ANALYSING THE OVERHEAD IN MOBILE AD-HOC NETWORK WITH A HIERARCHICAL ROUTING STRUCTURE

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Abstract-

Hierarchical routing is a common practice in actual Internet networks. This kind of routing allows nodes and routers to get small routing tables and small routing overhead. On the opposite side, routing in MANETs is flat; therefore, nodes have to learn how to reach each node in the network. It means large routing tables, impact in the look up algorithm and large routing overhead. In this paper we analyze the advantages of using hierarchical routing in MANETs under specific scenarios, showing the reduction of routing overhead from a factor of N^2 to N^2/k (being *N* the number of nodes and *k* the number of subnets).

I. INTRODUCTION

Currently mobile communications have become an important role for the people. Since these kinds of communications are considered less a luxury and more a necessity, the number of mobile users, services and devices grows quickly. Most of the researching efforts have been spent on the heterogeneous networks (integration of fixed networks with infrastructure Wireless Networks). However, during the past few years, essentials efforts have been done in the researching field of Mobile Ad-hoc Networking (MANET) [1], which is basically a wireless network without infrastructure.

One of the main issues in MANET researching is the routing. The principal results obtained into this area are the well-known AODV [2] (reactive) and the OLSR [3] (proactive) routing protocols. In MANET, every node requires to participate as a router, maintaining individually routes to other nodes. If the number of nodes grows largely, the number of routes will increase rapidly. This effect together with the mobility of nodes may increase the overhead due to the maintenance of the routes, consuming the scarce bandwidth in the MANET and therefore reducing the throughput. If we do not take into account the mobility, this scenario is something similar to what happened to the ARPAnet at the beginning.

The logical solution to reduce this overhead would be to use a hierarchical structure like the used in Internet, in which the nodes are aggregated into subnets to be handled as a single entity for routing purposes. However, this structure is difficult to apply in MANETs due to their dynamic and distributed nature. The main problems to solve in such hierarchical structure are the address acquisition under mobility scenarios, the dynamic creation and removal of subnets and the maintenance of already established sessions when a node moves from one subnet to other and changes its IP address.

We are proposing a scheme, which takes advantage of the fact that currently the nodes in MANETs can be grouped following physical or environmental constraints to apply this hierarchical structure. These formed clusters can be considered subnets of a MANET, giving the chance of representing multiple routes of a large number of nodes by a single route. Since the routing information is cutting down, a reduction in the overhead may be obtained [5].

This scheme is useful in scenarios like Wireless Mesh Networks (WMN) with nodes connected to infrastructures but those are the edge-points of a MANET, or in scenarios in which there are nodes with leader roles (e.g. an emergency network). Figure 1 (extracted from [4]) shows an example of an emergency situation in which a fire trop handle by the head quarters is sub-grouped in rescue teams. Each rescue team is controlled by a leader (fire chief). Rescue teams also are divided in rescue units composed of pairs of firemen with a rescue leader. The firemen trop forms a hierarchical structure with communications between the head quarters with the chief and the chief with the rescue unit leaders. Each rescue unit forms a cluster with communications within its own cluster and his rescue leader (intra-cluster communications) and with other clusters (inter-cluster communications), see [4]. From the communications point of view, each cluster is formed by a leader, usually it has more resources in terms of bandwidth, power, gateway connectivity, etc, (e.g. a fire-truck) relatively static and nodes that move in the disaster area. In a natural manner, mobile nodes attached to the leader node may form a subnet. If the mobile node moves it can be attached to another leader node. Now the question is whether it is more efficient if that node keeps the IP address or whether the node attaches and changes the IP address to one belonging to the new subnet.

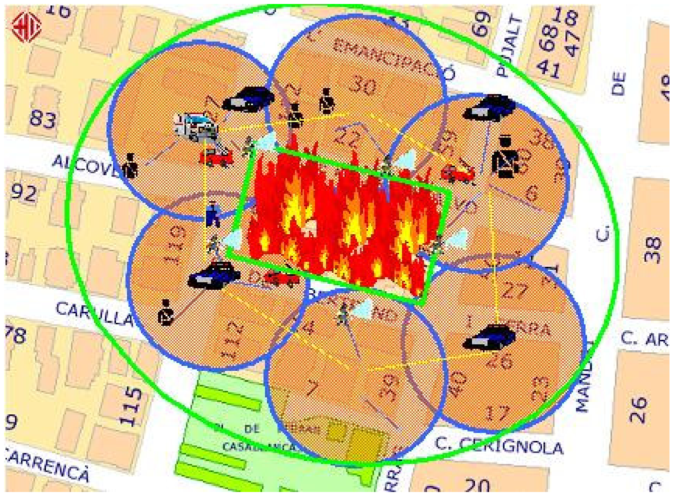

Figure1. Example of an emergency situation, in which a MANET can assume a hierarchical structure.

