Feng, Q., McGeehan, J. P., & Nix, A. R. (2007). Enhancing coverage and reducing power consumption in peer-to-peer networks through airborne relaying. In IEEE 65th Vehicular Technology Conference 2007-Spring, Dublin. (pp. 954 - 958). Institute of Electrical and Electronics Engineers (IEEE). 10.1109/VETECS.2007.205

Enhancing Coverage and Reducing Power Consumption in Peer-to-Peer Networks Through Airborne Relaying

Qixing Feng, Joe McGeehan, and Andrew R. Nix
Centre for Communications Research, University of Bristol
Merchant Venturers Building, Woodland Road, Bristol BS8 1UB, UK
Email: {roger.feng, j.p.mcgeehan, andy.nix}@bris.ac.uk

***Abstract*—Over the years peer-to-peer (P2P) multi-hop relays have been studied for mobile ad-hoc networks (MANETs) to overcome poor signal coverage and to improve connectivity. However, for an urban environment, particularly with a sparse mobile distribution, a ground relay is not able to achieve significant benefits, mainly due to the extremely high pathloss and shadowing encountered. Dedicated airborne relay nodes, at a height of hundreds or thousands of meters, can provide much better coverage, and hence improve the connectivity, decrease the number of hops, reduce the power consumption, and support co-operative relays when integrated into mobile ad-hoc networks. An air node can also act as the sink for current wireless sensor networks (WSNs). Despite these potential advantages, the coverage from an air node located directly above an urban operating environment has not been adequately investigated in the literature.**

This paper compares the advantages of airborne relaying compared to more conventional peer-to-peer mobile relays. Three channel types are considered, i.e. line-of-sight (LoS), obstructed LoS (OLoS), and non-LoS (NLoS), each with their own likelihood, pathloss, and shadowing models. The practical gain pattern of a hemispheric antenna, or a directional antenna, is also carefully considered for the air node. Comparisons of the air-to-ground (A2G) channel and the mobile P2P channel demonstrate that airborne relays can enhance the coverage and reduce the power consumption significantly.

Keywords-Coverage; power consumption; connectivity; peer-to-peer; airborne relaying; multihop; directional antenna

I. INTRODUCTION

The application of mobile peer-to-peer (P2P) networks are restricted by poor channel conditions, which leads to reduced propagation range, poor node coverage, and high power consumption [1]. Multi-hop P2P relaying has been used to overcome these limitations, but often requires a number of relaying hops, and thus suffers from long transmission latency and an unreliable physical link. It also requires a high node density to establish a connected link between a pair of nodes.

The limitations for P2P ad-hoc networks are directly caused by poor signal coverage from the ground-based mobile transmitters. To enhance coverage, a number of methods are discussed in [2]. For a P2P mobile network, one promising solution is to introduce dedicated relaying nodes that have high coverage to the ground mobiles. Since the air-to-ground (A2G) channel usually suffers less from ground clutter, airborne relaying nodes (ARNs) may be integrated into a ground based ad-hoc network to improve its connectivity. Although the distance between the transmitter (Tx) and the receiver (Rx) is usually much larger for an A2G channel (compared to a P2P channel), airborne relaying can benefit from the high gain of a narrow-beamwidth airborne antenna, compared to an omni-directional antenna on the P2P relay. The major advantage of A2G channels is that they tend to encounter much less severe fading and shadowing compared to P2P ground channels. LoS propagation is often dominant for A2G channels [3]. Even when the channel type is NLoS, an A2G channel will tend to suffer from less pathloss and shadowing variation [4].

Traditionally, coverage has been studied for a single channel type, usually NLoS, where the received power is represented by the inverse power law and a fixed shadowing variance [5]. However, for A2G channels, LoS propagation often dominates at high elevation angles from the mobile, and is also significant at low elevation angles [3]. A comprehensive study must take into account all channel types. In this paper, we take account of the likelihood of LoS and NLoS channel types; make use of available statistical models for the pathloss and shadowing; and investigate the advantages of an ARN in terms of coverage enhancement, connectivity improvement, and reduction in power consumption.

