Multi-Radio 무선 메쉬 네트워크에서의 토폴로지 제어를 위한 클러스터링 기법

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Clustering Approach for Topology Control in Multi-Radio Wireless Mesh Networks

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요 약

클러스터링은 ad hoc네트워크에서 확장성 개선과 네트워크 수명 연장뿐만 아니라 클러스터 내 멤버 관리기능과 링크용량을 개선해주는 토폴로지 제어 기법이다. 본 논문에서는 단말의 이동성과 네트워크의 이종성을 고려하여 multi-radio 무선 메쉬 네트워크를 위한 클러스터링 알고리즘을 설계하였다. 수학적 분석을 통하여 제안 알고리즘은 시간 t내에 종료되며, 메시지 제어 처리를 위한 복잡도는 각 노드 당 O(1)임을 알 수 있었다. 이는 본 제안 알고리즘을 적용함으로써 무선 메쉬 네트워크의 안정성, 연결성, 확장성과 에너지 효율성이 향상됨을 알 수 있었다.

ABSTRACT

Clustering is a topology control approach often used in wireless ad hoc networks to improve scalability and prolong network lifetime. Furthermore, it is also employed to provide semi-management functionalities and capacity enhancement. The usage of clustering topology control technique can also be applied to multi-radio wireless mesh network. This would utilize the advantages of the multi-radio implementation in the network. The aggregation would result to a more stable, connected, scalable and energy-efficient network. On this paper, we design a clustering algorithm for multi-radio wireless mesh network that would use these advantages and would take into consideration both mobility and heterogeneity of the network entities. We also show that the algorithm terminates at a definite time t and the message control overhead complexity is of constant order of O(1) per node.

키워드

multi-radio, topology, wireless mesh networks, clustering

Ⅰ. Introduction

A mesh network could be applied to a number of known systems. It could be a system of wireless sensors interconnected via mesh. Wireless Mesh Network (WMN) is composed of mesh routers and mesh clients. Mesh routers are the gateways/bridge and router of the network. On the other hand, mesh clients can be simpler than mesh routers in design but they could also still route packets. Mesh routers form the backbone and are essentially not mobile. Moreover, they do not have strict constraints on power consumption compared to mesh clients. Mesh clients are highly mobile

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and are likely to be battery powered. Figure 1 shows a diagram of wireless mesh network that is comprised of both wireless mesh routers and clients. The mesh clients form a sub- group within themselves and collectively form links leading to a mesh router.

Although, it has been shown that WMN has a number of advantages over other technology [1], it could be further enhanced by introduction of multi-radio components. A multi-radio system can be employed in a mesh network and this feature can be a facility to provide better energy management and improve capacity. Furthermore, this can be used as a general solution to handle mobility management. As we consider the presence of one or more radios in the same device, we would try to address solutions to common single-radio wireless problems. The advantages of multi-radio will be presented and how they can be used to enhance wireless mesh network will be described. We present a couple of things to consider in a multi-radio system that can be utilized for wireless mesh network.

The rest of the paper is organized as follows. Section II presents related works. Section III describes the clustering algorithm. Section IV presents the analysis. Finally, Section V concludes the paper.

Ⅱ. Related Works

The definition of topology control has evolved as researches proliferate to seek the most appropriate method. The foregoing goal of topology control is to provide an energy efficient network and it eventually grew as more protocols were developed. The nascence of topology control can be rooted from schemes that limit the number of neighbors of a node by controlling transmission power or reducing the transmit radius. [2], [3], [4] and [5] are some of the studies that discuss various ways to do transmit power adjustment. Prior to clustering, the most popular topology control protocols then were schemes that determine a set of connected representative nodes. GAF[6], Span[7], ASCENT[8] belong in this category. In GAF (Geographic Adaptive Fidelity), the network is divided into grids and

