Fair Clustering for Energy Efficiency in a Cooperative Wireless Sensor Network

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***Abstract*—In a WSN (Wireless Sensor Network), cooperative communications can provide improved energy efficiency which is one of the most important metric given that sensors usually have constrained energy. In this paper, we consider a WSN where sensors operate selfishly without centralized entity like as base station. The most of sensors do not tend to help spontaneously data transmission for others in a distributed WSN. We propose the fair cooperative communication scheme which encourages sensors to participate in cooperative communication by giving some reward. In other words, sensors can participate in the same cluster and help each other to cooperatively transmit data if the following two conditions are satisfied: 1) sensors have a plan to transmit data to nearby area, and 2) sensors are able to decode message coming from a representative cluster. Then, proposed scheme is more realistic and fair compared with existing scheme which makes sensors to participate in cooperative communication without reward. Moreover, simulation results show that the proposed scheme is more energy efficient than the existing schemes.**

I. Introduction

In a WSN, sensors can cooperatively transmit data to their destination sensors by exchanging data before transmission, which is called cooperative communication. The cooperative scheme is effective to improve the reliability of wireless channel in the WSN due to spatial diversity. Furthermore, compared the method to manage sensors individually, it is more advantageous to manage cluster unit which consists of sensors in order to use limited resources efficiently. This cluster concept supports the operation of the WSN very efficiently because nodes which participate in cooperative communication simultaneously can be grouped as a unit of cluster. Hence, in the WSN, many authors have researched cooperative communication combined with cluster concept for many years. In the WSN, every node is capable of sensing, communicating, and operating with limited battery energy. When battery of some sensors is burned out, the performance of entire sensor network can be degraded severely. Therefore, to minimize energy consumption in the WSN, a proper design scheme is required.

Duarte-Melo and Liu [1] proposed the model to consume energy efficiently based on contention and clustering mechanism in a heterogeneous WSN in view of medium access control layer (MAC). Depedri et al. [2] suggested the energy efficient protocol considering propagation channel model in physical layer (PHY). Wang et al. [3] suggested PHY, MAC and network (NET) cross-layer approach to determine an optimal number of clusters to minimize energy consumption. With the concept of sensor lifetime maximization, efficient energy consumption issues were studied by utilizing optimal routing and scheduling in [4]-[6].

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Given that sensors can monitor cooperatively the environmental measure such as temperature, humidity and wind velocity in a WSN, it is possible to use resource, bandwidth and power efficiently by using clustering and cooperation scheme. In [7], cooperative MIMO (Multiple Input Multiple Output) communication showed the result that it can improve energy efficiency by applying Alamouti scheme in a WSN. Zhou [8] suggested energy efficiency in a cooperative cluster based WSN when cluster node operates as a relay if correctly decoded. Finally, Ana proposed the sleep and awake sensor scheme to minimize energy consumption in [9].

In a cluster-based cooperative WSN, a lot of papers have proposed the scheme that node (sensor) transmits cooperatively data with other nodes in the same cluster to improve energy efficiency. Although the cooperative scheme shows better performance than non-cooperative scheme, it is difficult to cooperate in a distributed network where sensors tend to be selfish. To solve the problem, we proposed cluster based fair cooperative scheme in a WSN. In the scheme, nodes cooperatively transmit data by using fair cooperative MIMO technique if nodes transmit data to destination nodes which are located in neighboring area. For fair cooperative MIMO, multiple sensor nodes can collaborate each other as antenna array because sensors usually do not have multiple antennas.

The rest of this paper is organized as follows: the proposed system model in a cluster-based WSN is described in section II. Section III presents mathematical analysis for the proposed scheme. In section IV, the performance evaluations showing the comparison between proposed scheme and conventional schemes are explained. Some important conclusions are made in section V.