In this paper we evaluate analytically the expected overhead reduction generated by the routing protocol when we adopt a hierarchical routing scheme in MANET. We specifically evaluate the overhead incurred by the current routing protocols (reactive and proactive) used in MANET, then, we modify the obtained models to include the parameters to represent the hierarchical structure (subnet, address aggregation). Finally, we compare these models to get a preliminary idea of the reduction incurred by our proposal. The main objective of this paper is not to solve all the technological issues arisen in MANETs if subnetting solutions are approached but to show that an effort in that direction is valuable.

The rest of the paper is organized as follows: a generic description of the scenario characteristics and the challenges that we have to solve for integrating successfully the hierarchical routing to MANET are given in section II. Then, we present the analytical model of the overhead generated by the routing mechanisms. Finally, we have the conclusions and future work.

II. SCENARIO DESCRIPTION

We are proposing a scheme which takes advantage of the fact that currently the nodes in a MANET can be grouped following physical or environmental constraints. Figure 2 shows some of the following assumptions:

- Nodes form an area of size *A* around a leader node, and this area will correspond to an IP subnet of dynamic size, e.g. depends on the number of nodes attached to the area.
- Nodes form a multi-homed network with nodes of the same area and with nodes of other areas.
- A node is attached to an area and therefore has an IP address corresponding to that IP subnet area. IP addresses are used like host locators.
- When a node moves to other area has to acquire a new IP address corresponding to the new IP subnet.
- Every node knows each of its one-hop neighbours, e.g. using link sensing or a Hello protocol.
- A message sent by a node is received correctly within a finite time by all of its one-hop neighbours.

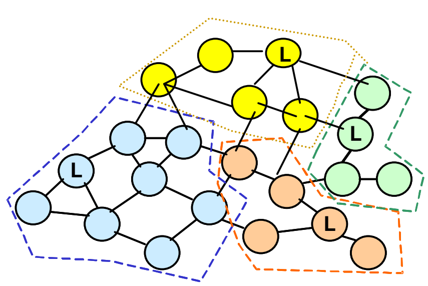

Figure 2. MANET nodes grouped to form subnets.

Taking into account these assumptions, some challenges like the subnet formation and address acquisition, the mobility of nodes between subnets, the intra-subnet routing, and the inter-subnet routing have to be solved.

1) Subnet Formation and Address Acquisition

In our proposed scheme the node needs a mechanism to detect a leader node and to get attach to it. The leader node is responsible to give an IP address to the node. In case the node roams to a new area, the node has to detect that is in a new area and to obtain an IP address from the leader node. Future work will be required to define a procedure that allows a node to get attached to an area and obtain an IP address within the subnet. There are several proposals in the literature on issues like address acquisition schemes and leader selection algorithms (e.g. DHCP or dynamic stateless address acquisition [6], [7], [8], [9] and [14]).

The main issues to solve by these kind of mechanisms are:

- Leader detection and selection
- Node Address Construction
- Duplicate Address Detection

2) Mobility between subnets

Mobility into the subnet is not a critical issue and it could be performed by the already proposed MANET routing protocols (AODV, or OLSR). Although, a mobility management between subnets looks necessary.

The proposed mobility management between subnets relies on the use of an USER ID like the node identification and the IP Address like the location indicator of the node. This approach breaks the IP paradigm of uniqueness between location and identity. Additionally, this approach allows supporting terminal and user mobility.

The approach could be based on the aforementioned Address Acquisition procedure for terminal mobility, the Session Initiation Protocol (SIP), [10] and [11], for streaming multimedia applications, and the Stream Control Transmission Protocol (SCTP) [12] with an enhancement for dynamic address reconfiguration [13] for the applications based on reliable transport protocol. It mainly provides mobility in two layers: network layer and the application, and for these reason our proposed scheme is so called Multi-layer.