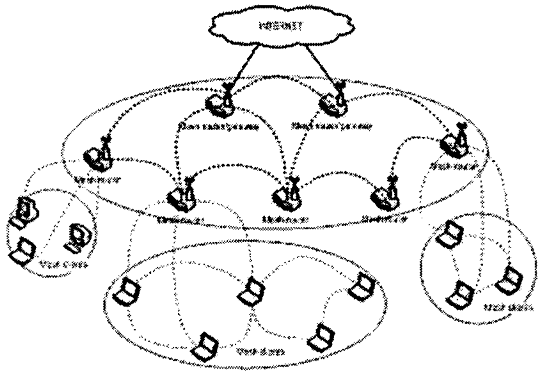

그림 1. 무선메쉬네트워크
Fig. 1. Wireless Mesh Network

designates one node as the representative for each grid cell. While in Span, certain nodes are assumed to a role of a coordinator based on connectivity criteria while other nodes are allowed to sleep and not to participate in routing. Similarly, ASCENT (Adaptive Self-Configuring sEnsor Networks Topologies) chooses which nodes are active for a given time with consideration of both connectivity and communication reliability. The emergence of clustering methods can be traced back with the introduction of two distributed algorithms: lowest-ID algorithm and highest connectivity algorithm which are discussed in detail in [9]. In these two algorithms, a clusterhead is chosen among certain group of nodes. As their names suggest, the former algorithm selects the node with the lowest ID while the latter selects the node with the highest connectivity. Although, originally, clustering have been developed for wireless ad hoc networks to provide a kind of infrastructure that would allocate resources and support multi-hop routing. Its energy efficiency potential has also been examined by applying it to wireless sensor networks. One of the first clustering protocol is LEACH (Low Energy Adaptive Clustering Hierarchy) [10] which is based on one-hop communication which transmits aggregated data of nodes from clusterhead to base station. Another one is HEED[11] "Hybrid, Energy-Efficient, Distributed", which is unlike LEACH, uses multi-hop communication and selects clusterhead in O(1) time. Similarly, EECS[12] "Energy Efficient Clustering Scheme" performs clustering by electing clusterhead with the most residual energy.

In [1], a detailed survey or wireless mesh network is presented. Some open issues regarding wireless mesh networks and detailed analysis on WMN-specific problems are mentioned. It is known that multi-radio implementation of WMN would greatly increase the capacity of the network. Multi-radio wireless systems have been considered to be the solution for common wireless problems like energy management, capacity enhancement and mobility management[13]. The researchers have shown that implementing both high power radio and low power radio on a device and altering its operation to run on low power radio during wake up phase and sending control messages improve power savings. They also showed that if a device can be tuned to hear different interfering channels with proper channel assignment and protocol, the capacity allocation can be greatly improved. Lastly, the delays created by hand-over can be minimized as nodes can associate to another access point, AP before it could disassociate with an old access point. Clustering is a method of dividing the network into clusters. It is architecture that can be applied to multi-radio wireless sensor network taking into account both heterogeneity and mobility[14]. A mobility-based clustering as [15] is proven to be adaptive and stable in ad hoc networks. Clusters are often employed to impose a hierarchical structure for scalability and spatial reuse. Clustering applied to multi-radio ad hoc network [16] is found to be also effective in capacity optimization when the clusters are of equal size.

There are several clustering algorithms, and an example is in [17]. In this method, they have presented a fully distributed multi-radio backbone synthesis algorithm which contributes an important feature of clustering methodology, that is, construction time is bounded by a constant time, independent of the number of nodes. Unlike most clustering algorithms that limit a one-hop cluster, [18] upper bounding the number of hops a node can be from its clusterhead, which the authors have shown, is fairer and more stable. Factors like how mobility affects cluster formation and how many nodes should form a cluster should be the basis for decision making. It is important however, that before any algorithm are to be introduced, a based model and efficiency should take into consideration. [19] has revisited mobility models that can be employed to ad hoc networks and [20] has shown how to compute time complexity in some well known clustering algorithm. The theories to be introduced on this paper are formulated with the guidance of the related literatures presented in this section.

Ⅲ. Proposed Model

3.1. Multi-radio Wireless Mesh Network System

The system to be described all throughout this paper is comprised of nodes in wireless mesh network environment, wherein the nodes belong into two categories: a mesh router or a mesh client.