II. System model and Problem statement

In a WSN, cooperative communication between nodes can improve the reliability and energy efficiency of the system. In this paper, the main issue is to obtain the optimal radius of cluster to minimize energy consumption based on fair cooperative communication. As shown in Fig. 1, it describes the characteristics of sensors (nodes). Also, it shows how to construct cluster and transmit data cooperatively in the WSN. Moreover, it represents that each node communicates with

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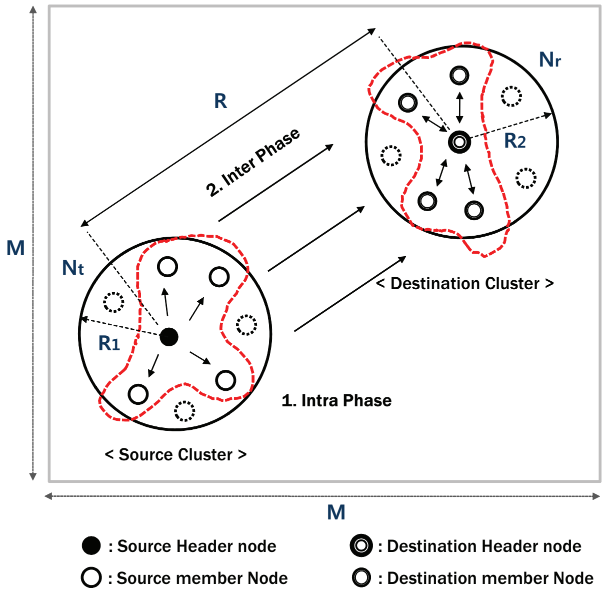

Figure 1. Proposed system model using cluster concept

cluster header node in only 1-hop, and a cluster header node is located in the center of its circled-cluster. According to the experimental analysis in [10], this structure can reduce more energy consumption than other structures which has k-hop cluster $(k > 1)$ or randomly-located cluster header node.

In our system model, it is assumed that the senders (source header node and source member node) and the receivers (destination header node and destination member node) have the structure of many-to-one or one-to-one mapping. It is because multiple senders are able to transmit their data to the same receiver at the same time. Furthermore, for fair cooperative communication, senders and receivers can be grouped as source cluster and destination cluster, respectively. Under the assumption that the distribution of nodes is uniform, the number of nodes which participate in cooperative communication increases as the radius of source cluster or destination cluster becomes longer. Given that sensors have limited functionality, we assume that sensors cannot transmit and receive data at the same time. Accordingly, data transmissions in intra and inter phase should be executed in two different time slot. Here, we assume that flat Rayleigh fading channel between two nodes is used at intra and inter phase.

The more senders participate in cooperative communication, the more receivers can decode data reliably. Accordingly, the outage probability becomes lower as the number of senders increases. However, total energy consumption increases since the number of senders and receivers increases. Hence, there exists trade-off relationship between outage probability and total energy consumption. From the fact that the number of nodes in source and destination cluster is proportional to the radius of each cluster as explained before, it is possible to find the optimum radius of cluster to minimize energy consumption if the outage probability satisfying the system requirement is given.

In Fig. 1, M denotes side length of the square entire system, R_1 and R_2 denote radius of source cluster and destination cluster, respectively. R denotes distance between two clusters, and the number of senders and receivers is denoted by N_t and N_r, respectively. Since senders and receivers have the structure of one-to-one mapping or many-to-one mapping, the number of senders is equal to or larger than the number of receivers. For example, if N_t is five, N_r is within the range of one to five since senders have a chance of transmitting data to the same receiver.

The cooperative communication process consists of two phases: The first phase is intra phase, and the second phase is inter phase. Before intra phase, it is assumed that locations of source header node and destination header node are predefined, and all nodes are aware of the location of other nodes. Here, we define that potential source (destination) member node is the node which could participate in source (destination) cluster. Accordingly, potential source (destination) member node would be included in source (destination) cluster as source (destination) member node if several conditions are satisfied. A detailed explanation will be given in the following two subsections.

