Journal of Southeast University (English Edition) Vol. 27, No. 1, pp. 1 – 7 Mar. 2011 ISSN 1003—7985

Cooperative algorithm for improving network connectivity in clustered wireless sensor networks

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Abstract: In order to improve network connectivity in clustered wireless sensor networks, a node cooperative algorithm based on virtual antenna arrays is proposed. All the nodes in the network are assumed to be clustered via Poisson Voronoi tessellation (PVT). The activation of the node cooperative algorithm is determined by the cluster heads (CHs) according to communication links. When the cooperative algorithm is activated, the CH selects cooperative nodes (CNs) from its members to form a virtual antenna array. With the cooperation, nodes can extend the inter-cluster communication range to directly contact with further nodes after a coverage hole is detected, or compensate for channel gains while inter-cluster transmission fails due to deep channel fading. Simulation results show that the proposed algorithm achieves better network connectivity and energy efficiency. It can reduce outage probability, sustain network connectivity and maintain operations as long as possible, which prolongs network operation time.

Key words: wireless sensor network; coverage; cooperative communication; operation time

doi: 10.3969/j. issn. 1003 – 7985. 2011. 01. 001

Wireless sensor networks (WSNs) typically consist of a large number of sensor nodes deployed over wide areas[1]. These sensor nodes can sense, measure, and gather information from the environment and, based on some local decision process, they can transmit the sensed data to the base station (BS). Nodes in the network normally have limited transmission ranges due to finite energy. Most of them cannot directly communicate with the BS. Multi-hop delivery is thus necessary for communication among nodes outside the transmission range. However, the connectivity between the BS and the source nodes may be corrupted due to various reasons[2], which prevents the remote data forwarding to the BS hop by hop. After the sensor network operates for a period of time, some nodes run out of their power. The nodes around the base station or on the route from a hot spot to the base station may drain their battery power very soon, since the probability of participating in the data transmission process is higher for them than that for other nodes. Thus the remote nodes may fail to send the data packets to the BS if the data packets need to be relayed by powerless nodes. In addition, the communication may be deteriorated when the signal-to-noise ratio (SNR) of the received signal falls below a certain threshold. It makes the destination node fail to decode data packets. In such scenarios, the ideas of extending node communication coverage and compensating for channel gains are attractive for improving network connectivity.

In general, clustering hierarchy is popular for WSN since it can efficiently decrease the number of transmitted messages to the BS by performing data aggregation or fusion which contributes to power conservation greatly. This paper develops a node cooperative algorithm in clustered sensor networks to guarantee the network connectivity and thereby maximize the network operation time. As the topological structure of clustering, multiple-input-multiple-out (MIMO) systems are considered to be extended to individual single-antenna nodes that cooperate to form virtual transmitting/receiving antenna arrays. With cooperation, nodes can share and coordinate their resources to enlarge their coverage ranges or enhance the detection performance, which is similarly achieved in MIMO wireless systems[3]. Simulation results show that the proposed node cooperative algorithm can reduce the outage probability and achieve higher coverage and connectivity.

1 System Model

Consider a wireless sensor network composed of multiple clusters of nodes, as shown in Fig. 1. All the nodes in the network are powered by batteries. Each node is equipped with a single isotropic antenna. The nodes in the network are randomly distributed according to a planar Poisson point process of spatial intensity ρ. Assume that for a particular realization of the process there are m nodes in the network and a node becomes a cluster head (CH) with probability p_{H}. Therefore, mp_{H} nodes become CHs on average. Supposing that clustering is performed via a Poisson Voronoi tessellation (PVT)[4], MIMO systems can be easily extended to individual single-antenna nodes. Any node that is not a CH joins the cluster of the closest CH. After the network is clustered, each CH is responsible for fusing the data collected from its members and then transmitting aggregated data to the BS on behalf of its cluster. For intra-cluster communication, direct transmission is assumed, while for inter-cluster communication, relay transmission is considered if the CHs cannot directly communicate with the BS. A CH determines the activation of cooperative communications according to link qualities and then selects cooperative nodes (CNs) within its members to form virtual transmitting/receiving antenna arrays. The framework of the node cooperative algorithm integrated in a wireless sensor network is illustrated in Fig. 1. When the inter-communication between clusters A and B is deteriorated by a deep channel fading,

Received 2010-11-11.

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Foundation items: The National Natural Science Foundation of China (No. 60872004, 60972026), the Important National Science and Technology Specific Projects (No. 2010ZX03006-002-01), the Research Fund of the National Mobile Communications Research Laboratory of Southeast University (No. 2010A08).

