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ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 12 (10): 2023-2029, 2013
ISSN 1812-5638 / DOI: 10.3923/itj.2013.2023.2029

Multicast Capacity of Multi-channel Multi-radio Wireless *Ad Hoc* Networks

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Abstract: The asymptotic multicast capacity of multi-channel multi-radio wireless *ad hoc* networks is discussed. An upper bound and lower bound of multicast capacity of multi-channel multi-radio wireless *ad hoc* networks which randomly and uniformly deployed in a square with unit area is derived. A concrete MAC and routing mechanism which can make the lower bound of multicast capacity feasible is designed. Especially, when the ratio of number of radio to number of channel is a constant, this paper shows that the upper bound and lower bound of multicast capacity has the same order, which is the same as the multicast capacity of single-channel single-radio wireless *ad hoc* networks.

Key words: Capacity, multicast, wireless *ad hoc* networks, multi-channel multi-radio

INTRODUCTION

Wireless *ad hoc* Networks are a type of wireless communication networks composed of dynamic networking nodes without any infrastructure. Compared with other communication networks, the wireless *ad hoc* network is characterized by distributed, limited bandwidth, unstable link and dynamic topology structure. These make the theoretical researches on wireless *ad hoc* network's capacity much more difficult than other communication networks. Gupta and Kumar (2000) firstly studied the static asymptotic capacity of wireless *ad hoc* networks. For a wireless network which composed of n static wireless network node distributed in the unit circle with a shared bandwidth W, if the wireless network node chooses the optimal position, the optimal flow distribution, the optimal transmission range (This network model can also be called the random wireless network), then under protocol model, the network can get the transmission capacity of $\Theta(W\sqrt{n})$ bit m/s; under physical model, the authors demonstrated that there are constants c, c′ so that the transmission capacity of $cW\sqrt{n}$ bit m sec^{-1} is feasible, while that of $c'Wn^{\frac{\alpha-1}{\alpha}}$ bit m sec^{-1} is infeasible, where α is the wireless transmission link's path attenuation factor. If the network is randomly and uniformly distributed in the unit circle (This network model can also be called the wireless random network), then under the protocol model, its capacity is:

$$\Theta\left(\frac{W\sqrt{n}}{\sqrt{\log n}}\right)$$

under the physical model, the capacity's upper bound is $O(\sqrt{n})$ and the lower bound is:

$$\Omega\left(\sqrt{\frac{n}{\log n}}\right)$$

With the concept of mutually exclusive domain, Agarwal and Kumar (2004) improved the transmission capacity upper bounds of random wireless network in the unit circle to:

$$\sqrt{\frac{8}{\pi}}\frac{W\sqrt{n}}{\sqrt{(1+\Delta)\sqrt{\Delta}\sqrt{2+\Delta}}}$$

bit m sec^{-1}; with the method of oval configuration, they improves the transmission capacity lower bounds to:

$$\sqrt{\frac{1}{\pi}}\frac{W\sqrt{n}}{\sqrt{(1+\Delta)\sqrt{\Delta}\sqrt{2+\Delta}}}$$

bit m sec^{-1}. Grossglauser and Tse (2002) and Diggavi *et al.* (2005) proved the movement of node, even the one-dimensional movement, can increase the network capacity to O (n). Keshavarz-Haddad *et al.* (2006) studied the wireless random network's transmission capacity and proved that the total wireless random network's transmission capacity is:

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$$\Theta\left(\frac{W}{\max\left(1,\Delta^{d}\right)}\right)$$

where, Δ, d are interference parameter and dimension of space. Li etc. firstly studied the multicast capacity of wireless random network. Li *et al.* (2007) gave an upper bound for wireless random network's multicast capacity and designed the multicast routing mechanism which based on idea of the "Comb Structure" so that the network can realize the multicast capacity in the same order with the upper bounds. Different from Li *et al.* (2007) and Shakkottai *et al.* (2007) studied the large scale wireless random network's multicast capacity. They proved that when a multicast session's destination node is:

$$k = O\left(\frac{n}{\log n}\right)$$

the network total multicast capacity is:

$$\Theta\left(\sqrt{\frac{n}{\log n}}\frac{W}{\sqrt{k}}\right)$$

when a multicast session's destination node is:

$$k = \Omega\left(\frac{n}{\log n}\right)$$

the network total multicast capacity is Θ (W). However, all the above results are derived under the condition that each network node is equipped with only one radio.

