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Autonomous Mobile Radios for Enhancing Wireless Communications through Wireless Tethering in Tunnel-Like Environments

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Abstract: An autonomous Mobile Radio (AMR) in a wireless network is a mobile robot with wireless communication capability whose mission is to achieve a network communications goal through control of its position. Wireless tethering is an AMR behavior for ensuring the quality of wireless links between an AMR and other nodes. We discuss the particular problem of autonomously penetrating a tunnel environment using wirelessly tethered AMRs. Using a realistic, experimentally-derived radio signal propagation model in an underground environment, we present a method of implementing tethering using a consensus variable protocol for motion control as well as a method of estimating the coverage range.

Keywords: Antennas, Wireless, Communication, Networks, Autonomous Robots, Consensus Variables

1. INTRODUCTION

Wirelessly networked mobile robots are being considered for use in a wide variety of cooperative tasks that can broadly be classified as mapping sensor readings throughout a given terrain or tracking objects based on their characteristic sensor readings. Recently, wireless networked mobile robots have also been considered as tools for enhancing a wireless network. For example, movement control of wireless mobile robots to bridge network gaps has been suggested [Basu and Redi (2004)] and wirelessly tethered exploration with mobile robots has been practically demonstrated [Pezeshkian et al. (2007)]. Wireless tethering is a method of ensuring inter-robot communications by controlling the movement of mobile robots such that they do not move out of communication range of other robots. A common approach, Line-of-sight (LOS)-based tethering, in which robots can only move until they lose optical LOS with each other [Sweeney et al. (2002)], is a reasonable assumption for high GHz, high bandwidth communications. For radio communications with lower bandwidth requirements, LOS tethering can be restrictive since the RF signals can propagate some distance around corners. For example, wireless tethering controlled by received signal strength (RSS) measurements allows direct non-line-of-sight (NLOS) links between robots, and has been reported to decrease the amount of time spent by a robot swarm in mapping a given environment, compared with LOS-based tethering [Thibodeau et al. (2004)].

In this paper, we consider wireless tethering in tunnel-like environments such as subterranean mines, building hallways, and urban canyons. In particular, we investigate an RSS-based tethering method using consensus variables, including a deterministic propagation model for a subterranean area in which the exploration path consists of straight tunnels and corners or bends. We then consider how to estimate the coverage area, given a number of AMRs.

In the work that follows, we use the term *autonomous mobile radio* (AMR) to refer to a mobile robot that uses mobility and repositioning to enhance wireless communications. We further define an AMR *behavior* as an autonomous movement or sequence of movements that the AMR makes for the primary purpose of restoring or improving a given network parameter, such as received signal strength. Such behaviors include wireless tethering and repositioning for enhanced signal strength. The latter will be addressed in future work. In general, any mobile wireless node could be programmed with AMR behaviours, even if its primary mission is sensing or exploration. Therefore, in a general sense, an AMR is any wireless mobile robot that can carry out AMR behaviours. We also point out that our research is motivated by the problem of emergency search and rescue in a tunnel environment such as a mine. A scenario whereby the AMR tethering behaviour is needed is depicted in Fig. 1, which shows an operator at the surface of a mine tele-operating a front-end-loader, with video and command signals relayed via several AMRs. As the front-end-loader moves deeper in the mine the AMRs space themselves out to maintain the best possible radio connection between all units in the system.

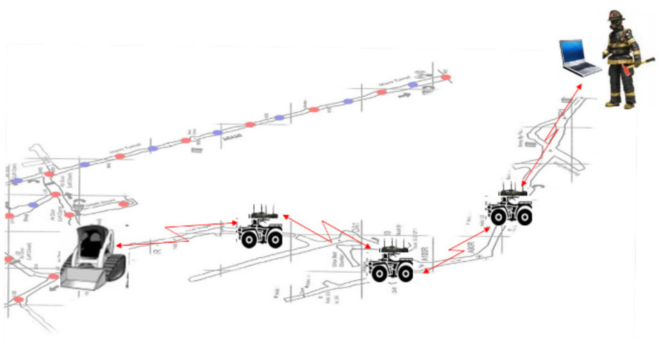


Fig. 1: A tethering application within a mine, with 4 AMRs maintaining communications with an operator outside.

