3: Packet format

$$\eta_p = \frac{P_{tc} + P_{amp} + P_{revc}}{R_s E_p}\left(1 - P_{sys}^T\right) \tag{11}$$

P^n_{sys} is the PPT system outage probability, $(1-P^T_{sys})$ is the probability that both the destination node D1 and D2 can correctly receive the information. Equation 11 provides the PPT system energy efficiency, therefore we also can obtain the consumed energy of transmitting 1 bit information in NC mode:

$$\begin{aligned} E_n &= \frac{1}{4l}\left[(n+2)P_{tc} + (n+2)P_{amp} + (n+5)P_{revc}\right]T_p \\ &+ \frac{1}{4l}\left[P_{id}T_{id} + (n+4)P_{st}T_{st} + (n+2)E_{enc} + (n+5)E_{dec}\right] \end{aligned} \tag{12}$$

Similarly, the energy efficiency in NC mode is:

$$\eta_n = \frac{P_{tc} + P_{amp} + P_{revc}}{R_s E_n}\left(1 - P_{sys}^N\right) \tag{13}$$

P^n_{sys} is the NC system-level outage probability. Equation 11 and 13 provide the system energy efficiency in two transmission modes. The lengthening of the error correction redundant code would cause the decrease the bit power consumed on the payload information, which would lead to the decrease of energy efficiency. On the other hand, the increase of the error correction performance would result in the improvement of transmission reliability and reduction of outage probability, which would lead to the increase of energy efficiency. When the packet scale was set, the reasonable optimization of payload scale and coding efficiency could increase the reliability and decrease the energy consumption.

System-Level outage probability

PPT outage probability analysis: PPT outage event is described as: the destination node fails to correctly receive the information from the source node. In Fig. 1a, the following equation is a description of the outage event that the receiving node D1 fails to correctly receive the information:

$$\overline{X_s} = \overline{X_{s1} \cap X_{s2} \cap \left[\bigcap_{i=1}^{n}\left(X_{k_i}\right)\right]^2} \tag{14}$$

$\overline{X_{s1}}$, $\overline{X_{s1}}$, $\overline{X_{k_i}}$ and $\overline{X_{k_i}}$ are, respectively the event that the next hope node of the corresponding node fails to correctly receive the information. $\bigcap_{i=1}^{n}(X_{k_i})$ expresses intersection, $\bigcup_{i=1}^{n}(\overline{X_{k_i}})$ expresses union. Assume that each outage event is independent, i.e., no problems such as hidden or exposed terminals among nodes and let

$P_b(\overline{x}) = 1-P(\overline{x})$, where $P(\overline{x})$ is the probability that event x occurs. Then, the system-level outage probability in PPT is:

$$P_{sys}^{T} = 1 - P_b\left(\overline{X_{s1}}\right)P_b\left(\overline{X_{s2}}\right)\left\{\prod_{i=1}^{n}\left[P_b\left(\overline{X_{k_i}}\right)\right]\right\}^2 \quad (15)$$

Let $P_{sr}(x) = 1 - \frac{2^R - 1}{P'_{amp}} L_{total} \cdot x$

where, $L_{total} = N_0 W\zeta/(\xi\eta)$, P'_{amp} is the power of power amplifier. If nodes utilize the power control technology, then the power of power amplifier is related to the distance between nodes. For the convenience of calculation, we assume the transmission power of each node equals. Combine Eq. 4 and 9, we can obtain:

$$\begin{cases} P_{sys}^{T} = 1 - \prod_{i=1}^{4} P_{sr}\left(d_i^{\alpha}\right)\prod_{i=1}^{n-1} P_{sr}\left(d_{k_i,k_{i+1}}^{\alpha}\right)^2 & n > 1 \\ P_{sys}^{T} = 1 - \prod_{i=1}^{4} P_{sr}\left(d_i^{\alpha}\right) & n = 1 \end{cases} \quad (16)$$

where, d_i is the distance of given nodes in Fig. 1, $d_{x,y}$ is the distance between node x and node y.

Let signal transmission rate be R_b, information rate R_n and code efficiency R_c. Their relationship is:

$$R_n \approx R_b.R_c \quad (17)$$

In fact, information rate R_n was slightly less than $R_b.R_c$, which was because of the transmission of ACK and packet overhead information. For instance, if the transmission system employed TTCM (Turbo Trellis Coded Modulation) with R_c of 2/3 and modulation mode of 8PSK, when the transmission rate was 444.6 kbit sec^{-1}, then information rate was 293.8 kbit sec^{-1}. From this example, we can see that the information rate was only less than $R_b.R_c$ by 2.6 kbit sec^{-1} (Hanzo *et al*., 2007).

