This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2010 proceedings.

A Novel Stability Weighted Clustering Algorithm for Multi-hop Packet Radio Virtual Cellular Network

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Abstract—**Cooperative communications exploit the spatial diversity inherent in multiuser system by allowing cooperation among users having a wide range of channel qualities. How to search the cluster-head and its member relay nodes to cooperate is important. Since nodes are coming into or out of the clusters time to time, the network topology is perturbed and the reconfiguration of the network is unavoidable. In this paper, we propose a new algorithm called stability weighted clustering algorithm (SWCA) to solve this problem. We define the stability by using a new metric of mobility. In the traditional WCA, the speed of every separate node is considered. However, our proposed algorithm introduces a new weight factor, which uses the relative speed of two nodes to represent the mobility of the network. Simulation results show that the SWCA achieves better stability than the traditional WCA while it performs almost the same performance as the WCA with respect to the dominant set update rate and the load balancing factor (LBF).**

Keywords-virtual cellular network;cooperative communications; clustering; stablity; WCA

I. INTRODUCTION

Much higher speed data services with peak data rates of 100Mbps-to-1Gbps are required for 4G systems [1]. To support such high speed transmissions, two important technical issues need to be addressed: spectrum efficiency and transmission power problem [2],[3]. To keep the transmit power the same as in the present system, a fundamental change of the wireless access network is necessary. One promising solution is to apply the multi-hop cooperative relay technique as in the multi-hop virtual cellular network (VCN) [4],[5].

The term “cooperative relay” typically refers to the technique which allows different relay nodes to share their resources to enhance transmission quality. With cooperation, a user who experiences a deep fading in its link towards the destination can utilize good channels provided by its relay nodes to achieve the desired quality of service (QoS). Any user can be a node in the network. A number of relay nodes form a cluster to cooperate. A relay node with good condition (i.e., low path-loss and/or low mobility) can be a cluster-head and serve its member relay nodes. The selection of the cluster-head and its member relay nodes is a very important problem.

The cluster-head and its member relay nodes are randomly distributed in the network. The concept of partitioning the geographical region into clusters (or small cooperative zones) has been presented in [6]. Any node can be a cluster-head if it satisfies some necessary conditions (such as the mobility, the transmission power, etc). After selecting the suitable node as a cluster-head, the other nodes become its member relay nodes.

Due to the mobility of the network, clusters may change dynamically [7]. Refs. [7-11] focused on partitioning the geographical region into clusters. However, most of the previously proposed approaches [8],[9],[11] for selecting the cluster-heads do not give an optimal solution. The previously proposed approaches cannot maximize the life time of clusters although they perform well in terms of dominant set update rate and the load balancing factor (LBF).The set of cluster-heads is known as a dominant set[13]. Dominant set update rate is defined as the frequency of a dominant set changing. It is desirable If the nodes can keep cooperate and communicate with the destination as long as possible (i.e., the network topology is kept stable as long as possible). Once the battery of cluster-head is run out, the cooperation is interrupted; the network topology is perturbed and the reconfiguration of the network is unavoidable. One of the well-known clustering algorithms is the lowest-ID heuristic algorithm [13]; however, it may lead to high battery power consumption of cluster-heads, leading to shorter life time of the clusters. The most popular clustering algorithm is the weighted clustering algorithm (WCA) [12]. It is necessary to keep the topology stable as long as possible. However, the WCA pays little attention to the stability of the network. In fact, with the association and dissociation of nodes into/from the clusters, the stability of the network topology is perturbed and the reconfiguration of the network becomes unavoidable.

In this paper, we propose a stability WCA algorithm (SWCA) which introduces a new stability weight factor. However, due to the dynamic nature of the network, it is very difficult to maintain a completely balanced system. A pre-defined threshold is introduced to achieve the load balancing and ensures that none of the cluster-heads are overloaded.

The remainder of the paper is organized as follows. Section II overviews the previous works. In Sect. III, the proposed SWCA is described in detail. Section IV evaluates by computer simulation dominant set update rate, LBF, and the average life time of the clusters. Finally, Sect. V offers some concluding remarks.

II. CLUSTERING ALGORITHMS AND STABILITY PROBLEM

A. Multi-hop network

The multi-hop network is formed by the nodes and the links connecting them as shown in Fig. 1. Any node can be a cluster-head if a certain condition is satisfied. The neighborhood of a cluster-head is the set of nodes which lie within its transmission range.

