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Radio Propagation at 900 MHz in Underground Coal Mines

Y. P. Zhang, G. X. Zheng, and J. H. Sheng

***Abstract*—This paper reports on experimental results of radio propagation in two underground coal mines. Measurements were performed at 900 MHz on horizontal and vertical polarization in typical coal mine operational zones. Values of propagation loss in dB/100 m are derived. Additional losses due to coal mine curvatures and common coal mining equipment obstructions are also presented. A hybrid tunnel propagation model consisting of the freespace propagation model and the modified waveguide propagation model is used to explain some measurement results. Based on these results, we believe that microcellular radio communications systems are feasible in coal mines.**

***Index Terms*—Microcellular radio communications, propagation of radio waves, underground coal mines.**

I. INTRODUCTION

RADIO propagation pertaining to mobile and personal communications has been an active area of research in recent years. Propagation measurements at various frequency bands have been performed to determine propagation characteristics in urban areas, office buildings, and factories [1]–[6]. Zhang and Hwang recently reported propagation measurements in tunnels [7]. Coal mines are another very important place where mobile and personal communications might be regarded as most important to improve productivity and safety [8].

Coal mines are underground labyrinths. Their complex layouts are determined by mining methods. In room and pillar mining, a number of parallel entries are driven through coal. A crosscut at right angles to the main entries installed every 30 m is required. The result is a maze of entries and blocks of coal. Coal is mined with continuous mining machines and shuttle cars. In longwall mining, a pair of parallel entries is driven through coal, separated about 100–300 m, and connected at the ends. Then, with a shearer, the coal across the longwall is cut and falls onto a conveyor; roof support in the working place is provided by hydraulic supports that are advanced as the coal is extracted.

Propagation measurements in room and pillar coal mines were performed at frequencies of 200, 415, and 1000 MHz [9]. A theory for radio propagation in room and pillar coal mines was also established [10]. Based on these studies, simple radio communication systems were developed and used in some room and pillar coal mines. However, no measurements of radio propagation in longwall coal mines have been reported. This is not strange because the suitable intrinsically safety measurement system and the permission to conduct experiments in longwall coal mines can not be easily obtained. Recently, the opportunity was given to measure radio propagation at 900 MHz within two longwall coal mines. In the following, the two longwall coal mines under test are detailed, the measurement system is briefly described, and the measurement results are analyzed and discussed.

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II. MEASUREMENTS

The measurements were made within two fully equipped and operational longwall coal mines. One is Guan Di mine located at Taiyuan Colliery, and the other is Wang Tai Po mine situated at JinCheng Colliery. Both are in Shanxi Province, northern China, about 400 km apart.

Fig. 1 shows the layout of Wang Tai Po longwall coal mine. Guan Di and other longwall coal mines in China have a similar design. It is seen that multiple passageways are developed to the mining area of a block of coal. These passageways are used for ventilation and transportation. The block of coal surrounded by a headgate entry, a longwall face, and a tailgate entry is to be mined. To characterize radio channels, classifying the physical characteristics of radio propagation environments into categories has been widely adopted. This approach is also used here. As illustrated in Fig. 1, we can classify the radio propagation environments of the longwall coal mine into two categories, that is, the passageways and the mining area. They will be detailed as follows.

A. Passageways

The passageways are often arched tunnels reinforced with concrete. Their cross-sectional areas vary from 12 to 15 square meters with a longitudinal length of up to tens of kilometers.

Trolley Passageway: The trolley passageways in Wang Tai Po and Guan Di mines are $4.0 \sim 4.2$ m wide and $3.0 \sim 3.5$ m high. There are metallic tracks on the tunnel floor. Tens of cascaded and dc powered trolleys run on the tracks to transport coal, miners, and material. Each trolley is 1.5 m high, 1.0 m wide, and 3.0 m long. The electricity lines for mining machines are on the left-hand wall. Explosion-proof lights are installed just beneath the tunnel roof at periodic intervals. The moving trolleys are believed to have great effects on radio propagation, but influences caused by the small fixed objects are usually negligible.

Belt Passageway: The belt passageway in Wang Tai Po mine is approximately $4.0 \sim 4.2$ m wide and $3.0 \sim 3.2$ m high. It is