Bandwidth efficiency R is the information rate that per 1 Hz can transmit. When the modulation mode is multiphase, the relationship among bandwidth, coding efficiency and modulation mode can be obtained from Eq. 17 as below:

$$R = R_c \log_2 M \quad (18)$$

where M is the code length determined by the modulation mode.

NC outage probability analysis: Additional information was needed for nodes to determine whether there's a possibility to code. In the topological model used in this study, destination node D1 and D1 needed to monitor the packets from source node S2 and S1 to implement NC. If a certain packet was failed to be monitored, the destination node couldn't compute the original data from the packet of intermediate node K_n, then an outage event occurred. The analysis method was similar as described in above section, NC system outage probability is:

$$\begin{cases} P_{sys}^{N} = 1 - \prod_{i=1}^{6} P_{sr}\left(d_i^{\alpha}\right)\prod_{i=1}^{n-1} P_{sr}\left(d_{k_i,k_{i+1}}^{\alpha}\right) & n > 1 \\ P_{sys}^{N} = 1 - \prod_{i=1}^{6} P_{sr}\left(d_i^{\alpha}\right) & n = 1 \end{cases} \quad (19)$$

SIMULATION AND RESULT ANALYSIS

This study employed MATLAB to analyze the energy efficiency of NC and PPT models. The simulative topological structure is shown in Fig. 1. To ensure the simulation fairness of the two models and reduce the complexity of simulation, we assume each distance *d* between nodes is equal and that the receiving and transmission antennas are omnidirectional. The related simulation parameters are presented in Table 2. We selected 2.5 GHz of ISM band as the system transmission frequency and utilized the low power consumption CMOS-RF module which was suitable for WSN as the transceiver module. Related parameters were referred to literature (Shuguang *et al*., 2004). In the absence of special instruction, the simulation employed BPSK modulation and the number of intermediate nodes n = 10.

During simulation, source node S1 and S2 respectively sent out a packet to the corresponding destination node D1 and D2. PPT utilized the traditional store-and-forward mode; while NC processed NC at intermediate node K1 and decoded at the destination node. Figure 4 presents the effect of the number of intermediate nodes on the system energy efficiency. When the number of intermediate nodes is below 3, because of the outage probability caused by NC monitoring route S1-D2 and S2-D1, as well as the additional monitoring consumption, the system energy efficiency is lower than that of PPT. But when the number is above 3, the decrease of transmission times leads to less transmission consumption in NC than that in PPT, therefore the system outage probability is improved with

Table 2: Simulation parameters

$f_c = 2.5$ GHz	$\eta = 0.35$
$\sigma^2 = N_0/2 = -174$ dBm	W = 250 kHz
$R_c = 0.8$	$G_tG_r = 1$
$\alpha = 4$	$\varepsilon = 1$
$T_{st} = 466$ μsec	$P_{st} = 60$ mW
$P_{revc} = 11.13$ mW	$P_{tr} = 5.75$ mW
$P_{idl} = 100$ mW	d = 50 m

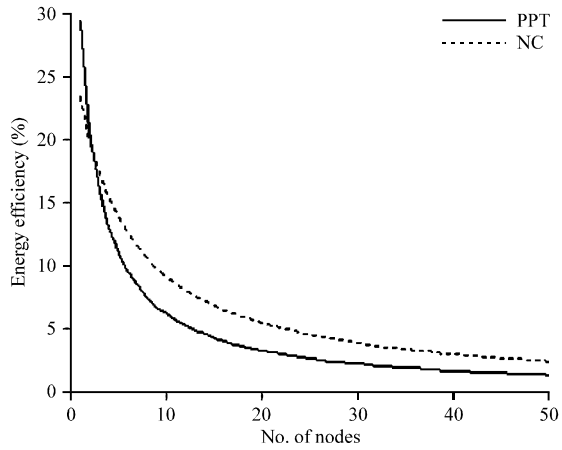

Fig. 4: Relationship between the number of intermediate nodes and energy efficiency