Nowadays, with the development of radio technology, a network node may be equipped with multiply wireless network radios. And there are multiply orthogonal channels which can be used by wireless network. Some researchers studied the multi-channel multi-radio wireless radio network's asymptotic capacity. Kyasanur and Vaidya (2005) analyzed the impact of the number of channel and radio to the network asymptotic capacity. Bhandari and Vaidya (2007a) analyzed the multi-channel multi-radio random wireless network's capacity with the limited radio. However, these researches are mainly focused on the network's unicast capacity.

The present study will discuss the multicast capacity of multi-channel multi-radio wireless *ad hoc* networks. For multi-channel multi-radio wireless *ad hoc* networks which randomly and uniformly deployed in a square with unit area, an upper bound and lower bound of multicast capacity of these networks are derived and a concrete MAC and routing mechanism which can realize the lower bound of multicast capacity is designed.

NETWORK MODEL

Suppose n wireless network nodes are randomly and uniformly deployed in a square with unit area, the set of all the wireless network nodes are denoted by $V = \{v_1, v_2, ..., v_n\}$. Each wireless network node is a source node of a multicast stream. From the remainder n-1 nodes, each multicast stream randomly chooses k-1 ($2 \le k \le n$) nodes as the destination nodes. Since each multicast source node can randomly select k-1 destination nodes from the other n-1 nodes, one network node may be the destination node of several multicast streams. From (Shakkottai *et al.*, 2007), the maximum number of multicast streams which choose a specific network node as destination node is:

$$\Theta\left(\frac{\log n}{\log\log n}\right)$$

with high probability. Suppose the number of available channel in the whole wireless network is c ($c \ge 1$), the total available bandwidth is W, if the bandwidth is equally distributed among several channels, then each wireless channel's bandwidth is $\frac{W}{c}$. Each wireless network node is equipped with m ($1 \le m \le c$) network interfaces, which enable the wireless network nodes can use several channels simultaneously to transmit or receive data. This study suppose that each network interface can transmit or receive data through each channel. The study use (m, c)-wireless network to represent this type of wireless network with c channels and m interfaces in each node. Suppose that all the network nodes in the wireless network have the same transmission range r. This study uses the protocol model (Gupta and Kumar, 2000) to describe the mutual interference in transmission, that is, each mode v_j can successfully receive the node v_j's message in channel l, if $d(v_i, v_j) \le r$ and the other transmission node v_k in use of channel l meet the conditions of $d(v_k, v_j) \ge (1+\Delta)\, d(v_i, v_j)$, $\Delta > 0$ where $d(v_i, v_j)$ denotes the Euclidean distance between node V_i and node V_j and Δ is a fixed constant.

Suppose each multicast stream's source node v_i sends data to all the destination nodes with the same speed $\lambda_k(n)$, limited by the wireless node's transmission capacity, the data sent by the multicast streams may be transmitted to the destination nodes by means of the multi-hop and store-forward. If there is a space-time scheduling which enable the data sent by each multicast stream's source node can be received by the corresponding destination with a high probability, then $\lambda_k(n)$ is said to be feasible. Because the network's node is randomly distributed and the destination node is randomly chosen, the network's multicast capacity is a random variable. Next definition precisely characters the each node's multicast capacity:

Definition: For any random wireless networks, if there are certain constant c>0 and c<c′<∞ satisfies:

$$\lim_{n\to\infty}\Pr\left(\lambda_k(n)=cg(n)\text{ is feasible}\right)=1,\liminf_{n\to\infty}\Pr\left(\lambda_k(n)=c'g(n)\text{ is feasible}\right)<1$$

then the order for each node's multicast capacity in random wireless network is defined as $\Theta(g(n))$.