Citation: Li Wenfeng, Shao Zhenhong, Shen Lianfeng. Cooperative algorithm for improving network connectivity in clustered wireless sensor networks[J]. Journal of Southeast University (English Edition), 2011, 27(1): 1 – 7. [doi: 10.3969/j. issn. 1003 – 7985. 2011. 01. 001]

CH B activates node cooperation at the receiving side to obtain data from CH A. When the next hop CH E cannot relay data, CH D and its selected CNs form a virtual transmitting antenna array to communicate with further destinations.

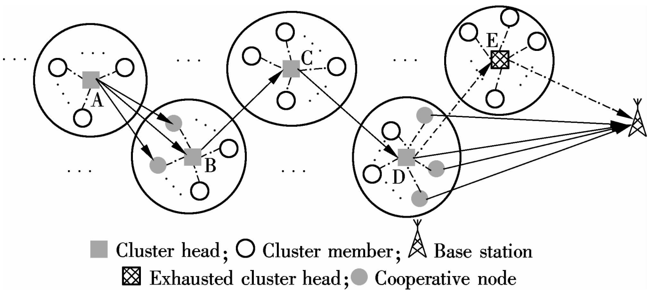

Fig. 1 Framework of node cooperation model

2 Protocol Description and Performance Analysis

Since virtual MIMO is an energy-consuming task, it is not a good idea to be activated every time in a resource constrained sensor network. In our algorithm, virtual MIMO is only activated to set up wireless links for relaying data packets when original links are interrupted due to the coverage hole or deep channel fading.

2.1 Algorithm description

The activation of the cooperative algorithm is determined by CHs according to the inter-cluster communication links in two scenarios: 1) The inter-cluster transmission fails when the coverage hole is detected; 2) The inter-cluster transmission fails when the channel enters a deep fading. In scenario 1, a virtual multiple-antenna transmitter is formed at the transmitting side to enlarge the coverage of the source CH to connect with further CHs outside the one-hop transmission range, as shown in Fig. 2(a). In scenario 2, a virtual multiple-antenna receiver is formed at the receiving side to compensate for channel gains, as shown in Fig. 2(b). The notations used in Fig. 2 are consistent with those in Fig. 1. The detailed transmitting/receiving cooperative algorithms are described in the following.

2.1.1 Transmitting cooperative algorithm

The source CH retransmits data if it has not heard replies after it has sent data to the next hop CH. If the source CH still has not heard any replies for a certain period of time T, it is considered that its next hop CH may be busy or has died and cannot relay data packets. The source CH then reselects the next hop CH within its one hop range. If the source CH cannot find any CH within its one hop range as the relaying CH, a coverage hole is detected and the node transmitting cooperative algorithm is activated. The source CH needs to enlarge the communication coverage by node cooperation to connect with distant nodes. The details of the transmitting cooperative algorithm are as follows:

1) The source CH broadcasts an RTS message within its cluster. Once a node in this cluster receives such a message, it will reply to a CTS, piggybacking its own ID and residual energy. According to the replied CTS, the source CH then selects proper members as CNs which are closer to the source CH and have more residual energy.

2) The selected CNs and the source CH form a virtual antenna array for uplink transmission. The source CH shares the data with selected CNs and then transmits the messages to the remote nodes together with its CNs simultaneously.