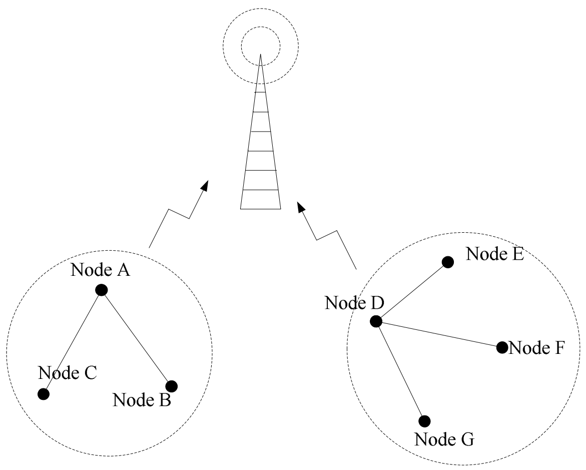

Figure 1. Multi-hop network.

The node degree (which will be introduced in detail in Sect. III), the transmission power, the mobility, and the battery power are considered to select a cluster-head. In this paper, the following assumption is used.

- The cluster-head is selected periodically.
- The cluster-head is able to communicate with its neighbors within the transmission range [14].
- Each cluster-head supports only δ nodes (where δ is the pre-defined threshold and a group of the nodes belonging to each cluster-head is called the member nodes) to guarantee that the network works efficiently and the nodes do not have any interruption in communicating with the destination. The reason for why the number of member nodes is limited to δ is for a cluster-head not to consume its battery power excessively.
- It is necessary to select a slowly moving node as a cluster-head to avoid frequent cluster-head change. Otherwise, the cluster-head may change frequently.
- The cluster-head consumes more battery power than ordinary nodes since the cluster-head has extra responsibilities to serve its member nodes.
- The battery power is determined by the transmission range (less power is required for a node to communicate with the one closer to it).

B. Previous popular algorithms

Three popular algorithms (i.e., lowest-ID heuristic algorithm [12], highest-degree heuristic algorithm [13] and WCA [12], [13] are overviewed below.

1) Lowest-ID heuristic algorithm: this algorithm assigns a unique ID to each node and selects the node with the lowest ID as a cluster-head. The lowest-ID algorithm was proposed by Baker and Ephremides [6],[7],[10] and is known as an identifier-based clustering. The cluster-head can delegate its responsibility to the next node with the lowest ID in its cluster. It has less frequent cluster-head updating and higher throughput performance than the highest-degree heuristic algorithm. However, a drawback of this algorithm is its bias towards nodes with smaller IDs, which may lead to high battery power consumption of certain nodes(cluster-head)[12].

2) Highest-degree heuristic algorithm: this algorithm is known as a connectivity-based clustering algorithm, which computes the node degree based on its distance from others. This algorithm was proposed by Gerla and Parekh [12],[13]. In this algorithm, each node broadcasts its ID to other nodes within its transmission range. The node with maximum number of neighbors is selected as a cluster-head. The computer simulation demonstrates[13] that the highest-degree heuristic algorithm achieves a low updating rate of cluster-heads, but provides low throughput.

3) WCA: this algorithm is the most popular algorithm. The WCA selects the nodes with the smallest combined weight. The combined weight W_v for each node is defined as

$$W_v = w_1\Delta_v + w_2D_v + w_3M_v + w_4P_v \quad , \tag{1}$$

where Δ_v is the node degree (it is desirable for a cluster-head to handle up to a certain number of nodes in its cluster); D_v is related to the energy consumption (it represents the transmit power); M_v is the mobility of the nodes (a node with lower mobility is a better choice as a cluster-head); P_v is the total (cumulative) time during which a node acts as a cluster-head (in another word, it represents the consumed battery power of the nodes). In equation (1), w_1, w_2, w_3, and w_4 are weighting factors which reflect the relative importance of Δ_v, D_v, M_v, and P_v, respectively and ; usually they are determined by experience.

It is desirable to keep the network topology stable as long as possible. The WCA takes into account the mobility of the nodes which is the average moving speed of every node until the present time. However, since the relative mobility between any two nodes is not considered, frequent reconfiguration of

Identify applicable sponsor/s here. If no sponsors, delete this text box. (sponsors) the network is unavoidable and hence, the association and dissociation of nodes into/from clusters perturb the stability of the network topology. The relative speed between the cluster-head and its neighbors must be considered. It is desirable to select a node, whose neighbor nodes do not move very quickly against that node, as a cluster-head. This paper focuses on this stability problem.

III. STABILITY WCA

The stability WCA consists of nine steps. Step 1 is used to search the possible cooperative nodes; steps 2 to 6 compute the factors which affect the selection of a cluster-head; and steps 7 and 9 select a cluster-head. Each step is described in detail below.