This study adopts the following asymptotic symbols: $f(n) = O(g(n))$ means there are constant d and positive integer N, for n>N, there is $f(n)\le dg(n)$; $f(n) = \Omega(g(n))$ means $g(n) = O(f(n))$; $f(n) = \Theta(g(n))$ means $f(n) = O(g(n))$, $g(n) = O(f(n))$.

UPPER BOUNDS FOR MULTICAST CAPACITY

This part will discuss the upper bounds multicast capacity of the multi-channel multi-radio wireless *ad hoc* network. Firstly a result about the length of Euclidean Steiner optimal tree is introduced:

Lemma 1 (Shakkottai *et al.*, 2007): For k nodes which randomly and uniformly distributed in the unit square, the length of Euclidean Steiner optimal tree which connects the k nodes is $o(\sqrt{k})$ with high probability, that is when k∞→, the probability of the length of Euclidean Steiner optimal tree is $o(\sqrt{k})$ convergence to 1.

The following theorem gives an upper bound of multicast capacity of (m, c)-wireless network.

Theorem 1: For static (m, c)-wireless network which composed of n wireless network node randomly and uniformly distributed in the unit area square, if each wireless network node is a multicast stream's source node and each multicast stream has k different random selected destination node, then each node's multicast capacity is:

$$O\left(\frac{Wm}{c\sqrt{k}}\sqrt{\frac{1}{n\log n}}\right)$$

with high probability.

Proof: Suppose the transmission of nodes be synchronous and time-slot. Without loss of generality, this study suppose that each time slot's width is 1 second and the rate of each multicast source node is $\lambda_k(n)$ bit sec^{-1}. Considering a bit b which is sent by multicast source node i, suppose the hop needed for b to reach all the multicast destination nodes is $H_i(b)$, then the hop for all the bits to arrive their corresponding destination nodes is $\sum_{i,b} H_i(b)$. These bits must arrive at all the multicast destination nodes in the limited time T. Suppose each bit data b from the multicast source nodes to all the multicast destination nodes undergoes the hop H (b) with high probability, since each network node's transmission radius is r, by Lemma 1, H (b) satisfies:

$$H(b)=\Theta\left(\frac{\sqrt{k}}{r}\right)$$

with high probability. Since the selection of the node's transmission radius r must guarantee the network's connectivity, similar to Gupta and Kumar (2000):

$$r>\sqrt{\frac{\log n}{n}}$$

is chosen to ensure the network be connected with high probability. Based on the protocol model and the method similar to Gupta and Kumar (2000), the number of node pair in the network which can transmit synchronously must satisfy:

$$S\le\frac{4}{\pi\Delta^2r^2}$$

Because there are m ($1\le m\le c$) network radios in each node and each wireless channel's network bandwidth is $\frac{W}{c}$, the transmitted data for each node in a time-slot is not more than $\frac{Wm}{2c}$. As the data sent by multicast source node must be transmitted to all the multicast destination node within the limited time T, so:

$$\lambda_k(n)TnH(b)\le TS\frac{Wm}{2c}$$

Therefore:

$$\lambda_k(n)\le\frac{2Wm}{nc\pi\Delta^2H(b)r^2}=\kappa\frac{Wm}{nc\sqrt{k}}\sqrt{\frac{n}{\log n}}=\kappa\frac{Wm}{c\sqrt{k}}\sqrt{\frac{1}{n\log n}}$$

where, κ is a constant.