Intra Phase : cluster formation

At first, by broadcasting message, source header node finds potential source member nodes within source cluster whose radius is R_1 to support fair cooperative communication. After potential source member nodes receive message from source header node, potential source member nodes could be included in source cluster as source member nodes if two necessary conditions are satisfied: the first necessary condition is that SNR (Signal to Noise Ratio) of the received signal of potential source member node is larger than SNR threshold level which is a minimum required level to decode the message, and the second necessary condition is that potential destination member node (which is supposed to receive data from potential source member node) must be in destination cluster whose radius is R_2. Hence, if two necessary conditions are satisfied, potential source (destination) member node is able to join into the source (destination) cluster as source (destination) member nodes in order to transmit their own data together based on fair cooperative communication.

Inter Phase : data transmission and reception

At inter phase, senders transmit data using cooperative MIMO. Since the number of senders and receivers is denoted by N_t and N_r as explained previously, the channel between source and destination cluster can be regarded as $N_t \times N_r$ cooperative MIMO channel. To get correctly original data from senders, each receiver has to exchange their received data after cooperative MIMO transmission. Given that OSTBC (orthogonal space time block coding) scheme is used, receivers can decode the received data easily because of unitary property of codeword.

III. Analytical Approaches

Based on the proposed model, we can derive the outage model and the energy consumption model mathematically in Fig. 2. At first, the source header node and the corresponding destination header node are assumed to be defined before intra phase as explained before.

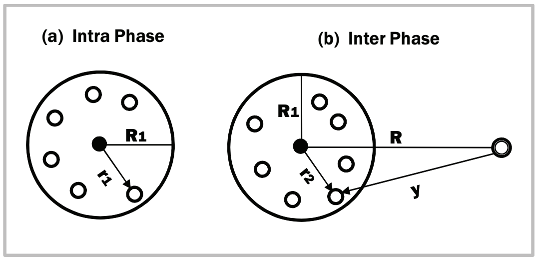

Figure 2. Mathematical outage model at intra and inter phase

Mathematical Outage Model

1) Intra Phase: From Fig. 2, the probability of nodes participating source cluster can be derived based on the probability model describing two necessary conditions: 1) potential source member nodes within a radius R_1 of source cluster should not declare an outage, 2) potential source member nodes must transmit data to potential destination member nodes within a radius R_2 of destination cluster. Hence, we can obtain an average number of source member nodes in a source cluster by using the above probability model. At first, we consider the outage probability of a potential source member node at arbitrary distance of r_1. The received SNR at the potential source member node can be written as follows

$$SNR_{intra} = \frac{k_1 r_1^{-\alpha} h_1^2 P_{t1}}{N_o W} < \gamma_{min} \tag{1}$$

$$where \qquad h_1 < \sqrt{\frac{N_o W \gamma_{min}}{k_1 r_1^{-\alpha} P_{t1}}} \tag{2}$$

Here, k_1 is constant indicating proportionality, h_1 is Rayleigh random variable, P_{t1} is transmission power of source header node, α is path-loss exponent, N_o is noise power spectral density, W is channel bandwidth, and γ_{min} is minimum SNR for detecting correctly received signal. By using cumulative distribution function (CDF) of Rayleigh random variable, the outage probability at distance of r_1 can be obtained as follows

$$\begin{aligned} P_{intra}^{out}(r_1) &= P\{h_1 < \sqrt{\tfrac{N_o W \gamma_{min}}{k_1 r_1^{-\alpha} P_{t1}}}\} \\ &= 1 - exp(-\tfrac{1}{2\sigma_h^2} \tfrac{N_o W \gamma_{min}}{k_1 r_1^{-\alpha} P_{t1}}) \end{aligned} \tag{3}$$

