A Preferential Attachment Model for Primate Social Networks

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***Abstract*—Wildlife monitoring is an enormous organizational challenge due to the required time and effort for setting and maintaining it. It is particularly difficult when the observed species has a complex social hierarchy and different roles for the members in the social group.**

In this paper, we introduce an approach to model a primate social network. The primates have complex social behaviors and network structure. As a result, there is a need for realistic computational models to fully understand and analyze the social behavior of such animal groups. We propose a novel spatial cut-off preferential attachment model with a center of mass concept to model the characteristics of the primate groups and a role determination algorithm, which groups the primates into their roles in the society based on the data collected by the wireless sensor and actor networks (WSAN). The performance of the monitoring and role determination algorithms, the applicability of the network formation and the mobility models are evaluated through extensive simulations. The results show that the proposed primate group models deliver networks with properties similar to real-life primate groups in terms of social network characteristics.

I. INTRODUCTION

The characteristics of various animal groups have been analyzed by using collected data from both wildlife and lab experiments [1]. Animal monitoring becomes challenging when the observed species group possess a complex social structure as it requires simultaneous monitoring of multiple individuals and their interactions. For instance, the complex social organization of primate groups requires continuous and long-term monitoring to gather sufficient data [2]. In fact, the social characteristics of primate groups have been investigated in various experiments, but many aspects of their social life remain to be analyzed [3], as real-life and long term movement data is missing for most of the primate groups [1], [4]. It is still a challenge for researchers to find out how primate groups would behave and how their social affiliations might change in their natural habitats in the long run. Hence, realistic models of primate networks are critical to analyze their behaviors and to run experiments.

In this paper, we propose an approach to model the social life of primate groups. The initial formation of the animal network and the movement of the animal group must be modeled according to real-life observations and must reflect the social structure of the group. Consequently, it is crucial to use a suitable mobility model derived from the expected and observed mobility patterns. We propose a novel spatial cut-off preferential attachment model and a center of mass concept for modeling the social network connections and the movement models of the group. We use wireless sensor and actor network (WSAN) [5] technology to collect data from the primate network. WSANs have not been used for monitoring primates in the past. However recent improvements in size, weight, energy consumption and sensing capabilities of sensor nodes as well as their self-organizing aspects make WSANs suitable for wildlife monitoring [6], [7]. WSANs can overcome the issues of conventional approaches for wildlife monitoring, which require technically sophisticated processes [8]. For instance, most of the current monitoring methods are highly invasive on the environment and animals under study, which is highly challenging, in particular when periodical resampling is needed. We present a monitoring system model, where primates and their environment are equipped with wireless sensor and actor nodes for continuous data collection. The system aims to collect data from a primate group by building a WSAN among the members of the group and stationary nodes in the environment. The sensor nodes observe events and a limited number of more powerful actor nodes process this information and react accordingly.

The contributions of this work are twofold. We approach the challenge of primate group movement modeling from a social network perspective, adapting the concept of preferential attachment to introduce two network formation and mobility models for primate groups. However, there is no limitation in the node degree of existing preferential attachment social network models, which violates the naturally known attachment limitations for different members in a social primate group. Thus, the first contribution is using a cut-off preferential attachment scheme based on the spatial relationship among the nodes and integrated with the Lévy walk mobility model [9], thus defining a computational model for the foraging of primate groups. The second contribution is the role determination algorithm, which uses the collection of the spatial-temporal relationships to automatically and locally decide on the role of each animal in the society. The social network characteristics of the primate groups created by the model are verified by comparisons with the analyses conducted on real-life primate networks. We modeled the monitoring system composed of wireless sensor and actor nodes in the OPNET modeler with a modular design.

The remainder of this paper is organized as follows. The related work is presented in Section II. The detailed descriptions of network formation and group mobility are provided in Section III, and the data collection method and role determination algorithm are presented in Section IV. We discuss the simulation results in Section V and conclude in Section VI.

II. Related work

A. Group mobility

The models for the generation of movement patterns are essential for the analysis of animal behavior. Hence, the insufficiency of public domain real-life data motivates the development of mobility models. In this section, we present the most current literature on group mobility models and the *"preferential attachment"* method in particular, since we use it in our mobility model.

For the simulation of animal groups and swarms, a variety of mobility models have been proposed. The Reference Point Group Mobility (RPGM) by Hong et al. [10] describes mobility coherence in the movement of a mobile host, i.e. hosts at different positions head towards the same target (or reference point). In RPGM, each group has a logical center, which is not the geographical one, but that defines the entire group's movement behavior similarly to our approach based on the center of mass concept. The node deployment in RPGM is usually random uniform and the nodes have their own random movement in addition to the group motion. In the Virtual Track model (VT model) by Zhou et al. [11], nodes follow *switch stations* deployed in the map, creating virtual tracks. Group nodes are distributed along the virtual tracks while the individual nodes are deployed in the whole area. The switch stations have features allowing the nodes to split into several groups after leaving the switch station. These aspects can be often found in the mobility of animal groups such as birds or primate groups, which split when a new leader founds a new troop. Musolesi et al. [12] approach the problem of the absence of realistic data to model movement patterns from a social perspective. Their model groups collection of nodes together based on social relationships among the individuals. The groups are mapped to a topographical space, including the strength of social ties, and a node belonging to a group moves inside the corresponding group area towards a goal using the Random Waypoint model [13]. In contrast, in our approach we use the Lévy walk model, which has been proposed as an adequate mobility model in most of the animal foraging patterns, such as spider monkeys [14]. Groups in the model of Musolesi et al. [12] also move towards randomly chosen goals with random speeds. As in the model of Hong et al. [10], Musolesi et al. [12] permits changes in the group affiliation based on sociability factor parameter. In our previous work, we also studied the problem of the absence of realistic data for group mobility from a social network perspective [15].

The network formation and mobility models introduced in this paper use the preferential attachment concept, which was implemented by Borrel et al. [16] for designing the mobility model called Pragma. Preferential attachment was introduced by Barabási and Albert [17] to explain a common property of many large networks, according to which the vertex connectivities follow a scale-free power-law distribution. Pragma assumes preferential attachment to centers of interest, considering that individuals move towards attractors, which appear and disappear. Thus, the model describes independent nodes that exhibit a collective behavior. Pragma achieves a scale-free spatial distribution in population growth.

B. Social network analysis for primates

Traditional primate relationship analyses focus on dyadic associations. However, all of the primate members and their interactions as a hierarchical group must be taken into consideration for a proper understanding of social structures in a primate society [3]. Therefore, we focus on the hierarchical structure of the primate group and the role of each primate in this hierarchy. Some traditional studies provide important information on the roles of individuals in primate groups [18], [19] and the results of such studies have started to be integrated with modern social network analysis methods and improved by the utilization of extensive data analyses and quantification [20]. Recent results show that social network analysis is indeed useful for the interpretation of primate social structure and organization [21], [2], [22].

Kasper and Voelkl [21] emphasize the importance of the quality of relationships in primate social systems and discuss a set of network measures for social network organization. The analysis includes results of 70 primate groups from 30 different species. Clark [2] studies the spatial association and social interaction data collected from a group of zoo-housed primates. Results of social network analysis reveals important characteristics of primate groups when proximity among individuals is not forced. Sueur and Petit [23] use movement patterns along with network metrics such as centrality and clustering coefficient to understand the roles, rankings and associations in the social group. Matsuda et al. [24] use similar network parameters as Sueur and Petit [23] to compare the intra-group relationships in primates, and their results show the important potential of contribution that social network analysis has for primate social bond analysis. Flack et al. [25] show the importance of individuals with high clustering coefficient on group stability and conflict management using experiment results to quantify instability of group structure in terms of reduced mean degree, increased clustering, reduced reach, and increased assortativity. Herein, we also use centrality and clustering coefficient to compare the network characteristics of our model and real life primate networks.