The remainder of this paper is organized as follows. In section II we describe the link models used in this research. Section III examines the power consumption for LoS propagation, and makes comparisons for various airborne heights and P2P channels. In section IV, we demonstrate the advantages of airborne relays in a practical environment. Finally, the main results are summarized in Section V.

II. LINK MODELS

A. Channel Models

This research makes use of conventional and recently proposed channel models [3][4][6]. To make a fair comparison between P2P and A2G channels, the value of each parameter in the models is derived for the same operating environment, a central area (around 1km×1km in size) of the City of Bristol.

1) Channel types and their likelihood

In an urban environment, radio propagation is often obstructed by buildings and foliage. In fact, knife-edge

1550-2252/$25.00 ©2007 IEEE

diffraction theory and the ground-reflected pathloss model [7] indicate that a LoS path for a P2P channel can only exist over a limited transmission distance, even if the terrain is flat and there is no obstruction. In practice, radio channels are modelled for different types, usually LoS, OLoS and NLoS. A LoS channel features a direct path that is clear from any obstruction. A channel whose direct path is partially obstructed by trees is classified as OLoS. If a channel is blocked by buildings it is classified as NLoS.

A high likelihood of LoS propagation is one of the advantages of A2G channels. In [3], a theoretical model was proposed to estimate the probability of the combined LoS/OLoS propagation, i.e. free of building blockages. For P2P channels, the LoS probability is very small, but should not be neglected in an accurate study. We reproduce the data for LoS probability using the figure in [6].

2) *Mean path loss L_b* and *Shadowing variation L_s*

The received signal power is well-known to fluctuate about a mean value, and thus the pathloss is modelled as a mean pathloss (MPL) and a shadowing variation.

The mean pathloss (L_b) is conventionally modelled using an n^{th} power law [7]:

$$L_b = b_0 + 20\log_{10} f(\mathrm{MHz}) + 10n\log_{10} d(\mathrm{m}), \tag{1}$$

where b_0 is a constant, f is the carrier frequency, and d is the Tx/Rx separation distance. For P2P channels, the LoS channel was found to follow the free space pathloss equation, whereas the pathloss index n for a NLoS channel can be up to 5.86 [6]. The MPL for A2G channels is found to be more conveniently modelled as two independent parts: free space pathloss and an extra loss represented as a function of the elevation angle [4].

The shadowing variation was found to follow a Normal distribution around the mean pathloss (in dB) [4][6][7]. Thus, shadowing (in dB) can be modelled as a zero-mean, Normally distributed random variable. Its cumulative distribution function (CDF) is thus represented as:

$$D(L_s) = \frac{1}{2} + \frac{1}{2}\operatorname{erf}\left(\frac{L_s}{\sqrt{2}\sigma}\right), \tag{2}$$

where σ^2 is the variance, and erf(x) denotes the error function.

In previous research [5][7], the coverage was studied with a constant standard deviation, σ. However, in practice σ is a distance-dependent, or elevation-angle-dependent, variable. This paper uses the models proposed in [3-4] and [6] for the air-to-ground channels and the P2P channels respectively.

B. *Antennas*

For a P2P mobile terminal, an omni-directional antenna is usually used with vertical polarization. The typical antenna gain is 2dBi (for a half-wavelength dipole).

