A new hierarchical beam search algorithm for wireless ad hoc networks in multipath channel scenario

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ABSTRACT

For the beam search algorithms proposed by some existing literatures cannot always find the global optimal beam in multipath channel and the single communication link may easily be broken, the node at the edge of a wireless ad hoc network will encounter a temporary outage problem, which means it will be isolated from the network. To solve this problem, we propose a new hierarchical beam search algorithm which can be performed on some marginal nodes. The algorithm will take advantage of the multipath channel and find some available communication beams together with the global optimal beam. The main idea of our algorithm is to increase the opportunity to find multiple local optimal beams. The selected number of beams at each level is greater than or equal to the number of paths. In last level, we selectively delete beams and then obtain a plurality of local optimal beams which can be alternative communication beams for the marginal node. Furthermore, we can also get the global optimal beam simultaneously, which are included in these local optimal beams. The simulation results show that, comparing with the exhaustive search algorithm, it has almost the same success rate, but lower search complexity to get a number of alternative beams. Comparing with binary search algorithm, the proposed algorithm has higher success rate to find the global optimal communication beam in multipath environment.

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1. Introduction

Wireless ad hoc network is self-organized without relying on any external infrastructure [1, 2]. It has found a wide range of applications in data collection, military, disaster relief, and law enforcement applications, etc. In such networks, one of the fundamental requirements is connectivity among all nodes. A node pair is usually connected with each other directly or via multi-hop through intermediate nodes.

With the wide application of wireless communication technology like ad hoc networks, the millimeter-wave technology which can achieve Gbps data rate has received widespread attention. There will be a great potential of adopting millimeter-wave technology in ad hoc networks to obtain better performance in the future. However, the millimeter-wave communication system must overcome the problem of high propagation path loss in high frequency band [3]. Fortunately, it is suitable to adopt large scale antenna and utilize the tech of beam-forming to achieve link budget [4]. Recently, different beam-forming schemes which have been proven as a promising solution to improve the performance of the networks are proposed in some literatures. Those schemes adopt narrow beam pattern which can focus most energy of the signal and reduce the interference between each communication link. Given these advantages of beam-forming, the ad hoc networks’ connectivity, hop distance and capacity will be positively affected.

For wireless ad hoc networks, neighbor discovery (ND) is an essential process to realize self-organization [5, 6]. But after the ad hoc network has been set up successfully through the ND management procedures, the temporary outage problem is its major defect. That is to say a node at the edge of ad hoc network will be isolated when its communication link is blocked for a while. We will talk about its shortcoming and give a solution with analog beam-forming technology in this paper.

The analog beam-forming technology based on coherent antenna array have been successfully applied on IEEE 802.15.3c and IEEE 802.11ad [7, 8]. Since analog beam-forming technology is essentially a problem of beam search, it searches for suitable beam by switching detection based on a fixed codebook. The beam search algorithms of the above standards are based on two phase traversal search strategy. Comparing to the exhaustive search algorithm, they reduce the complexity of beam search to a certain degree. However, these algorithms will also cost much time with the increase of codebook because such algorithm based on traversal search will still be affected by the dimension of the codebook.

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The papers [9,10] model the search problem as two-dimensional numerical optimization problem, and use the modified Rosenbrock or Powell algorithm to decrease the complexity. The papers [11,12] propose a binary search algorithm which give a further cut of the complexity.

Actually, the above mentioned algorithms [9,10,11,12] are essentially belong to hierarchical beam search strategy, and those algorithms are only suitable for the single path channel. The single path channel means a path's energy is far greater than that of other paths. In other words, the beam searched by those algorithms isn't likely to be optimal in multipath scenario. But the reality channel is usually multipath [13,14,15], so the link selected in multipath scenario may be vulnerable since its channel gain isn't strong enough. Furthermore, single communication path may easily be broken by various interference in real environment. Then it will bring a temporary outage problem as said before. So, this paper designs a new hierarchical search strategy to find several available beams for the networks. In the meanwhile, it also contains the optimal communication beam in the found beams. Then, even though the global optimal link is blocked, we can adopt another beam. Thus it can keep connectivity among all nodes. On the other hand, the new strategy also solves the issues that the beam search algorithms proposed by some existing literatures cannot be applied to multipath channel.