The following are assumptions for wireless mesh routers:

- Mesh routers are not mobile
- Mesh routers are evenly distributed in the system
- Mesh routers are mains powered
- Mesh routers are equipped with two radios
  - Low power radio
  - High power radio

For wireless mesh clients:

- Mesh clients are mobile
- Some mesh clients move in a groups
- A node can have individual movement
- Mesh clients are battery powered
  - Low power radio

Both node entities do not have GPS (global positioning system) in them; therefore, the following assumption is helpful:

- Nodes are deployed in a static channel. It means that signal fading and multi-path effects are not considered.

The architecture can be viewed as a layered approach wherein the lowest layer is composed of wireless mesh clients and the upper layer is composed of wireless mesh routers. It is known that the multi-tiered network structure will guarantee network scalability.

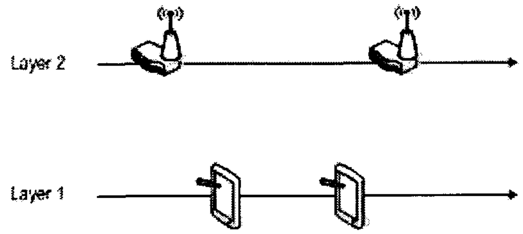

그림 2. 무선메쉬네트워크를 위한 2계층 아키텍쳐
Fig.2 The 2-layered architecture for Wireless Mesh Network

In this architecture the mobility and heterogeneity of the network has been taken into consideration. The mobility of the mesh clients is their group mobility while heterogeneity is defined as the differences of mesh clients and routers in terms of capability, capacity and power consumption.

3.2. Mobility Pattern

As described earlier, WMN is composed of different entities interworking to form a dynamic system. The reason why we need to consider mobility is to account for the nature of wireless mesh network and test our proposed algorithm for stability.

The choice of mobility pattern in WMN should take into account the heterogeneity of the network. WMN is composed of different type of nodes. These differences between the network nodes should dictate the mobility pattern to be used in the system.

For this purpose, we would like to use the Mobility Vector Model [21]. The mobility of the node is expressed by (1).

$$\vec{M} = \vec{B} + \alpha \vec{V} \tag{1}$$

Where:

$\vec{M}$ - mobility vector (xm, ym) or (rm, Θm)

$\vec{B}$ - base vector (xb, yb) or (rb, Θb)

$\vec{V}$ - deviation vector (xv, yv) or (rv, Θv)

α - acceleration factor

Base Vector defines the major direction and speed of a node. A Deviation Vector stores the mobility deviation from the base vector. The α provides smooth speed transition in the mobility metric. Each vector can be represented in two ways, it could be a Cartesian vector(x_m, y_m), (x_b, y_b), (x_v, y_v) or a polar vector (r_m, θ_m), (r_b, θ_b), (r_v, θ_v). The mobility vector described in (1) would only apply to wireless mesh clients since wireless mesh routers are not mobile. The group mobility can be represented by defining the base vector as the group movement while the deviation vector represents the individual movements.

3.3. The Algorithm

The clustering topology control algorithm is divided into 2 phases. First is the formation mesh backbone and the other phase is clustering. A node is a neighbor of another node if they are within the transmission range from each other.

1. Phase 1: Formation of Mesh Backbone

The formation of mesh backbone is initiated by the mesh routers via their high-powered radios. Since wireless mesh router are essentially immobile and mains powered. This phase shall be done at one time only.

The algorithm will start with routers sending Hello_1 messages to all neighbors. In case of a tie, a weight factor is introduced. Weight could be ID or any stability measure. Figure 3 shows the algorithm for mesh backbone formation. P_R is defined as received power.

2. Phase 2: Clustering

The wireless mesh nodes will form a group according to their mobility pattern. Therefore, from (1), nodes with similar base vectors are in the same group and have links to each other. The clustering algorithm starts with wireless mesh routers. The wireless mesh routers will disseminate Hello_2 messages using their low-powered radio to wireless mesh clients. If another wireless mesh router received this type of hello message, it will only ignore and discard the message. The pseudocode in Figure 4 shows how this phase is done. The hello message on this phase contains weight information as well.

After this phase, clusters are formed with mesh routers as clusterhead and mesh clients as cluster nodes.