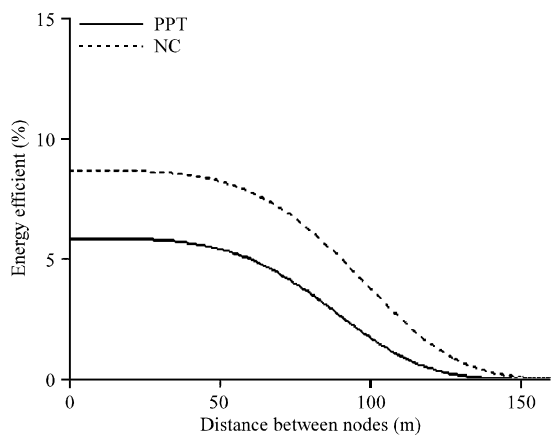

Fig. 5: Relationship between node distance and energy efficiency

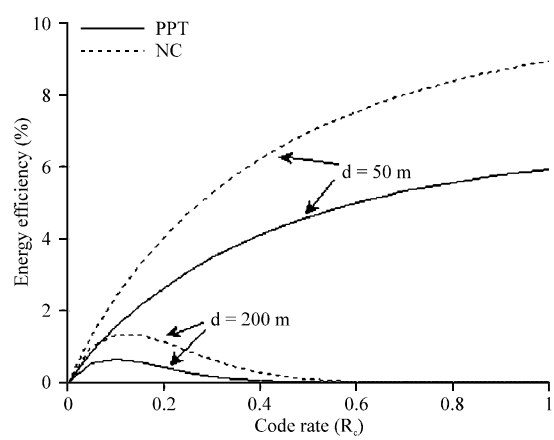

Fig. 6: Relationship between coding efficiency and energy efficiency

better reliability. As the number of intermediate nodes increases, the system outage probability increases, which results in the decrease of energy efficiency. Assume the energy efficiency of 5% as the energy effective threshold, the maximum number of intermediate nodes that PPT can support is 12, while that of NC reaches 21.

The distance between nodes had direct influence on the system outage probability. The increase of the node distance would cause the increase of path loss and system outage probability, thus the energy efficiency went down. Figure 5 shows the relationship between the node distance and energy efficiency. Figure 5 indicates: when the number of intermediate nodes is 10, the maximum energy efficiency of NC and PPT is respectively 9 and 6%; when d<50 m, since the receiving SNR is relatively high, the outage probability is quite low and the energy output maintains at a relatively stable value; as the distances lengthens, the path loss grows, the receiving SNR gradually declines, which will cause the rise of outage probability and the reduction of system energy efficiency; when d = 140 m, the energy efficiency approaches 0.

As to a communication system, coding efficiency was a significant parameter to balance system reliability and effectiveness. When the coding efficiency was high, if the channel condition and transmission frequency were set, the transmission rate was relatively high, but the error rate was also relatively high; on the contrary, when the coding efficiency was low, the error rate was generally low, but the transmission rate was relatively low because of the relatively long error correction redundancy. In order to give a better expression of the relationship between coding efficiency and energy efficiency, Fig. 6 provides the data when the node distances are respectively 50 m and 200 m. As shown in Fig. 6, when the distance is 200 m, the energy efficiency grows as R_c increases, which is because the payload information ratio to the whole packet increases and the energy consumed on the payload information also increases. However, the system error rate also grow as R_c increases and the energy efficiency approaches 0. When the distance is 50 m, Γ_{SNR} is relatively high, which can satisfy the reliable transmission when the coding efficiency is 1, therefore the energy grows as the coding efficiency increases.

Figure 7 illustrates the effect of modulation orders on energy efficiency. Take Phase Shift Keying (PSK) modulation mode for example, we compared the energy efficiency among BPSK, QPSK, 8PSK and 16PSK. From BPSK to QPSK, the energy efficiency corresponding to NC and PPT rose respectively by 60.86 and 58.32%; while from QPSK to 16PSK, only 42.74 and 39.72%, respectively. Although as the modulation order increased, the band

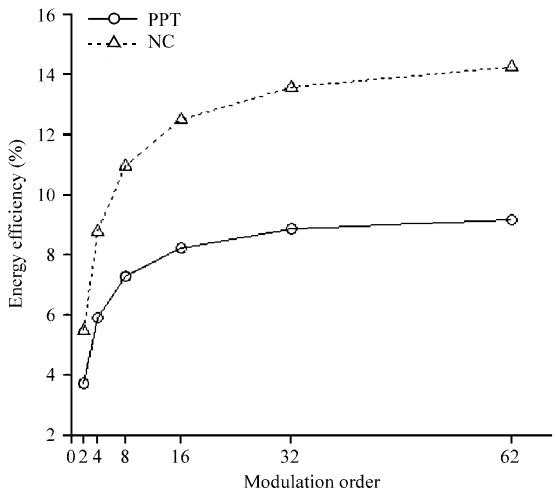

Fig. 7: Relationship between modulation orders and energy efficiency

efficiency increased too, yet it also resulted in the increase of outage probability. Therefore, adjusting the modulation order was an effective strategy to balance energy efficiency and outage probability. Figure 7 indicates that the energy efficiency of NC is superior to that of PPT. Take QPSK for example, the energy efficiency of NC was higher than that of PPT by 49%.

