

A Cluster-based Cooperative Communication Architecture in Mobile Ad-hoc Wireless Sensor Networks with Rayleigh Fading Environments

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Abstract — In this paper, we propose a cluster-based Cooperative communication Architecture (Coop) in Mobile Ad-hoc Wireless Sensor Networks (MAWSN) with Rayleigh fading environments. The main features and contributions of this paper are as follows. First, the proposed Coop uses the clusters as underlying structures to support stable transmission services. Second, the proposed Coop uses the cluster-based cooperative communication to efficiently support packet delivery ratio with multi-hop power saving transmission. Third, we consider a realistic approach based on mobile ad-hoc nodes with sensing function as well as fixed sensor nodes in sensor fields while the conventional research for sensor networks focus on mainly fixed sensor nodes. Fourth, we present a theoretical analysis with outage probability for the proposed cooperative transmission. The performance evaluation is performed via simulation and analysis.

Keywords — Cooperative communications, Clustering, Network lifetime, Network stability, Mobile ad-hoc wireless sensor networks (MAWSN)

1. Introduction

Sensor networks [1] which is new family of wireless networks consist of a large number of sensor nodes that are densely deployed. In sensor networks, there are a wide range of applications areas [1] such as military, healthcare, and home networks. In military application, the rapid deployment, self-organization, and fault tolerance characteristics of sensor networks make them a very promising sensing technique for military command, control, communications, computing, intelligence, surveillance, reconnaissance, and targeting systems. In healthcare application, sensor nodes can also be deployed to monitor patients and assist disabled patients.

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Some other commercial applications include managing inventory, monitoring product quality, and monitoring disaster areas. However, sensor networks consist of hundreds to thousands of nodes that are designed for unattended operation. Therefore, unlike conventional networks the main goals of sensor networks are prolonging the lifetime of the network and prevent connectivity degradation through aggressive energy management as the batteries can not usually be replaced because of operations in hostile or remote environments. Realization of these applications of sensor networks requires mobile ad-hoc wireless sensor networks (MAWSN) techniques. MAWSN present dynamic, sometimes rapidly changing, random, multi-hop topologies and the mobile nodes communicate with each other over wireless links. In these environments, the stability of networks (routes) is one of the critical issues. However, there are no fixed infrastructures to support the stability of networks (routes) in MAWSN.

High energy utilization efficiency is a stringent design criterion for MAWSN since the batteries can not usually be replaced because of operations in hostile or remote environments. In addition, reliable communications over wireless channels which is a difficult problem due to fading is another requirement. A feasible solution is to take full advantages of idle sensor nodes, namely relays, in the vicinity of the transmitting node to relay the original signal to its destination. This not only benefits from path-loss reduction but also enables nodes to use each other's antennas to obtain an effective form of spatial diversity without the need for physical antenna arrays. Additionally, a constraint on node size which requires each sensor node to be equipped with single-antenna makes such a solution very appropriate in MAWSN scenario. The ways the idle sensor nodes process the signals received from a desired node are known as cooperative protocols. So far, there are three basic cooperative protocols, namely amplify-and-forward (AF), decode-and-reencode (DR) and decode-and-forward (DF). AF requires inter-user CSI (Channel State Information) available at the destination which is hard to obtain, and suffers noise enhancement at the relays that degrades bit error rate(BER) performance. DR

using convolutional codes, turbo codes and TCM (Trellis Coded Modulation) achieves the best performance among three protocols while it is so complicated in encoding and decoding. Thus, the DR is not so good for implementing on sensor nodes. DF appears to be a proper choice for cooperation in MAWSN because it demonstrates the lowest complexity (each receiver only needs CSI of the channel it is listening).

Therefore, we need an infrastructure to support the stability of networks (routes) as well as a transmission technique with high energy utilization efficiency for efficient power saving transmission in MAWSN. In this paper, we focus on the following issues such as network lifetime, and networks (routes) stability to support efficient packet delivery ratio(PDR) among recent issues [2,3,4] in the points of view of the MAWSN.

The rest of this paper is organized as follows. Section 2 presents the proposed cluster-based cooperative communication architecture. Section 3 presents a theoretical analysis for the proposed cooperative transmission. Finally, the paper is closed with the conclusion in section 4.

2. The Proposed Cooperative Communication Architecture

Figure 1 shows the basic concepts of the proposed cluster-based cooperative communication architecture.