C. *Animal monitoring*

Approaches currently used by biologists in ape and monkey monitoring employ wildlife tracking collars [26], camera traps [27] and subcutaneous implants [28] for animal tagging and data collection [29]. Collars and implants provide more granular data compared to camera traps, and tracking collars are the most widely used data collectors. The properties of collars vary according to the equipped hardware such as radio transmitters, GPS receivers and activity sensors. For instance, VHF transmitters on these collars require a short distance to transmit the collected data from the collars to the receivers used in the environment. Hence, the current technology used in the field to collect data requires additional personnel and time.

Utilization of a WSAN might improve data collection in terms of time and effort despite the constraints of natural environments [30]. Environmental scientists and zoologists have already been using sensor nodes for wild life animal monitoring and tracking. These technologies are utilized to collect data from wild terrestrial areas and transmit them to the remote databases [31]. In some of these applications, the sensor nodes are attached to the animals, forming a wireless ad hoc network of mobile nodes [32]. ZebraNet [33] is one of the first studies, in which the animals carry custom tracking collars with global positioning system (GPS) capability and form a mobile sensor network for data recording and monitoring across a large area. Wark et al. [32] apply sensor network technology to farming and their approach also includes collars worn by animals. This system utilizes both static and mobile nodes measuring the state of a complex dynamic system comprising climate, soil, pasture, and animals. Naumowicz et al. [6] deployed a WSN on Skomer Island, Wales to investigate the behavior and spatial ecology of the Manx Shearwater seabirds. The system informs the scientists with high resolution data about the arrival and departure of the birds and the environmental parameters such as temperature or humidity. Handcock et al. [7] uses a large cattle enterprise to demonstrate the potential for combining GPS collars and satellite images in a WSN to monitor behavioral preferences and social behavior of cattle in Northern Australia. The sensor nodes are also used to monitor the functioning of the animal body or a particular organ [34]. In this type of applications, the sensors are implanted within the animal body to collect and transmit information by forming a WSN. The reduced cost compared to other tracking systems, particularly when sensor nodes are equipped with solar technology, is also an advantage of using sensor networks [29].

III. Network formation and mobility

In this section, we introduce our network formation and mobility models for the primate groups. The behaviors of primate societies and their social networks show great variety. Primates have complex social lives with families, affections, and politics of their own. Denham [35] presents a topology of primate societies according to social behaviors of different populations. According to this topology, a model is created for relations among environmental factors and primate social organization to define different types of primate societies.

The environmental inputs used in Denham's model include multiple factors such as the space and resource allocation, social motivations and mating strategies. After analyzing the primates according to these factors, Denham specified three important parameters namely, food predictability, food density and anti-predator strategy. Categorization of primates according to these parameters results in eight possible groups.

Only five of the groups defined in Denham's model are observed in nature and we concentrate on the group with the highest number of species including baboons, macaques, langurs, howlers, gorillas and chimpanzees. This group is defined to be living in a low food predictability, high food density environment and having an active anti-predator strategy. The animals stay close to each other while foraging and the groups are structured either as one-male-several-female or multimale-multifemale [35]. We have chosen this kind of group to analyze since the primate types that form it have been studied many times by researchers both in lab and wildlife environments. Therefore, there are studies and data on their social network structure and the roles of individual group members, making it the best candidate for validation purposes. The information and assumptions used in our approach thus follow the general guidelines about this group.

The members of the selected primate group have different roles depending on the gender, age, strength and affinity. These roles are listed as follows:

- *Alpha male*: The alpha male leads the group in daily travels and has exclusive breeding rights to the females. Generally there is one leader alpha male in each troop.
- *Adult female*: Adult females usually compete to stay close to the alpha male. Generally there are three or four adult females in each group.
- *Juvenile male*: Juvenile males tend to stay not very close to alpha males since the alpha male can see them as threats to his authority. Maturing males usually leave their family groups to establish either their own band or to join a bachelor group.
- *Juvenile female*: A juvenile female stays closer to the troop compared to juvenile males and may change family groups a number of times.
- *Newborn and infant*: A newborn forms a very close relationship to its mother, rarely straying more than a few steps from her side for three to four years.

The roles and characteristics of the primate group are critical inputs for the introduced network formation and mobility models, as different primate groups would exhibit different social structures. The models presented in this paper provide a base model that can be adapted accordingly.

A. *Network formation*

The initial distribution of nodes in the environment is important when modeling the structure of a society. We introduce two approaches for initial network formation. While both approaches utilize the social structure information of the primate group under consideration, the first approach is based on the preferential attachment method and the second approach uses the center of mass concept.

1) Preferential attachment approach: The *preferential attachment* concept was implemented by Borrel et al. [16] for designing the mobility model called Pragma. Preferential attachment was introduced by Barabási and Albert [17] to explain a common property of many networks, according to which the vertex connectivities follow a scale-free power-law distribution. Pragma assumes preferential attachment to centers of interest, considering that *individuals* move towards *attractors*. Thus, the model describes independent nodes that exhibit a collective behavior, which is similar to a primate network, where there is an alpha male as the main *attractor*, who leads the group. The result of the deployment of nodes according to preferential attachment is a *scale-free* network [36], where the node degrees can be shown to follow a power law distribution [17].

There is no limitation in the original preferential attachment model for the degree that a node can have. In our approach, however, we modify preferential attachment to be effectively used for animal societies, considering — based on the literature on primate groups — that there is a limit of 1-hop neighbors for each member of the group according to its role in the social network, and that the social structure is clustered such that there are subgroups within the entire animal group. For example the alpha male in an ape society is generally accompanied by multiple females, which are surrounded by their offspring almost all the time. The original preferential attachment model violates the known connection limitations for members in a group. We then introduce a new parameter, called *maximum degree* (d_{max}), to include these social structure properties.

The network deployment is initialized by positioning two nodes in the area such that they are connected to each other. The decision process on the deployment of a new node joining the network is given in Algorithm 1. When a new node is added to the network, an existing node is selected to be linked to this new node. A node's probability of being selected is proportional to its degree compared to the other nodes in the network (Equation 1). This is implemented in Algorithm 1 by first calculating the sum, S, of the degrees of all nodes in the network. Then a random number, x_s, is selected between 0 to S. The algorithm steps through each node to connect the new node. In this process, if a node's degree is greater than x_s, that node is selected to connect the new node and if a node's degree is smaller than x_s, x_s is decremented by the degree of the node. In our approach, a new deployed node cannot be connected to another node in the network, which has a degree equal to or larger than d_{max}. Therefore, an existing node's probability, P, of being selected depends not only on the node's degree but also on the d_{max} defined for the animal group. After the node reaches d_{max}, P is reduced to a constant value P_c based on the characteristics of the animal society (Equation 1). P_c is taken as 0, since a node's degree cannot become larger than d_{max}.

$$P(i) = \begin{cases} \frac{d_i}{\sum_{j=1}^{N} d_j} & \text{if } d_i < d_{max} \\ P_c & \text{if } d_i \geq d_{max} \end{cases} \quad (1)$$

Algorithm 1 Deployment of a new node

$S = \sum_1^N d_i$
$x_s =$ Random number between 0 and S
$d_a =$ Degree of node a
$N_l =$ Number of leaders
$N_{max} =$ Maximum number of leaders
for Each node a in the area **do**
    if The new node is not connected **then**
        if $(d_a > x_s)$ & $(d_a = d_{max} - 1)$ & $(N_l < N_{max})$ **then**
            Connect the new node
            $N_l = N_l + 1$
        else if $(d_a > x_s)$ & $(d_a < d_{max-1})$ **then**
            Connect the new node
        end if
        $x_s = x_s - d_a$
    end if
end for
if The new node is not connected **then**
    New node is solitary
end if

In our application scenario, we consider a multi-male multi-female structure with one group leader. Each ape in the network can be in the group of only one alpha male and there cannot be a link between two alpha males. Hence the links which are against these rules, are removed as the networks are formed. The preferential attachment based network formation method is extendable by adding more species-specific features. For instance, as an ape group moves in its environment, the leader of the group avoids close encounters with other groups. Therefore, the links between groups with separate alpha males are removed after the nodes are deployed and the roles are assigned.