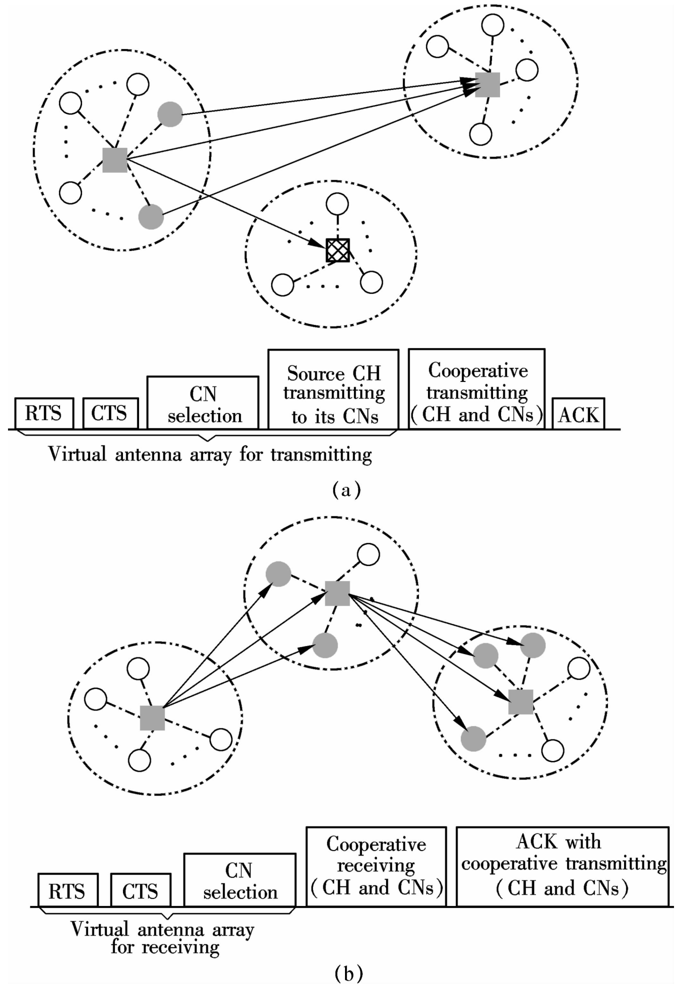

Fig. 2 Virtual transmitting/receiving antenna array. (a) Transmitting cooperation; (b) Receiving cooperation

3) The living CHs which are close to the BS hear such packets and then return CTS messages. If the source CH receives such CTS messages via the virtual antenna array, it selects a proper CH as the next hop node accordingly and then informs the selected CH.

4) When the source CH sets up the link with the remote CH successfully via the virtual antenna array, it can continue to forward data to the BS.

Note that the source CH also receives the ACK messages via a virtual antenna array which can overcome the path loss even if the ACK messages are from remote distances. In addition, the relay transmission can be based on distributed space-time coding.

2.1.2 Receiving cooperative algorithm

During the inter-cluster transmission process, if the SNR of received packets falls below a certain threshold γ_{th}, an outage is defined to have occurred. The relaying CH will fail to decode and forward data packets. To compensate for channel gains, the relaying CH activates cooperative protocol to receive data. The details of the receiving cooperative algorithm are as follows:

1) The CH first sends out an RTS to its members and then selects proper members as CNs to form a virtual multiple-antenna receiver according to the replied CTS, which is

similar to step 1 in section 2.1.1.

2) The CH relies on the virtual antenna array to receive the data.

3) After decoding the received data successfully, the receiving side will reply an ACK message to the previous hop CH according to the protocol.

Note that the radio channel is symmetric so that the source CH may also fail to obtain an ACK due to the channel fading if the receiving CH replies the ACK directly. Hence, the ACK message will be sent via the virtual antenna array to compensate for channel gains.

For a pair of CHs with inter-cluster communication, the transmitting and receiving cooperative algorithms will be activated at the source and the destination, respectively, if the coverage hole and the deep channel fading are both detected. In addition, the node cooperation is equivalent to non-cooperation in the case that the CH fails to select CNs.

2.2 Performance analysis

For brevity, analysis is done over the Rayleigh fading channel with additive white Gaussian noise (AWGN) on an average path loss $\Omega = E[\alpha^2]$, where α is the Rayleigh fading factor. The analysis can be also extended to other fading channels such as Rician and Nakagami.

2.2.1 Extending the coverage of sensors

Extending the communication coverage by node cooperation is applicable for scenario 1. MIMO systems are extended to individual single-antenna nodes that cooperate to form multiple-antenna transmitters, as shown in Fig. 2(a).

It has been shown that MIMO systems can support higher data rates under the same transmit power budget and bit error rate (BER) performance requirement as a SISO system. An alternative view is that for the same throughput and energy requirement, the communication range of a MIMO system is larger than that of a SISO system. We first model the energy consumption of the proposed node cooperative algorithm and compare the value with that of the reference SISO system under the same throughput and BER requirement. With the same energy efficiency, our proposed cooperative algorithm can communicate over longer distances. The number of cooperative nodes can be determined according to the transmission distance.

While the source CH activates the cooperative algorithm, it selects M_0 nodes from its members to form a virtual multiple-antenna array. Hence, there exist $M = M_0 + 1$ signal paths. The node cooperative algorithm employed here is similar to MISO.

Given the transmission energy per bit per node as E_t. The required energy per bit[3] at the receiver is

$$E_r = E_t \frac{G_t G_r}{(4\pi)^2 (d/\lambda)^{\alpha}} \tag{1}$$

where d is the transmission distance; λ is the carrier wavelength; G_t, G_r are the antenna gains for transmitting and receiving, respectively.

Supposing that the channel fading matrix is $\boldsymbol{H}$, the transmit powers of M CNs are equal. The SNR at the receiver can be written as

$$\gamma = \frac{E_r / M}{N_0} \| \boldsymbol{H} \|^2 \tag{2}$$

where N_0 is the one-side AWGN spectral density at the receiver.