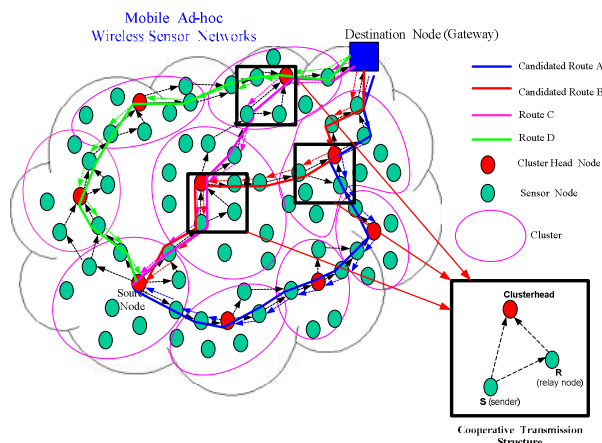


Figure1. The proposed cooperative communication architecture

The architecture consists of three parts as follows. **The first part** is the underlying clustering structure [5, 6] which can stably support both construction of routing routes and the cooperative transmission services together. This article [6] in detail explains the underlying clustering structure with the basic concepts and performance results. In this paper, we present just the basic concepts of the clustering structure. Figure 2 explains the basic concepts of the underlying clustering structure. In MAWSN, clustering [5,6] is the method which aggregate nodes into groups (clusters) to provide a convenient framework for the development of important features such as routing,

bandwidth allocation, mobility and topology management. The underlying clustering structure presented for supporting both construction of routing routes and cooperative transmission services is based on mobility concepts (individual mobility, group mobility) and the availability of position information via a reliable position locating system (i.e. GPS). The main idea of the clustering is to combine both physical and logical partitions of the network, as well as the concept of relative mobility in order to improve the stability in the clustered topology. In MAWSN, communications are often among teams which tend to coordinate their movements. This collaboration among members of the same team makes it possible to partition the network into several groups, each with its own mobility behavior. A group may consist of clusters that present similar mobility characteristics. Several groups can be hierarchically merged into one group depending on the mobility of each group. The presented underlying clustering algorithm in order to construct and maintain the various clusters consists of five steps such as mobility information dissemination, calculation of mobility metrics, initial (tentative) cluster construction, cluster merging, cluster maintenance/reconstruction. Finally, each constructed cluster consists of one cluster head and several mobile sensor nodes.

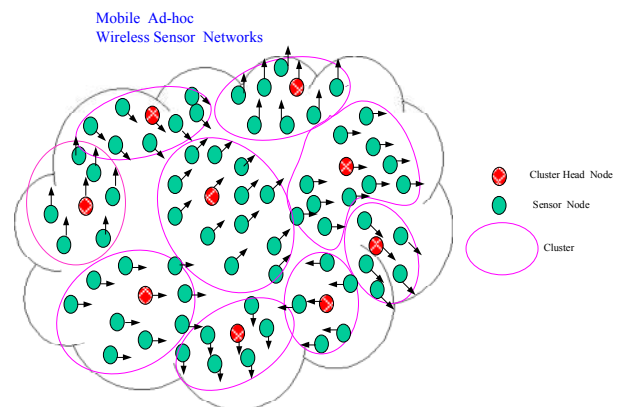


Figure2. The basic concepts of the underlying clustering structure to support cooperative communications efficiently.

The second part is the construction of routing routes which have mesh paths via cluster heads over the constructed clusters between a source node and a destination node (gateway).

The third part is the cooperative data transmission which uses the cooperative operation over the constructed routing routes. Figure 3 describes transmission scenarios for clustered wireless sensor networks while figure 4 illustrates the operation of the cooperative-aided data transmission over the routing routes.

3. The Theoretical Analysis

The proposed cooperative transmission protocol which is a typical communications protocol [7-10] is performed over the underlying clustering structure presented in the previous section 2. The underlying clustering structure consists of several clusters, each with its cluster head.