Fig. 1 shows an example sequence for network formation. In this scenario, d_{max} and P_c are taken as five and zero respectively. Hence the nodes with a degree of d_{max} during deployment are no longer candidates for new nodes to get connected. In Fig. 1(e), the roles assigned to the nodes are shown. There are two alpha males in the society and it can be seen in the previous frame that they are connected by a link (thicker line). This link is removed after the roles are assigned according to the species specific rules under consideration, observing that there cannot be a link between two alpha males.

2) Center of mass approach: In this approach, the nodes are distributed in the area according to a predefined structure. This structure depends on the type of the species under observation and the distribution of roles in this species' social network.

The center of mass concept is used in accordance with the hierarchy in the animal society. The animal society is divided

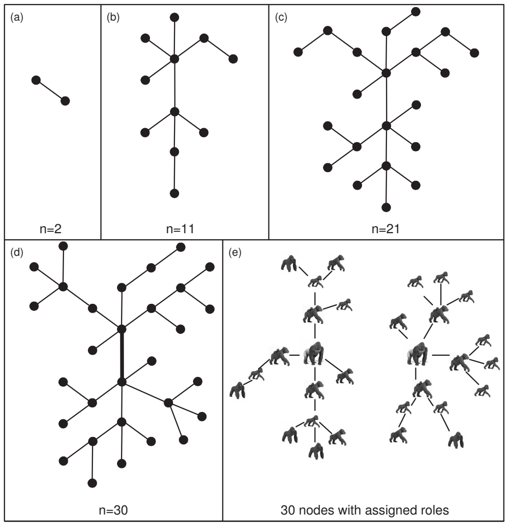


Figure 1. Deployment of nodes by preferential attachment based method.

into subgroups such that each subgroup's center of mass is their leader from the higher level group. For instance, the breeding females form a group and their center of mass is taken as the alpha male. Similarly, a mother ape is chosen as the center of mass for its offspring. This method can also be applied to other animal groups with hierarchical social structures. According to the center of mass approach, the coordinates of the nodes around the leader must satisfy the following equations:

$$x_s = \sum_{i=1}^{N} \frac{x_i}{N} \qquad\qquad y_s = \sum_{i=1}^{N} \frac{y_i}{N}$$

where (x_s, y_s) is the position of the leader and N is the number of nodes in that subgroup. This method is extendable for different scenarios. For instance if a mother has four infants, the possible positions of these nodes can be limited depending on their ages so that two of them will be very close to the mother whereas the others keep a larger distance from her.

B. Mobility model

Lévy walk is observed as the mobility model in most of the animal foraging patterns, such as jackals [37] or spider monkeys [14] and it is recognized as an optimal way to find randomly dispersed objects [38]. It is a random walk with step-lengths distributed according to a heavy-tailed probability distribution. Lévy walks are Markov processes and after a large number of steps, the distance from the origin of the random walk tends to reach stable distribution that is the Fourier transform of the moving distance of a single random walk whose PDF is given by Rhee et al. [39] as in Equation 2.

$$f_{z,\alpha}(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-izt} \phi(t) dt \tag{2}$$

where $\phi(t) = e^{-|Ct|^{\alpha}}$ and C is a constant.

The distribution can be approximated by a power law of the form $y = x^{-\alpha}$ where $0 < \alpha < 2$. Each step in Lévy walk can be expressed by a tuple $L = (1, \theta, \Delta t_f, \Delta t_p)$. Δt_f indicates the walking duration and it is chosen for each walk from a probability distribution $P(l)$. Δt_p specifies the pause time at the end of a walk and θ is the random direction taken by a node. A Lévy walk contains many short walks and a small number of long walks, but the resulting pattern depends heavily on the value of α. As α becomes greater, the number of short walks increases.

One of the most common behaviors observed in diverse species is that they live in groups and follow the leaders of their groups. Researchers have various explanations such as the increased safety or breeding opportunities in a group for these behaviors. In nature, the alpha male makes the decisions for the selection of paths that the group follows, and in our scenario the alpha male role in a group is assigned to a node in the network formation phase. Similarly, the mobility model of the group depends on the movements of the alpha male in the introduced mobility models. The alpha male moves according to a Lévy walk and the movements of other members of the group are directed mainly by the alpha male's path. This path is used as the main input when positioning the nodes at each time instant. Two additional methods supplementary to Lévy walk are used to determine the mobility of each node, and are defined as follows.

1) Preferential attachment based method: This method complements the preferential attachment based formation. After the nodes are deployed, based on the moves of the nodes leading their corresponding groups, the moving directions of the other nodes are probabilistically decided. The probability is defined according to the nodes' roles and levels of proximity to their group leaders. Since the deployment attributes of nodes such as their assigned degrees and roles determine their initial positions, these attributes and therefore the preferential attachment method also affect the decisions on the movements of the nodes.

Each animal moves based on the mobility of its neighbor with highest degree, its distance to this neighbor and this neighbor's moving direction. This is a characteristic of the mobility model, which matches with the hierarchical structure of animal swarms. Hence the mobility of the offspring is based on the mobility of its mother, whose movement in turn depends on the mobility of the alpha male. This structure also provides consistency with our approach based on a Lévy walk for the alpha male in such a way that we obtain a Lévy walk pattern for the whole group.

When the group moves, the animals close to their leaders tend to stay close to the same position relative to such leaders. For instance, the newborns or infants are generally at most only a few steps away from their mothers. However, juvenile animals forage in the environment and may walk in other directions. As they become adults, they may leave the group. In order to include these characteristics, the nodes in close proximity of their leaders follow the leaders with a high probability, which decreases slowly as the distance of the node

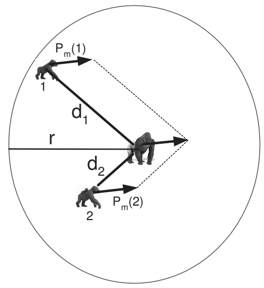


Figure 2. An example showing moving probabilities for females.

to the leader increases. Consequently, the model provides a Lévy walk pattern to the group while providing possibilities for rare behaviors such as a bachelor male group formation. The probability $P_m(i)$ of a node to move in the same direction with its highest degree neighbor with transmission range r_a is defined as follows:

$$P_m(i) = \sqrt{\frac{r_a - l_i}{r_a} + c_1} + c_2$$

where l_i is the distance between the nodes. The constants c_1 and c_2 are included to provide the functionality of adjusting the probability calculation for different species types or network requirements. Fig. 2 demonstrates an example of two females 1 and 2 with their corresponding probability values $P_m(1)$ and $P_m(2)$ to move in the same direction with the alpha male, depending on their distances to the alpha male. They move in any other random direction with probability $1 - P_m(i)$.

2) Center of mass method: This method is used to determine the positions of all animals at each time instant after the deployment of the nodes according to the center of mass approach and the determination of the main path of the group. A node's neighbors at one lower hierarchically level move in a coordinated fashion to have that node's position as their center of mass at all times.

This method allows a more controlled mobile network compared to the preferential attachment method since the hierarchical structure of the system remains in its initial format throughout the network lifetime.

IV. Data collection and role determination

The data collected from animal monitoring systems are used for the analysis of animal behavior. Therefore, the animal social structure must be considered in the design of the data collection algorithms. In this section, we introduce our data collection and role determination algorithms, both of which make use of characteristics of the primate social structure.

