Availability of Ad Hoc Wireless Networks of Unmanned Ground Vehicles with Group Mobility

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Abstract
Maintaining network availability is critical to teams of mobile unmanned ground vehicles (UGV) and requires a realistic mobility model for accurate calculation. Mobile ad-hoc networks (MANET) have been extensively studied using the random waypoint mobility model. But to more exactly model teams of unmanned systems and their relative positions, we provide a model of communication states using the reference point group mobility (RPGM) model. We consider the unique requirements of unmanned systems as having two data rate thresholds. The analysis includes log-normal shadowing and determines the probability that each team member has received power above a threshold while moving. The analysis results allow computation of network availability in different topologies. We conclude with a discussion of various methods for overcoming shadowing and small-scale fading effects in order to maintain high network availability of MANETs.

1. Introduction
Unmanned systems are increasingly operating as teams, multiplying their sensors and capabilities to perform tasks faster or over larger areas. For effective pursuit of these goals, the team members must exchange data. This data exchange needs to occur in the various types of terrain (e.g. urban, mountainous, inside buildings) in which the unmanned systems operate. This requires an adaptable communication network that moves with the team. The communications subsystems are tasked to overcome the inherent environmental effects, in order to keep the communication network available. Network availability is defined here as the probability that all nodes in a topology are able to connect with each other via some communication path.

Mobile ad hoc networks (MANET) make it possible for nodes to communicate without any permanent infrastructure. The member nodes of a MANET must perform tasks such as entering and leaving the network, determining neighbors, and providing their own routing. After the network is established in some form, useful data exchange occurs among the nodes with some data traffic pattern. Both the maintenance and data exchange modes of the MANET require adequate link state. And this must be accomplished with dynamic link states which accommodate the mobility of the network’s members. This link state is characterized by the signal power at the receiver of the link.

There are many factors inherent to MANETs that collectively cause the link state to change, and only a few are mentioned here. Each node is constrained by transmit power, and this is directly proportional to received power at the other node. The MANET nodes are dynamic, and have a relative motion among themselves. As distance increases, the received signal power decreases according to a path loss exponent. Another factor is fading, which can be large- or small-scale. One large-scale fading example is shadowing. It is caused by the interaction of a signal with the local environment and has a log-normal distribution about the distant-dependent mean [1]. The commonality of these factors is their decrease in the received signal power, generally degrading the link state of each node.

UGV teams are an example application of MANETs, where each system (robot) is considered a node in the network. The received signal power is influenced both by distance between the nodes and their environment; we focus first on distance. To analyze distance among UGV teams in a MANET, we use a description of the movement of each individual UGV as a node. These relative positions over time can be represented by mobility models, which describe the movement of a group of unmanned systems (nodes) in a MANET.
instant in time of a mobility model describes the absolute positions of nodes, from which signal strength is found. So the MANET is composed of many nodes each with a link state changing in time. Nodes with a deficient state are unavailable to the network and we will quantify the metric of network availability. In summary, the mission (movement) of the UGV team is described by a mobility model, which determines network availability in time.

The most common mobility models are the variants of the random waypoint model. This model is analytically tractable, and has been studied for effects on: link changes [2], clustering [3], network capacity [4], link lifetime [5], and link stability [6]. A de facto standard, this mobility model describes random, uncorrelated movements for a large network of nodes. The difficulty of using the random mobility model is that the mobility characteristics are very different from real-life scenarios. A realistic mobility model is important because different mobility models have an influence on the performance of the routing protocols [7] [8] [9]. To remedy this, more recent research has matched a large network mobility model to empirical data [10].