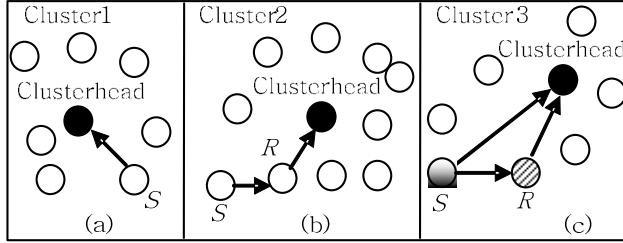


Figure 3. Transmission scenarios for clustered wireless sensor networks. (a) Direct-transmission., (b) Multi-hop transmission, (c) Cooperative transmission

The function of cluster heads is to assign the time on which sensor nodes can transmit data to them based on a TDMA (Time Division Multiple Access) approach and to aggregate data from nodes in their cluster before sending these data to the base station (i.e., gateway). Therefore, high energy dissipation in communicating with base station is spread to all sensor nodes in MAWSN. Let's consider certain clusters as shown in figure 3. The information sent from a sensor node can reach its cluster head in the following ways:

- **Direct transmission (see Figure 3(a)):** sensor node sends its data directly to the cluster head without the help of any intermediate nodes, namely relays.
- **Multi-hop transmission (see Figure 3(b)):** sensor node has to pass through several relays (i.e., intermediate nodes) before reaching the cluster head. The relay's role is to simply decode the data. The relay node receives the data from the preceding node and encode the message again prior to retransmission to the next node. The cluster head detects the original data only based on the signal received from the last node (nearest to the cluster head). It is known that this protocol can only extend range or save transmit power while it achieves no diversity gain (diversity order of 1).
- **Cooperative transmission (see Figure 3(c)):** This protocol is an extension of the multi-hop protocol where the receiver combines the data from the desired source node and all its relays instead of only from the last relay as for the multi-hop protocol. A wide variety of cooperative transmission protocols [7-10] were proposed. However, because majority protocols require the channel estimation, these protocols leads to an additional increase in information processing energy while they can still bring many advantages such as diversity gain, coverage extension, energy saving, etc. The maximum diversity order these protocols can achieve equals the total number of cooperating nodes.

3.1 System Model

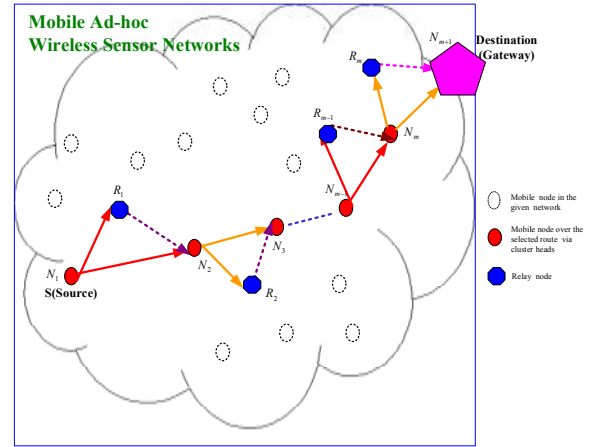


Figure 4. The system model of the cooperative transmission in the cluster-based mobile ad-hoc wireless sensor networks

We consider a mobile ad-hoc wireless sensor networks (MAWSN) that consists of clusters and has a selected route consisting of nodes $N_1, N_2, N_3, \dots, N_m, N_{m+1}$ via cluster heads as shown in figure 3. Where N_1 is a source node and N_{m+1} is a destination node. In each hop, there is a relay that assists the transmitting node to forward the information towards the next hop. Therefore, we exploit a cooperative diversity hop by hop.

Consider that the nodes are randomly distributed over the network area and the channels between two nodes are subjected to flat Rayleigh fading plus AWGN. Each node has a single half duplex radio and a single antenna. The baseband equivalent received signal at node j due to the transmission of node i for symbol n is given by

$$r_{i,j}(n) = \alpha_{i,j} s(n) + \eta_j(n) \quad (1)$$

where $\eta_j(n)$ is AWGN noise sample with variance $N_0/2$ per dimension at terminal j , $\alpha_{i,j}$ is fading coefficient between node i and j . $s(n)$ is the signal transmitted by node i .

We consider flat Rayleigh fading, hence $\alpha_{i,j}$ is modeled as independent samples of zero mean complex Gaussian random variable with variance $\sigma_{i,j}^2$ per dimension. The fading coefficients are constant over the channel coherent time. To take path loss in account, we can model the variance of channel coefficient between node i and j as a function of distance between two nodes [9] as

$$\sigma_{ij}^2 = d_{ij}^{-\beta} \quad (2)$$

where β is so called path loss exponent that varies from 2 to 6 on the basis of channel environment and d_{ij} is the distance between node i and j .