A. Data collection structure

The data collection network considered in our approach is a network composed of actor and sensor nodes. The actor nodes distributed in the environment are *stationary* whereas the actor nodes attached to the primates are considered as 'mobile' actor nodes since the primates move in the environment. The primates equipped with the actor nodes are selected according to their roles in the social structure of the group. As male relationships are typically characterized by competition, intolerance and dominance, the groups usually have a single alpha male that leads the group and are accompanied by adult females, which have continuous connections to the young members of the group. Therefore, we consider the alpha male as the clusterhead that is the central individual in the society with either one or multi-hop connections to all members of the group. As the clusterhead, the alpha male in a group is equipped with an actor node. All the other members of the group are equipped with sensor nodes. Fig. 3 shows a possible implementation of the data collection network for a primate society.

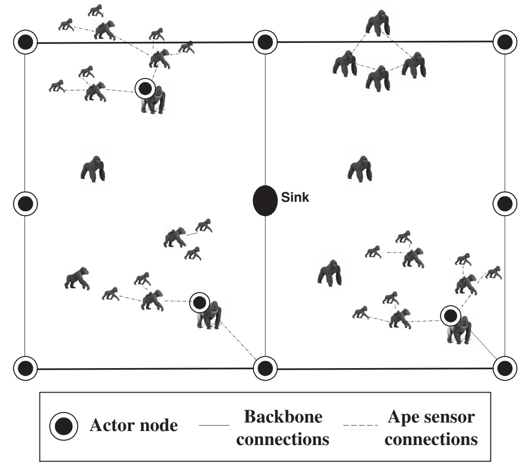


Figure 3. Application scenario of apes.

The network structure is formed and maintained by state-transition rules defined only by local information. The nodes rapidly update their attributes as the network structure changes. A sensor node can be affiliated with both stationary and mobile actor nodes in the network, keeps a maximum weight value for each actor node it receives packets from and does not build a state or history of the whole network. Each actor node has a weight value k, which corresponds to the maximum hop count in the network. In other words, k is the maximum hop distance from an actor node to a leaf node and it can be arranged according to the requirements specific to the observed animal group. Each actor node encodes the packets with its own node ID and weight value k.

When a sensor node receives a packet from an actor node, the packet is retransmitted if its weight is less than the sensor node's weight for that actor node. Otherwise, the sensor node drops the packet to avoid unnecessary traffic and energy consumption in the network. The weight $W_A(s)$ of each sensor node corresponds to k-hop distance of a sensor node to an actor node. The condition, in which a sensor node does not receive any weight updates corresponds to the loss of connection for the sensor node, which may refer to a solitary animal. In that case, the sensor node sets its hop value to the minimum value defined for the network. Then it operates only in *listening* mode and does not transmit any packets.

Algorithm 2 The state transitions of a node s

$w_a(s)$: The weight of node s for actor node a
p_v: The time period for a node's weight value v
$max(w(Neigh(v_s)))$: M
if Received a local update **then**
  if s is not affiliated with an actor node **then**
    $w_a(s) = 0$
  else if $M = k$ **then**
    $w_a(s) = k - 1$
  else if $(M! = k)\&(M > w_a(s))$ **then**
    $w_a(s) = M - 1$
  else if $M < w_a(s)$ **then**
    $w_a(s) = w_a(s) - 1$
  else if $Neigh(v_a) = O$ **then**
    $w_a(s) = 0$
  end if
  if $w_a(s)_{last} \neq w_a(s)$ **then**
    Update $p_{w_a(s)_{last}}$
    $t_{w_a(s)changed} = t_{current}$
  end if
end if

Algorithm 3 Determination of roles

$w_m(s)$ =Weight of node s for actor node m
k =Actor node weight
t_{hp} = Time for high proximity
t_{lp} = Time for low proximity
if $w_m(s) \neq 0$ **then**
  if $t(w_m(s) = k - 1) > t_{hp} \& w_m(Neigh) = w_m(s) - 1$ **then**
    s is on a Female
  else if $t(w_m(s) = k - 1) > t_{lp}$ **then**
    if $t(w_m(s) = k - 2) > t_{hp}$ **then**
      s is on an Infant
    else
      s is on a Juvenile female
    end if
  else
    s is on a Juvenile male
  end if
else if $Neigh(s) \neq 0$ **then**
  s is on a bachelor group male
else
  s is on a solitary animal
end if

Algorithm 2 utilizes the spatial proximity between two nodes to decide on the weights of the sensor nodes. The weight information for the nodes in a group is collected at the corresponding mobile actor node and transferred to the backbone whenever it is possible. The periods of time for the acquired weight values are also calculated and updated in Algorithm 2 to be employed by actor nodes as in Equation 3.

$$p_{w_a(s)_{last}} = p_{w_a(s)_{last}} + t_{current} - t_{w_a(s)_{last}changed} \tag{3}$$

where p_v is the time period for a node's weight value v and $w_a(s)$ is the weight of node s for actor node a. Information about a group can be collected by more than one actor node.

B. Role determination

In the hierarchical social structure of primates, each member has a role in the group depending on the gender, age, strength and affinity. We present a role determination algorithm, which uses the spatial-temporal interaction patterns in the network to decide on the roles of the primates. This role determination algorithm can make use of the data collected by the WSAN, which captures and records movement and social interactions among primates continuously as the individuals move around in their natural social environment.

Algorithm 3 gives the basic role determination process and the utilized rules. The transmission range, time and cardinality of the actor node affiliation group are the parameters defining the rules for role assignment of the animals. The thresholds of these values can be generalized according to the animal group under observation while the rules are very specific for the social network of primates.

Algorithm 3 uses the basic roles defined for all primate communities in which this paper focuses on. The individuals closest to the alpha male are the adult females. If a primate is determined as an adult female with offspring, the distance analysis is executed with varying transmission range in order to check the distances of the offspring. This is used as a method to decide on the ages of the primates since infants stay close to the mother ape for most of the day as well as when they are sleeping. Additionally, this analysis helps to decide on the data aggregation points in the network since mothers are suitable data aggregation points for the data gathered from the offspring.

The feedback from the system is used to make new decisions. As the mobile actor nodes collect information from the network and bring it to the backbone, the sink will update the roles of the apes depending on the feedback from the network. If the feedback shows that a group of juvenile males form a bachelor group, one of these animals is chosen as the data collection gateway for the group. This is efficient in terms of data collection and energy efficiency.

The determined roles of the nodes in the network must be combined with the social network analysis methods to understand the characteristics of primate networks. Studies on primate societies show the importance of social network analyses and different aspects of network statistics [2] on understanding and identifying social structures of primates. One of the most common metrics in these studies is the clustering coefficient [21], used to measure the extent to which vertices adjacent to any vertex v are adjacent to each other [40]. Another commonly used metric is the eigenvector centrality, which measures the influence of nodes in the network by assigning relative scores to all nodes based on the number of edges such that a connection to a high-scoring node contributes more to the score of a node than a connection to a low-scoring

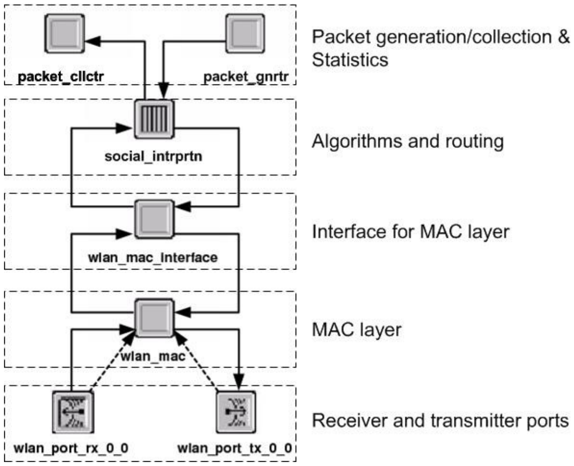


Figure 4. Node design for ape monitoring WSAN.

node.