Small teams have spatially dependent mobility [11] hence a group mobility model is appropriate. However, less emphasis has been placed on group mobility models because they are difficult to analyze except in simulation. The use of group mobility models via simulation is explored in [7] [8]. These use the RPGM model (introduced in Section 2), but only in ‘groups of groups’. These simulations revealed a broad relationship where mobility influences the routing protocol. Instead, we seek to motivate rich analytical work as in the random waypoint model, but for group mobility models. We begin to fill in the intermediate steps, by relating the RPGM model with a single group to the metric of network availability. It is network availability that is related to protocol performance, but is easier to compute. Full network simulations can determine protocol performance, and are able to account for factors such as data traffic, routing algorithms, and more complex environmental factors. However, it is hoped that the analytical work we provide can more accurately explain the relationship between mobility and protocol performance.

The rest of this paper is organized as follows, Section 2 describes the RPGM model. Section 3 discusses the communication model using this group mobility model for two control topologies. Section 4 discusses ways to improve network availability. Finally, our conclusions are listed in Section 5.

2. Reference Point Group Mobility Model

The Reference Point Group Mobility (RPGM) model [12] describes the physical positioning of each node with reference to a group center. The group center, $C$, moves along an arbitrary path with time, as in Fig. 1. Each node, $n_i$, $i \in \{1...N\}$ in the group of $N$ nodes is assigned a reference point which is defined with respect to the group center, $C(t)$, by the vector $\overrightarrow{R}_i$. At all times, the node stays within its mobility circle, a radius of $r_i$ from its reference point. At each time step (in a simulation) the node’s reference point moves with the group motion vector, $\overrightarrow{m}_g(t)$. Figure 1 shows one node’s mobility circle at two points in time. The position of each node, $p_i(t)$, is found by vector addition of a node motion vector $m_i(t)$ to the reference point.

$$p_i(t) = C(t) + \overrightarrow{R}_i + m_i(t) \quad (1)$$

The node motion vector is a random vector providing uniform distribution of position across the mobility circle. The node motion vector is independent from the node’s previous location.

![Figure 1. Reference Point Group Mobility model [12] with red dots indicating random node positions within a mobility circle.](image)

The movement of small teams of UGVs can be described by the RPGM model. There are two control topologies of interest that can be represented within the RPGM: clusterhead and mesh. In the clusterhead topology, each node communicates only with the clusterhead node, similar to a sensor network which funnels data to a central node. This can represent a manned control system that is controlling many UGVs. The clusterhead topology can also describe a larger, more capable robot that
communicates directly with a group of smaller robots. Such a centralized team might use a TDMA MAC protocol. This paper focuses on this clusterhead control topology and its data traffic model.

The mesh topology allows any number of connections between nodes of the team. This can represent a more autonomous team of unmanned systems exchanging data among other nodes during a mission. With substantial data flow among all nodes, such a decentralized team may use a CSMA MAC protocol.

### 3. Communications within the RPGM model

Having described the motion of UGVs, we now consider the data flow between these member nodes of the MANET. Unmanned systems that are sensing the environment need to transmit high data rate information such as video. They also transmit telemetry and receive control information at a lower data rate. In operation, the telemetry and control information is of higher priority than the sensor data. When the communications link is weak, the telemetry, control, and management information must be supported, but the sensor information may tolerate temporary interruption. The communication state diagram for each node is therefore described by Fig. 2.

![Communication state diagram](image)

**Figure 2. Communication state diagram for each node of a MANET**

Each unmanned system has a threshold data rate (minimum) that determines the difference between the states. These thresholds can also be expressed in terms of signal power at the receiver. Maximum data rates or capacities have a well understood relationship to the signal-to-noise ratio (SNR) and bandwidth. Assuming that bandwidth and noise are fixed, then a received signal power at the receiver corresponds to a data rate.

The IEEE 802.11 standard generally serves to demonstrate that the received signal strength is aligned with a data rate. Table 1 lists the modulation coding schemes (MCS) supported in IEEE 802.11a. In the standard, the MCS is dynamically adjusted based on signal strength. For very strong signals, higher data rates can be supported.