For simplicity, let us consider binary PAM signals where the two signal waveforms are $s_1(t) = g(t)$ and $s_2(t) = -g(t)$. The energy in the pulse $g(t)$ is ε_b. Since the two signals are equally likely to be transmitted, the average probability of received error is

$$p_b = \frac{1}{2}p_1 + \frac{1}{2}p_2 = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{2\varepsilon_b/N_0}}^{\infty} e^{-x^2/2} dx = Q\left(\sqrt{\frac{2\varepsilon_b}{N_0}}\right) \tag{3}$$

where p_1 and p_2 are the probabilities of received errors for s_1 and s_2, respectively; the ratio ε_b / N_0 is the signal-to-noise ratio per bit; $Q(x)$ is the Q-function defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-t^2/2} dt \qquad x \geqslant 0 \tag{4}$$

According to the Chernoff bound theory[5], it yields

$$p_b \leqslant \left(\frac{E_r}{MN_0}\right)^{-M} \tag{5}$$

Thus,

$$E_r \leqslant \frac{MN_0}{p_b^{1/M}} \tag{6}$$

Taking the upper bound of E_r, the transmit energy E_{bt} per bit is

$$E_{bt} = \frac{(4\pi)^2 d^{\alpha}}{G_t G_r \lambda^{\alpha}} \frac{MN_0}{p_b^{1/M}} \tag{7}$$

Let $q(M) = M / p_b^{1/M}$. It can be proved that $q(M)$ is a monotone decreasing function while M is in the interval $[1, N]$. The value of N is related to p_b. The smaller p_b is, the bigger N is. For example, $p_b = 0.02$ corresponding to $N = 4$, and $p_b = 0.005$ corresponding to $N = 5$. Hence, if $1 < M \leqslant N$, then $q(M) > q(1)$. It will consume less transmit energy while a virtual multiple transmitting antenna array is employed under the same throughput and BER requirement. As a result, if keeping the same transmitting energy or power, the communication range will be enlarged.

Usually, the next hop neighboring CH is closer to the source CH. Without loss of generality, suppose that the next hop neighboring CH is the nearest CH to the source CH. Hence, if this neighboring CH fails to relay the data, it is considered that the source CH will communicate with the 2nd or 3rd nearest CH by a virtual antenna array.

According to the Poisson property, in a Poisson point process in $\mathbf{R}^2$ with intensity ρ, the distance R_n between a point and its n-th neighbor in a sector θ is distributed according to the generalized Gamma distribution[6-7]

$$f_{R_n}(r) = e^{-\rho\theta r^2} \frac{2(\rho\theta r^2)^n}{r\Gamma(n)} \tag{8}$$

The expected distance is

$$E[R_n] = \left(\frac{1}{\rho\theta}\right)^{1/2}\frac{\Gamma(n+1/2)}{\Gamma(n)} = \left(\frac{1}{\rho\theta}\right)^{1/2}(n)_{1/2} \quad (9)$$

where $(n)_{1/2}$ is the Pochhammer symbol notation, and

$$(n)_{1/2} = \frac{(2n)!\sqrt{\pi}}{n!(n-1)!4^n} \quad (10)$$

For efficient routing, suppose that the source CH selects the CH which lies within an angle $0<\theta<\pi$ of the source-destination axis as the next hop to relay the data.

Since all the nodes are distributed according to a homogeneous 2D Poisson point process of spatial intensity ρ and a node becomes a CH with probability p_H, CHs are also distributed as per an independent Poisson process of intensity $p_H\rho$.

Accordingly, the mean Euclidean distance from a CH to its 1st, 2nd and 3rd nearest neighboring CHs can be obtained as

$$E[R_1] = \left(\frac{1}{\rho\theta}\right)^{1/2}(1)_{1/2} = \frac{1}{\sqrt{2p_H\rho}} \quad (11)$$

$$E[R_2] = \left(\frac{1}{\rho\theta}\right)^{1/2}(2)_{1/2} = \frac{3\sqrt{2}}{4\sqrt{p_H\rho}} \quad (12)$$

$$E[R_3] = \left(\frac{1}{\rho\theta}\right)^{1/2}(3)_{1/2} = \frac{15\sqrt{2}}{16\sqrt{p_H\rho}} \quad (13)$$

To guarantee the connectivity of the inter-cluster overlay while the node cooperation is activated for scenario 1, the radio range d of the virtual antenna array should be $E[R_2] \leqslant d \leqslant E[R_3]$. Substituting $d=E[R_2]$ and $d=E[R_3]$ into Eq. (7), the value of M can be estimated under the certain transmit power, throughput and BER requirements.