Finally, note that although many communications parameters such as bit error rate and packet drop rate could be used for network quality-control, here we focus on received signal power or strength (RSS) since it can be directly related to the distance from the transmitter through a proper propagation model. Our work is carried out at 2.4GHz, to be consistent with many common wireless networking systems.

2. WIRELESS TETHERING

Wireless tethering is a fundamental behavior that enables AMRs to autonomously follow a leader and explore a given area without the risk of losing wireless contact with each other. The radio range between AMRs in environments such as subterranean mines and tunnels may be quite limited compared to the free space range, and therefore, several AMRs will be necessary to cover a 1D curvilinear path that includes several bends, such as the one shown in Fig. 2, which depicts an arbitrary path within the Colorado School of Mines Edgar Experimental Mine in Idaho Springs, CO.

Fig. 2: Possible stopping positions for wirelessly tethered AMRs along a 1D curvilinear path in a subterranean mine.

Assume that a group of *Z* AMRs is tasked with exploring an unmapped part of the environment, and that AMR-1 is connected to a stationary base-station. The object for the team of AMRs is to follow the leader, AMR-*Z,* as far as possible along a given path such as shown in Fig. 2. Let $P_{i,j}$ be the RSS of the j^{th} AMR, measured at the i^{th} AMR. Then, one possible simple tethering algorithm is based on a *pushing force* [Peeke (2006)] to stop an AMR moving away from a node when the link between them is threatened. This method can be described as follows: set AMR-1 through AMR-Z in motion from the start of the path, moving away from the base-station (node 0), whose position defines the origin. First, AMR-1 stops when $P_{1,0}<=P_{min}$, where P_{min} is a predefined minimum power necessary to maintain communications at the desired level. Next, AMR-2 stops when $P_{2,1}<=P_{min}$. The stopping condition for the i^{th} AMR is then $P_{i,i-1}<=P_{min}$. At the completion of the algorithm, all robots will be spaced such that the received power from the previous AMR in the chain is approximately P_{min}. This guarantees that all forward links are within acceptable limits. However, due to variations in antenna gain, transmit power, and receiver sensitivity, the reverse links may not be acceptable. Another method of tethering implementation is to use a *pulling force* along the path to move an AMR in the direction of a node when the link to it is threatened. In this method, the i^{th} AMR will begin moving to follow the $(i+1)^{th}$ AMR when $P_{i,i+1}<=P_{min}$. In this scenario, AMR-Z will begin moving first, and then AMR-(Z-1) will follow suit. This guarantees good reverse links, but not good forward links, and does not ensure that AMR-1 will remain in contact with the base station.

Using a *virtual physics* approach, a combination of push/pull forces can be applied to achieve balance in both forward and backward links, and thereby achieve symmetric links in the chain. Virtual physics-based robot motion control has been discussed in the literature [Shucker et al. (2006)], but not, to our knowledge, with respect to RSS-based wireless tethering. One method of accomplishing force-balancing wireless tethering is through a consensus process: the leader moves first, and others move via consensus to maintain identical $P_{i,j}$. In other words, throughout motion, $P_{i,i-1}= P_{i,i+1}$. Motion continues until $P_{i,i-1}= P_{i,i+1}=P_{min}$. This process leads to balanced exploration over time, which means that all links between nearest neighbors are symmetric at each moment in time. The consensus method relies on the magnitude and time-rate of change of RSS between neighbors. In section 4, we discuss a consensus variable based algorithm to balancing push/pull forces and moving through a 1D path such as that shown in Fig. 2. In Section 5 we compute how far a chain of robots can be expected to go using the consensus approach in a given mine environment before $P_{i,i+1}=P_{min}$ and compare this distance to that obtained using LOS tethering. First, however, in the following section, we discuss the propagation model used to simulate the tethering algorithm and to compute coverage distances.