Here, as r_1 increases to infinity, P_{out} becomes 1, which means that all nodes at infinite distance are in outage. Since it is assumed that distribution of nodes is uniform in a circle shaped cluster, the probability distribution $f(r_1)$ of nodes at r_1 is expressed as follows

$$f(r_1) = \frac{2r_1}{R_1^2} \qquad where \qquad 0 < r_1 < R_1 \tag{4}$$

In the derivation of Eq. (4), path loss exponent is assumed to be 2, which is a reasonable value in local wireless sensor communications. From the results of Eq. (3) and Eq. (4), the average outage probability $\overline{P_{intra}^{out}(R_1)}$ in a source cluster can be drawn as follows

$$\begin{aligned} \overline{P_{intra}^{out}(R_1)} &= \int_0^{R_1} P_{intra}^{out}(r_1) \times f(r_1) dr_1 \\ &= 1 + \tfrac{2\sigma_h^2 k_1 P_{t1}}{N_o W \gamma_{min} R_1^2} (exp(-\tfrac{1}{2\sigma_h^2} \tfrac{N_o W \gamma_{min}}{k_1 P_{t1}} R_1^2) - 1) \end{aligned} \tag{5}$$

Next, under the assumption that potential destination member nodes don't exist within the source cluster, the average probability that potential destination member nodes might be within a radius R_2 of destination cluster is denoted by $\overline{P_{intra}^{sd}(R_1, R_2)}$ which can be expressed as area ratio of *destination cluster area to total system area except source cluster area* since all nodes are distributed uniformly.

$$\overline{P_{intra}^{sd}(R_1, R_2)} = \frac{\pi R_2^2}{M^2 - \pi R_1^2} \tag{6}$$

From the results of Eq. (5) and Eq. (6), we can derive the average number of source member nodes $N_t - 1$ $(total\ senders - source\, header\, node)$ which would participate in fair cooperative communication at inter phase as following

$$N_t - 1 = \left\lfloor \pi R_1^2 \rho \times \left(1 - \overline{P_{intra}^{out}(R_1)}\right) \times \overline{P_{intra}^{sd}(R_1, R_2)} \right\rfloor \tag{7}$$

Herein, it is assumed that the uniform distributed density denotes ρ in the system model.

2) Inter Phase: With N_t, the outage probability can be obtained at inter phase. Based on a similar way used at intra phase, we assume that some nodes in destination cluster can be decided to be in outage state if received SNR is less than given SNR threshold. By one-to-one or many-to-one mapping, the number of receivers is less than the number of senders. i.e. $N_t \geqq N_r$. Hence, N_r can be defined as a discrete uniform distributed random variable within a range of $[1, N_t]$ based on R_1, R_2 at intra phase. When N_t and N_r nodes participate in fair cooperative MIMO communication and each N_r node decodes its data correctly, the outage probability can be derived as follows, which was suggested in [11].

$$P_{inter}^{out}(R_1, R_2) = P_{inter}^{out}(N_r) \approx SNR_{inter}^{-N_r} \tag{8}$$

Here, SNR_{inter} is the total sum of each received SNR from N_t nodes at arbitrary one node in destination cluster, and N_r is determined by R_1 and R_2. At inter phase in Fig. 2(b), SNR_{inter} can be expressed as follows

$$SNR_{inter} = \sum_{N_t} \frac{k_2 y^{-\alpha} h_2^2 P_{t2}}{N_o W} \tag{9}$$

Here, k_2 is constant indicating proportionality, h_2 is Rayleigh random variable, P_{t2} is power of sender, and y is distance between arbitrary one source node and one destination node at inter phase. Then, y can be derived by using the law of cosines as follows

$$y = (r_2^2 + R^2 - 2r_2 R cos\theta)^{\frac{1}{2}} \quad where \quad 0 < r_2 < R_1 \tag{10}$$

Hence, y can be defined as terms of r_2 and R. Under the assumption that path loss exponent is 2, Eq. (9) can be drawn as following using Eq. (10).