The network's multicast capacity is also restricted by the multicast destination node's acceptability. Since each node's has not more than:

$$\Theta\left(\frac{\log n}{\log\log n}\right)$$

multicast stream destination node with high probability and each node's acceptability is $\frac{Wm}{c}$ bit sec^{-1} and since each node has:

$$\Theta\left(\frac{\log n}{\log\log n}\right)$$

inflow multicast stream, each multicast stream's rate is:

$$O\left(\frac{Wm}{c\sqrt{k}}\sqrt{\frac{1}{n\log n}}\right)$$

with high probability.

As 2≤k≤n, when n is large enough, so:

$$\sqrt{\frac{1}{kn\log n}} \le \frac{\log\log n}{\log n}$$

therefore each multicast stream's rate is:

$$O\left(\frac{Wm}{c\sqrt{k}}\sqrt{\frac{1}{n\log n}}\right)$$

with high probability .

Especially, when $\frac{m}{c} = \Theta(1)$, then λ_k (n) is:

$$O\left(\frac{W}{\sqrt{k}}\sqrt{\frac{1}{n\log n}}\right)$$

with high probability, which is the same order with upper bounds for each node's multicast capacity when each node is only equipped with one network radio shown by Li *et al.* (2007).

THE LOWER BOUND OF MULTICAST CAPACITY

In the previous section, an upper bound of multicast capacity for the multi-channel multi-radio wireless *ad hoc* network is given and this part will derive a lower bound of multicast capacity for the multi-channel multi-radio wireless *ad hoc* network. Firstly, a Lemma is introduced:

Lemma 2 (Bhandari and Vaidya, 2007a): Suppose m, c is positive integers, the network capacity for (m, c)-wireless network can arrive at least of $\frac{1}{2}$ capacity of the $\left(1,\left\lfloor\frac{c}{m}\right\rfloor\right)$-wireless network.

Hence in the following constructive process, (1, c)-wireless network is merely concerned, whose conclusion can be extended to the general (m, c)-wireless network through lemma 2. Firstly the straight line parallel to the side of the square is introduced in order to divide the unit area square into small square units with the area of:

$$a(n) = \frac{100\log n}{n}$$

so there are $\left\lceil\frac{1}{a(n)}\right\rceil$ small square units. For such small square units, Kyasanur and Vaidya proved the following lemma:

Lemma 3 (Bhandari and Vaidya, 2007b): If:

$$a(n) \ge \frac{50\log n}{n}$$

then each small square unit has Θ (na (n)) network nodes with high probability.

So the selection:

$$a(n) = \frac{100\log n}{n}$$

satisfy the condition of lemma 3, which ensure each small square unit has Θ(log n) network nodes with high probability. Suppose each network node's transmission radius r (n) is:

$$\sqrt{\frac{500\log n}{n}}$$

then the selected transmission radius can guarantee the network is connected with high probability. With the method of Manhattan multicast routing algorithm in Li *et al.* (2007), a multicast tree which include the multicast source nodes and all of their destination nodes is constructed. The Manhattan routing algorithm can be described as follows:

Manhattan multicast routing algorithm:

Denote the set of the multicast source node v_i and all the k-1 destination node as U_i. Based on lemma 11 in Li *et al.* (2007), an Euclidean minimum spanning tree connecting all the nodes in U_i is constructed. Denote the obtained Euclidean minimum spanning tree as EMAST (U_i)

- For any link uv in EMAST (U_i), find a corresponding Manhattan path uωv to connect the nodes u and v. By the network's connected dominating set, connectu, u, ω and ω, v with the shortest path
- If the above procedures can't form a tree, then remove all the nodes excluding U_i. Denote the finally multicast tree corresponding to U_i as MT (U_i)

For the above Manhatten multicast routing algorithm, Li *et al.* (2007) has proved the following conclusions:

Lemma 4 (Li *et al.*, 2007): If each multicast source node employs the Manhattan multicast routing algorithm, then the number of the multicast stream which passes each small square unit is $O(\sqrt{kn\log n})$ with high probability.

