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Review Paper

Scalability in Ad Hoc Networks: The Effects of its Complex Nature

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Abstract

One of the expected properties of the ad hoc networks is the ability to increase its size to receive new nodes and configure new applications without affecting the quality of services. This property, called scalability is affected by the decentralized nature of ad hoc networks making it necessary to develop mechanisms that allow a large number of nodes work together without affecting network performance. The following article describes how the scalability of the ad hoc networks are directly related to routing algorithms, the need of cooperation, competition for resources, the network architecture and the heterogeneous nature of the nodes.

Keywords: *Ad Hoc Networks, Network architecture, Game Theory, Scalability.*

1. Introduction

The ad hoc network are a totally different paradigm to traditional networks, it does not have any preexisting infrastructure and the nodes have complete autonomy to configure its participation in the network. This decentralized nature has resulted in the occurrence of emergent properties and generates the need to incorporate certain features on nodes that allow them being configured and integrated as part of the network without affecting its performance.

One of the expected properties in ad hoc networks is the ability to increase its size by receiving new nodes and configuring new applications without affecting the quality of services. This property called scalability is one of the main challenges in the design of protocols and is a fundamental feature to achieve ad hoc networks with a deploy high capacity. The following paper describes how the complex nature of ad hoc networks affects the scalability of a network and how this property is related to the routing, cooperation mechanisms, network architecture and the existence of heterogeneous nodes.

This paper is organized as follows: the first section introduce the main characteristics of ad hoc networks, the emergent properties of its complex nature and the different network arquitectures; the second section describes the main factors that affect the scalability of the network and the results obtained for different architectures.

2. Ad Hoc Networks Nature

Ad hoc networks are self-organized computing systems consisting of a set of nodes that communicate with each other through wireless connections and does not rely on a preexisting infrastructure to operate. Each node configures its participation in the network autonomously, knowing only the information of the neighbors who are in their transmission range. Its main features are: [5, 24]:

- **Autonomous Operation**: Ad hoc networks are adaptive and have the ability to configure themselves without any external control.
- **Dynamic Topology:** The nodes are able to move randomly, it could cause changes in the topology and communication failures [22, 25].
- **Cooperation Needed:**The goal of cooperation between nodes is to find a balance that allows to operate in a distributed manner, share resources and maximize network performance [26, 14].
- **Energy Managment**: Wireless devices have batteries with limited capabilities. An efficient power management ensures the operation of the nodes as long as possible [9].
- **Heterogeneous Nodes**: Nodes, generally have different levels of resources (storage capacity, mobility level, available energy) making it possible to classify them according to their individual characteristics.

2.1. Expected Properties:

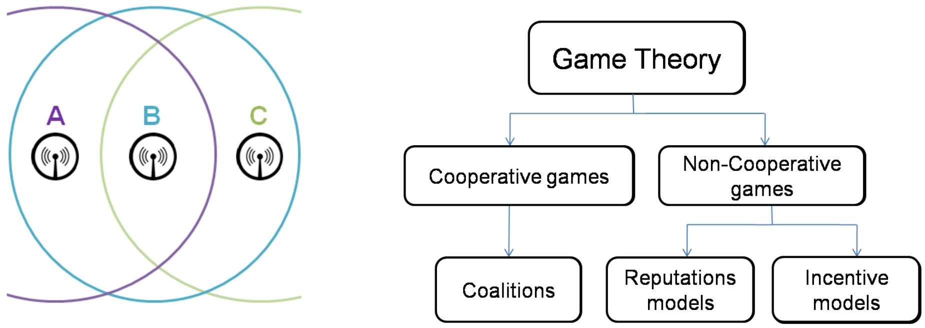
Some properties that expecting to be implicit in the network and improve its ability to respond to frequent changes in the topology, routing, and the behavior of the nodes are [8]:

- **Availability:** The network should have the ability to maintain configuration parameters to ensure communications along possible nodes failures.
- **Optimal Decisions:** The nodes should be able to select configuration parameters that enable them to maximize their performance under constant changes in the network state.
- **Confidentiality:** The sent data over the network only should be read by authorized receivers.
- **Scalability:** The network should be able to increase its size and handle properly the growing amount of work without losing quality of services.

2.2. Emergent Properties

The appearance of emergent properties in ad hoc networks is a consequence of the interaction between nodes when they try to reach a global organization in a dynamic way. These new properties are derived from cooperative work between nodes and are impossible when they act individually [8]. Below are some of these properties, as well as the mechanisms used in their control:

- **Hidden Terminal Problem**: It arises from the lack of a centralized control that allows to manage efficiently communications between nodes. In figure 1a is possible to observe how the node A is outside the transmission range of the node C, making impossible to establish a direct communication between them. The node B communicates with both, but A and C may cause interference when they try to communicate simultaneously with B assuming that the transmission medium is free. In response to this problem the 802.11 standard introduces the RTS/CTS (*request to send/clear to send*) although effective it does not solve the problem completely [31].
- **Competitive Environments and Game Theory**: The emergence of competitive environments in ad hoc networks is directly related to the need for cooperation among network members, but before analyzing this property is necessary to know two implicit features in the behavior of the nodes. First, the rationality is the ability of the nodes to take decisions repeatedly trying to satisfy a particular purpose, and finally the intelligence is considered as the ability of nodes to create strategies that allows them to maximize their benefits from its knowledge of the network [27].