$$
\begin{aligned}
&SNR_{inter} \\
&= \sum \frac{k_2 y^{-\alpha} h_2^2 P_{t2}}{N_o W} \\
&= \frac{k_2 h_2 P_{t2}}{N_o W} \frac{N_t}{\pi R_1^2 R} \times \{R_1\{ln(R_1^2+R^2)-2\}+2R\,tan^{-1}(\frac{R_1}{R})\}
\end{aligned} \tag{11}
$$

Hence, at inter phase, the average outage probability can be obtained by averaging Eq. (8) over $N_r \in [1, N_t]$ which is discrete uniform random variable.

$$
\overline{P_{inter}^{out}(R_1, R_2)} = \sum_{N_r \in [1, N_t]} SNR_{inter}^{-N_r} \times \frac{1}{N_t} \tag{12}
$$

Mathematical Energy Model

For fair cooperative communication, sensors consume their energy at each intra and inter phase. According to [7], the proposed energy consumption model can be described as

$$
E_{total}(R_1, R_2) = E_{intra}(R_1, R_2) + E_{inter}(R_1, R_2) \tag{13}
$$

Here, E_{intra} is the energy consumption at intra phase and E_{inter} is the energy consumption at inter phase. In Eq. (13), it shows intuitively that the amount of energy consumption is proportional to radius of source and destination cluster. Accordingly, E_{intra} and E_{inter} can be obtained as

$$
E_{intra}(R_1, R_2) = E_{tr-broad} + E_{ct} + \lfloor \rho\pi R_1^2 - 1 \rfloor E_{cr} \tag{14}
$$

$$
\begin{aligned}
E_{inter}(R_1, R_2) = N_t(E_{tr-coop} + E_{ct}) + N_r E_{cr} + \\
N_r(E_{tr-broad} + E_{ct}) + N_r(N_r - 1)E_{cr}
\end{aligned} \tag{15}
$$

In Eq. (14) and Eq. (15), N_t and N_r is a function of R_1 and R_2 as explained previously. $E_{tr-broad}$ means the broadcasting energy consumption used to broadcast data to nodes within source or destination cluster. E_{ct} is the circuit energy consumed to transmit signal by using modulation and coding. E_{cr} means the circuit energy consumed to receive signal by using demodulation and error detecting. The cooperative transmission energy consumption at inter phase is denoted by $E_{tr-coop}$, which is consumed by all senders for cooperative MIMO. In Eq. (14), the term $E_{tr-broad} + E_{ct}$ means broadcasting and transmission circuit energy consumption by only source header node, and the term $\lfloor \rho\pi R_1^2 - 1 \rfloor E_{cr}$ denotes that $\lfloor \rho\pi R_1^2 - 1 \rfloor$ (the cardinal number of all potential source member nodes in a radius R_1 of source cluster) nodes use reception circuit energy while attempting to receive the signal from a source header node. In Eq. (15), the term $N_t(E_{tr-coop} + E_{ct}) + N_r E_{cr}$ means the energy consumption when N_t and N_r nodes participate in cooperative MIMO. The term $N_r(E_{tr-broad} + E_{ct}) + N_r(N_r - 1)E_{cr}$ means the energy consumption used by N_r nodes in destination cluster because they have to exchange received data each other to obtain their original data. Combining the energy model with the outage model, optimization problem is expressed as

$$
\begin{array}{ccll}
min & E_{total}(R_1, R_2) & & \\
s.t. & \overline{P_{intra}^{out}(R_1)} & \leqq & P_{threshold}^{out} \\
 & \overline{P_{inter}^{out}(R_1, R_2)} & \leqq & P_{threshold}^{out} \\
 & R_1, R_2 & > & 0
\end{array} \tag{16}
$$

Herein, $P_{threshold}^{out}$ is threshold outage probability to guarantee system performance in a WSN. This value is equally applied at intra and inter phase. In Eq. (16), optimal source and destination cluster radius can be obtained to minimize energy consumption given that the outage requirement is satisfied.