V. Simulation Study

A. Simulation environment and design

The performance analysis of our approach was carried out by extensive simulations in the OPNET modeler [41]. We propose a WSAN based on Lagrangian approach for tracking the animals [30]. The technologies used for the Lagrangian modeling are individual-based, invasive, in form of a mark or device which is fitted on the animals [30]. They are designed specifically to retrieve data with high quality. In addition, the identity data can be directly inferred because the device is fitted on a specific animal. There are various sensor technologies used for the Lagrangian approach of animal tracking [30]. We aim to show that the information collected by using the WSAN system can be used to understand the social structure of a primate group.

The protocol stack of the node model created in the OPNET modeler and the main functionalities of its modules are presented in Fig. 4. The node model for sensor and actor nodes is designed according to the OSI model communication layers so that the capabilities of each module correspond to the functionalities of a particular layer.

There are various MAC layer protocols proposed for sensor networks. Each of these protocols has specific characteristics, advantages and disadvantages depending on the type of network it is designed for. Since our solution resides mostly in the routing layer, we aim to employ a standard and unbiased MAC layer for our protocol. Therefore, we used the standard 802.11 wireless local area network (WLAN) model as the MAC layer protocol when designing our nodes in the OPNET modeler. The WLAN receiver and transmitter form the physical layer of a sensor node model. The attributes of the underlying IEEE 802.11 MAC layer are presented in Table I. The simulation settings include a queue size of 20 packets and a data rate of 10 packets per second, and the transmission power T of a node is specified as an attribute in the node design by means of the OPNET transceiver pipeline implementation. The

TABLE I
MAC layer attributes of nodes

Attribute	Value
Physical characteristics	Direct sequence
Transmit power (W)	$8.02 \cdot 10^{-6}$
Packet reception power threshold (dBm)	-95
Channel settings	Auto assigned
Short retry limit	7
Long retry limit	4
PCF	Disabled
HCF	Not supported

relation between the transmission power and the transmission range r of a node is defined as $T = \left(\frac{4\pi r}{0.12476}\right)^2 \cdot 10^{-12.5}$. The transmission range of a sensor node is assumed to be 10 meters in a simulation area set as 1750 $\times$ 1750 meters. This is a sufficient size for simulation purposes, since on average gorillas move about 400 to 1000 meters in average per day [4].

The WLAN MAC layer interface forms the data link layer and constitutes the interface between the WLAN MAC layer and the upper layers. The "social_intrprtn" in Fig. 4 is where our approach is mainly implemented. State transition, social role determination, and routing are carried out in this process module. Modules named as "pckt_cllctr" and "pckt_gnrtr" together serve as the remaining higher layers for the node model. The "pckt_gnrtr" module is responsible for creating packets when the sensor node is required to transmit data or control information, and the "pckt_cllctr" generates responses for the queries of other nodes. It is also used to collect statistical information about the node.

Each layer of the model shown in Fig. 4 works independently and interacts with its corresponding upper and lower layers through channel streams. This approach provides modularity for both the design and the modification of the model. Each module can be replaced by a different module design with minimum effect to the other layers, which is an important advantage of our modular design. MAC layer and WLAN MAC layer interface can be replaced by other technologies such as Zigbee 802.15.4 if it is required by the sensor design choices.

The Lévy walk mobility model is used with $\alpha = 1.9$ and $\beta = 1.6$, which are the values for the foraging pattern of the considered gorilla troup based on the observed values in nature [14], [4]. The segment-based trajectory modeling is used to create a Lévy walk mobility. The trajectory consists of multiple points defined by the Lévy walk with the given α and β values, and are created and assigned to nodes as attribute values in OPNET. The random waypoint mobility model is also used in a group of simulations with speed uniformly distributed between three and eight kilometers per hour and pause time uniformly distributed between 50 and 150 seconds. The range of values for these metrics are determined by using the documented observations on gorillas [4], the primate type chosen for simulation studies. Gorillas live in socially organized groups ("troops"). The roles of the individual animals in the society build up a hierarchical structure, which is shown

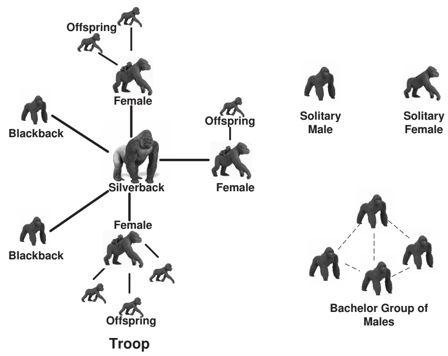


Figure 5. Gorillas live in socially organized groups.

TABLE II
AVERAGE NUMBER OF ANIMALS IN 1^{st} NETWORK FORMATION SCENARIO

Degree	0	1	2	3	4	5	6	7	8	9
Pref. Att.	0	7.03	1.83	0.93	0.46	0.30	0.21	0.18	0.13	0.09
PABD	0.23	6.30	2.27	0.73	0.53	0.83	0	0	0	0

in Fig. 5 for our application scenario.

B. Simulation results

1) Network formation: The proposed network formation model is tested against the original preferential attachment model in two sets of simulation studies. In the first set of simulations, the deployment of only a single troop is considered. Gorilla troop populations in nature usually range from 2 to 12 members and the average troop size is 9. The total of 50 simulation runs were executed and in each simulation, 11 nodes are deployed in the area. In Table II, the average number of nodes for each node degree value is presented for the original preferential attachment and our preferential attachment based network formation and deployment model (PABD).

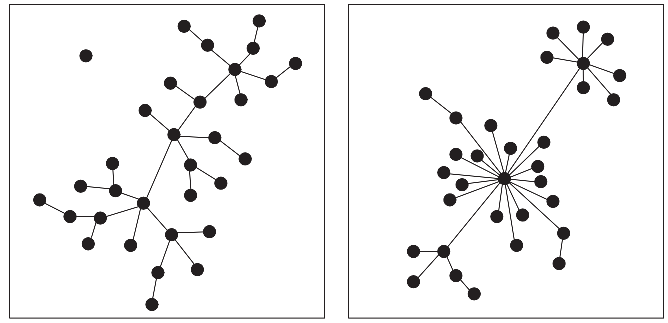
There are 32 nodes deployed in the area for each simulation of the second set of network formation experiments. Table III shows the average number of nodes for each degree value, for the original preferential attachment and PABD.

The results given in Tables II and III indicate that our network formation method produces gorilla troops with social relational properties similar to the troops in nature. The first result indicating this observation is that the degree distribution is more homogeneous compared to network formation by the original preferential attachment while none of the nodes exceeds a certain degree value. Another important result is that the solitary gorillas can be observed only in some scenarios of our network formation method.

One of the network formation cases by PABD, which has

TABLE III
AVERAGE NUMBER OF ANIMALS IN 2^{nd} NETWORK FORMATION SCENARIO

Degree	0	1	2	3	4	5	6	7	8	>8
Pref. Att.	0	20.33	5.97	2.11	1.20	0.60	0.47	0.33	0.20	0.79
PABD	0.66	17.45	5.17	2.93	2.03	3.03	0	0	0	0



(a) Deployment by PABD. (b) Deployment by pref. attachment.

Figure 6. Node formation by our approach and by preferential attachment.

number of connections close to the average values, is presented in Fig. 6 to demonstrate the results visually. The figure shows that most of the nodes are directly connected to only a few nodes in the preferential attachment model, which is not observed in a gorilla society [42]. According to Fossey [42], the dominant silverback is the group's undisputed leader, who is ordinarily bonded to three to four adult females for life. Therefore, these are the one hop neighbors to the central animal, silverback, in the social network. The juvenile animals try to keep their distances to the silverback, while they spend time with adult females. Therefore, the high degree of specific nodes in Fig. 6 does not match the characteristics of gorilla social networks.