3.2 Outage probability analysis

In this paper, we focus on the end-to-end (source node-to-destination node) outage performance of the cooperative multi-hop scenario shown in figure 4. For hop i node N_i transmits data to node N_{i+1} with the help of relay R_i . We define the outage probability of hop i between two nodes, N_i and N_{i+1} , as

$$P_{out}(i) = \Pr[I(N_i, N_{i+1}) < R] \quad (3)$$

where $I(N_i, N_{i+1})$ is the mutual information between N_i and N_{i+1} , and R is the target rate of the system.

We consider the system fails to find a relay at hop i and a non-cooperative direct transmission (DT) has taken place between node N_i and N_{i+1} . Now, the outage probability of direct transmission can be given as

$$\begin{aligned} P_{out}^{DT}(i) &= \Pr[I(N_i, N_{i+1}) < R] = \Pr[\log(1 + \gamma |\alpha_{N_i, N_{i+1}}|^2) < R] \\ &= \Pr\left[|\alpha_{N_i, N_{i+1}}|^2 < \frac{2^R - 1}{\gamma}\right] \end{aligned} \quad (4)$$

where $\gamma = P/N_0$.

Now, we consider $\alpha_{i,j}$ has Rayleigh distribution, so $|\alpha_{i,j}|^2$ has exponential distribution with parameter $\sigma_{i,j}^{-2}$. Therefore, using the CDF of $|\alpha_{i,j}|^2$ we can easily calculate the outage probability of direct transmission as

$$P_{out}^{DT}(i) = 1 - \exp(-\sigma_{N_i, N_{i+1}}^{-2} \frac{2^R - 1}{\gamma}). \quad (5)$$

The relay will forward the information (data) when the received SNR at relay satisfies a predefined threshold. In this protocol, the relay will forward the received information if it satisfies the predefined rate R , otherwise it will be silent. The mutual information between N_i and N_{i+1} can be given as [7]

$$I(N_i, N_{i+1}) = \begin{cases} \frac{1}{2} \log(1 + \gamma |\alpha_{N_i, N_{i+1}}|^2); & I(N_i, R_i) < R \\ \frac{1}{2} \log(1 + \gamma [|\alpha_{N_i, N_{i+1}}|^2 + |\alpha_{R_i, N_{i+1}}|^2]); & I(N_i, R_i) \geq R \end{cases} \quad (6)$$

where $I(N_i, R_i)$ is mutual information between N_i and R_i , and given as

$$I(N_i, R_i) = \frac{1}{2} \log(1 + \gamma |\alpha_{N_i, R_i}|^2). \quad (7)$$

Since the two events in equation (6) is mutually exclusive, so the cooperative outage probability for hop i can be written as

$$\begin{aligned} P_{out}^{CT}(i) &= \Pr[I(N_i, N_{i+1}) < R] \\ &= \Pr[I(N_i, R_i) < R] \times P_{1,i} + \Pr[I(N_i, R_i) \geq R] \times P_{2,i} \end{aligned} \quad (8)$$

where $P_{1,i} = P_{out}^{DT}(i)$ represents the outage probability of direct transmission between node N_i and N_{i+1} , and $P_{2,i}$ is the outage probability of cooperative transmission between node N_i and N_{i+1} with the help of relay R_i , and given as

$$\begin{aligned} P_{2,i} &= \Pr\left[\frac{1}{2} \log(1 + \gamma \{|\alpha_{N_i, N_{i+1}}|^2 + |\alpha_{R_i, N_{i+1}}|^2\}) < R\right] \\ &= \Pr\left[|\alpha_{N_i, N_{i+1}}|^2 + |\alpha_{R_i, N_{i+1}}|^2 < \frac{2^{2R} - 1}{\gamma}\right]. \end{aligned} \quad (9)$$