IV. Performance Evaluations

We compare two conventional schemes with our proposed scheme. The first conventional scheme is a non-cooperative scheme (direct communication) mostly used in real world. The second conventional scheme is an unfair and cooperative scheme as suggested by [8], in which source member nodes (relays) only assist the source header node (cluster header) without sufficient rewards. In this section, the proposed scheme is called a fair and cooperative scheme. In the simulation environment, nodes are uniformly distributed, and the Rayleigh flat fading channel with $\alpha = 2$ is used. Moreover, $k_1 = k_2 = 1$, $E_{ct} = 150mW$, $E_{cr} = 100mW$, $W = 1MHz$, $N_o = -174dBm/Hz$, $\rho = 0.01$ and $P_{threshold}^{out} = 0.01\%$ are used.

Firstly, in case of $R_2 = 6.4m$, we examine the energy consumption per bit according to the change of R_1. As shown in Fig. 3, the proposed scheme has more efficient energy consumption than two conventional schemes. For example, at $R_1 = 4m$, the amount of energy consumption is reduced by about 52% compared to the non-cooperative scheme and about 30% compared to the unfair and cooperative scheme. In the fair and cooperative scheme, we can see that the energy consumption per bit becomes lower given that R_1 increases up to about $4m$. It is because the amount of saving energy by fair cooperative transmission is larger than the energy amount wasted to form and maintain cluster. More precisely, reliability of wireless channel is improved by diversity gain which is introduced by cooperative communication. Also, the more wireless channel is reliable, the less packet or data are being dropped. Accordingly, cooperation is able to use less energy given that the amount of transmitting data is constant. However, when R_1 is increased above $4m$, this advantage disappears since the energy amount saved by cooperation is decreasing while the energy amount wasted by cluster overhead is increasing. Although the energy consumption per bit of the unfair and cooperative scheme is more efficient than that of the non-cooperative scheme in some interval of R_1, it has still worse performance than the fair and cooperative scheme since nodes are required to use energy to just relay data of others in the unfair and cooperative scheme. In fixed radius of destination cluster, there exists optimal source cluster radius which is about $4m$ to minimize energy consumption.

Next, in case that R_1 is fixed to $6.4m$, the proposed scheme is more energy efficient than other two schemes as shown in Fig. 4. For example, at $R_2 = 3.5m$, the amount of energy consumption is reduced by about 66% compared to the non-cooperative scheme and about 48% compared to the unfair and cooperative scheme. Because the fair and cooperative scheme has more independent channel between source cluster and destination cluster compared to two other schemes, it can obtain more diversity gain as R_2 increases. Hence, it transmits more reliably and uses less energy given that the amount of sending data is constant. On the other hand, two conventional schemes are not able to get diversity effect since