CONCLUSIONS

The application of NC could effectively diminish the transmission times. This theory changes the way of information transmission, which has a huge impact on the existing transmission mode. As to WSN which puts emphasis on energy saving, the characteristics of NC determine the prospect of WSN application. In this study, we developed a WSN energy efficiency analysis model based on NC. Besides pursuing higher energy efficiency, we also considered the effect of outage probability on it, analyzed the node energy consumption and system outage probability based on butterfly network, obtained the energy efficiency equation of WSN applying NC and studied the relationships among network parameters (number of intermediate nodes and distance between nodes), system parameters (coding efficiency and modulation orders) and energy efficiency. Theoretical derivation and simulation results indicate: compared with the traditional transmission mode, NC mode effectively decreases transmission times and outage probability, increases the transmission reliability and improves the energy efficiency of nodes.

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REFERENCES

Ahlswede, R., N. Cai, S.Y.R. Li and R.W. Yeung, 2000. Network information flow. IEEE Trans. Inf. Theory, 46: 1204-1216.

Hanzo, L., P.J. Cherriman and J. Streit, 2007. Video Compression and Communications: From Basics to H.261, H.263, H.264, MPEG4 for DVB and HSDPA-Style Adaptive Turbo-Transceivers. 2nd Edn., Wiley-IEEE Press, USA., ISBN: 978-0470518496, Pages: 702.

Hunter, T.E., S. Sanayei and A. Nosratinia, 2006. Outage analysis of coded cooperation. IEEE Transact. Inf. Theory, 52: 375-391.

Lee, T.H., 1998. The Design of CMOS Radio-Frequency Integrated Circuits. Cambridge Univ. Press, Cambridge, UK.

Ning, C. and T. Chan, 2011. Theory of secure network coding. Int. J. Comp. Inf. Sci., 14: 421-437.

Sankarasubramaniam, Y., I.F. Akyildiz and S.W. Mclaughlin, 2003. Energy efficiency based packet size optimization in wireless sensor networks. Proceedings of the 1st IEEE International Workshop on Sensor Network Protocols and Applications, April 2003, Anchorage, Alaska, USA., pp: 102-112.

Shuguang, C., A.J. Goldsmith and A. Bahai, 2004. Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks. J. Selected Areas Commun., 22: 1089-1098.

Shuguang, C., A.J. Goldsmith and A. Bahai, 2005. Energy-constrained modulation optimization. Trans. Wireless Commun., 4: 2349-2360.

Shukui, Z., F. Jianxi and C. Zhiming, 2010. Reliable cooperative data transmission mechanism for wireless sensor networks. J. Commun., 31: 30-40.

Wei, C., Y. Li and X. Fei, 2010. Trusted network coding in wireless Ad hoc networks. Proceedings of the Global Telecommunications Conference, December 6-10, 2010, Miami, Florida, USA., pp: 1-5.

Woldegebreal, D. and H. Karl, 2008. Network-Coding-based cooperative transmission in wireless sensor networks: Diversity-multiplexing tradeoff and coverage area extension. Proceedings of the 5th European Conference on Wireless Sensor Networks, January 30, 2008, Bologna, Italy, pp: 513-520.

Woldegebreal, D.H. and H. Karl, 2010. Energy efficiency model of network-coded cooperation in wireless sensor networks. Proceedings of the 4th International Conference on Sensor Technologies and Applications, July, 2010, Venice, Italy, pp: 513-520.

Yeung, R.W., 2008. Network coding for information security. Proceedings of the 3rd International Conference on Communications and Networking in China, August 2008, Hangzhou, China, pp: 382-386.

Zhengjian, Z., T. Qingping and Z. Peidong, 2008. Security broadcast based on linear network coding in WSN. Proceedings of the International Conference on Computer Science and Software Engineering, December 12-14, 2008, Wuhan, China, pp: 919-922.

Zhixue, Z. and R.W. Yeung, 2009. A general security condition for multi-source linear network coding. Proceedings of the International Symposium on Information Theory, January, 2009, Cairo, Egypt, pp: 1155-1158.