Ad Hoc Networks 37 (2016) 389–403

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Node selection optimization for collaborative beamforming in wireless sensor networks

Geng Sun [a,b], Yanheng Liu [a,b], Jing Zhang [a,b], Aimin Wang [a,b,*], Xu Zhou [a,b]

[a] College of Computer Science and Technology, Jilin University. Changchun, Jilin 130012, China
[b] Key Laboratory of Symbolic Computation and Knowledge Engineering of Ministry of, Education, Jilin University. Changchun, Jilin 130012, China

ARTICLE INFO

Article history:
Received 11 February 2015
Revised 30 June 2015
Accepted 27 August 2015
Available online 16 September 2015

Keywords:
Wireless sensor networks
Circular arrays
Firefly algorithm
Beamforming

ABSTRACT

The communication distance and the energy of the nodes are limited in large-scale wireless sensor networks (WSNs). Collaborative beamforming is an effective way to solve such problem. However, the distribution of node location is not uniform, which leads to poor performance of the mainlobe and causes the high sidelobe level (SLL). This paper presents a novel collaborative communication method based on node selection optimization algorithm (NSOA). The method to calculate the optimal number of array nodes and to select the optimal array nodes for setting up a virtual antenna array are shown in NSOA. NSOA has the ability to select the CB nodes with optimal excitation amplitude and excitation phase by firefly algorithm to obtain the optimal radiation beampattern. In addition, energy consumption and communication delay of the nodes can be reduced. Simulation results show that the maximum SLL of the radiation beampattern obtained by NSOA is lower comparing with those obtained by the CCB and CSNA, meanwhile, the convergence rate of NSOA is faster than that of CCB. Compared with the traditional clustering routing algorithm, NSOA has advantages in terms of communication delay, energy consumption, and prolonging network lifetime.

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1. Introduction

Wireless sensor networks (WSNs) have been widely deployed in numerous fields because data are often required to be accurately sent to distant destinations. However, the transmit power and communication distance of individual nodes are restricted [1]; thus, the information will not be directly sent to the sink node. This phenomenon brings inevitable communication delay and serious energy imbalance through hop-to-hop communications, which is unacceptable for certain applications with high requirements of timely communication, such as disaster detection and battlefield environment [2]. Moreover, multiple data forwarding greatly increases the probability of data transmission failure and reduces the reliability of communication. Meanwhile, energy restriction is also a problem in WSNs. Thus, improving the energy efficiency of the nodes is very important [3].

Collaborative beamforming (CB) is an effective way to solve the aforementioned problems [1,2]. As the transmission power and the communication radius of single node are limited, it does not have sufficient power to communicate directly with the base station (BS). Therefore, sensor nodes form a virtual antenna array and the array nodes could directly communicate with the BS or the sink node using CB, thereby reducing communication delay. CB can improve the signal gain, reduce the energy consumption of the single node, and prolong the network lifetime. However, the distribution of node location is usually not uniform [4]. Huang conducted an analysis on CB performance with arbitrary distribution of the nodes and presented the similarities and differences of CB performance between the arbitrary node antenna array and the uniform node antenna array [5], such

* Corresponding author at: College of Computer Science and Technology, Jilin University. Changchun, Jilin 130012, China. Tel.: +8615044002282.
E-mail address: wang_ai_min@126.com (A. Wang).

http://dx.doi.org/10.1016/j.adhoc.2015.08.031
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as the beampattern and 3dB bandwidth. Ahmed et al. proposed an analysis of CB performance for WSN based on the Gaussian distribution, the complementary cumulative distribution function (CCDF) and 3dB bandwidth of the CB array are shown in research [6,7].

In CB, the performance of the mainlobe and the sidelobe level (SLL) of the beampattern are significantly affected by the array shape and the selection method of the array element. The position error of the nodes leads to a wide first null beam width (FNBW) and high SLL. Ref. [8] presented a novel array node selection algorithm that limits the maximum SLL. This algorithm shows the selection method of CB in multi-BS environment, but does not analyze the number of array nodes. Refs. [9,10] presented the node selection method of linear antenna array to reduce the maximum SLL. However, the optimal number of the array nodes is still undetermined. Ref. [11] presented the CB node selection algorithm in circular antenna array based on single BS networks. The locations of the nodes are optimized. The beampattern of the algorithm was also compared with the beampattern of uniform linear array (ULA) and circular sensors array (CSA). However, the amplitude of the excitation is not optimized simultaneously and the problem of optimal number of array element nodes is not considered. The algorithms in references [8–12] considered the optimization of the beampattern, but disregarded the energy of each node.