Figs. 7 and 8 show the distributions of node degrees for preferential attachment and our approach in a log-scale. Even though the number of nodes is not very large, the power law linearization in a log scale is observed. This behavior is not observed in PABD as our network formation model extends the preferential attachment to be effectively used for animal societies. When a node has the maximum degree (d_{max}) defined for the group in consideration, it becomes ineligible for a new deployed node to get connected. Therefore, Fig. 7 and 8 show that the probability of adding a link to a node in PABD depends not only on its degree but also on the d_{max} defined for the group in consideration.

2) Roles: In the first set of experiments, nodes move according to the random waypoint mobility pattern. The simulation runs were executed with the same initial conditions and the average percentage of roles are determined by our role determination algorithm.

In Fig. 9, the percentages of the troop members over the simulation period are given. The percentages of the animals, which are not members of the troop, are given in Fig. 10. The time spent with the neighboring individuals is used in the algorithm when deciding on the roles and all the calculated time periods are short for neighboring nodes in the beginning. Therefore, the identified roles for group members change over time, particularly in the beginning, which causes the fluctuation in the values shown in Fig. 9. According to the confidence interval analysis on the first set of experiments, the percentage for each role is expected to fall within $\pm 11\%$

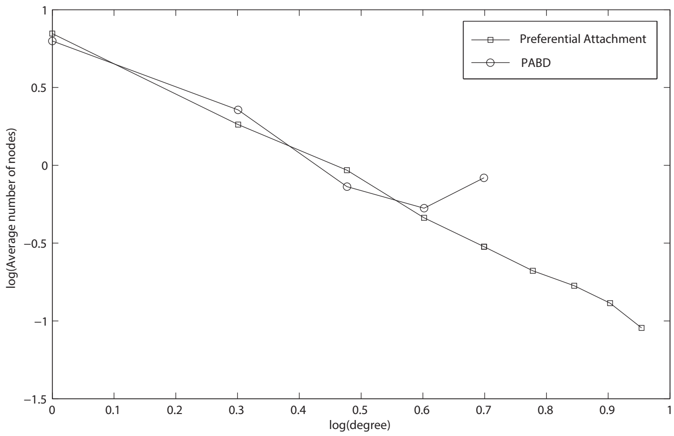


Figure 7. Degree distribution by PABD and preferential attachment for 11 nodes.

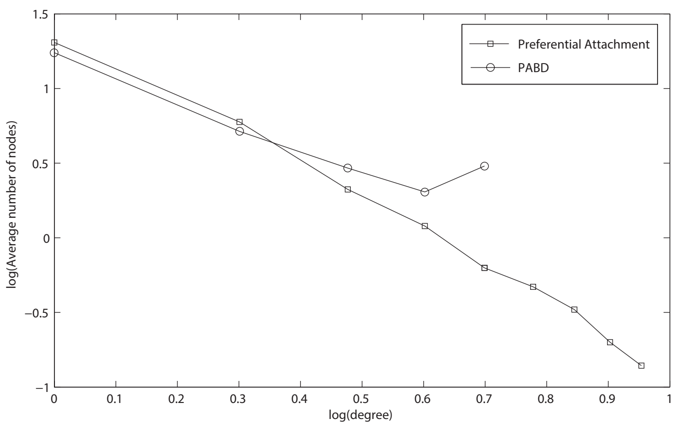


Figure 8. Degree distribution by PABD and preferential attachment for 32 nodes.

of the resulting value with 95% confidence.

Fig. 9 and 10 show that the number of solitary males increase with the simulation time and this role clearly becomes dominant in the society. The other roles have similar shares, mostly depending on their initial conditions. The solitary males in the nature walk alone in the habitat and they generally get affiliated with multiple troops over time. Hence this is an expected property for the society with random mobility with a starting condition in which most of the nodes are close to each other. Most of the nodes get departed from the troop as the time passes by and the algorithms change their assigned roles to solitary males as they start to lonely range in the area.

In the second set of experiments, the nodes move in a Lévy walk with center of mass mobility pattern. The simulations are executed with the same conditions as in the initial set of experiments and the average percentage of roles are determined by our approach. The change in the percentage of the members and the non-members of the troop over simulation time are given in Fig. 11 and 12. According to the confidence interval analysis on the second set of experiments, the percentage for each role is expected to fall within $\pm 4\%$ of the resulting value with 95% confidence.

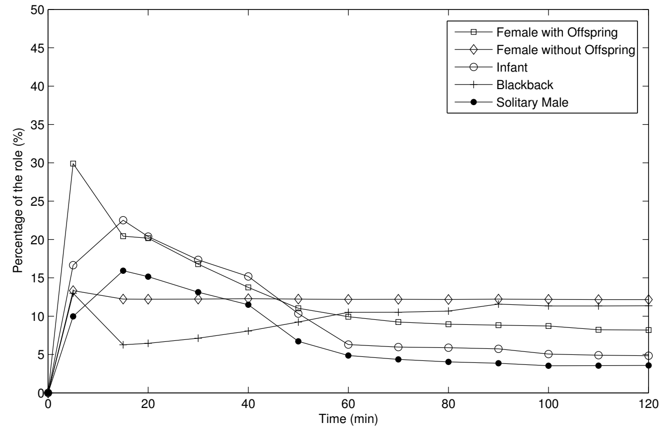


Figure 9. Percentages of troop members vs. time in random walk scenario.

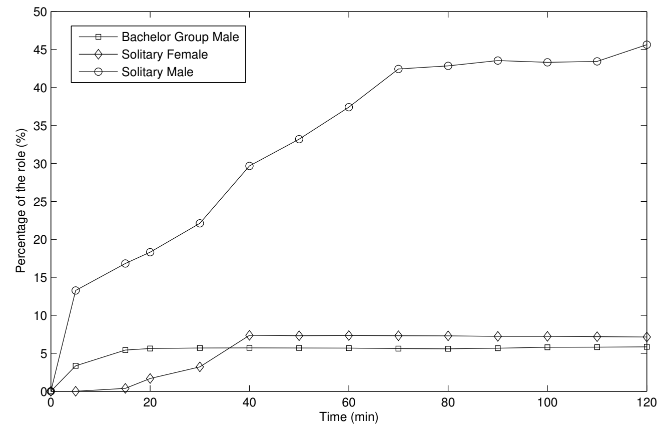


Figure 10. Percentages of troop non-members vs. time in random walk scenario.

Similar to the simulations with random walk, the percentage of each role fluctuates at the beginning of the simulation. After the short fluctuation period, the roles in the Lévy walk become stable and match the starting roles. In accordance with its design purpose, Lévy walk with center of mass mobility pattern provides an animal group with a stable role distribution. Therefore, the fluctuation range is smaller and the fluctuation time is shorter compared to a random walk.

In the third set of experiments on roles, the mobility of the nodes is defined by the Lévy walk with preferential attachment extension. The results of the simulation runs, which show the percentage of members and non-members of the troop over time are given in Fig. 13 and 14. The results show that the percentage of each role fluctuates at the beginning of the simulation similarly to the initial experiment set with random mobility. This characteristic demonstrates that the role decision process requires a period of time to assign the correct roles to the animals. According to the confidence interval analysis on this set of experiments, the percentage for each role is expected to fall within $\pm 7\%$ of the resulting value with 95% confidence.