3) Intra and Inter subnet routing

Some enhancements to the existing MANET routing protocol are needed to allow interaction between them and the Address Acquisition mechanism. By default, reactive protocols like AODV does not require large changes because its standard [2] allow address aggregation, allowing adopting this hierarchical scheme.

For the case of hierarchical routing with proactive protocols like OLSR, the scheme requires a new routing mechanism to allow the address aggregation (inter-subnet routing). Since the subnets are assumed fixed (leader node is mainly static) in our scenario, the mechanism could take benefit of this fact.

Future work will be required to define these mechanisms and modifications needed by the current routing protocols to interact with our proposed hierarchical structure.

III. ANALYTICAL MODEL

To validate our proposal we use some well-known analytical models of reactive and proactive routing protocols [15], hierarchical subnetting [17], and cellular systems [16]. First than all we will present briefly each model. The model for MANET routing protocols let us estimate the control overhead generated in a fixed network, and the control overhead due to the mobility. After that, we apply some hierarchical routing (subnetting) parameters to the model, estimating the new control overhead generated by the routing protocols for a fixed Network. Then, with the expressions obtained and the cellular system models we can estimate the control overhead due to the subnetting and the mobility. Finally, we compare the estimations obtained to validate our proposal.

A. MANET Routing Protocols Models

These models were developed and validated in [15], to compare the traffic control overhead and their bandwidth cost generated by reactive and proactive protocols. It takes into account the network density, the mobility, the traffic creation, and the traffic density. The parameters used to model the network are: the number of nodes N, the average live time of a link T_b ($T_b = 1/\mu$, where μ is the link breakage rate) to model the mobility, the average length of a route L which depends mainly of the shape of the network. Additionally, the model assumes that μ and L remain constants, and the network always remain connected.

1) Reactive protocol model

Since the route creation in reactive protocols depends mainly of the data traffic creation and diversity, the following parameters are used: the average number of route creation λ (Route Requests), and the average number of active routes per node a, such active route is a pair where the source continuously sends packets to the destination.

We also have to take into account the parameters that depend on the protocol, see [15]: the average number of emissions for a route request (could include the route reply messages) B_r, and the route request optimization factor o_r, which depends of the network and the traffic parameters ($o_r = B_r / N$). For a pure flooding protocol, if we include the Route Reply from the destination, we get that; $o_r = 1 + j / N$, where j is the number of reply messages. According to [5] the Route Requests are the responsible for the majority of the routing overhead in networks running AODV, so, we could expect $o_r \approx 1$.

In a Fixed Network a reactive protocol produces λN route requests every second. These requests will generate $\lambda o_r N^2$ control packets in the network. We can express the control overhead due to the routing protocol by:

$$O(N) = o_r \lambda N^2 \qquad (1)$$

The mobility in the MANETs can be represented by the link breakage and creation. Being the link breakage the most important factor to model the reaction of the routing protocols to mobility, because the protocols have to react quickly to the breakages when the link is actively used to transmit data. Therefore, when a link breakage is detected, the protocol will basically issue a new route request to repair routes using that link.

If we have aN routes in the network, there will be aNL active links, such that $\mu(aNL)N$ packets will be generated by a link breakage. Basically the reactive protocol will issue a new route request to repair routes using that link. This route request could be either initiated by the source of the route or by the node detecting the link breakage. For the latter case this gain may be integrated in the parameter o_r. For the more pessimistic case the overhead due to the mobility is expressed by:

$$O(N) = o_r \mu a L N^2 \qquad (2)$$

2) Proactive protocol model

A proactive protocol mainly depends on the regular emission of control packets, having the advantage of not generating any overhead at route creation, because their fixed control traffic overhead includes the cost of the route creation.

The parameters concerning to the proactive protocol are, see [15]: the packets for proactively discovering the local topology (hello packets) emitted by a node per second h_p, and the topology broadcast packets emitted by a node during a second for allowing global knowledge of the topology t_p. These parameters are expressed in terms of rates. To react to topological changes the active next hop AN_p is defined; it corresponds to the average number of active links per node, and it is used to evaluate what topology changes may trigger additional control traffic. Since proactive protocols can take advantage from their knowledge of the topology in order to optimize broadcasting, a broadcast optimization factor o_p is denoted ($o_p = B_p/N$), where B_p denotes the average number of emissions to achieve a topology broadcast.