- Step 1: Find the neighbor nodes v' which are within its transmission range of each node v as

$$d_v = \text{Number}\left[\left\{\text{distance}\left(v, v'\right)\right\} < R_{tx\_range}\right] , \quad (2)$$

where d_v denotes the degree defined as the number of neighbor nodes whose distances are shorter than the transmission range R_{tx_range}.

- Step 2: For each node v, compute the degree difference as $\Delta_v = \left|d_v - \delta\right|$, where δ is the pre-defined threshold to ensure that nodes have high throughput [12]. The cluster-head should not handle a large number of nodes as its member nodes because of the resource limitation (i.e., the limited battery power) even if all of them lie within its transmission range. This is because high power consumption is necessary if the cluster-head communicate with too many nodes. In the computer simulation, we assume δ=2.

- Step 3: Compute the sum of the distances associated with all of its neighbors as

$$D_v = \sum_{v \neq v'} \left\{\text{distance}\left(v, v'\right)\right\} , \quad (3)$$

which represents the differences in degree of nodes.

Larger transmit power is required as the communication range is increased. The received signal power is attenuated inversely proportionately to the $2\sim4^{\text{th}}$ power of the distance in urban areas [3]. The battery power consumption of a node in a cluster is determined by the distance between the cluster-head and the node. The cluster-head consumes more battery power than its member nodes.

- Step 4: Calculate the relative speed of each node as

$$V\left(v, v', t\right) = \sum_{v' \in C_v} \left\{V\left(v, t\right) - V\left(v', t\right)\right\} , \quad (4)$$

where $V\left(v, t\right)$ and $V\left(v', t\right)$ are the speed vectors of node v and v', respectively, at time t. Both the speed and the direction ($0^{\circ}\sim360^{\circ}$) of the node must be considered. The mobility of a node is determined by the average relative speed over a period of time T as

$$M_v = \frac{1}{T} \sum_{t-T}^{t} \left|V\left(v, v', t\right)\right| . \quad (5)$$

- Step 5: Compute the cumulative time P_v during which the node v acts as a cluster-head. P_v implies how much battery power have been consumed and is much larger for a cluster-head than for an ordinary node.

- Step 6: Compute the stability of the network. The link connecting the two nodes is regarded stable if the relative mobility $M_v^{rel}(v')$ between node v and node v' meet the following condition

$$\text{If } M_v^{rel}\left(v'\right) < 0 , \text{ then } \left|M_v^{rel}\left(v'\right)\right| < M_{\min}^{Threshold} \quad (6)$$

$$\text{If } M_v^{rel}\left(v'\right) > 0 , \text{ then } M_v^{rel}\left(v'\right) < M_{\max}^{Threshold} , \quad (7)$$

where $M_{\min}^{Threshold}$ and $M_{\max}^{Threshold}$ are two thresholds of the relative mobility, which are predetermined system parameters .If $M_v^{rel}\left(v'\right) < 0$, node v and node v' are moving in opposite directions while if $M_v^{rel}\left(v'\right) > 0$, node v and node v' are moving in the same directions. $M_{\min}^{Threshold}$ and $M_{\max}^{Threshold}$ are the minimum and maximum values of $M_v^{rel}(v')$, respectively.

The HELLO message (the neighbor nodes broadcast this message to other nodes [20]) is exchanged more than 3 times between two nodes (node v' and node v) [21] when they are cooperating.

The relative mobility $M_v^{rel}(v')$ between node v and node v' is defined as

$$M_v^{rel}\left(v'\right) = 10 \cdot 1og \frac{rxP_{v' \to v}^{(2)}}{rxP_{v' \to v}^{(1)}} + 10 \cdot 1og \frac{rxP_{v' \to v}^{(3)}}{rxP_{v' \to v}^{(2)}} + \cdots + 10 \cdot 1og \frac{rxP_{v' \to v}^{(m)}}{rxP_{v' \to v}^{(m-1)}} , \quad (8)$$

where $rxP_{v' \to v}^{(m)}$ is the received signal power in the m-th link when node v' transmits its signal to node v.

The value of $\left|M_v^{rel}\left(v'\right)\right|$ needs to be relatively small in order to ensure both the stability and low battery power. The overall degree of the relative mobility between the node v and its neighbor nodes is defined as

$$\overline{M}_v = \sum_{v'=1}^{K} \frac{\left|M_v^{rel}\left(v'\right)\right|}{M} , \quad (9)$$

where K is the number of neighbor nodes belonging to node v and $M = M_{\min}^{Threshold}$ ($M = M_{\max}^{Threshold}$) if $M_v^{rel}\left(v'\right) < 0$ ($M_v^{rel}\left(v'\right) \geq 0$).