3. DETERMINISTIC PROPAGATION MODEL FOR A TUNNEL ENVIRONMENT

We assume communications only between nearest neighbors in the 1D chain of AMRs. We model straight tunnels with a path loss exponent of 1.5, since waveguiding is the dominant propagation method. A path loss exponent less than 2 has been observed in waveguides by others for horizontal polarization, and our previous measurements have obtained a path loss exponent of approximately 1.5 for horizontal polarization [Weiss et al. (2008)]. We assume that movement into a branch tunnel causes corner or bending losses of approximately 3dB/m over a distance of about 12m beginning at the junction, and that beyond 12m after the junction, bending losses cease and the path loss exponent returns to 1.5. We have measured this bending/corner loss in our own experimental work and it is consistent with UHF measurements found in the literature [Lee and Bertoni (2003)]. We do not consider large-scale or small-scale fading in this preliminary model, since we are focusing on the effects of corners and bends; such effects will be included in future work.

Based on the above considerations, for the path shown Fig. 2, the received power from a given transmitter can be represented mathematically as shown in (1), where P_T is the transmit power, G_T and G_R are the transmit and receive antenna gains, λ is the wavelength, $n=1.5$ is the path loss exponent, ζ~3dB/m is an attenuation constant that describes bending or corner losses, r denotes the distance along the path which begins at a stationary basestation, r_1, r_2, and r_3 are the locations of the bends between tunnel segments, and d=12m, represents the region where corner losses dominate:

$$P_R(r) = \begin{cases} P_T G_T G_R \left(\frac{\lambda}{4\pi}\right)^2 & r = 1m \\ P_R(1)\frac{1}{r^n} & 1 < r \le r_1 \\ P_R(r_1)\, e^{-0.1\zeta(r-r_1)} & r_1 < r \le r_1 + d \\ P_R(r_1+d)\left(\frac{r_1+d}{r}\right)^n & r_1 + d < r \le r_2 \\ P_R(r_2)\, e^{-0.1\zeta(r-r_2)} & r_2 < r \le r_2 + d \\ P_R(r_2+d)\left(\frac{r_2+d}{r}\right)^n & r_2 + d < r > r_3 \end{cases} \tag{1}$$

The path loss is usually large enough to lose the wireless link before the 3rd tunnel segment, and therefore the last two piecewise functions are usually not necessary.

Using the propagation model in Equation (1), we modelled the received power for the forward link along the path shown in Fig. 2, assuming all bends have the same bending losses given by 3dB/m. Based on a map of the Edgar Mine, the tunnel segment lengths are 67, 3, 27, 30, 12, and 30m respectively, beginning with the origin at the upper left-hand corner, marked by the base station position. To represent a typical 802.11b/g system the frequency is 2.4GHz, the transmit power is 17dBm, the antenna gain is 5dBi at each node, and the receiver sensitivity is -85dBm. The received power for the forward path, $P_{i,i-1}$ is shown in red in Fig. 3, assuming AMRs have been positioned at each location where the RSS reaches -85dBm. The AMR positions are shown as black squares and the positions of the bends are shown as blue lines. This figure shows that only 3 AMRs are necessary to explore this path, with AMR-3 extending beyond the final 30m segment. However, if the antenna gain is reduced to 0dBi, then Fig. 4 shows that 4 AMRs will be needed to explore the same path, since AMR-3 only makes it to about 145m.

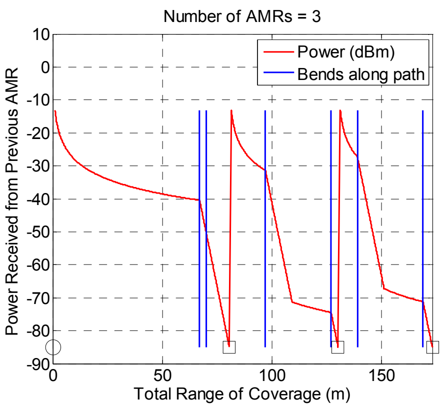


Fig. 3: Received power variation for the forward path, for an antenna gain of 5dBi. AMR positions: □; Basestation: ○.