In a proactive protocol $h_p N$ hello messages are produced per second in the entire network, initiating $t_p N$ topology emissions, which generate $t_p\, o_p N^2$ packets. The overhead produced can be represented by

$$O(N) = h_p N + o_p t_p N^2 \qquad (3)$$

Quantifying the overhead generated in reaction to mobility is similar as with reactive protocols. A node detecting a link breakage on a route will transmit an additional topology broadcast packet. In average a node is on aL routes, and several routes may have the same outgoing link. However, the probability that the next hops for these routes are the same is certainly greater than the probability that the destinations for these routes are the same. With the introduction of the average number of active links of a node AN_p parameter, the total overhead due to mobility in a proactive protocol is expressed by

$$O(N) = o_p \mu A N_p N^2 \qquad (4)$$

With the expressions presented above, we can note that the number of nodes in the network dominates the overhead in an exponential manner $O(N^2)$ for both types of routing protocols. The cost of these routing protocols becomes prohibitive as the number of nodes in the network gets large.

B. Applying hierarchical routing (subnetting) to the routing protocols

In hierarchical routing any node keeps complete routing information about nodes that are close to it, and lesser information about nodes located further away from it. The reduction of the routing information is achieved partitioning the network (creating subnets). We propose to form the subnets with a 2 level hierarchical clustering based scheme [17], assuming all the nodes are uniformly distributed in the network and in each subnet for the scope of this analysis.

To apply subnets a new parameter must be included in the model: the number of subnets in the network $\boldsymbol{k}$. To guarantee full connectivity in the network one node at least must maintain a route to each node into the same subnet, and a route to each subnet in the network. From this, the network must have ***(k-1)+N/k*** routes per node. Therefore, the first advantage in subnetting is the reduction of the routing table and the saving in the look up algorithm.

1) Reactive protocols with subnets

When we introduce subnets to the reactive protocol reactive protocol model, we include the average number of route creation $\boldsymbol{\lambda_I}$ by a node to other nodes into the same subnet, the average number of route creation $\boldsymbol{\lambda_E}$ by a node to other subnets, and the average length of a route $\boldsymbol{q}$ to another subnet. We remind you that we are interested in knowing what is the overhead saving (if there is) in a MANET using a reactive protocol like AODV, and not in solving the technological aspects of AODV using subnets. We leave that study as a second step.

Applying the new parameters to the aforementioned model for a fixed network (1), we have $\boldsymbol{N\lambda_I}$ route requests for routes to nodes into the same subnet produced each second, and $\boldsymbol{N(k-1)\lambda_E}$ route requests per second for routes to nodes located in other subnets. Therefore, the overhead generated by these requests can be expressed by

$$o_r \lambda_I \frac{N^2}{k} + o_r \lambda_E (k-1) N \left(\frac{N}{k} + q \right) + S$$

Where S represents the cost of finding out the routes to other subnets (S = $(k-1)^2 N/k$). Assuming that the probability of having a route to a subnet is much higher (P(cache) ≈ 1) than having a route to a particular node, this cost is only paid few times, therefore during a period of time long this value will be small (because is not a rate). Since the $\boldsymbol{q}$ value is very small compared with the number of nodes N in the network, and S is constant during the time, we consider these two values not relevant for our analysis. From this we have

$$O(N) \approx o_r \lambda_I \frac{N^2}{k} + o_r \lambda_E (k-1) \frac{N^2}{k} \qquad (5)$$

Since the nodes are uniformly distributed, and assuming that λ_I and λ_E are independent from each other and have the same probability occurrence, we can represent $\lambda = \lambda_I + (k-1)\lambda_E$. Expressing (4) in terms of λ we obtain

$$O(N) \approx o_r \lambda \frac{N^2}{k} \qquad (6)$$

To model the overhead due to the mobility we divide it in two components

$$O(N) = O_s(N) + O_H(N) \qquad (7)$$

The first term $O_S(N)$ represents the overhead due to the mobility of nodes into the subnet. And the second one $O_H(N)$ represents the overhead due to the change of subnet. This overhead is produced because each time that a node changes of subnet, it must change its address. The process to acquire a new address and to attach it to the node ID implies a message exchange.