As an example, if 8 Mbit/sec were required for control data, and 20 Mbit/sec were required for sensor data, then there would be two thresholds among the MCS. One between MCS 0 and 1 separating “deficient” from “adequate” communications, corresponding to a minimum sensitivity of -81dBm. Similarly, a threshold between MCS 3 and 4 would separate “adequate” from “high data rate” communications.

The listed sensitivity values are the minimum signal levels as measured at the antenna connector of the receiver [13]. These minimum signal levels ensure a certain maximum packet error rate.

<table>
<thead>
<tr>
<th>MCS</th>
<th>Modulation</th>
<th>Code</th>
<th>Rate (Mbit/sec)</th>
<th>Min. Sensitivity (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>64-QAM</td>
<td>3/4</td>
<td>54</td>
<td>-65</td>
</tr>
<tr>
<td>6</td>
<td>64-QAM</td>
<td>2/3</td>
<td>48</td>
<td>-66</td>
</tr>
<tr>
<td>5</td>
<td>16-QAM</td>
<td>3/4</td>
<td>36</td>
<td>-70</td>
</tr>
<tr>
<td>4</td>
<td>16-QAM</td>
<td>1/2</td>
<td>24</td>
<td>-74</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>3/4</td>
<td>18</td>
<td>-77</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>1/2</td>
<td>12</td>
<td>-79</td>
</tr>
<tr>
<td>1</td>
<td>BPSK</td>
<td>3/4</td>
<td>9</td>
<td>-81</td>
</tr>
<tr>
<td>0</td>
<td>BPSK</td>
<td>1/2</td>
<td>6</td>
<td>-82</td>
</tr>
</tbody>
</table>

The signal levels can be converted to a distance based on the widely used path loss equation, with a chosen transmit power and path loss exponent [1]. So the data rate corresponds to a signal level and a distance. From this, a communications model based on the clusterhead topology is shown in Fig. 3, where the two threshold data rates are now represented by distance, via range rings from the center node. The two threshold values are range rings that separate the field into three regions. Within the physical region 3, the signal exceeds the upper signal threshold, supporting the ‘high’ data rate. Region 2 supports the ‘adequate’ data rate, and is separated from region 1 by the lower signal threshold. Region 1 has a
‘deficient’ data rate. As the node moves in its mobility circle, it may change communication state.

The RPGM model describes the absolute motion of a group of nodes. To represent the clusterhead topology, we place a node at the position C. For communications analysis within the group of nodes that travels together, the $m_g$ vectors can be set to zero. Then the random motion of the nodes within their mobility circles can continue in simulation time. This preserves the value of interest to the communications analysis: the relative motion and positions of the group of nodes.

![Figure 3. RPGM communications model, showing different regions where communication states exist.](image)

Using this communication model, we next determine each node’s coverage. The node coverage, $\kappa$, is the probability that the received signal power, $P_r$, exceeds a threshold, $\gamma$, as the node moves in its mobility circle.

$$\kappa = \text{Pr}[P_r > \gamma]$$

(2)

We will consider the lower threshold value in the following discussion.

### 3.1. Node coverage (no fading)

A simplistic, and possibly accurate enough, approximation of node coverage can be illustrated using Fig. 3. This approximation would disregard fading and assume the communication regions are based only on range. This approximation assumes that in region 1, the node is not connected to the center node, and is therefore disconnected from the network.

From the RPGM model, we assume that each node’s position within its mobility circle is uniformly distributed. So the fraction of each mobility circle that is not in region 1 is the node coverage. This value of node coverage based only on range, $\kappa_r$, is

$$\kappa_r = \frac{A_2 + A_3}{A_{total}}$$

(3)

where $A_j, j \in \{2,3\}$ is the area of the mobility circle that is within region $j$, and $A_{total}$ is the area of the mobility circle. These areas are calculated using the overlapping circles method detailed in the Appendix.