The experiment also shows that a Lévy walk with preferential attachment extension is an appropriate choice for the

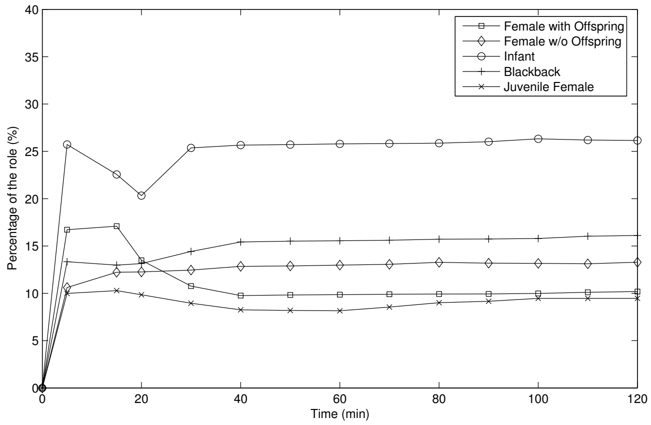


Figure 11. Members of the troop vs. time in Lévy walk with Center of Mass approach.

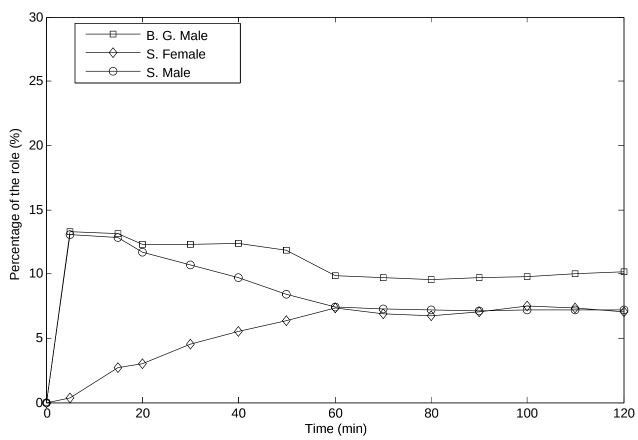


Figure 12. Non-members of the troop vs. time in Lévy walk with Center of Mass approach.

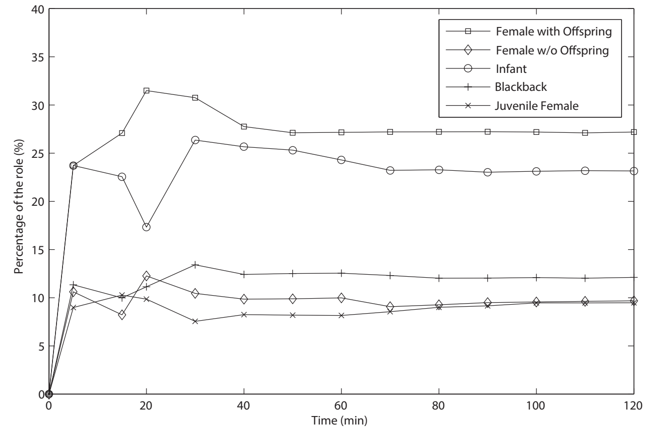


Figure 13. Members of the troop vs. time in Lévy walk with preferential attachment.

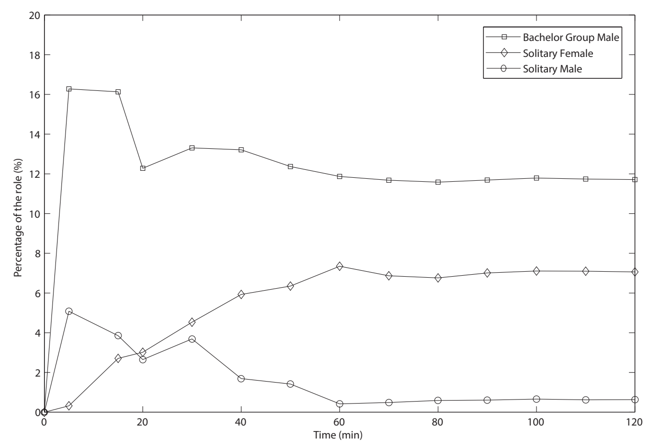


Figure 14. Non-members of the troop vs. time in Lévy walk with preferential attachment.

mobility model, since the resulting average percentages of the roles are close to the observed structure of the gorilla societies [42]. Fossey [42] describes a typical group as one dominant silverback, one or two blackbacks, three to four sexually mature females, and from three to six juveniles and infants.

3) Rules: The introduced approach for social role determination can be applied to different types of ape groups by modifying its rules or by creating new metrics. Fig. 15 and 16 show results for two different metrics chosen for the simulation scenarios with our preferential attachment based mobility (PABM), center of mass based mobility (CMBM) and random walk (RW). For the first case, it is assumed that the role distribution of the mobile society must be the same as the role distribution in the stationary case. The metric for Fig. 15 is the ratio of roles distributed in the mobile scenario to the roles distributed in the stationary case. For Fig. 16, the metric is the ratio of solitary animals to all animals in the society. These results show that CMBM produces results according to its design purpose such that the cluster structure remains the same as the initial conditions. The results also demonstrate the probabilistic nature of PABM since it differentiates from the initial formation with a certain probability.

4) Network analysis: In this set of simulations, we compared our approach to real life primate networks using multiple social network metrics. We compare the characteristics of five real-life primate networks to the primate networks created by our approach. Two of these five groups are chimpanzees [2], two of them are macaques [43], [20] and one of them is a capuchin group [44].

Fig. 17 shows the clustering coefficient and eigenvector centrality values for real-life data and our simulations. The results show that our approach produces networks with similar characteristics to real-life primate social networks. The calculated clustering coefficient values are within the 10% variance of their mean. The average clustering coefficient of our simulation results, which is in $\pm 2\%$ interval of this value with 95% confidence, falls within the 5% variance of the mean clustering coefficient. The values for eigenvector centrality are even closer to each other. The difference between the average eigenvector centrality value of our approach and the chimpanzee networks are less than 0.1%.

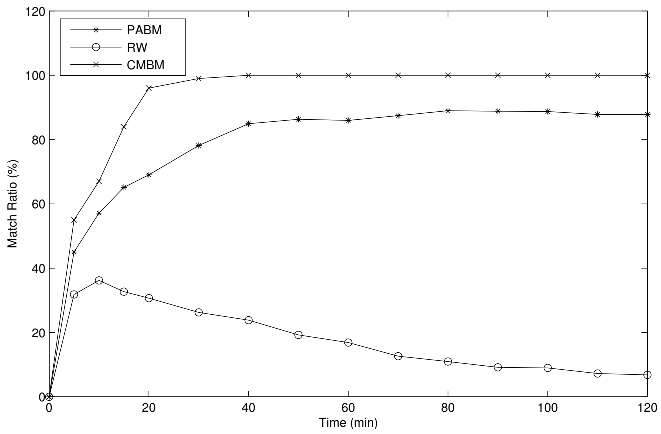


Figure 15. The ratio of roles in mobile scenario to stationary scenario for different mobility models.

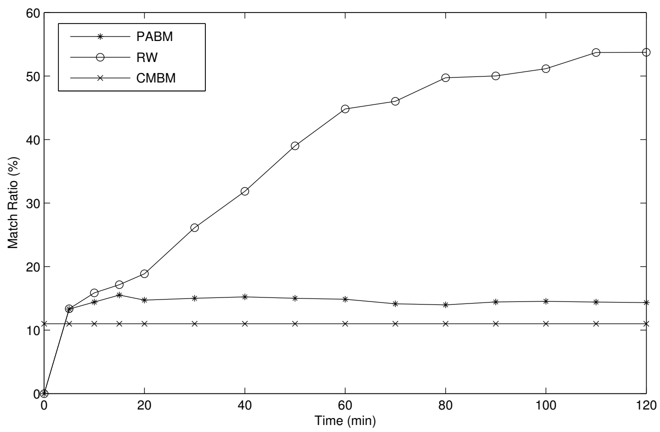


Figure 16. The ratio of solitary animals to all animals in the society for different mobility models.