Distance-based propagation models such as presented in Equation (1) can be used to a-priori calculate the approximate stopping positions of the AMRs *if a map of the path is given.* However, if the exact path is unknown, the model is less useful, since the locations of the bends are critical to determining the received power, as evidenced by Equation (1) and Figs. 3 and 4. Therefore, a wireless tethering algorithm based on knowledge of distance alone is not likely to produce useful results; rather, measurement of the received power is necessary. However, propagation models are useful in evaluating different tethering algorithms as shown in Section 4, and in the prediction of tethering range for different representative path types, as will be shown in Section 5.

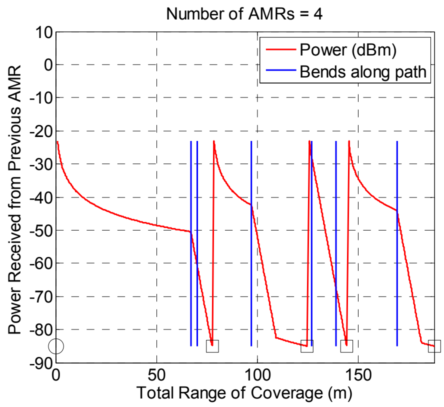


Fig. 4: Received power variation for the forward path, for an antenna gain of 0dBi. AMR positions: □; Basestation: ○.

4. WIRELESS TETHERING ALGORITHM

In this section, we use the propagation model in Equation (1) to demonstrate an algorithmic approach to wireless tethering, where the goal is for the AMRs to space themselves out between a mobile leader and a stationary base station. The "spacing" objective is that each AMR is separated equally in RSS. Note that there are numerous results in the literature for such a problem, where the goal is to achieve some type of vehicle formation. Most such results focus on formations in terms of physical location in space. See, for instance, [Beard et al. (2008)], which considers the spacing of N vehicles around a fixed perimeter. Here, however, we take our metric to be in terms of RSS. While not conceptually different, our result will not necessarily give equal separation of the AMRs in physical space, but rather a non-uniform spacing as in Fig. 2.

Let each AMR be located at x_i, ordered so that $x_{i+1} > x_i$. Let the RSS between and AMR and its two closest neighbors in physical space, be denoted $RSS_{i+1,i}$ and $RSS_{i,i-1}$ (an AMR might be able to measure RSS from units other than its two closest neighbors, but the algorithms we present here will only use nearest neighbor measurements). Using (1) above, we can write the RSS between two AMRs as:

$$RSS_{i+1,i} = \left(\frac{\kappa^2\alpha^2}{(x_{i+1}-x_i)^{1.5}}\right)\left(10^{-\frac{z}{10}(d_{\mathrm{Bend}})}\right)P_T \tag{2}$$

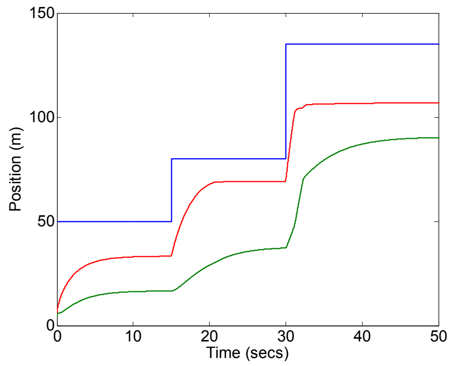
where d_{Bend} is the distance of any bends between the two AMRs and the other parameters are constants characteristic of the RF frequency and physical environment. κ^2 and α^2 are constants consisting of the parameters G_T, G_R, and λ. $(x_{i+1}-x_i)$

is the separation between the two nodes – referred to as r in Equation (1). z is ζ, the bend attenuation constant, and a path loss exponent n=1.5 has been used. Using this expression for RSS, we first propose the following motion control algorithm, based on the so-called consensus variable approach to coordinating the behavior of multiple entities [Beard et al. (2004)]:

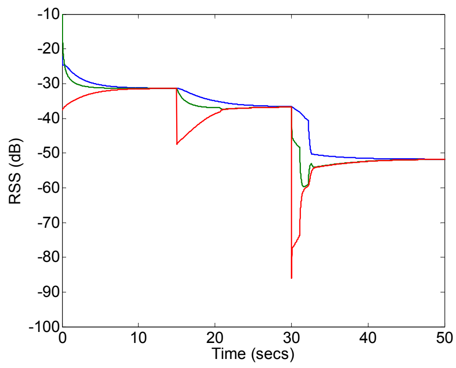
$$\dot{x}_i = -k_i^p 10\log\left(\frac{\kappa^2\alpha^2}{(x_{i+1}-x_i)^{1.5}}\right) + k_i^p 10\log\left(\frac{\kappa^2\alpha^2}{(x_i-x_{i-1})^{1.5}}\right) \quad (3)$$

Here $k_i^p > 0$ are gains that can be chosen as design variables (though not addressed here in technical detail, due to our ordering convention in our definition of RSS, the minus sign in the first part of (3) is required to ensure convergence). The motivation for (3) is that AMR$_i$ should stop moving when the difference in RSS between itself and AMR$_{i+1}$ is the same as that between itself and AMR$_{i-1}$. This problem can be cast as the problem of first-order consensus with a leader [Moore et al. (2005, 2007)] and it is easy to show in simulation that (3) will achieve the desired result for the case of a leader that is stationary (or moves to new positions as a step change).

Fig. 5 shows the result of running (3) for three AMRs using the tunnel path from the Edgar Mine shown in Fig. 2. Fig. 5(a) shows the individual AMR motions while Fig. 5(b) shows the resulting signal strength measurement $RSS_{i+1,i}$. Notice that if the objective has been achieved then all the RSS measurements should move to the same values at each point in time. Clearly in this example the objective is met, as



(a)

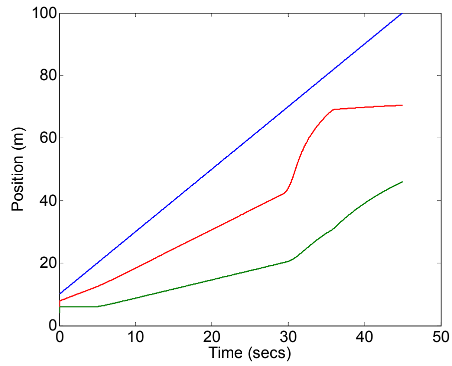


(b)

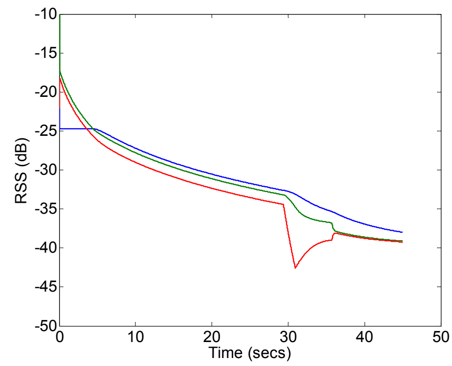
Fig. 5: First-order consensus response to a static leader with a step change: (a) individual AMR motions; (b) RSS values. The leader is shown in blue.

seen in Fig. 5(b). Notice, however, that in physical space, the AMRs are not equally spaced, reflecting the fact that the $RSS_{i+1,i}$ equations are different between AMR pairs due to the bends in the path.

Unfortunately, the algorithm given in (3) is inadequate when the leader is moving continuously. Fig. 6 shows the result when (3) is applied to the example where the leader is moving with a constant velocity. While at first glance the behaviour in Fig. 6(a) seems correct because of the unequal separation in physical space, in fact the RSS values between adjacent AMRs are not going to the same value, as seen in Fig. 6(b).