The link breakage is assumed in our model like the main component of the overhead in reaction to mobility. After adding subnets to the reactive protocol model we will have two scenarios. The first scenario is presented when the broken link corresponds to a link between two nodes that are into the same subnet, and for this case the route repair will be local to the subnet. In that case a flooding in the subnet is enough to repair the route, and it is not necessary to repair from the source. The second one, is presented when the broken link corresponds to a link between two nodes that are located in different subnets. For this case the route has to be repaired from the source of the route. If we have *aNL* active links in the network; the overhead $O_S(N)$ due to mobility could be represented by

$$o_r \mu a L \frac{N^2}{k} \leq O_s(N) \leq o_r \mu a L N^2 \qquad (8)$$

Due to the difficult to quantify exactly the emissions of control packets in reaction to mobility, we decided to express it between two quotes, corresponding each one to the aforementioned scenarios (the best and the worst cases). We have to note that often several routes have identical destinations and the majority can be repaired locally, meaning that the overhead will be close to the lower bound the mayor part of the time.

2) Adding mobility between subnets to the model

Since a subnet corresponds to a cluster, which is based on the on the proximity (# of hops) to a cluster head (leader node), forming an area around this cluster head. Despite of the variable size of this area (subnet), we assume a subnet of a fixed size, for this analysis. Therefore, we can assume that a node moving between subnets behaves like a node moving in a cellular system.

For our analysis the most important parameter related to the mobility is the probability of subnet (area) boundary crossing. According to [16], an approximate evaluation for cellular system performance is obtained through models based on fluid flow assumptions. The following conditions are needed to derive a simple expression:

- The nodes and their traffic are uniformly distributed over a given subnet (area or cell).
- The nodes have a mean velocity of $\boldsymbol{v}$ and their directions of movements are uniformly distributed over $[0,2\pi]$.

With the aforementioned conditions the subnet crossover rate $\boldsymbol{\eta}$is given by

$$\eta = v \frac{P}{\pi S}$$

Where $\boldsymbol{P}$ corresponds to the perimeter of the subnet, and $\boldsymbol{S}$ is the area of the subnet.

If we denote the time spent by a node within a given subnet (dwell time) [18], [19]by the random variable $\boldsymbol{T_h}$. The mean dwell time $\boldsymbol{E(T_h)}$ can be calculated by knowing the subnet crossover rate [20], [21], that is

$$E(T_h) = \frac{1}{\eta}$$

Which correspond to the average number of handoffs.

Additionally, the dwell time is assumed exponentially distributed (the residing time of a node in the actual subnet is not related with the residing time of the same node in a previous subnet, memory less system). So, the probability of subnet boundary crossing is given by

$$P(T_h) = \eta e^{-\eta t}$$

If our Address Acquisition procedure generates $\boldsymbol{h}$ packets in average, and if we have $\boldsymbol{N/k}$ nodes per subnet, we will have $\boldsymbol{kh\eta(N/k)}$ packets in average due to the change of subnet in the entire network. Now, we can represent the overhead due to change of subnet by

$$O_H(N) = h \eta N \qquad (9)$$

Finally replacing (8) and (9) in (7), we can approximate the overhead in the routing protocol model with hierarchical subnetting due to mobility to

$$O(N) \approx o_r \mu a L \frac{N^2}{k} + h \eta N$$

3) Proactive protocol with subnets

When we apply hierarchical routing with a proactive protocol, a mechanism to find out the routes to reach other subnets is needed. Within the scope of this study we introduce the parameter $\boldsymbol{\varphi}$ to represent the cost of finding out these routes, and leaving the description and evaluation (identify the value of the parameter φ) of the aforementioned mechanism for a future study.

With the proactive protocol, each node emits h_p hello messages per second, and now each t_p is emitted to the nodes that are close to it (to all the members of the subnet). The overhead generated is given by

$$O(N) = h_p N + o_p t_p \frac{N^2}{k} + \varphi \qquad (10)$$

In addition, the parameter φ includes the cost of emitting the routes to other subnets to each node. Despite of all this routing information have a cost, we can expect this cost is much lower compared to the overhead without hierarchical routing, because this cost does not depend of a N^2 factor like in the proactive and reactive protocols, and because the procedure can take advantage of the partial knowledge of the topology and the characteristics of the scenario.