(a) Hidden Node **(b)** Game Theory

Figure 1: Emergent properties

The increase in the rationality of the nodes implies that the actions they take are guided by their particular interests, participate in the network implies an additional resource consumption and can lead the nodes to consider reasons to cooperate in the communications taking care about its own profits. This rational behavior generates new scenarios where resources competition, selfish behavior and cooperation among nodes become intrinsic elements of the nature of ad hoc networks [26, 14].

In Figure 1b is possible to observe the models used in game theory to study competitive environments in ad hoc networks [15]. First, cooperative games appear with coalitions of nodes that have the same goal and where there are not selfish behaviors, being the logical organization of the tasks the more relevant problem [18]. An example of this nature can be seen in sensor networks, widely used in environmental monitoring and vehicular networks [16, 11]. For non-cooperative games appear schemes based on reputation and incentives models, trying to achieve cooperation among nodes with different goals [28].

2.3. Network Architecture

The network architecture describes the design of the network, specifying their configuration, functional organization and a set of necessary protocols for its operation. Ad hoc networks have two types of architectures [32]:

- **Flat Architecture:** In a flat architecture all nodes perform routing and packet forwarding in an independent way and without any external control [7]. In the figure ref fig:flat is possible to observe an ad hoc network with a flat architecture where is necessary to use intermediate nodes to achieve communications.

- **Hierarchical architectures:** This kind of architectures are generated by clustering algorithms, when groups of geographically adjacent nodes and connected among them are created , these groups are created dynamically and can be adapted to the needs of the network (routing improve, reduce energy consumption, enhance cooperation). In the figure 2b is possible to observe an ad hoc network with a hierarchical architecture of two layer.

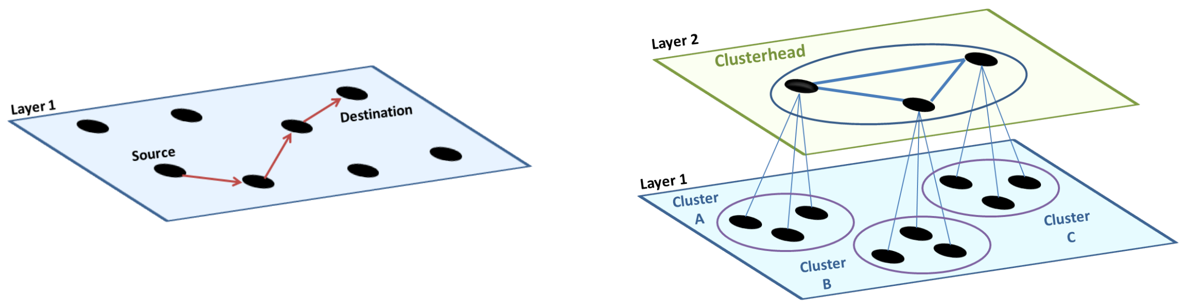
The use of clustering algorithms has the following advantages [30, 29, 6] :

- A cluster can assign functions to their nodes. The most common role is as a leader node called clusterhead, which is responsible for transmitting all packets of its nodes and helping to establish communication with other clusters.

- A suitable assignment of tasks improves the performance of transmission medium access protocols, routing tables and energy use.

- Several interconnected cluster improve the coordination of the nodes in the transmission of packets.

- Hierarchical architectures reduce significantly the routing tables because the nodes only need to have information about its own cluster and not about the all of network.



(a) Flat Architecture **(b)** Hierarchical Architecture

Figure 2: Network Architecture

3. Scalability in Ad Hoc Networks

Due to the massive use of wireless devices is necessary to develop ad hoc networks with the ability to reacting properly to the increase in the number of nodes without losing quality of the service. Achieving scalability in the ad hoc networks is one of the main challenges in protocols design and is one required feature to achieve ad hoc networks with high deployability.

Some factors that affected scalability in ad hoc networks are:

- **Routing:** The scalability is directly related to the routing algorithms, but even with a better routing algorithm, the main limitation is the nature multi-hop of communications. The need of use intermediate nodes in communications causes the size of routing tables making proportional to the number of nodes in the network.
- **Heterogeneous networks:** The existence of heterogeneous nodes added with the cooperation need, make necessary to ensure that the tasks assigned to a node are not over of its level of resources (processing, memory, available energy) otherwise it may cause delays or communications failures.
- **Selfish behaviours:** The increase on the nodes rationality, result in the emergence of selfish behavior. These behaviors appear when a node acts maliciously, trying to benefit from the network its own, without collaborating with other nodes.

3.1. Scalability on Flat Architectures:

Flat architectures have scalability problems due to the size of the routing tables is proportional to the number of nodes in the network, however, it work well in small networks where the routing and power consumption is low [7]. To measure the scalability of a network with a flat architecture, is necessary to define the transport capability [13] as the adding of the products between the number of the bits and the distance which they are carried out by unit of time. To analyze this property it is considered two kinds of networks, arbitrary networks where the nodes, the traffic destiny and the source can be located in any place, and the random networks where the nodes and the traffic are located in an uniform probability in the space.