(a)



(b)

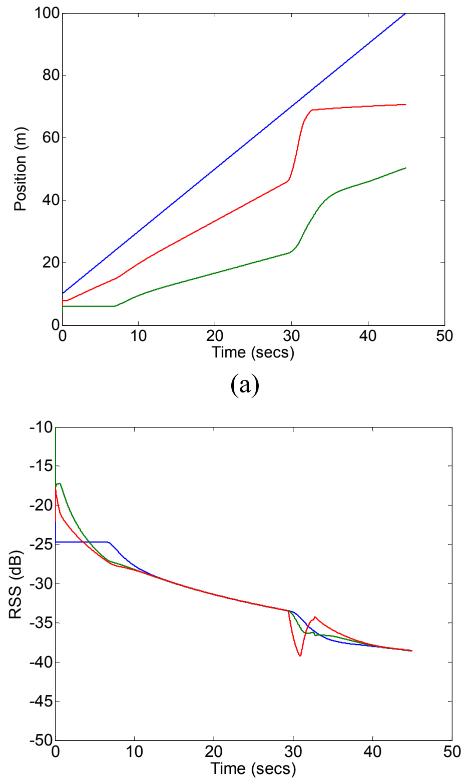
Fig. 6: First-order consensus response to a moving leader: (a) individual AMR motions; (b) RSS values. The leader is shown in blue.

To remedy the problem seen in Fig. 6 for the case of a moving leader it is necessary to use a higher-order consensus algorithm [Moore et al 2], which re-writes (3) as:

$$\ddot{x}_i = -k_i^p RSS^{dB}{}_{i+1,i} + k_i^p RSS^{dB}{}_{i,i-1} - k_i^d \frac{d}{dt}(RSS^{dB}{}_{i+1,i}) + k_i^d \frac{d}{dt}(RSS^{dB}{}_{i,i-1}) \quad (4)$$

Again $k_i^p, k_i^a > 0$ are gains that can be chosen as design variables. The distinction in (4) is that we adapt to the motion of each AMR not just using the error in RSS between AMRs, but by also using the error in the time rate of change of RSS. This is called a second-order consensus problem. Fig. 7 shows the result for the same scenario as in Fig. 6. Clearly in this case the desired affect is achieved, as the adjacent RSS strengths all go to the same value.

Note that many consensus algorithms for formation control and the earlier referenced work on higher-order consensus assume linear models for the consensus protocol, whereas both (3) and (4) are highly nonlinear. To prove convergence analytically, we will need to turn to more recent results on nonlinear consensus protocols [Bauso, et al. (2006)]. Such proofs are a focus of our ongoing work.



(a)

(b)

Fig. 7: Second-order consensus response to a moving leader: (a) individual AMR motions; (b) RSS values.

5. ESTIMATION OF WIRELESS TETHERING RANGE IN A REGULAR TUNNEL ENVIRONMENT

In Section 3, a simple deterministic propagation model was presented for modeling the received power in a 1D path within a tunnel environment. This model was used in Section 4 to demonstrate a tethering algorithm. In this section, we use the propagation model to obtain estimates of the maximum tethering range for a given number of AMRs. Once again, we note that fading is not included in this preliminary work.

It is clear from an intuitive standpoint that RSS-based NLOS tethering will give a larger tethering range than LOS-based tethering. It is also clear that with larger gain antennas (or higher transmit powers), a higher amount of power will couple into the branch tunnels, and result in an increase in tethering range. Requiring lower bandwidth will reduce the minimum received power necessary for the link, and this as well will increase the range. However, we would like to quanitify the range that can be expected using RSS-based tethering in common environments, with typical wireless parameters. Such quantification will aid in mission planning, to determine both the wireless parameters and the number of AMRs necessary to cover a given range within the application environment.

For this study, we choose a subterranean application environment, laid out regularly as in the room and pillar architecture of a typical coal mine, shown in Fig. 8. The length of a single block is l=30m (~100ft), which is reasonable for a coal mine. The total path, such as shown in Fig. 9, consists of a combination of straight tunnels and bends. B is the distance between bends, in units of blocks. That is, we assume that all path segments are B blocks in length. Three example exploration paths are shown in Fig. 9, for B=1, 2 and 3. A path with B=1 includes bends after every block, wheras a path with B=2 has bends after every two blocks.