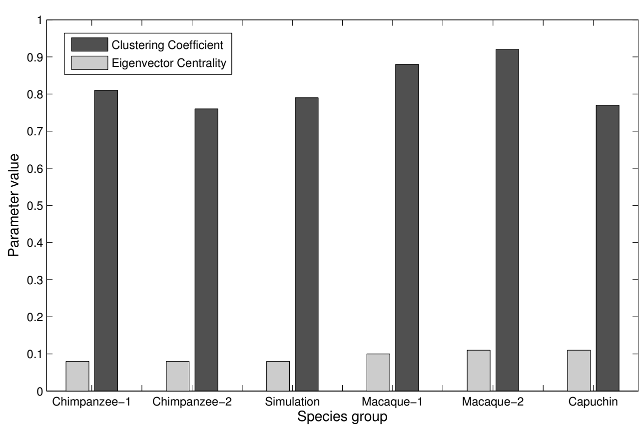


Figure 17. Clustering coefficient and eigenvector centrality values for real life data and our simulations.

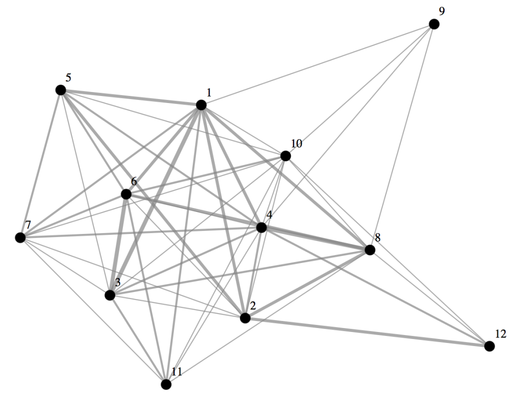


Figure 18. Network graph formed by using data of a real-life chimpanzee group.

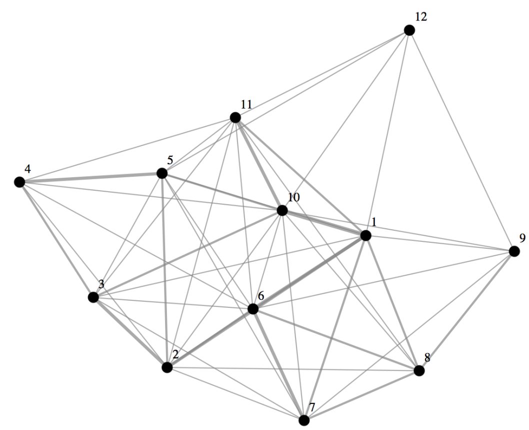


Figure 19. Network graph formed by using our simulations of a gorilla group.

The proximity of the individuals throughout the time is used to create the network graphs of real-life primate data and our approach. When creating the graphs, the members of the group form the nodes of the network while the edges are drawn according to the time spent together. Edges are assigned with four different levels of weights to differentiate the strength of ties. Fig. 18 shows the graph of a chimpanzee social network [2] formed by real-life data and Fig. 19 shows the graph of a gorilla social network generated by our approach.

Table IV shows the average values of edge count, vertex count and vertex degree for the social networks of real life primate groups and our simulations. Results show that the networks created in the simulations have similar characteristics to the real-life primate networks also in terms of these parameters. The mean for the ratio of edges to vertices is 3.77 with values ranging from 3 to 4.08. The value of this ratio for our simulations is 3.83. Therefore, the density of the simulated social network is similar to the densities of real life primate networks. The vertex degree of our simulations is only 3% higher than the mean vertex degree, which shows the realistic social interaction structure of the simulated primate network.

5) Subgroups in the network: Modularity-based clustering is applied in this set of simulations. Networks with high

TABLE IV
NETWORK PROPERTIES OF ANALYZED APE GROUPS

	Chimp Group 1	Chimp Group 2	Sim. results	Macaque Group 1	Macaque Group 2	Capuchin
Edge Count	49	46	49	37	33	27
Vertex Count	12	12	12	10	9	9
Vertex Degree	8.17	7.67	8.17	7.4	7.33	6

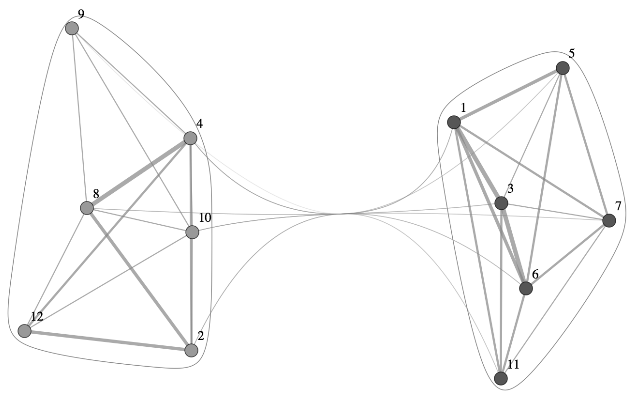


Figure 20. Subgroups of the chimpanzee network.

modularity have dense connections between the nodes within modules but sparse connections between nodes in different modules, and therefore modularity can be used for detecting community structure. Biological networks exhibit a high degree of modularity [45].

Application of modularity-based clustering to the groups analyzed in simulation study showed that each network has either two or three subgroups. The number of individuals in these groups has a range between three and six. Fig. 20 shows two subgroups of the chimpanzee social network depicted in Fig. 18.

Fig. 21 shows three subgroups of a gorilla social network, the graph of which is presented in Fig. 19. There are subgroups in all primate social networks. For instance, a mother and her offspring would form a social subgroup. Essentially, the detection of these subgroups improves the investigation of the groups.

Fig. 20 and Fig. 21 are important for the detection and presentation of primate communities, which form small cohesive groups. Therefore, these small groups provide information on the community structure additional to the roles determined by our approach.

Subgroup information is also useful for the next installation or replacement of sensor and actor nodes in the same network. For instance, the number of actor nodes can be arranged according to the number of subgroups to improve data collection.

VI. CONCLUSION

In this paper, we introduce a new approach to model primate social networks based on network formation and mobility algorithms to provide a complete primate group model. Our

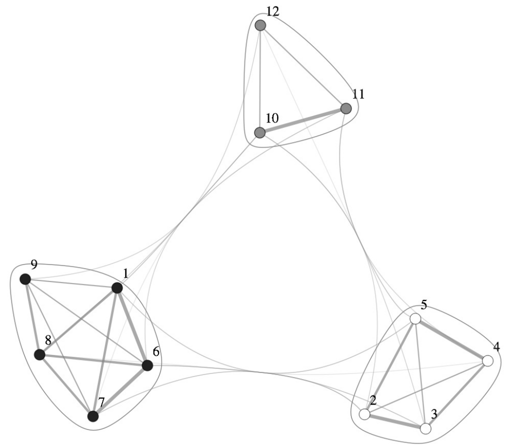


Figure 21. Subgroups of the network created by our simulations.

methods are based on the center of mass and preferential attachment concepts. The preferential attachment model is extended for the formation and mobility models according to the characteristics of the animal groups, and these models are also extendible with properties specific to observed animal species. We also propose a WSAN based strategy for monitoring primate networks, where each animal is equipped with a sensor node for the monitoring of the social system. We show that the data collected by a WSAN can reveal the roles of the primates in their hierarchical social structure. Simulation results show that the outputs of preferential attachment node formation and mobility models match the characteristics of the animal groups under consideration. In the case of gorillas, it is also shown how the role determination method helps in capturing the social structure of the group.

Extensions of this work include application and modification of the proposed approaches to different animal groups. As another future direction, the role determination algorithm can be extended for human social networks with hierarchical structures such as an office environment. Our monitoring strategy can be extended with an actor node positioning strategy, which can improve data collection, area coverage and energy savings.

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