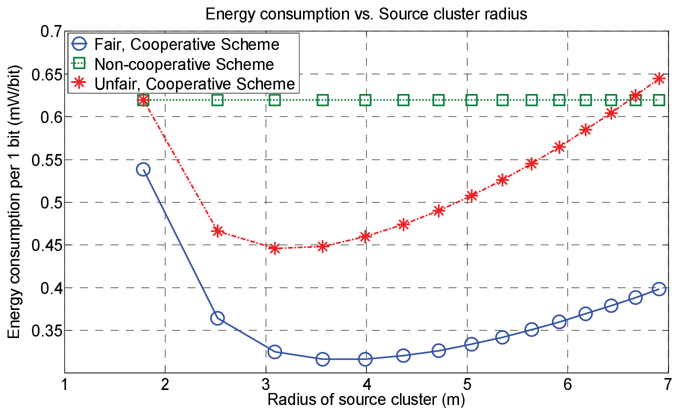

Figure 3. Energy consumption vs. source cluster radius

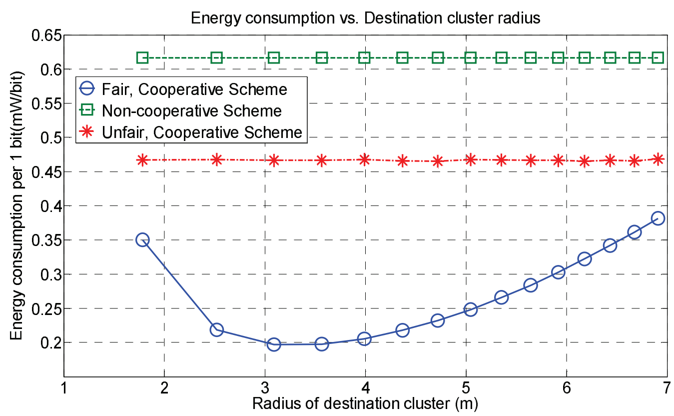

Figure 4. Energy consumption vs. destination cluster radius

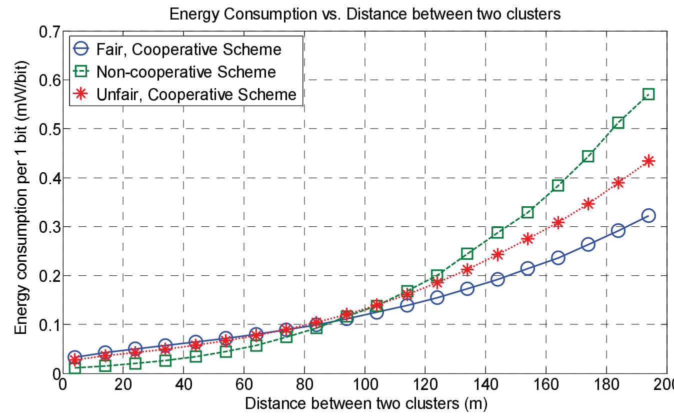

Figure 5. Energy consumption vs. distance between two clusters

the number of independent channels is constant in spite of the change of R_2. Then, two conventional schemes have constant energy consumption per bit regardless of increase of R_2. However, if R_2 is larger than about $3.5m$, the fair and cooperative scheme requires more energy to form destination cluster including many nodes. Then, in the fair and cooperative scheme, the performance becomes worse because the amount energy wasted by cluster formation is larger than the amount of energy saved by diversity gain. In Fig. 4, it shows that the optimal destination cluster radius is about $3.5m$ in the case of source cluster with fixed radius.

Finally, we observe the energy efficient consumption per bit with varying R in the case of $R_1 = R_2 = 6.4m$ in Fig. 5. The fair and cooperative scheme consumes additional energy to construct source and destination clusters compared with the non-cooperative scheme, and to construct destination cluster compared with the unfair cooperative scheme. Then, the amount of energy saved by diversity gain is smaller than the amount of energy used to construct clusters in short distance in case of the fair and cooperative scheme. However, given that $R > 90m$, the fair and cooperative scheme consumes less energy per bit than two conventional schemes since cooperative transmission can transmit data more reliably than direct transmission in long distance. Also, the fair and cooperative scheme does not generate unnecessary energy use which is used to just relay data of other nodes in the unfair and cooperative scheme. Hence, the fair and cooperative scheme has better performance than two conventional schemes when $R > 90m$.

V. CONCLUSIONS

In this paper, we suggested the efficient energy consumption method based on fair cooperative communication in a cluster-based WSN. The sensor tends to be selfish in a distributed network. Hence, by using the way that nodes help each other to transmit their data cooperatively, energy efficiency and fairness can be improved at the same time. Through numerical analysis and simulation results, it has been shown that the proposed scheme consumes much less energy than two conventional schemes. Furthermore, we have obtained the optimal radius of destination and source cluster to minimize energy consumption in the proposed system.

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