For the A2G radio channel, circularly polarized antennas are commonly used to reduce the polarization mismatch loss. A single-lobe antenna, with its boresight orientated in the vertical direction, is used in the air node. The normalized gain pattern (with a maximum gain of 0dBi) for a single-lobe symmetric-beamwidth antenna can be approximated in a cosine form [8]:

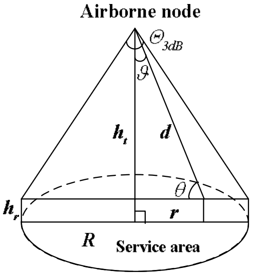


Fig. 1. Footprint of an airborne node on the ground

$$\widetilde{G} = \cos^m \vartheta, \quad 0 \le \vartheta \le \pi/2, \tag{3}$$

where ϑ is the angle with respect to the boresight, with a range from 0 to $\pi/2$; Θ_{3dB} is the half-power beamwidth (HPBW); and m can take integer and non-integer values. Since $\cos^m(\Theta_{3dB}/2) = 0.5$, m is related to Θ_{3dB} by $m = -1/\log_2\cos(\Theta_{3dB}/2)$.

A hemispheric or directional antenna can be used in the air node, dependent upon the required beamwidth. For a practical antenna with a circularly symmetric beamwidth $\Theta_{3dB} \le 120°$, its maximal gain is approximately [8]:

$$G_0 \approx \frac{30{,}000}{\Theta_{3dB}^2[\deg]} \approx \frac{9.1385}{\Theta_{3dB}^2[\mathrm{rad}]}. \tag{4}$$

Whereas when $\Theta_{3dB} \ge 120°$, the antenna may be more accurately modelled as a hemispheric antenna with a maximum gain of 3dBi.

In Fig. 1, an airborne antenna serves an area with radius R. We use two factors k and τ to simplify the expressions: $k = h_t/R$, $\tau = r/R$ (τ ranges 0 – 1), where r is the distance from the centre. Hence, assuming $h_t - h_r \approx h_t$ and the slant angle of the airborne node is 0, the HPBW is given by:

$$\tan(\Theta_{3dB}/2) = R/(h_t - h_r) \approx R/h_t = 1/k. \tag{5}$$

The angle at a distance r with respect to the boresight can be represented as:

$$\cos\vartheta \approx k/\sqrt{k^2 + \tau^2}. \tag{6}$$

The antenna gain can be represented as a function of the two ratios, i.e. k and τ.

C. *Link model*

In a wireless communication system, let P_T and P_R denote the transmit and received powers respectively, L_0 denote the circuit loss (such as amplifier efficiency, etc.) in the Tx, G_T and G_R denote the antenna gains in Tx and Rx respectively, L_b denote the mean pathloss, and L_s denote the shadowing loss. Thus, the received signal power is:

$$P_R = \frac{P_T G_T G_R}{L_0 L_b L_s}. \tag{7}$$

The received power must exceed a threshold γ_{th}, usually the receiver sensitivity. Hence, the transmit signal should not suffer a pathloss (*PL*) greater than a critical value - maximum tolerable path loss (MTPL, ξ_0), which is expressed as:

$$\xi_0 = \frac{P_T G_T G_R}{L_0 \gamma_{th}}. \tag{8}$$

Like the effective isotropic radiated power (EIRP) [7], we define an effective isotropic pathloss (EIPL) from the transmitter: $EIPL = L_b L_s / G_T$, and thus the MTPL is revised as:

$$\xi_r = \frac{\xi_0}{G_T} = \frac{P_T G_R}{L_0 \gamma_{th}}. \tag{9}$$

Therefore, $PL \leq \xi_0$ is equivalent to $EIPL \leq \xi_r$. However, the EIPL determines the required minimum power consumption, and hence is more suitable for comparisons between two transmitting systems with different transmit antennas, as the beamwidth and gain for the air antenna are dependent on the service area and the air height. Without loss of generality, we assume $L_0 = 1$, $G_R = 1$.