In this paper, we define the stability as the ratio of the relative mobility and the number of stable links as

$$S_v = \frac{\overline{M}_v}{e^{N_{link}}} \quad , \tag{10}$$

where N_{link} is the number of stable links. Instead of N_{link}, $e^{N_{link}}$ is heuristically introduced to avoid that the denominator becomes 0 when $N_{link} = 0$.

- Step 7: Calculate the final weight W_v for each node v as

$$W_v = w_1\Delta_v + w_2 D_v + w_3 M_v + w_4 P_v + w_5 S_v \tag{11}$$

  where w_1, w_2, w_3, w_4, and w_5 are the weighting factors reflecting the importance of the corresponding system parameters. Eq.(11) is similar to Eq.(1), but, the stability S_v is added as a new factor. In this paper, we use fixed values of w_1, w_2, w_3, w_4, and w_5 which are determined by experience [13].

- Step 8: The node with the smallest W_v is selected as the cluster-head. All the member nodes belonging to the cluster-head are no longer necessary to proceed to Step 9.

- Step 9: Repeat steps 2-8 for the remaining nodes which are not yet selected as a cluster-head or not yet selected as a member of the cluster-head.

IV. SIMULATION RESULTS

Simulations are done to compare the cluster-head updating rate, LBF, and the average life time of clusters. The simulation conditions are shown in Table 1.

Table 1. SIMULATION CONDITIONS

Pre-defined threshold δ (number of nodes)	2
Number of nodes in the network	30
Network tracking time	1000 s
Position of nodes	Nodes are uniformly distributed in an area of 100m×100m
Speed of nodes	Random over [0-5 m/s]
Directions of nodes	Random over [0°-360°] and the moving direction of each node changes every five seconds
Consumed battery power	Initial consumed battery power 0-5 mw
Received power between the neighbor nodes	Random over [0-100 mw)
Threshold $M_{\min}^{Threshold}$ to determine relative mobility	3 (dB)
Threshold $M_{\max}^{Threshold}$ to determine relative mobility	5 (dB)
Weights (w_1, w_2, w_3, w_4, w_5)	(w_1, w_2, w_3, w_4, w_5)=(0.5, 0.0, 5, 0.05, 0.05, 0.35) by experience following to [13]
Transmission range R	0-100 m

The dominant set update rate is a very important measure to compare different clustering algorithms [11]. The dominant set update rate (times/sec) are shown in Fig. 2 for different algorithms. It can be seen from Fig. 2 that as the transmission range increases, the cluster-head updating rate increases at beginning and reaches the maximum when the transmission range approaches around 15m; however, as the transmission range increases beyond 15m, the dominant set update rate starts to decrease and gradually approaches. According to [3], According to [3], the received signal power is given by $P_r \propto P_t \times d^{-\alpha}$, where P_t is the transmit power and α is the path loss exponent ranging between 2 and 4, depending on the propagation environment. Therefore, the transmission range should be $d \propto (P_t / P_r)^{1/\alpha}$ for the given required receive power. However, in the computer simulation, the transmit power is assumed to be 1.5mW for the transmission range of 15m.

When the transmission range is 30m, the dominant set update rate is 0.365 times/s for SWCA while it is 0.325 times/s for the highest-degree algorithm, 0.352 times/s for WCA, and 1 times/s for the lowest-ID algorithm. The SWCA has less updating rate than WCA and the highest-degree algorithm has the highest updating rate while the lowest-ID has the lowest rate. The reason for this is that the SWCA takes into account the stability in the weight computation. Using the lowest-ID algorithm, since all cluster-heads are those nodes with smaller IDs, the cluster changes quite rarely and hence the dominant set update rate is extremely small. For example, the node with the smallest ID will be a cluster-head forever and it will not change at all.

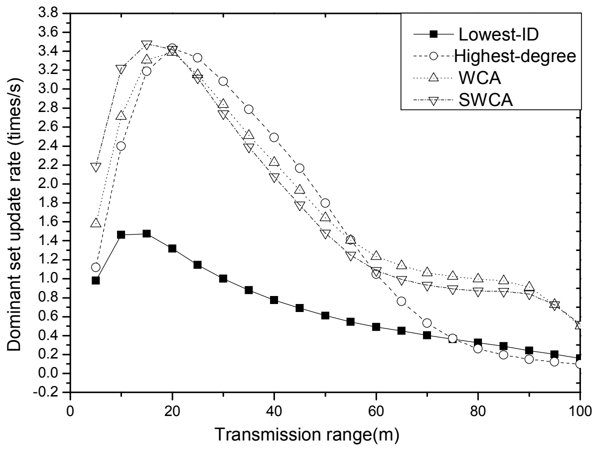

Figure 2. Cluster-head updating rate.