2.2.2 Compensating for channel gains

Compensation for channel gains by node cooperation at the receiving side is suitable for scenario 2. When the SNR of received messages from a previous hop CH falls below a certain threshold which means that the channel enters a deep fading; the relaying CH activates the node receiving a cooperative algorithm to compensate for channel gains.

The relaying CH selects M_0 nodes from its members as CNs to form a virtual antenna array for receiving data. Thus $M(M=M_0+1)$ independent Rayleigh fading channels are available at the receiving side. Each channel is called a diversity branch.

As illustrated in Fig. 2(b), the node cooperation algorithm deployed here is similar to selection diversity. Accordingly, the mean SNR $\bar{\gamma}$ offered by node cooperation (selection diversity) can be expressed as[3]

$$\bar{\gamma} = \Gamma\sum_{k=1}^{M}\frac{1}{k} \quad (14)$$

where Γ denotes the average SNR for a single branch (when no diversity is used). It can be seen that the average SNR by using a virtual receiving antenna array naturally increases.

In our system, the relaying data adopts a decoding-and-forwarding transmission mode. To further quantitatively determine the advantages that can be achieved by node cooperation, the error detections of the received data packets are analyzed with and without node cooperation, respectively. Since error detection is usually done at the packet level rather than the symbol level, the analysis is based on packet error rate (PER) rather than symbol error rate.

Given the average transmission energy per symbol as E_t, the average received SNR corresponding to each branch is

$$\Gamma = \frac{GE_t}{N_0 d^\alpha} \quad (15)$$

where N_0 is the one-side AWGN spectral density at the receiver; d is the inter-cluster distance between the transmitting and receiving clusters; G is a constant that is defined by the signal frequency, antenna gains, and other parameters. The instantaneous received SNR γ_i for a branch has an exponential distribution as[8]

$$f(\gamma_i) = \frac{1}{\Gamma}e^{-\gamma/\Gamma} \qquad \gamma_i \geqslant 0 \quad (16)$$

An approximate PER[9] which is conditional on each instantaneous value of γ_i at the destination node is given by

$$P_{PER}(\gamma_i) \approx \begin{cases} 1 & 0<\gamma_i<\gamma_{pn} \\ a_n\exp(-g_n\gamma_i) & \gamma_i \geqslant \gamma_{pn} \end{cases} \quad (17)$$

where a_n, g_n, and γ_{pn} are parameters that are dependent on the packet length, modulation, coding, and other factors. The values of these parameters under different modulation schemes are provided in Ref. [9]. It can be seen that the instantaneous SNR should be greater than γ_{pn}; otherwise, the destination node fails to decode the packet. Accordingly, the value of threshold γ_{th}, which is used for determining whether the channel enters a deep fading or not, can be set as $\gamma_{th}=\gamma_{pn}$.

However, the probability that a single branch has an instantaneous SNR γ_i less than γ_{pn} is

$$p_\gamma[\gamma_i \leqslant \gamma_{pn}] = \int_0^{\gamma_{pn}} f(\gamma_i)\,d\gamma_i = \int_0^{\gamma_{pn}}\frac{1}{\Gamma}e^{-\gamma/\Gamma}d\gamma_i = 1-e^{-\gamma_{pn}/\Gamma} \quad (18)$$

Accordingly, for a single branch which has an instantaneous value of γ_i, the average probability that the destination node fails to decode the data packet is

$$p_{err\_s}(\gamma_i) = p_\gamma[\gamma_i \leqslant \gamma_{pn}]P_{PER}(\gamma_i) + p_\gamma[\gamma_i > \gamma_{pn}]P_{PER}(\gamma_i) = 1-e^{-\gamma_{pn}/\Gamma} + a_n e^{-g_n\gamma_i-\gamma_{pn}/\Gamma} \quad (19)$$

The p_{err_s} averaged over Rayleigh fading is given as

$$\bar{p}_{err\_s} = \int_0^\infty p_{err\_s}(\gamma_i)f(\gamma_i)\,d\gamma_i = 1-e^{-\gamma_{pn}/\Gamma} + \frac{a_n}{1+g_n\Gamma}e^{-\gamma_{pn}/\Gamma} = \frac{a_n}{1+g_n\Gamma} + \left(1-\frac{a_n}{1+g_n\Gamma}\right)(1-e^{-\gamma_{pn}/\Gamma}) \quad (20)$$

Substituting Γ into Eq. (20), it can be expressed as

$$\bar{p}_{err\_s}(E_t, d) = 1-\left(1-\frac{a_nN_0d^\alpha}{N_0d^\alpha+g_nGE_t}\right)\exp\left(-\frac{\gamma_{pn}N_0d^\alpha}{GE_t}\right) \quad (21)$$