The rest of this paper is organized as follows. In Section 2, a geometric channel model is presented. In Section 3, a new beam search algorithm is introduced in detail. In Section 4, performance evaluation is given.

2. Channel model

In order to be able to take advantage of the millimeter wave technology, node devices in ad hoc networks can replace the original omnidirectional antenna system with smart antenna system. Comparing to omnidirectional antenna system, smart antenna technology enhances the overall performance significantly for ad hoc networks by increasing a certain complexity and hardware cost.

This paper will adopt the geometric channel model which is also adopted in papers [13,14,15]. Moreover, a linear array antenna system is considered too. Due to the extremely short wavelength, the multipath components in millimeter-wave communication system are mainly composed of direct path and reflected path when we don't consider the scattering and diffraction components. The channel model and antenna structure are shown in Fig. 1.

The channel matrix $H$ of this model can be expressed as

$$H = \sqrt{N_x N_y} \sum_{l=1}^{L} \alpha_l g(\phi_l) h(\theta_l)^{\dagger}$$

where $(\cdot)^{\dagger}$ is the conjugate transpose operation, $N_x$ and $N_y$ are the number of transmitter and receiver respectively, $L$ is the number of multipath component, $\alpha_l$ is the complex gain of path $l$, $\alpha_l$ conforms to Complex Gaussian distribution, $\theta_l \in [0, 2\pi]$ and $\phi_l \in [0, 2\pi]$ are the angle of arrival and departure, $g(\phi_l)$ and $h(\theta_l)$ represent steering vector functions for transmitter and receiver respectively. In this paper, we consider the system with half-wave spaced uniform linear arrays. The steering vector can be written as

$$g(\phi) = \frac{1}{\sqrt{M}} \left[ 1, e^{j(2\pi \phi_1)/d}, e^{j(2\pi \phi_2)/d}, \ldots, e^{j(2\pi \phi_{M-1}/d)} \right]$$

where $d$ is the space between two antenna elements, $\lambda$ is the wavelength of signal. $h(\theta_l)$ can be written as a similar fashion.

We also use $W_t$ and $W_r$ to represent the codebook of transmitter and receiver respectively, $W_t$ and $W_r$ represent the corresponding beams. When transmitter transmits training sequence $x$, the receive signal of receiver can be expressed as

$$y = \sqrt{N_x N_y} W_t^H H W_r x + W_r^H n$$

where $n$ is the normalized white Gaussian noise vector. The received signal-noise-ratio (SNR) can be expressed as

$$\gamma = \frac{\|\sqrt{N_x N_y} W_t^H H W_r x\|^2}{\|W_r^H n\|^2}$$

We suppose there are $L$ paths. Taking the impact of multipath into account, this paper’s purpose is to find multiple available communication beams and globe optimal beam for ad hoc networks.

3. The proposed beam search algorithm

3.1. Temporary outage problem in ad hoc networks

After the ad hoc network is set up successfully, then all nodes in the network can perform data transmissions by using the millimeter wave band with smart antenna. However, when a node pair’s distance is so far that one node moves within a range which can still be treated as in the scope of the communication beam pattern’s main lobe. Then, the communication link between the two nodes will be broken when a node is moving behind an obstacle, or some objects are moving to the middle of the link. In a word, we can think that there is an obstacle between the link. At this time, the node will be possibly isolated from the rest of the node devices if it’s at the border of network and there are not any more neighborhoods around it. For example, node $A$ and $B$ in Fig. 2 may easily be separated from the network.

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