The LBF is plotted in Fig. 3. The LBF is defined as

$$\text{LBF} = \frac{N_{cluster}}{\sum_{i=1}^{N_{cluster}} \left(N_{i\_memeber} - \overline{N}_{member}\right)^2}, \tag{12}$$

where $N_{cluster}$ is the number of clusters in the network, $N_{i\_memeber}$ $(1 \le i \le N_{cluster})$ is the number of the member nodes of the i-th cluster, $\bar{N}_{memeber} = (N_{total} - N_{cluster})/N_{cluster}$ is the average number of neighbor nodes over all cluster-heads with N_{total} being the total number of nodes in the network. It is obvious that the larger the LBF becomes the better the loading balance is.

It can be seen from Fig. 3 that the LBF is large if the transmission range is either too short or too long. If the transmission range is between 10 to 60m, the LBFs of SWCA and WCA are similar, while it is significantly lower for the highest-degree heuristic algorithm (the highest-degree heuristic algorithm often results in the uneven distribution of member nodes in each cluster, resulting in a lower LBF). When the transmission range is longer than 70m, the LBF of the highest-degree heuristic algorithm is higher than other algorithms. This is because the number of cluster-heads is close to 1, thereby increasing the LBF dramatically.

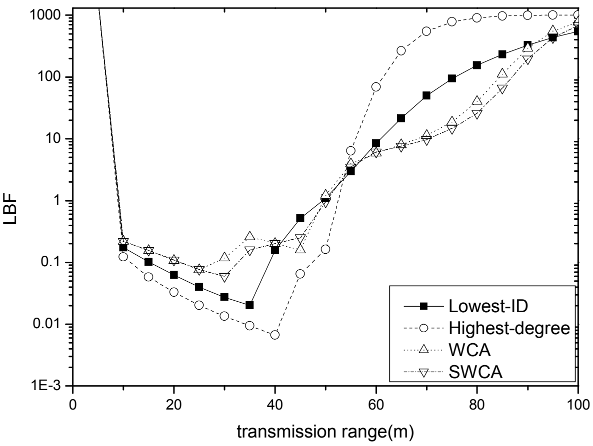

Figure 3. LBF.

The average life time of clusters is plotted in Fig. 4. The lowest-ID heuristic algorithm has the longest life time; however, the SWCA provides a better stability than WCA since SWCA introduces a new factor representing the stability S_v (see Eq.(11)) to make the life time longer. If the transmission range is 40m, the average life time is 610s for the SWCA while it is 802s, 610s, and 583s for the lowest-ID heuristic algorithm, highest-degree heuristic algorithm, and WCA, respectively. In the case of the lowest-ID heuristic algorithm, the node with smaller ID is selected as a cluster-head, so it has a relatively longer life time than other algorithms.

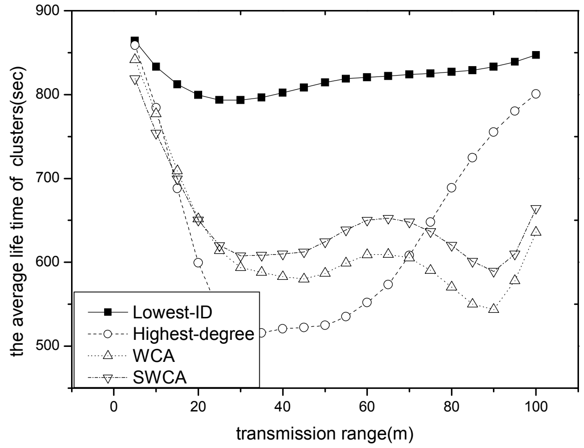

Figure 4. Average life time of clusters.

V. CONCLUSIONS

This paper proposed the stability weighted clustering algorithm (SWCA), which takes into account the network stability in the weight computation. The simulation results show that the SWCA can achieve a better stability than traditional WCA while it provides the cluster-head updating rate and the LBF comparable to the WCA. Note that in this paper, we assumed the constant number of arrival users as assumed in [12],[13]. It is left an interesting future study to adapt the weight factors to changing number of coming users.

ACKNOWLEDGMENT

This study was supported by China National Science Foundation under Grand No. 60872016 and Program for New Century Excellent Talents (NCET-08-0157) in University.

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