The probability that the destination node correctly decodes the packet for direct transmission is

$$\bar{p}_{\mathrm{cor\_s}} = 1 - \bar{p}_{\mathrm{err\_s}} = \left(1 - \frac{a_n N_0 d^{\alpha}}{N_0 d^{\alpha} + g_n G E_{\mathrm{t}}}\right)\exp\left(-\frac{\gamma_{\mathrm{pn}} N_0 d^{\alpha}}{G E_{\mathrm{t}}}\right) \tag{22}$$

The probability that all M independent diversity branches receive signals which are simultaneously less than γ_{pn} is

$$p_{\gamma}[\gamma_1, \gamma_2, \ldots, \gamma_M \leqslant \gamma_{\mathrm{pn}}] = (1 - \mathrm{e}^{-\gamma_{\mathrm{pn}}/\Gamma})^M = p_M(\gamma_{\mathrm{pn}}) \tag{23}$$

where $p_M(\gamma_{\mathrm{pn}})$ is the probability of all branches failing to achieve an instantaneous SNR greater than γ_{pn}. If a single branch achieves an SNR greater than γ_{pn}, then the probability that SNR > γ_{pn} for one or more branches is given by

$$p_M[\gamma_i > \gamma_{\mathrm{pn}}] = 1 - p_M(\gamma_{\mathrm{pn}}) = 1 - (1 - \mathrm{e}^{-\gamma_{\mathrm{pn}}/\Gamma})^M \tag{24}$$

The average probability that the virtual receiving antenna array receives an error data packet is

$$p_{\mathrm{err\_m}}(\gamma_i) = p_M(\gamma_{\mathrm{pn}}) p_{\mathrm{PER}}(\gamma_i) + p_M[\gamma_i > \gamma_{\mathrm{pn}}] p_{\mathrm{PER}}(\gamma_i) = a_n \mathrm{e}^{-g_n \gamma_i} + (1 - a_n \mathrm{e}^{-g_n \gamma_i})(1 - \mathrm{e}^{-\gamma_{\mathrm{pn}}/\Gamma})^M \tag{25}$$

Given an average SNR Γ, the probability of Eq. (25) averaged over Rayleigh fading is given as

$$\bar{p}_{\mathrm{err\_m}} = \int_0^{\infty} p_{\mathrm{err\_m}}(\gamma_i) f(\gamma_i)\,\mathrm{d}\gamma_i = \frac{a_n}{1 + g_n \Gamma} + \left(1 - \frac{a_n}{1 + g_n \Gamma}\right)(1 - \mathrm{e}^{-\gamma_{\mathrm{pn}}/\Gamma})^M \tag{26}$$

Substituting Γ into Eq. (26), it can be expressed as

$$p_{\mathrm{err\_m}}(E_{\mathrm{t}}, d) = \frac{a_n N_0 d^{\alpha}}{N_0 d^{\alpha} + g_n G E_{\mathrm{t}}} + \left(1 - \frac{a_n N_0 d^{\alpha}}{N_0 d^{\alpha} + g_n G E_t}\right) \cdot \left[1 - \exp\left(-\frac{\gamma_{\mathrm{pn}} N_0 d^{\alpha}}{G E_{\mathrm{t}}}\right)\right]^M \tag{27}$$

The probability that the virtual receiving antenna array correctly decodes the packet is

$$\bar{p}_{\mathrm{cor\_m}} = 1 - \bar{p}_{\mathrm{err\_m}} \tag{28}$$

Compared $\bar{p}_{\mathrm{err\_s}}$ with $\bar{p}_{\mathrm{err\_m}}$, $\bar{p}_{\mathrm{err\_m}} < \bar{p}_{\mathrm{err\_s}}$. It can be seen that the probability $\bar{p}_{\mathrm{cor\_m}}$ increases as M increases, since it is always guaranteed to be above the specified threshold. Thus, node cooperation for receiving data packets offers an average improvement in the link margin. In addition, according to Eqs. (27) and (28), the value of M can be estimated. The proposed node cooperative algorithm does not require additional transmitter power or sophisticated receiver circuitry. Therefore, it is suitable for wireless sensor networks.