III. POWER CONSUMPTION FOR LOS CHANNELS

For a LoS channel in a given service area with a radius R, the EIPL from an airborne node is:

$$EIPL_A = \frac{L_f}{G_{T,A}} = \left(\frac{4\pi}{\lambda}\right)^2 \frac{d^2}{G_{T,A}} = \left(\frac{4\pi}{\lambda}\right)^2 \frac{R^2(k^2+\tau^2)}{G_{T,A}}, \tag{10}$$

where L_f is the free space pathloss, $G_{T,A}$ is the antenna gain of the airborne node, λ is the wavelength, and d is the Tx/Rx separation distance. It is determined by a factor $V(k, \tau)$:

$$V = \frac{(k^2+\tau^2)}{G_{T,A}}. \tag{11}$$

When $k \to \infty$, V can be computed as:

$$V[dB] = \lim_{k\to\infty}(10 \log V) = -3.588 + 3\tau^2. \tag{12}$$

This expression can be used for $k \geq 3$ with sufficient accuracy, as shown in Fig. 2. It indicates that when $h_t \geq 3R$, increasing the height of the airborne node does not significantly change the power consumption (or equivalently, the propagation range). This occurs since the directional antenna gain can compensate for the excess loss caused by the increasing air height. However, in practice, increasing the height of the airborne node may improve the likelihood of LoS. Given an operating area, we can decide the height of the air node mainly based on the likelihood of LoS. In addition, the EIPL determines the minimum required transmit power, which is shown from the above expressions to be proportional to the square of the radius of the service range for LoS propagation. These results may also be suitable for high altitude platforms (HAPs)[9].

For a P2P LoS channel, the EIPL from a mobile transmitter is:

$$EIPL_M = \frac{L_f}{G_{T,M}} = \left(\frac{4\pi}{\lambda}\right)^2 \frac{r^2}{G_{T,M}} = \left(\frac{4\pi}{\lambda}\right)^2 \frac{R^2\tau^2}{G_{T,M}}, \tag{13}$$

where $G_{T,M}$ is the antenna gain of the mobile node and takes a value of approximately 2dBi for a half-wavelength dipole. We now compare the power consumption between A2G and P2P channels:

$$\frac{EIPL_A}{EIPL_M} = \frac{(k^2+\tau^2)}{G_{T,A}} \frac{G_{T,M}}{\tau^2}. \tag{14}$$

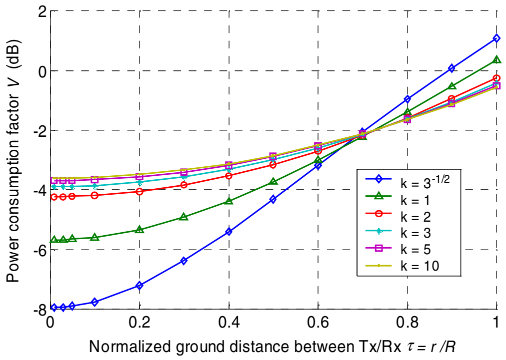


Fig. 2. Power consumption for various airborne heights

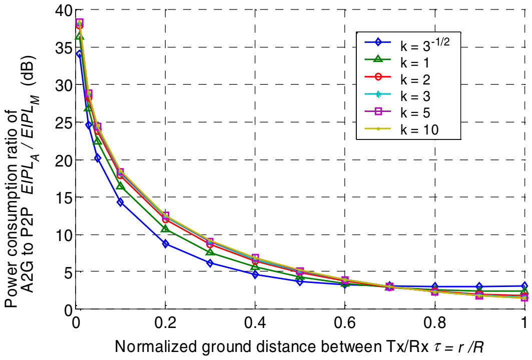


Fig. 3. Power consumption ratio of A2G to P2P

When $k \to \infty$:

$$\frac{EIPL_A}{EIPL_M}[\text{dB}] \approx -3.588 + 3\tau^2 - 10 \log \tau^2 + G_{T,M}. \tag{15}$$

This result is also suitable for $k \geq 3$, as shown in Fig. 3. It indicates that an A2G LoS channel does not have an advantage in terms of power consumption in a free-space channel. Particularly within a short distance to the centre, the A2G link suffers much higher loss. However, as mentioned earlier, P2P LoS propagation only exists over very short distances, even when there is no obstruction from buildings and foliage. At longer distances, the ground-reflected pathloss model may be valid and the pathloss is much higher than the A2G LoS loss. Thus, P2P relaying is preferred over short distances (using multi-hop links where necessary). However, at longer distances, airborne relaying can be used to reduce the number of hops at the cost of affordable extra loss (much less than the NLoS path loss).