### 3.2. Node coverage with fading

Shadowing has a strong effect on node coverage. Instead of smooth edged circles, a random variable which represents shadowing influences the received power, creating a jagged-edged circle of coverage. Similarly, this change from a discrete assumption for communication to a probability distribution has an analogue in sensor range detection [14].

To consider the effect of shadowing on communications, we first describe the distance between transmitter and receiver. Referring to Fig. 3, we consider the case of one point fixed at the center, and the other moving within a mobility circle. The distance $R$ from the fixed center to center of the mobility circle is not the mean of the distances to the points in the mobility circle. The probability density function (PDF) of this distance, $d$, is the distance PDF. This distance PDF is not symmetric around $R$, but skewed; and has a mean greater than $R$. As shown in the Appendix, an approximation of the distance PDF for a mobility circle of radius $r$ is

$$f_d(d) = \frac{2}{\pi r^2} \sqrt{r^2 - (d-R)^2}.$$

(4)

This approximate distance PDF is symmetric and closely resembles the actual distance PDF when the value $R \gg r$. As shown in Fig. 6, this increases the radius of curvature, $R_c$, making the area $B_1$, a better approximation of the area $B_1 + B_0$.

To determine the node coverage, we note that the mean value of the received signal changes with distance. The standard deviation of the shadowing also increases with distance. We however use the simplifying assumption of a fixed standard deviation $\sigma$, as in [15]. The threshold value $\gamma$, of course, doesn’t change with distance. The value $\kappa_r$ is then expressed as an integral of the product of the
position PDF and the probability that the received power at that distance is greater than the threshold,

$$\kappa_c = \int_{R-r}^{R+r} f_r(d) Q\left(\frac{\gamma - \mu(d)}{\sigma}\right) \delta d.$$  \hspace{1cm} (5)

In (5), the mean value of the received power is a function of the transmitted power, $P_t$, the loss at the reference distance, $R$, and the path loss exponent, $n$:

$$\mu(d) = P_t - L(R) - 10n \log\left(\frac{d}{R}\right).$$  \hspace{1cm} (6)

Unfortunately, there is no closed form expression for (5), and straight line approximations of the position PDF have lengthy solutions. A fast approximation of $\kappa_c$ can be obtained by a single calculation at the distance $R$, by

$$\kappa_c \approx Q\left(\frac{\gamma - \mu(R)}{\sigma}\right) = Q\left(\frac{\gamma - (P_t - L(R))}{\sigma}\right).$$  \hspace{1cm} (7)

To verify this, a Monte Carlo method is used to give an estimate of the coverage probability, using [1]

$$P_r = P_t - L(R) - 10n \log\left(\frac{d}{R}\right) + X$$  \hspace{1cm} (8)

where the effect of shadowing is represented as a zero mean Gaussian random variable, $X$, with standard deviation $\sigma$, and so the estimate

$$\hat{\kappa}_c = \Pr[P_r > \gamma]$$  \hspace{1cm} (9)

Figure 4 shows that the value of $\hat{\kappa}_c$ closely tracks $\kappa_c$ over values of $\gamma$ for a typical scenario.

3.3. Node coverage by composite method

The composite method is based on the observation that in certain regions, the shadowing is negligible. Using the method in the Appendix, we designate the area of the mobility circle that is within region $j$ as $A_j$, $j \in \{1, 2, 3\}$, as in Figure 5. Then in region 3, assuming the signal power is sufficient to disregard shadowing, that fraction $A_3/A_{total}$ for each mobility circle is considered as not experiencing shadowing, with $\kappa_{3} = 1$. Similarly, in region 1, assuming the signal power is sufficiently weak that shadowing is disregarded, then $\kappa_{1} = 0$. Then for each mobility circle, the node coverage is a weighted sum as:

$$\kappa = \sum_j \kappa_j / \kappa_{j}$$  \hspace{1cm} (10)

Figure 5. Composite method of coverage calculation with shadowing regions.