3 Simulation Results

This section presents the numerical results corresponding to the cooperative algorithm discussed above. Here, the proposed node cooperative algorithm is integrated with a typical multi-hop clustering algorithm, HEED[10]. In simulations, the nodes are randomly scattered in square areas according to a Poisson point process of intensity ρ. To be more realistic, all the nodes will not simultaneously sense the data. Suppose that the rate of sensing the data by a node is also according to a Poisson process of intensity 0.1 bit per time unit. The length of each data packet is fixed to 200 bits. The parameters $a_n = 67.732\,8$, $g_n = 0.981\,9$, and $\gamma_{\mathrm{pn}} = 6.328\,1$ dB for PER calculation are obtained from Ref. [9]. Assume that all the packets received from the cluster members can be aggregated into a single packet. Each experiment is run 50 times and the results are averaged. Most of the simulation parameters are listed in Tab. 1. The simulation results are provided in Figs. 3 to 6.

Tab. 1 Simulation parameters

Type	Parameters	Value
Network	Network grid	From (0, 0) to (1 000, 1 000)
	Base station	At (0, 0)
	Initial energy/(J · battery^{-1})	2
Radio model	e_0/(nJ· bit^{-1})	50
	ε/(pJ· (bit· m^2)$^{-1}$)	10
Application	Cluster radius/m	125
	Data packet size/bit	200
	Round/frame	100

Fig. 3 illustrates the comparison of outage probability with or without a node receiving cooperation under different average SNRs. The number of nodes in the network is set as 1 700. As shown in Fig. 3, the outage probability reduces when the system is integrated with the node receiving cooperative algorithm. The transmission success probability thus increases accordingly, which helps in sustaining network connectivity and maintaining operations. The network performance is improved.

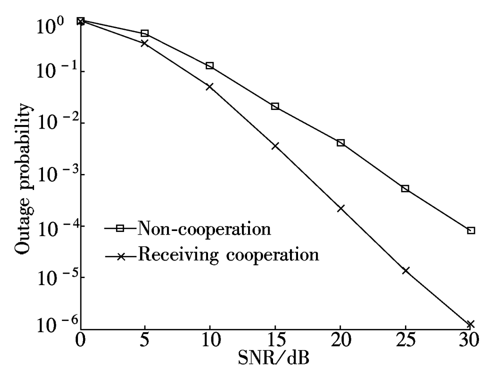

Fig. 3 Comparison of outage probability integrated with or without node receiving cooperation

Fig. 4 evaluates the energy efficiency influenced by the node receiving cooperative algorithm. Overall communication energy consumed by all the nodes after 15 rounds for HEED integrated with and without the node receiving cooperative algorithm are summed and normalized for different average SNRs. A round is of duration T during which a burst of data is collected and forwarded to the BS. The simulation parameters are the same as before. As illustrated in Fig. 4, total system energy consumption decreases as average SNR increases. However, with node receiving cooperation, the system consumes less energy when the SNR is lower. It proves that the proposed node receiving cooperative algorithm achieves better energy efficiency when the channel enters deep fading.

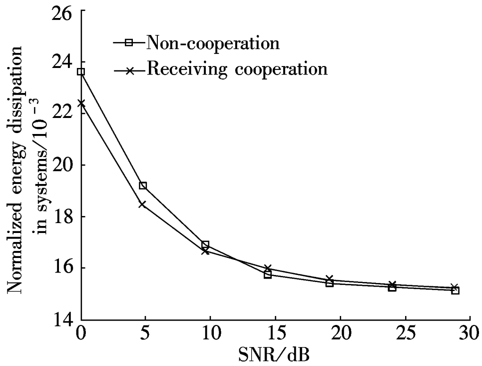

Fig. 4 Total system energy dissipation with or without node receiving cooperation

Fig. 5 shows the time when nodes first lose the coverage with or without node cooperation under different node densities is compared. Here losing the coverage means that the source CH fails to build a route to contact with further relaying CHs when the coverage hole is detected. The initial number of nodes in the network is set as 500, 800, 1 100, 1 400, and 1 700, respectively. The receiving threshold γ_{th} is set as 10 dB. The other parameters are the same as before. It can be seen that the network integrated with the node transmitting cooperative algorithm maintains the whole system connectivity longer. This is because the communication range of the source CH is extended when the original next hop CH is inactive, which makes the source CH find a remote active CH as the relaying CH. The connectivity in the network is thus guaranteed. Here, that the node is inactive refers to that the node is powerless or busy and thus cannot relay the data.