Since there are $O(\sqrt{kn\log n})$ network nodes in each small square unit with high probability and $O(\sqrt{kn\log n})$

multicast streams which passes each small square unit with high probability, By the method of TDMA, a multicast scheduling and network channel allocated mechanism can be designed in order to achieve the lower bound of multicast capacity. Firstly in order to make the multicast stream uniformly distributed in each small square unit, the following multicast stream allocation mechanism is adopted: For any multicast stream starting from a small square unit, this study allocate the multicast source node to this multicast stream; for any multicast stream ending in a small square unit, the multicast destination node will be allocated to the multicast stream; for the multicast stream relaying in each small square unit, each multicast stream will be uniformly allocated to the node with the least allocated multicast stream up to now. In each small square unit there are Θ (log n) wireless network nodes with high probability and there are no more than $O\left(\sqrt{kn\log n}\right)$ multicast streams passing the small square unit with high probability. By the above multicast stream allocated mechanism, then each network node has:

$$O\left(\sqrt{k}\frac{\sqrt{n}}{\sqrt{\log n}}\right)$$

multicast stream as its relay node with high probability. Besides, since each node is a multicast stream source node and there are:

$$\Theta\left(\frac{\log n}{\log\log n}\right)$$

multicast destination node with high probability, from the above multicast stream allocated mechanism, the number of mostly allocated multicast stream in each small square unit is:

$$1+\Theta\left(\frac{\log n}{\log\log n}\right)+O\left(\sqrt{k}\frac{\sqrt{n}}{\sqrt{\log n}}\right)=O\left(\sqrt{k}\frac{\sqrt{n}}{\sqrt{\log n}}\right)$$

With the help of Manhattan multicast routing algorithm and multicast stream allocated mechanism, a multicast routing graph is constructed. The vertex of multicast routing graph is the network node in the wireless network. For any network node A or B in the graph, each multicast stream flowing from A to B can be represented by a edge linking A and B in the multicast routing graph. Since there maybe several multicast streams flowing from network node A to B, the obtained multicast routing graph is multi-graph. From the analysis on multicast stream allocated mechanism, each node's degree is:

$$O\left(\sqrt{k}\frac{\sqrt{n}}{\sqrt{\log n}}\right)$$

with high probability in the multicast routing graph. From the Edge Colouring Theory in (Bondy and Murty, 1976), the obtained multicast routing graph's edge colouring is:

$$O\left(\sqrt{k}\frac{\sqrt{n}}{\sqrt{\log n}}\right)$$

with high probability. Since each network node has only one network rado, one time-slot can be divided into:

$$O\left(\sqrt{k}\frac{\sqrt{n}}{\sqrt{\log n}}\right)$$

sub time-slot.(It is called the Edge Colouring Time-slot). Therefore, when the edge colouring time-slot's width is:

$$\Omega\left(\frac{1}{\sqrt{k}}\sqrt{\frac{\log n}{n}}\right)$$

which enable the multicast stream flowing into or out of one node to transmit at least in one edge colouring time-slot.

Since the synchronous transmission in the vicinity of nodes may interfere with each other. In order to avoid the mutual interference, an interference graph is constructed. The vertex of interference graph is also the wireless network's network node. If the two networks nodes' synchronous transmission can result in interference, there is an edge between the two nodes in the interference graph. Suppose each node's transmission range to be:

$$\sqrt{\frac{500\log n}{n}}$$

and the small square's edge to be:

$$\sqrt{\frac{100\log n}{n}}$$

with the method of lemma 4 in Gupta and Kumar (2000), there are at most constant small square units to interfere. Since each small square unit has Θ (log n) network nodes with high probability, each network node at most is associated with O (log n) edges in the interference graph, that is, the interference graph's maximum degree is Θ (log n) with high probability. From the graph's vertex colouring theory, the vertex colouring number of a graph with maximum degree d is at most d+1. Thus the vertex colouring number of interference graph is O (log n) with high probability, i.e. there is a constant t such that the interference graph can be vertex colouring with t100 log n colours. Since each edge colouring time slot can be divided into:

$$\left\lceil \frac{100t\log n}{c} \right\rceil$$

smaller time slot (vertex colouring time slot), such that the vertex with colouring number p ($1 \le p \le 100t \log n$) transmission data by using of (p mod c)+1 channel during the $\left\lceil \frac{p}{c} \right\rceil$ vertex colouring time slot. Since the length of each edge colouring time slot is:

$$\Omega\left(\frac{\sqrt{100\log n}}{\sqrt{kn}}\right)$$

and each edge colouring time slot partition into:

$$\left\lceil \frac{100t\log n}{c} \right\rceil$$

vertex colouring time slot, the length of each vertex colouring is:

$$\Omega\left(\frac{\sqrt{100\log n}}{\sqrt{k}\sqrt{n}\left\lceil \frac{100t\log n}{c} \right\rceil}\right)$$

with high probability. By the construction of multicast routing graph and multicast interference graph, then each network node can successful transmission data by a channel during a vertex colouring time slot. Since the capacity of each channel is $\frac{W}{c}$, the multicast capacity of wireless network is:

$$\Omega\left(\frac{W\sqrt{100\log n}}{\sqrt{k}\sqrt{n}c\left\lceil \frac{100t\log n}{c} \right\rceil}\right)$$

with high probability. Since:

$$\left\lceil \frac{100t\log n}{c} \right\rceil \le \frac{100t\log n}{c} + 1$$

the multicast capacity of per network node is:

$$\Omega\left(\frac{\sqrt{100\log n}}{\sqrt{k}\sqrt{n}\,(100t\log n + c)}\right)$$

with high probability. With reference to lemma 2, the following theorem is obvious:

Theorem 2: For the (m, c)-wireless network whose nodes are randomly and uniformly distributed in the unit square, the multicast capacity of each node is:

$$\Omega\left(\frac{\sqrt{100\log n}\,c}{\sqrt{k}\sqrt{n}\,(100t\log nc + m)}\right)$$

with high probability, where t is a constant.

Especially, when $\frac{m}{c} = \Theta(1)$, then each node's multicast capacity is:

$$\Omega\left(\frac{W}{\sqrt{k}\sqrt{n\log n}}\right)$$

with high probability in (m,c)-wireless network, which in correspondence with the upper bound of multicast capacity of each node under the occasion of $\frac{m}{c} = \Theta(1)$. Thus when $\frac{m}{c} = \Theta(1)$, the each node's multicast capacity of (m, c)-wireless random network is:

$$\Theta\left(\frac{W}{\sqrt{k}\sqrt{n\log n}}\right)$$

CONCLUSION

This study studies the asymptotic multicast capacity of multi-channel multi-radio wireless *ad hoc* network. An upper bound of multicast capacity for the static randomly and uniformly distributed multi-channel multi-radio wireless *ad hoc* network within a unit square is derived and a MAC and routing mechanism to realize the throughput:

$$\Omega\left(\frac{\sqrt{100\log n}\,m}{\sqrt{k}\sqrt{n}\,(100t\log nc + m)}\right)$$

with high probability in the (m, c)-wireless an hoc network is designed. Especially, when $\frac{m}{c} = \Theta(1)$, a tight bound:

$$\Theta\left(\frac{W}{\sqrt{k}\sqrt{n\log n}}\right)$$

for the (m, c)-wireless network is got, which is in the same order with multicast capacity of the single channel single radio wireless network. This has proved that if there is not a big difference between the number of radios and the number of channels in the network, each network node's multicast capacity won't cause great damage. The further researches include the multicast capacity of multi-channel multi-radio wireless *ad hoc* network's with the limited radios, the impact of moving nodes to multicast capacity and multicast capacity in the information theory.

ACKNOWLEDGMENTS

This work is supported in part by Shandong Science and Technology Research Plan (No.2011GGX10114) and by ChunLei Program of Shandong University of Science and Technology.

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