Similar to equation (4) and (5), we can write the outage probability between N_i and R_i as

$$\Pr[I(N_i, R_i) < R] = 1 - \exp(-\sigma_{N_i, R_i}^{-2} \rho). \quad (10)$$

Therefore, we can obtain the success probability between N_i and R_i as

$$\Pr[I(N_i, R_i) \geq R] = \exp(-\sigma_{N_i, R_i}^{-2} \rho). \quad (11)$$

We will derive the end-to-end (ETE) (i.e., source node to destination node) outage probability (P_{out}^{ETE}) of our proposed cooperative transmission in the given MAWSN. We consider M -hops cooperative routing route while all the hops are independent. We assume L is a number of hops which has successfully selected a relay. Where L is a subset of M (i.e. $L \in M$). So, the end-to-end(ETE) outage probability (P_{out}^{ETE}) for the M -hops cooperative routing is simple multiplication of outage probability of each hop and can be given as

$$P_{out}^{ETE} = 1 - \prod_{i \in L} (1 - P_{out}^{CT}(i)) \prod_{j \notin L} (1 - P_{out}^{DT}(j)). \quad (12)$$

4. Performance Evaluation

4.1 Simulation Scenario and Frameworks

The performance evaluation of our protocol is accomplished via simulation using the Optimized Network Engineering Tool (OPNET) and analysis. A mobile ad-hoc wireless sensor networks(MAWSN) consisting of 50 nodes that are placed randomly within a rectangular region of 1 km x 1 km is modeled in the simulation. Each node is modeled as an infinite-buffer, store-and-forward queuing station, and is assumed to be aware of its position with the aid of a reliable position location system (i.e., GPS). The mobile nodes are assumed to have constant radio range of $Z=250\text{m}$. The radio range is used to construct a route and find the most stable relay at each hop of this route, but it is not used in data transmission over Rayleigh fading channel. We use the random mobility scenario, in which the speed and the direction of each move are uniformly distributed with speed range $[0, v_{\max}]$ km/h and direction range $[0, 2\pi]$ respectively. During the simulation, a node moves around the network and if a mobile arrives at the boundary of the given network coverage area, the node reenters into network.

4.2 Performance Metrics

The performance metrics for simulation and analysis are as follow:

- **PDR:** the ratio of the number of packets received at destination to the number of packets transmitted at source.
- **Outage Probability:** the probability that the system model is in outage.

4.3 Results of performance evaluation

In the analysis, we approximate as $PDR \approx 1 - P_{out}^{ETE}$. That is we compare the simulation results (PDR) with the analysis results (Outage Probability) in the same figures (Figure 5 – Figure 8) by using the equation (12) and the relationship $PDR \approx 1 - P_{out}^{ETE}$ ($PDR \approx 1 - \text{Outage Probability}$). Therefore, in the Figure 5 – Figure 8 all Coop(analys) present analysis results as $PDR \approx 1 - P_{out}^{ETE}$ ($PDR \approx 1 - \text{Outage Probability}$) while all coop(simulation) illustrate simulation results as just PDR.

Figure 5 and figure 6 show the packet delivery ratio (PDR) as a function of SNR when the value of mobility ($v_{\max}$) is fixed. As we can see in these figures, the simulation results and the theoretical results are very

similar. Also we can see the PDR of the proposed cluster-based **Cooperative communication (Coop)** increases when the SNR increases. However, we can see the PDR is not so much different according to the mobility in figure 5 and figure 6. The reason is that the radio range ($Z=250\text{m}$) is used to construct a route and find the most stable relay at each hop of this route, but it is not used in cooperative data transmission over Rayleigh fading channel.

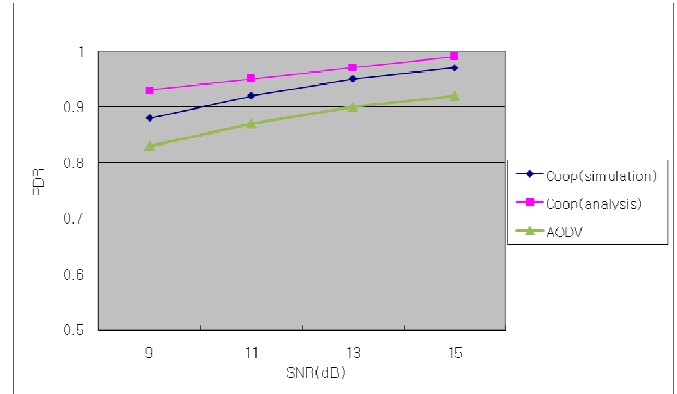


Figure5. Packet delivery ratio (PDR) as a function of SNR when the value of mobility is fixed ($v_{\max} = 20$ km/h)