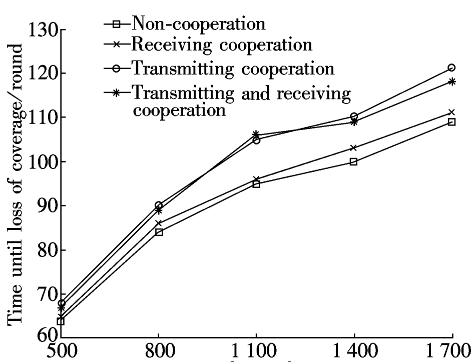

Fig. 5 Time until the loss of coverage with different node densities

After the network has been running for some time, some nodes drain their power which may cause coverage holes. Fig. 6 compares the energy efficiency in such a scenario with or without the node transmitting cooperative algorithm. It shows the average energy consumption per round for different remaining alive nodes. The initial number of nodes in the network is set as 1 700. The other parameters are the same as those in Fig. 5. As can be seen from Fig. 6, the network integrated with the node transmitting cooperative algorithm achieves higher energy efficiency since it reduces the control overhead for finding new routes supported by remote nodes when a coverage hole is detected, which saves the energy consumption due to void retransmission.

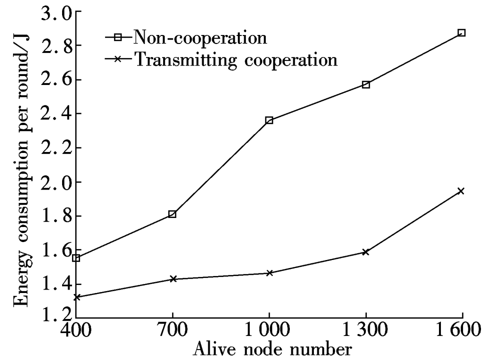

Fig. 6 Average energy consumptions per round for different numbers of alive nodes

4 Conclusion

A node cooperative algorithm based on virtual MIMO is proposed in a clustered WSN to improve network connectivity and communication reliability. In the proposed algorithm, the activation of node cooperation is determined by CHs according to the quality of the links. With cooperation, nodes extend the communication range to make contact with distant nodes directly when a coverage hole is detected, or to compensate for channel gains when transmission fails due to deep channel fading. Simulation results show that the proposed algorithm can reduce outage probability and achieve higher coverage and connectivity. It can be extended to the application of a similar clustered WSN.

References

[1] Yick J, Mukherjee B, Ghosal D. Wireless sensor network survey [J]. *Computer Networks*, 2008, **52**(4): 2292 – 2330.

[2] Zhang Qian, Zhang Yaqin. Cross-layer design for QoS support in multihop wireless networks [J]. *Proceedings of the IEEE*, 2008, **96**(1): 64 – 76.

[3] Proakis J G. *Digital communications* [M]. 5th ed. New York: McGraw-Hill Science, 2008.

[4] Xu P. Voronoi cells, probabilistic bounds, and hypothesis testing in mixed integer linear models [J]. *IEEE Transactions on Information Theory*, 2006, **52**(7): 3122 – 3138.

[5] Furrer S, Dahlhaus D. Multiple-antenna signaling over fading channels with estimated channel state information: performance analysis [J]. *IEEE Transactions on Information Theory*, 2007, **53**(6): 2010 – 2027.

[6] Srinivasa S, Haenggi M. Distance distributions in finite uniformly random networks: theory and applications [J]. *IEEE Transactions on Vehicular Technology*, 2010, **59**(2): 940 – 949.

[7] Haenggi M. On distances in uniformly random networks [J]. *IEEE Transactions on Information Theory*, 2005, **51**(10): 3584 – 3586.

[8] Simon M K, Alouini M S. *Digital communication over fading channels: a unified approach to performance analysis* [M]. 2nd ed. New York: Wiley-Interscience, 2005.

[9] Liu Q, Zhou S, Giannakis G B. Cross-layer combining of adaptive modulation and coding with truncated ARQ over wireless links [J]. *IEEE Transactions on Wireless Communications*, 2004, **3**(5): 1746 – 1755.

[10] Younis O, Fahmy S. HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks [J]. *IEEE Transactions on Mobile Computing*, 2004, **3**(4): 366 – 379.

分簇无线传感器网络中提高网络连通性的协作算法

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摘要:针对分簇无线传感器网络提出了一种基于虚拟天线阵列的协作算法. 该算法通过节点间的协作来提高网络连通性,所有节点均按照泊松 Voronoi 网格模型进行分簇,簇首根据通信链路决定是否激活节点协作;若节点协作算法被激活,簇首从其成员中选择适合的节点作为协作节点共同组成虚拟天线阵列. 通过协作,可扩展簇间的通信范围从而与远方节点直接通信以避免出现通信覆盖盲区,或者可补偿信道增益以防止由于信道深衰落所导致的传输失败. 仿真结果表明,协作算法在通信过程中具有更好的连通性及能量效率,可有效降低接收端的丢包率,维持网络的连通性,从而延长网络的工作时间.

关键词:传感器网络;覆盖;协作通信;工作时间

中图分类号:TN915