3. Maintenance

Since wireless mesh routers are more powerful in terms of hardware than wireless mesh clients then it would be smart to add a kind of maintenance scheme in them. Mesh routers should poll their respective cluster nodes if they are still reachable. This is a trivial mechanism and can be implemented in a number of ways. Wireless mesh clients can be idle or sleep mode during this phase since, only the mesh routers do the polling, the network could save energy and prolong network lifetime since the power in wireless mesh clients will not be depleted right away. This poses no problem on wireless mesh routers since they are mains-powered.

3.4. Application Scenarios

[12] cites some application scenarios for multi-radio wireless sensor networks. Similarly, we could apply those scenarios in wireless mesh networks. Wireless mesh network can be viewed as:

Example 1: We could think of the mobile mesh clients as sensor nodes while the mesh routers are the sinks. These sensor nodes are attached to children to monitor their location. The sink will monitor the location of the children. An alert will be generated if any of the children goes out of the secure area.

Example 2: In a smart home with wireless mesh routers mounted, the sensors/wireless mesh clients are scattered around to provide information regarding physical/ psychological state without intervening one's privacy.

Ⅳ. Analysis

Since, Phase 1 and Phase 2 are being executed using different radios; these two phases can be done simultaneously. This saves time and initial start ups in the network. The messages are sent via different radios and this reduces traffic. Overhead is not a problem since hello messages always come from mesh routers. Capacity is utilized efficiently since one mesh router is assigned to one cluster. Also, since P_R and mobility is taken into account, stability is guaranteed.

In this section, we try to analyze the performance of the algorithm by proving some of claims.

Lemma 1: All wireless mesh routers are interconnected at the end of Phase 1.

Proof: Since the nodes are uniformly distributed throughout the network, a mesh router would surely be associated at the end of Phase 1. Given a mesh router on a space $G(R)$ of arbitrary size s, there exists another mesh router R_l within a transmission range T_R in a uniformly distributed space, such that a mesh router has at least one neighbor R_n that exist and one hello_1 message received which can be a candidate for association.

Lemma 2: There exists at most one mesh router in the vicinity of another for mesh router that can be associated.

Proof: We could denote R as the set of all mesh routers and R' is the set of mesh routers that have the highest P_R or highest weight within its T_R where $\forall R_n \varepsilon R'$, $R_n'' = \{R_x | d(R_x, R_n) <= T_R, R_x \varepsilon R\}$. We also define $R_x \varepsilon R_n''$ belongs to R' which is a contradiction of the Lemma. Based on the algorithm, $R_n.P_R > R_y.P_{R'}$ $\forall R_y \varepsilon R_n''$. Since $R_x \varepsilon R_n''$, then $R_n.P_R > R_x.P_{R'}$. If R_x belongs to R', then $R_x.P_R > R_y.P_R$ which is a contradiction. Therefore, if $R_n \varepsilon R'$ and $R_x \varepsilon R_n''$, the statement $R_x \varepsilon R'$ is false.

Lemma 3: A wireless mesh router could send a maximum of k number of hello_1 messages. Thus, the control overhead complexity is of constant order of $O(1)$ per node.

Proof: The length of each hello messages is fixed length. The information, like ID and other stability measure in mesh routers are kept unchanged. Also, since the mesh routers do not move along the space G, it is always have a maximum of k neighbors at a given time. Obviously, there is no need for another run of Phase 1 since at the end of the procedure, all mesh routers are associated, thus giving the algorithm to end at a definite time.

Lemma 4: A group of wireless mesh clients will be associated by the end of Phase 2.

Proof: Since, one of our assumptions is that wireless mesh routers are uniformly distributed about *G*, therefore, on any point G_{xy} space there is an equal probability that a mesh router is present. Thus, a group of mesh client will receive at least one hello_2 message from a mesh router.

Lemma 5: It takes one run of procedure Phase 2 to form initial clustering.