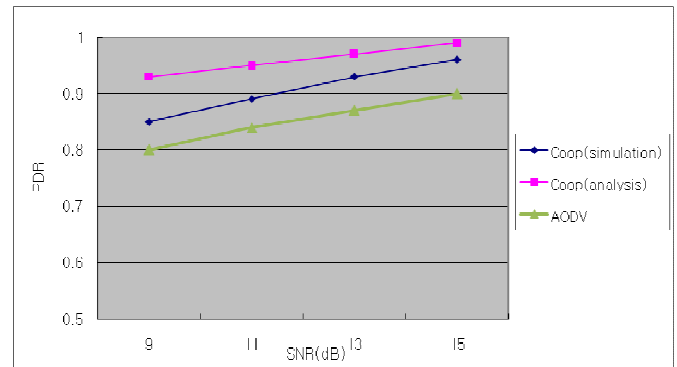


Figure 6. Packet delivery ratio (PDR) as a function of SNR when the mobility is fixed ($v_{\max} = 40$ km/h).

In the figure 7 and figure 8, we fix the SNR and show the PDR as the function of mobility. As we can see in these figures, the simulation results and the theoretical results are almost same. However, we can see the PDR of the cooperative data transmission decreases when the mobility increases while the PDR increases when the SNR increases.

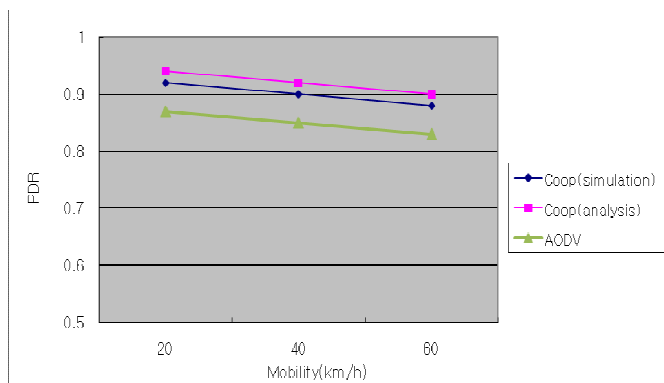


Figure7. Packet delivery ratio (PDR) as a function of mobility when the value of is fixed (SNR= 11dB).

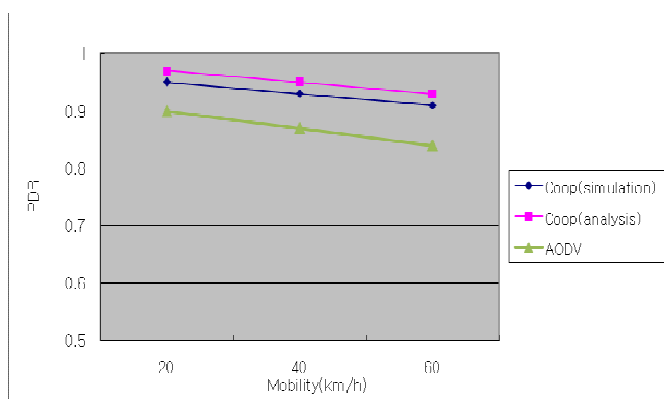


Figure 8. Packet delivery ratio (PDR) as a function of mobility when the value of SNR is fixed (SNR= 13dB).

5. Conclusion

In this paper, we propose a cluster-based **Cooperative** communication architecture (**Coop**) for mobile ad-hoc wireless sensor networks (MAWSN) with Rayleigh fading environments. The **Coop** uses the clusters as underlying structures to stably support both construction of routing routes and cooperative transmission services together. We consider a realistic approach based on mobile ad-hoc nodes with sensing function as well as fixed sensors in sensor fields while the conventional research for sensor networks focus on mainly fixed sensor nodes. We present a theoretical analysis with outage probability for the cluster-based cooperative transmission. In performance evaluation, we present packet delivery ratio (PDR) and outage probability respectively. We present PDR as a function of both SNR and mobility respectively, and compare the results of simulation and analysis. We can see the PDR increases with the increased SNR by using the cooperative transmission. From the comparison, we can see the results of simulation and analysis are very similar and the proposed cooperative communication architecture can efficiently support data transmission services with the increased SNR and prolong the network life-time in MAWSN.

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