The overhead generated in reaction to mobility is represented by the expression (7) where the second component (O_H) is the same expressed in (9), and the component O_s will be expressed by

$$O_s = o_p \mu A N_p \frac{N^2}{k} + \varphi \qquad (11)$$

The first part corresponds to the overhead generated by a link breakage, such that the topology is only updated locally. Here is evident that a local topology change does not have to generate control overhead in the entire network, because certainly the nodes located further away are not affected by these changes. The main idea behind this assumption is that if a node knows how to reach a subnet, it is not necessary to know how the topology in that subnet is. This assumption is similar to the idea of Internet in which an Autonomous System (AS) does not know how is organized another AS and only knows how to reach that AS. Again, we have the parameter φ in the second part of the expression, to represent the overhead generated in reaction to a link breakage between subnets.

Finally replacing (9) and (11) in (7) we obtain

$$O(N) = o_p \mu A N_p \frac{N^2}{k} + \varphi + h\eta N$$

To acquire an order of magnitude of the reduction in the overhead generated by the MANET routing protocols after applying hierarchical routing we draw two comparable expressions like (1) and (6). Figure 4 shows a comparison between a reactive protocol and a reactive protocol with 4 subnets (of an square shape).

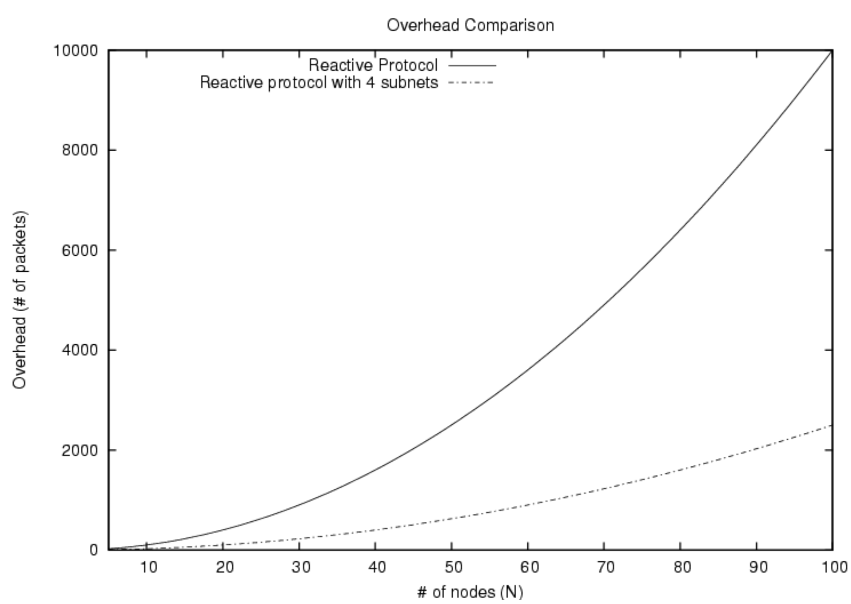

Figure 3. Overhead comparison between a reactive protocol and the same protocol with subnets.

The overhead reduction observed in the figure gives us a margin, which is enough to add some overhead generated by the modifications and new mechanisms needed to introduce hierarchical routing to MANET, and to keep an important reduction.

In both cases, proactive and reactive protocols with hierarchical routing, we observe an $O(N^2/k)$overhead, which depending of k value could be significant, despite of the cost incurred by the changes and mechanisms generated by the addition of hierarchical routing to MANET.

In addition we can expect a reduction of the topology packets (bandwidth) for the case of proactive protocols, and a reduction in the delay incurred to acquire a route for the case of reactive protocols.

IV. CONCLUSIONS

We presented a scenario in which adding hierarchical routing to MANET produces a reduction in the routing overhead. We also described the architecture (identify the modifications and the new mechanisms) needed to add the hierarchical routing. Finally we demonstrated analytically the expected reduction in the overhead generated by the MANET with hierarchical routing under a specific scenario.

We notice that this study only obtains preliminary results, that allow us justify the current efforts to integrate the hierarchical routing to MANET. Some of the activities are: the subnet formation and address acquisition, the mobility of nodes between subnets, the intra-subnet routing, and the inter-subnet routing (modifications to the existent routing protocols). We think that an effort to integrate existing schemes with the corresponding modifications to support subnetting in MANETs could be valuable.

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