Proof: Because of Lemma 3, this is a trivial case of a time definite algorithm. Repeated calls to Phase 2 depend on the implementer and the mobility of the system (*a*, [*B*, *V*] vectors). Thus, the time complexity of the algorithm in Phase 2 is upper-bounded by a constant value such as a mobility factor.

```
Procedure PHASE_1{
  For each wireless mesh router
  { Status = Not Associated;
    Send Hello_1 msg to each neighbors;

    For each Hello_1 msg received{
    {
      If (Pk from a neighbor is the highest for all){
        Status = Associated /*using high-powered radio*/
      }
      Else {
        Status = Not associated
      }
    }

    If Status = Not associated{
      For each Hello_1 msg received{
      {
        If (Weight from a neighbor is highest for all){
          Status = Associated /*using high-powered radio*/
        }
        Else {
          Status = Not associated
      }
    }

    If status = Not associated {
      Establish link to the nearest mesh router with status = associated
      Status = associated
    }
  }
}
```

그림 3. 1단계: 메쉬백본 형성
Fig. 3. Phase 1: Formation of mesh backbone

```
Procedure PHASE_2(test){
  If (test = Pk){
    For each Hello_2 msg received
    {
      If (Pk from a neighbor is the highest for all){
        Status = Associated /*using low-powered radio*/
      }
      Else {
        Status = Not associated
      }
    }
  }
  If (test = weight){
    For each Hello_2 msg received{
    {
      If (Weight from a neighbor is highest for all){
        Status = Associated /*using low-powered radio*/
      }
      Else {
        Status = Not associated
      }
    }
  }

  If Status = Not associated and test = Pk{
    Call Procedure PHASE_2(weight)
  }
}
```

그림 4. 2단계: 클러스터링
Fig. 4. Phase 2: Clustering

Lemma 6: The whole algorithm is upper-bounded by a definite time $\max\{t_1, t_2\}$.

Proof: Both Phase 1 and Phase 2 do not go into infinite loop and finish at a definite time t as proven by Lemma 1 and Lemma 5. Moreover, the two algorithms can be done at the same time because of multi-radio advantage of mesh routers, hence, making total time, *t* smaller. Let say, that Phase 1 would be finished at time, t_1 and Phase 2 at time, t_2, therefore if the two algorithms will be executed at different times, the total time for it to finish would be $t_1 + t_2$. On the other hand, when the two algorithms will be executed at the same time because of multi-radio approach, it is bounded by the slower algorithm, which is $\max\{t_1, t_2\}$. It is easy to see that, $t_1 + t_2 > \max\{t_1, t_2\}$.

We conducted a simple simulation experiment. The initial number of nodes is 100. A group mobility is used to model movement of nodes with group velocity between [0, 50m/s], size of the system is 1 x 1 km.[2] Among *n* nodes, 0.20n are mesh routers. Minimum transmission range is 10m and maximum is 100m. Initial battery for mesh clients is 2J. Figure 5 shows how clustering prolong network lifetime and exhibits scalability. Despite of increasing number of nodes, it does not decrease/lessen the network lifetime. This shows how clustering could be beneficial in energy efficiency as well as scalability.

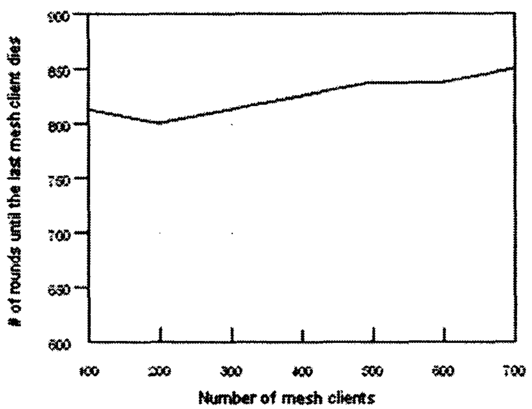

그림 5. 시뮬레이션 결과
Fig. 5. Simulation Result

V. Conclusion

This paper presents a clustering algorithm for multi-radio wireless mesh network. The introduction of multi-radio in the network is fully utilized to bring out its advantages for this kind of network. Clustering in multi-radio environment is proven to be effective in prolonging lifetime and stability of the network.

For our future work, we would like to extend and analyze our work with regards to non-uniform node distribution system.

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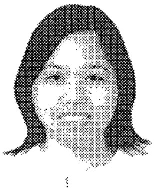
저자소개



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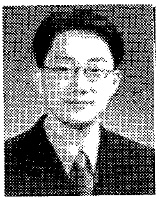

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