To considerate a successful transmission in just one hop, it uses two kinds of interferences, the protocol model where interference is generated by the distance between the nodes and the physical model where the interference is generated by the relationship between the noise/signal (SNR). In the table 1 is possible to see the result obtained for the transport capability based on the static networks without existence of cooperation and where the traffic patterns are generated in uniform random way.

Latest works improve the establish limits by Gupta and Kumar [13]. In [12, 10] it shows the movement and the cooperation between the nodes like a way to improve the traffic capability $\Theta(1)$, but without establish limits for communication delays. In [23] it studied the scalability in military networks based traffic patterns under potential law and where it shows an increase in the network capability from a practical way.

In the results obtained by Gupta and Kumar [13] it is posible to observe a network with n nodes, the traffic capability of one node decrease in $\Theta(\frac{1}{\sqrt{n}})$ when the number of nodes increases. These results are independent of the

Table 1: Transport Capacity [23]

	Protocol Model	Physical model
Networks	$\Theta(\frac{1}{\sqrt{n}})$	$\Theta(\frac{1}{n^{1/\alpha}})$
Networks	$\Theta(\frac{1}{\sqrt{n}\cdot log(n)})$	$\Theta(\frac{1}{\sqrt{n}})$

routing protocol, from transmission medium access and any other control protocol being the principal limitation in the moment to design long ad hoc networks with flat architecture.

3.2. Scalability on Hierarchy Architectures:

Scalability in a hierarchical architecture is related to the level of resources available in a network layer and the tasks that it has to perform, the upper layers must be able to hold the additional workload, that implies serving like intermediaries in communication of the network without losing quality of the services [20, 21, 30].

In this type of architecture there are two ways to achieve scalability [3, 17]:

- **Horizontal Scalability:** To scale horizontally new nodes are added to a layer of the network to help manage the increased workload over this layer, this improve stability and overall system performance.
- **Vertical Scalability:** To scale vertically more resources are added to a particular node (processor, memory, energy), this improve the network performance and help to centralize workload on that node.

Both models have advantages and disadvantages, but the key to achieve scalability in a hierarchical architecture is to reach a balance between the tasks assigned to a node and its level of resources. Below it describes Two types of clustering algorithms that attempt to improve the distribution of tasks between the nodes of the network

Load-Balancing Clustering: The workload which implies to serve as clusterhead is related to the number of nodes that it can manage. To generate a hierarchical structure is necessary to establish limits on the number of nodes that can form a cluster. The clustering algorithms for load balancing set upper and lower limits on the number of nodes that can form a cluster, avoiding the existence of too big clusters that could overload the clusterhead, and too small clusters that generate too many routes in the upper layers of the network. Among the most representative algorithms are AMC *(Adaptative Multi-hop Clustering)* [20, 21] and DLBC *(Degree-Load-Balancing Clustering)* [1].

Combined-Metrics-Based-Clustering : These kind of algorithms consider factors such as storage capacity, level of mobility, available energy and number of neighbors nodes. Its main goal is to generate a combination of these parameters into a single value that will become the criteria to classify the nodes by its capacity [30].

One of the most representative algorithms of this type is the WCA *(Weighted Clustering Algorithm)*.This algorithm considers four parameters for each node of the network. First it will be $\Delta = |d - \delta|$ where d is the amount of neighbors nodes and δ is the optimum amount of nodes that could be handled by the clusterhead. The second parameter D represents the add of the distances from the node to its neighbors. The third M represents the average speed of the node, and the last parameter P, refers to the additional energy consumption when a node becomes in a clusterhead [4]. The final step after achieving parameters is to calculate the weight of the node in the following manner:

$$W = w_1\Delta + w_2D + w_3M + w_4P \tag{1}$$

Where w_i with $i = 1, 2, 3, 4$ and where $\sum_{i=1}^{4} w_i = 1$ are values normalized and allow to give more importance to one of the parameters according to the needs of the network.The selected node as clusterhead is which received the smallest of the weights and will be responsible for the communications of other nodes. There are improvements to the algorithm *WCA* as suggested in [2, 19] where nodes with low energy levels stay outside of the choice in order to reduce the number of nodes to evaluate.

The hierarchical architectures arise as a vertical response to scalability problems presented in flat architecture. This kind of architecture increases the network capacity by improving the quality of communications, routing and topology control and it is a good alternative to achieve scalability in ad hoc networks. [32, 33, 30].

4. Conclusion

- Due to the massive use of wireless devices, it is necessary to generate communication networks with the ability to perform appropriately to the growth of the network without losing quality of the services. Achieving scalability in ad hoc networks is one of the major challenges in the design of protocols and is one of features needed to achieve ad hoc networks with high deployability
- The scalability of an ad hoc network is directly related to routing algorithms, the cooperation needed, the network architecture and the distribution of resources among nodes.
- Finally we wonder if it is possible to establish one function from the amount of resources in the lower layers of the network to determine the level of resources required in the upper layers to avoid problems with quality of service in the network?

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