Up to this point, we have shown that the probability of coverage for a single node in shadowing can be computed in a variety of ways, next this is applied to a network of nodes.
3.4. Network availability

The node coverage probability gives a measure of the ‘connectedness’ of one node over one link. The computed values of $\kappa$, represent a percentage of area (mobility circle) in which the received signal power is sufficient for communication, which is above the lower threshold. Because the position is uniformly distributed over this area with time, the values of $\kappa$ are also a percentage of time above the lower signal threshold. These nodes can be connected to each other by different topologies.

For the clusterhead control topology, each of the nodes is only connected to the center node. With regard to the lower signal threshold, each value of $\kappa$ is the probability that each node is connected to the center node. A network metric from the node coverages is the probability of availability of the cluster. It can be simply found as the product of all the node coverages [16]

$$P_A = \prod_{n=1}^{N} \kappa_n$$

(11)

and represents the probability that all nodes are connected.

The mesh control topology permits nodes to communicate with many other nodes in the group. Although the mesh network probability of availability also uses the $\kappa$ from each node, the calculation is substantially more complex [16].

For either topology, if the higher threshold is used to calculate each node’s $\kappa$ value, the $P_A$ value would represent the probability that the network was in the ‘high data rate’ state.

3.5 Heterogeneous unmanned teams

On a larger scale, it is possible to have a configuration with the center node composed of an unmanned aerial vehicle (UAV) and the other nodes as UGVs, similar to the clusterhead topology. The obvious advantage is no shadowing at the receiving antenna on the UAV, similar to the composite method of section 3.3. A consideration with the increasing altitude of the UAV is that the distance PDF approximation has a smaller variance. However, because the typical elevation angles of the UAV to the UGV are 10 degrees or less [17], the elliptical approximation of the distance PDF is still valid. So, the three-dimensional extension of the RPJM model to include a UAV as the center node is reasonable.

4. Improving the Communications State

The data exchanged among unmanned systems is of paramount importance for successful performance of team tasks. The previous section showed that the availability of the communications network is directly related to the received signal power. We now turn to solutions to the problems mentioned, with the objective of improving the probability of availability of the network.

Large scale fading (shadowing) is the signal power attenuation due to motion over large areas. A common method to correct shadowing is to increase total radiated power by an amount called the fade margin. This can be done in two ways: through increased power at the transmitter or increased antenna gain in the direction of the receiver. More effective use of directional antenna gain is seen in Multiple-Input/Multiple-Output (MIMO) systems, which can use feedback to determine channel characteristics and adjust power on different antennas to steer antenna beams.

Our paper dealt with the Gaussian distributed shadowing, not the Rayleigh distributed multipath fading. But, the effects of large-scale (shadowing) and small scale (multipath) fading are additive at the receiver. The receiver sees both of the effects, and receives the instantaneous composite multipath/shadowed signal. These phenomena differ in scale by distance. And by the extension to mobile scenarios, they also differ in scale by time. The fast responses of a MIMO system with beam steering overcome weak signals but also can ‘steer’ to mitigate the effect of shadowing obstacles. So the solutions designed to offset multipath fading can also remedy some of the effects of shadowing.

Diversity is used to improve the received signal-to-noise ratio (SNR) in multipath fading. In diversity reception, multiple copies of the same signal are redundantly received over two or more fading channels, then combined in a way to increase the overall SNR. The low probability of deep fades in all channels at the same time is what improves the SNR.

Some implementations of diversity focus on time. Such techniques as simple repetition, or interleavers with error correction coding provide a way that even if bursts of a message are lost due to fading, the whole message can be recovered. The benefit of the interleaver on the error performance increases with the velocity of the transmitter, receiver, or objects in the channel, so this is useful for the MANET.