Energy saving is always the focus of WSNs because of the limited energy of a single node. Many clustering routing algorithms have been proposed to reduce the energy consumption of the nodes. The low energy adaptive clustering hierarchy algorithm (LEACH) [13] uses circular random clustering methods and each node has the opportunity to become a cluster head in rotation. However, LEACH assumes that each node has enough power to communicate with the BS by using single hop; this will cause huge energy consumption with the increase of distance between the cluster head and the BS. Actually, conventional sensor nodes do not have enough power to communicate with the BS by single hop, LEACH is not suitable for large-scale WSNs. Cross Unequal Clustering Routing Algorithm (CUCRA) [14] is a multi-hop communication mode algorithm and it is based on the idea of competition radius and the radius is considered with the energy factors, the competing radius is a variable and decreased with the reduction of the nodes' remaining energy. However, it will lead too much number of cluster heads and resulting in longer transmission delay.

The current paper analyzes the influence of array shape for the antenna array beampattern and shows the basis for selecting the circular antenna array. In addition, a novel node selection optimization algorithm (NSOA) is presented. This algorithm determines the optimal number of array nodes based on the energy. The excitation amplitude and excitation phase of the array nodes were optimized by firefly algorithm (FA) [15]. Compared with other CB algorithms, the mainlobe is narrow and the SLL is acceptable in this proposed algorithm. Moreover, the performance of communication delay and the network lifetime are better than the traditional clustering routing algorithm.

The rest of paper is organized as follows. Section 2 covers model and analysis. Section 3 shows a new method called node selection optimization algorithm. The simulations of the proposed algorithm and its analysis are shown in Section 4. Section 5 shows a discussion of heterogeneity of the environment of the links. Finally, conclusion of the paper and future research directions are given in Section 6.

2. Models

2.1. Network model

Several reasonable assumptions should be considered to facilitate the discussion. Considering the monitoring area is M_a and its size is A^2, M_a is randomly covered by the N isomorphic sensor nodes, and every node does not move after deployment. In addition, the network has the following characteristics:

(1) The nodes use omnidirectional antenna; the maximum excitation current is I_{max}; and I_{max} is adjustable.
(2) The nodes in the network are randomly deployed and each sensor node recognizes its own location coordinates.
(3) Every sensor node has similar perception radius R_s and communication radius R_c.
(4) The initial energy E_{intial} for each node is similar.
(5) Scattering and reflecting do not occur in the communication channel.
(6) The time synchronization problem for the nodes has been solved by a number of time synchronization algorithms [16].

2.2. Energy model

According to the characteristics of WSNs, energy consumption of band communication comprises majority of the whole network. This paper uses the energy consumption model according to Ref. [17–19]:

$$E_{node} = \begin{cases} kE_{elec} + k\varepsilon_{fs}d^2), d < d_0 \\ kE_{elec} + k\varepsilon_{amp}d^4), d \geq d_0 \end{cases} \tag{1}$$

where E_{elec} is the electronics energy that depends on factors, such as digital coding; k is the bit number. ε_{fs} and ε_{amp} denote the amplifier energy that depends on the required receiver sensitivity and the receiver noise figure, respectively; and d is the distance between the two nodes. If d is relatively shorter than the threshold d_0, propagation loss can be modeled as a free-space model. By contrast, if d is greater than or equal to the threshold d_0, propagation loss can be modeled as a multi-path attenuation model. This paper assumes that scattering and reflecting do not occur on the entire communication channel; thus, the channel only uses the following free-space model [17]:

$$E_{node} = kE_{elec} + k\varepsilon_{fs}d^2 \tag{2}$$

2.3. Analysis of antenna array model

2.3.1. Analysis of array shape

The shapes of antenna arrays are usually rectangular, square, hexagonal, and circular. For example, the part wherein a square array cuts down the outer part of the inscribed circle can be observed in a circular antenna array.

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