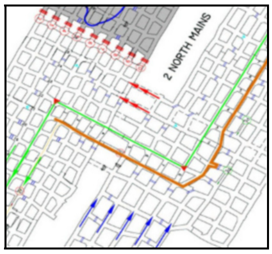


Fig. 8: Map of a portion of the Sago Mine, West Virginia, showing the block structure of the mine [MSHA (2006)].

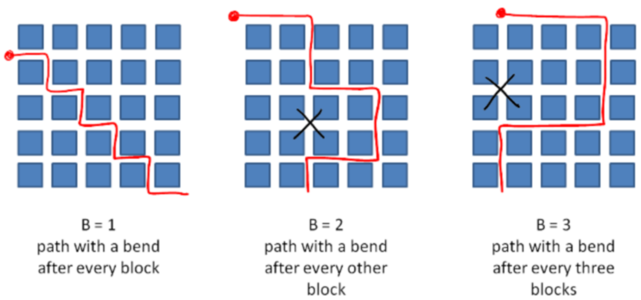


Fig. 9: Exploration paths with different values of B, the number of blocks per segment in the path. 'X' denotes an obstruction such as a cave-in.

The question we address is: what is the maximum tethering range along an infinitly long path, for a given number of AMRs and a specified value of B? We have calculated the tethering range for 4 AMRs along 8 infinitely long paths characterized by B=1,2…8, and present this data in Fig. 10. For a path with bends occuring every block (B=1, distance between bends = 30m), 4 AMRS can cover a distance of 242m with 5dBi gain antennas and 180m with 0dBi antennas. For comparison, if LOS-based tethering is used, only 120m can be covered in either case, since each AMR stops just around a bend. When the path has bends every two blocks (B=2, distance between bends = 60m), the RSS-based tethering is predicted to cover 480m with 5dBi antennas and only 240m with 0dBi antennas. As B is increased, the RSS-based tethering approaches LOS-based tethering, with each AMR stopping right after a bend. This is because larger B represents larger losses in the straight segments between bends, and therefore the significant bend losses quickly bring the RSS below the threshold value. On the other hand, for small *B*, the losses in the straight segment are small compared to the acceptable losses, and therefore the bend losses, though significant, are not detrimental to the link. It is evident from these simulations that in order to reap the full benefits of RSS-based tethering, high-gain antennas are desirable.

As demonstrated by these calculations, typical tethering ranges can be predicted for typical operating conditions. The calculations in Fig. 10 were carried out for typical operating parameters for a 2.4GHz 802.11b/g network in a coal mine.

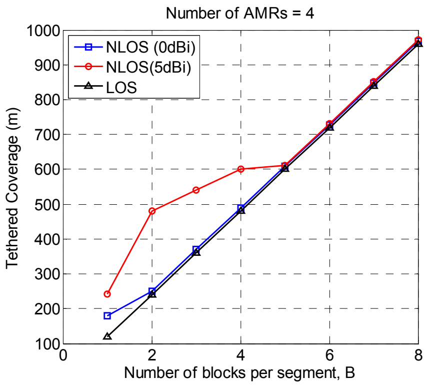


Fig. 10: Tethering range as function of number of blocks between bends along a 1D curvilinear path.

6. CONCLUSIONS

In this paper, we have used a realistic tunnel propagation model to demonstrate through simulation, an RSS-based wireless tethering algorithm for a 1D chain of AMRs exploring a subterranean environment. The algorithm allows all AMRs to move simultaneously along the exploration path while being equally spaced in RSS-space, though they may be nonlinearly spaced physically. This equal spacing in RSS-space balances the bandwidth between nearest neighbors such that no link the chain can be a bottle-neck. The movements are also constrained such that the RSS may not fall below a preset threshold necessary to maintain wireless communications. This allows the AMRs to explore a subterranean area without risking loss of communication due to LOS limitations. We have also shown that compared to AMRs with LOS-based wireless tethering, the total exploration range for NLOS-based wirelessly tethered AMRs in coal mines may be almost be twice as high, when moderately high gain antennas are used.

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