Spatial diversity can be implemented by multiple antennas at the receiver. The signal from a single transmitter takes multiple paths in space, and these are combined at the single receiver. Some combining
methods require knowledge of the channel which is gained by a training sequence, and this channel estimate must be periodically refreshed. A MANET’s mobility influences the rate at which the channel conditions change (e.g., coherence time) affecting the combining methods. Some receivers may not have the space to accommodate multiple receivers. A variety of spatial diversity for this space constraint is the use of two orthogonally polarized antennas at the receiver.

Space time coding is used with MIMO systems. A basic one, such as Alamouti coding, requires no knowledge of the channel, but cleverly orthogonalizes any channel for diversity. With knowledge of the channel at the receiver, space time codes can increase either diversity (signal power) or multiplexing (data rate) gain. This tradeoff is useful to the moving nodes of a MANET.

The many and growing types of diversity techniques are not only effective at combating fading, but are also combined with other techniques. The end result is a more complex, but adaptable communications system.

5. Conclusion

Unmanned system teams must maintain a readily available communications network in many environments for successful operation. They can form a MANET and these are well modeled by group mobility models. We examined the RPGM model specifically, in shadowing, as a further step to accurately model communications of this moving group.

The calculation of coverage probability, \( \kappa \), was demonstrated in multiple forms. The analytical solution was found to be exceedingly complex for use, but the approximation of \( \kappa \) was shown to be a quick and accurate calculation at nominal parameter values. These values of coverage probability can then be used to calculate the probability of availability for different topologies.

The further analysis of fading with the RPGM model will hopefully yield more understanding of which techniques can best overcome fading for teams that compose a MANET. The probability of availability is the key parameter linking mobility and successful network performance.

References


Appendix

This appendix presents the calculation of the probability that a uniformly distributed node position within a circle of radius \( r \), is within the boundary of a circle of radius \( R \). The centers of the two circles are not co-located, as in Fig. 6. The calculation is in two parts, corresponding to regions \( B_1 \) and \( B_2 \). The arbitrary x-axis joins the centers of the two circles.

![Figure 6. Calculation of uniformly distributed node probability with radius \( r \) within boundary of circle of radius \( R \).](image)

For the region \( B_1 \), the uniform distribution of the node position simplifies the calculation of the marginal density to an equivalent integral of

\[
f_x(x) = \int f_{xy}(x,y)dy = \frac{1}{\pi r^2} \int_{-\sqrt{r^2-x^2}}^{\sqrt{r^2-x^2}} dy
\]

where the origin is at the center of the circle of radius \( r \). This reduces to

\[
f_x(x) = \frac{1}{\pi r^2} \sqrt{r^2-x^2} \quad |x| \leq r.
\]

The value of \( p \) is defined next. From the triangle with sides \( r, R, \) and \( R \), the angle \( \alpha \) can be found from the law of cosines,

\[
\alpha = \cos^{-1}\left( \frac{r^2 + R^2 - R^2}{2rR} \right).
\]

The angle \( \beta \) is the supplementary angle of \( \alpha \). Then the distance \( p \) can be found by

\[
p = r \cos \beta.
\]

The PDF can then be integrated to find

\[
\Pr[B_1] = \int_{-\infty}^{\infty} f_x(x)dx
\]

The probability that the node is in region \( B_2 \), \( \Pr[B_2] \) is found by first finding \( \theta \), then using the equation for the area. The angle \( \theta \) can be found from the law of cosines,

\[
\theta = 2 \cos^{-1}\left( \frac{R^2 + R^2 - r^2}{2RR} \right).
\]

The area of the circular segment, \( B_2 \), is found by [18]

\[
B_2 = \frac{1}{2} R^2 (\theta - \sin \theta)
\]

The uniform distribution of the node position allows the computation of the \( \Pr[B_2] \) as:

\[
\Pr[B_2] = \frac{1}{\pi r^2}
\]

The probability that a uniformly distributed node position within a circle of radius \( r \), is within the boundary of a circle of radius \( R \), is then found to be the sum \( \Pr[B_1] + \Pr[B_2] \).