IV. COVERAGE AND POWER CONSUMPTION IN A PRACTICAL ENVIRONMENT

In the free-space pathloss model, the propagation range and power consumption are deterministic values given the configurations of the radio terminals and the operating frequency. However, in a practical environment, the received power is a log-Normally distributed random variable due to the effect of shadowing. Statistically, we define the likelihood of the received signal power above a threshold as the coverage. The local likelihood measured at a given distance is the local coverage. The likelihood measured in a service area, which is equivalent to the percentage of the received signal coverage above a threshold in a service area, is called the area coverage, or the useful service area [5][7].

Radio coverage was dealt with in [7], on the assumption that the received power follows an inverse power law with distance, and the shadowing is log-Normally distributed with a constant variance. The method only considers one channel type, and cannot be used in more practical channels with multiple radio propagation schemes, i.e. LoS, NLoS and OLoS. Moreover, the local coverage for P2P channels is independent of the radius of the service area. Whereas for A2G channels, the maximum attainable gain of the directional antenna is dependent on the radius *R* of the service area, therefore, the local coverage is also related to *R*, and thus the coverage is much more complicated.

A. Local coverage

The local coverage F_l is the probability that the received power P_R is larger than the threshold γ_{th}, or equivalently, the pathloss is not greater than the MTPL. According to (7) and (8) and representing the terms in dB, we can deduce the local coverage at distance *r*:

$$\begin{aligned} F_l &= \mathrm{P}(P_R(r) \geq \gamma_{th}) = \mathrm{P}(L_b + L_s \leq \xi_0) \\ &= \mathrm{P}(L_s \leq \xi_0 - L_b) = \mathrm{P}(L_s \leq \xi_r + G_T - L_b). \end{aligned} \tag{16}$$

This probability is determined by a Normal distribution function, expressed with ξ_r, allowing different transmitting systems to be compared for the same power consumption.

For multiple channel types, let $P_{ch\,i}$ denote the probability of occurrence of the channel type *i*; $L_{s,\,ch\,i}$ and $L_{b,\,ch\,i}$ denote the shadowing and the MPL for channel type *i*, respectively. The local coverage is now given by:

$$F_l = \sum_i P_{ch\,i} \mathrm{P}(L_{s,ch\,i} \leq \xi_r + G_T - L_{b,ch\,i}) \cdot \tag{17}$$

Fig. 4 shows the local coverage of a peer mobile and an air node (for a service area with a radius of 500m) for a revised MTPL of 100dB. An airborne node demonstrates superior coverage over a ground node for the same degree of power consumption. For 90% local coverage, the maximum distance for a mobile is only 40 meters, whereas for an air node it is greater than 150 meters.

B. Area coverage

Statistically, the area coverage is the average local coverage of a service area. Given the probability density function (PDF) of the distance between an arbitrary point and the transmit node, *p*(*r*), the area coverage is given as:

$$F_a = \int_r p(r) \cdot F_l dr \cdot \tag{18}$$

For a disk area with radius *R*, the PDF can be simply derived:

$$p(r) = \frac{2r}{R^2}, \quad 0 \leq r \leq R. \tag{19}$$

Then, the area coverage for a disk area where the transmit node is located at its centre is:

$$F_a = \frac{2}{R^2} \int_0^R r F_l dA \cdot \tag{20}$$

The area coverage is closely related to the connectivity (the probability of a successful connection). For a P2P network with uniformly distributed mobiles in a disk area with radius *R*, the PDF of the distance *r* between two arbitrary nodes is given in [10]:

$$p(r) = \frac{4r}{\pi R^2} \cos^{-1}\left(\frac{r}{2R}\right) - \frac{2r^2}{\pi R^3} \sqrt{1 - \frac{r^2}{4R^2}} \cdot \tag{21}$$

The direct P2P connectivity can be computed from (18). For a mobile-air-mobile (MAM) relayed link, the connectivity is approximately F_a^2, since the two direct mobile-air links must both be connected.

Fig. 5(a) and Fig. 6 show the area coverage and the connectivity for a revised MTPL of 100dB for a disk service area with radius up to 500m. The advantage of higher coverage for an air node leads to higher MAM connectivity. By improving the revised MTPL to 120dB, as shown in Fig. 5(b), the area coverage is almost ideal.

Having discussed the area coverage and the connectivity, the power consumption for a desired coverage area (or a desired direct P2P or MAM connectivity) can be obtained. Fig. 7 shows the relationship between the area coverage and the power consumption (represented by the revised MTPL) in two areas. In a small area, as shown in Fig. 7(a), the mobile node also has good coverage, but the air node can save a significant degree of power (at least 40dB for 90% coverage), and thus provide a highly desirable benefit. Whereas in Fig. 7(b), the coverage of a mobile node is too low for a practical MTPL, and thus a sparsely distributed mobile network occurs over large areas, when P2P relays are used.

V. CONCLUSIONS

Since an A2G channel usually has a high likelihood of LoS, and compared to a P2P channel has much less severe shadowing in NLoS propagation (plus the benefits of a directional antenna to compensate for the extra pathloss due to the high air height), it offers superior coverage relative to a P2P mobile relay. Therefore, air relays can be integrated into P2P networks to extend range, improve connectivity, and lower power consumption.

The airborne nodes are best used for long-hop relays, since long-hop P2P relays suffer from very high pathloss, and short-hop multiple P2P relays are inefficient and suffer considerable delay and jitter. The features of airborne relays make them well suited to reduce coverage ‘holes’, particularly in sparse mobile networks. Airborne relays are also useful for deployment in emergency scenarios, such as public safety.

Air nodes can be used as the sink for current wireless sensor networks, and as relay nodes between ground mobiles and high altitude platforms, or satellites, to support global communication.

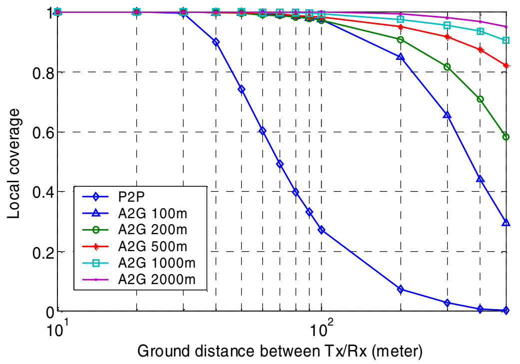
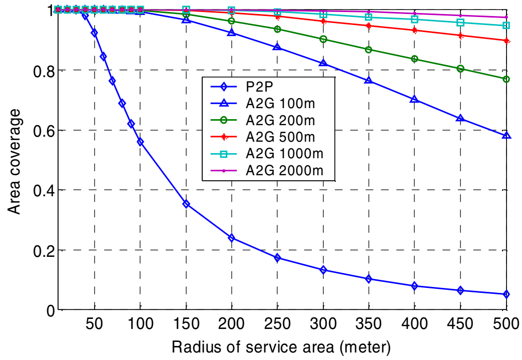
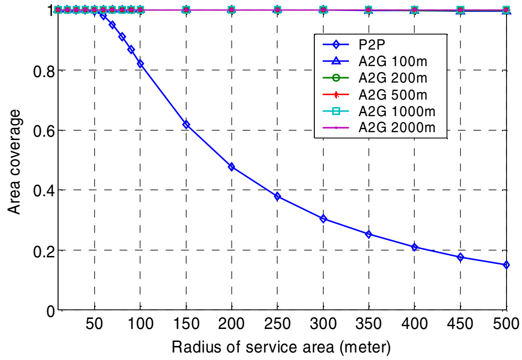


Fig. 4. Local coverage



(a) $\xi_r = 100$dB



(b) $\xi_r = 120$dB

Fig. 5. Area coverage

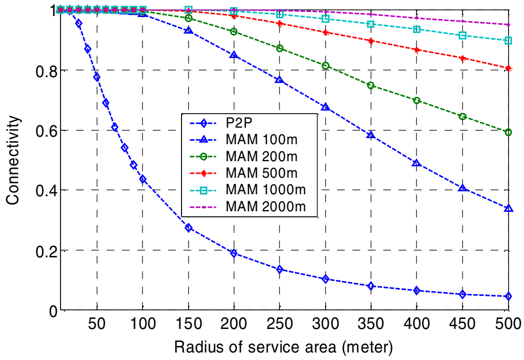
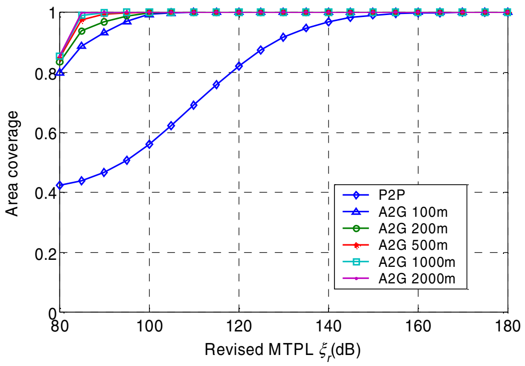
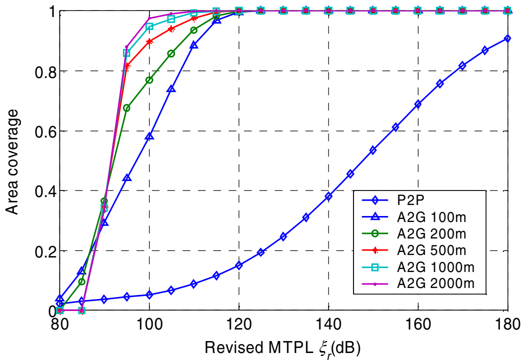


Fig. 6. Connectivity for a direct P2P link and a MAM link



(a) $R = 100$m



(b) $R = 500$m

Fig. 7. Power consumption

REFERENCES

[1] R. Ramanathan, J. Redi, "A brief overview of ad hoc networks: challenges and directions," *IEEE Commun. Mag.,* vol. 40, no. 5, pp.20-22, May 2002

[2] D. D. Falconer and J.-P. DeCruyenaere, “Coverage enhancement methods for LMDS,” *IEEE Commun. Mag.*, vol. 41, no. 7, pp. 86-92, July 2003.

[3] Q. Feng, E. K. Tameh, A. R. Nix, and J. McGeehan, “Modelling the Likelihood of Line-of-Sight for Air-to-Ground Radio Propagation in Urban Environments,” in *Proc. IEEE GlobeCom’2006*, Nov. 2006.

[4] Q. Feng, J. McGeehan, E. K. Tameh, and A. R. Nix, “Path Loss Models for Air-to-Ground Radio Channels in Urban Environments,” in *Proc. IEEE VTC’06 Spring*, May 2006.

[5] W. Jakes, *Microwave Mobile Communications*, New York: John Wiley, 1974.

[6] Z. Wang, E. Tameh, and A. Nix, “Statistical peer-to-peer channel models for outdoor urban environments at 2GHz and 5GHz,” in *Proc. IEEE VTC’04 Fall*, Sept. 2004.

[7] T. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ: Prentice Hall PTR, 2002.

[8] C. Balanis, *Antenna Theory: Analysis and Design*, 2nd ed. John Wiley & Sons, Inc., 1997.

[9] B. El-Jabu and R. Steele, “Cellular communications using aerial platforms,” *IEEE Trans. Veh. Technol.*, vol. 50, no. 3, May 2001.

[10] E. W. Weisstein, "Disk Line Picking," From *MathWorld*--A Wolfram Web Resource, http://mathworld.wolfram.com/DiskLinePicking.html.