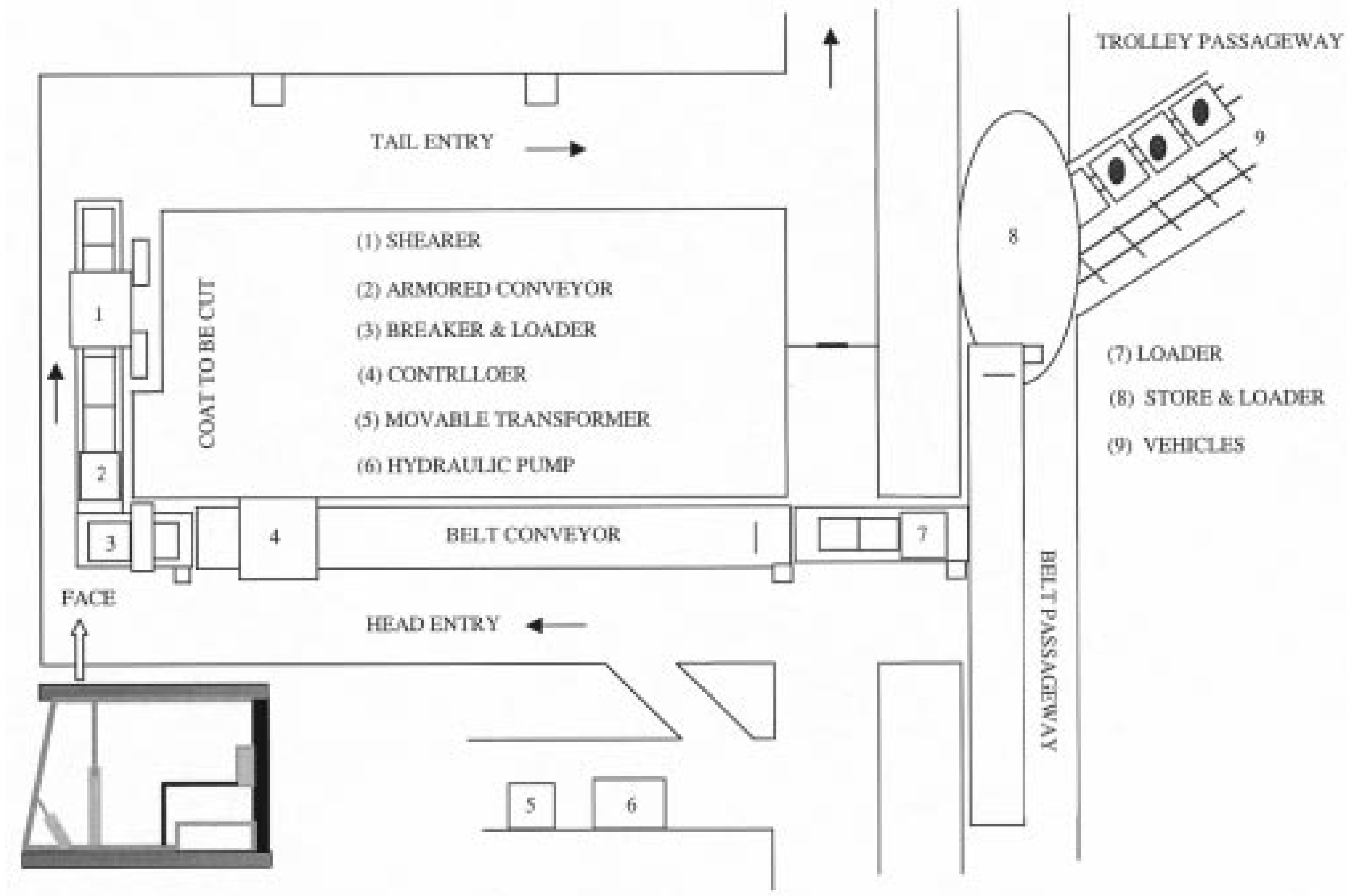

Fig. 1. Layout of Wang Tai Po coal mine.

inclined 30 degrees with respect to the surface. A 2.0–m-wide conventional belt is permanently installed to transport coal and material. The belt at the height of 1.0 m above the floor is driven by three conveyors and is supported by steel beams.

B. Mining Area

The mining area, which consists of the headgate entry, the longwall face, and the tailgate entry, keeps moving as coal is being cut. As a result, the length of both entries is gradually reduced.

Gate Entries: Both headgate and tailgate entries are parallel driven through virgin coal seam. The resultant trapezoidal confined spaces are very irregular and rough. As illustrated in Fig. 1, fresh air enters the headgate entry and flows across the longwall face to remove methane along the tailgate entry to the main air return passageway. Miners and material travel in the headgate entry. Equipment such as a coal breaker, stage loader, and power substation are positioned near the face in the headgate entry. An extendable belt is installed along the headgate entry to transport coal to the main haulage facilities. Movable transformers and hydraulic pumps are located at a crosscut in the vicinity of the headgate portal. In the tailgate entry, there exist a few witches and switches. The Wang Tai Po entries reinforced with metallic supports have a height of 2.2 m, a roof width of 3.7 m, and a floor width of 4.5 m. The Guan Di entries reinforced with log supports have a height of 3 m, a roof width of 2.8 m, and a floor width of 3.2 m. The entries in both coal mines have almost the same cross-sectional area of 9.0 square meters.

Longwall Face: The longwall face is illustrated in the left bottom corner of Fig. 1. It is seen that heavy but movable metallic equipment is installed. Coal is cut by a shearer running along the longwall face and falls onto an armored conveyor. The roof is supported in the working area by hydraulic props that follow the advancement of the longwall face and provide a continuous metallic roof for the protection of the miners. For face no. 3 in Wang Tai Po, it was supported by 110 hydraulic props with a length of 165 m and a height of 1.5 m, while for face no. 9 it was supported by 100 hydraulic props with a length of 150 m and a height of 2.0 m. The face in Guan Di was 180 m long and 3 m high supported by 120 hydraulic props. All hydraulic props were ZZ-3600 series. They made three longwall faces with the same width. The top width was 4.4 m and the bottom width was 4.7 m. An AM 500 shearer and SGB-764 armored conveyor were used in the faces.

For the measurements, an FM portable radio system operating at 900 MHz was used as the transmitter. The power to the transmitting antenna was fixed at 16 dBm. The radiated continuous wave was picked up by the receiving antenna connected to an R/S ESV receiver. The sensitivity of the receiver was -120 dBm. Both transmit and receive antennas were 3-dB quarter-wavelength whips. In the passageway measurements, the transmit antenna was positioned 1.0 m away from the left wall and 1.5 m above the floor, while for the mining area measurements the transmit antenna was located on the framework of the loader in the headgate and on the top of the armored con-

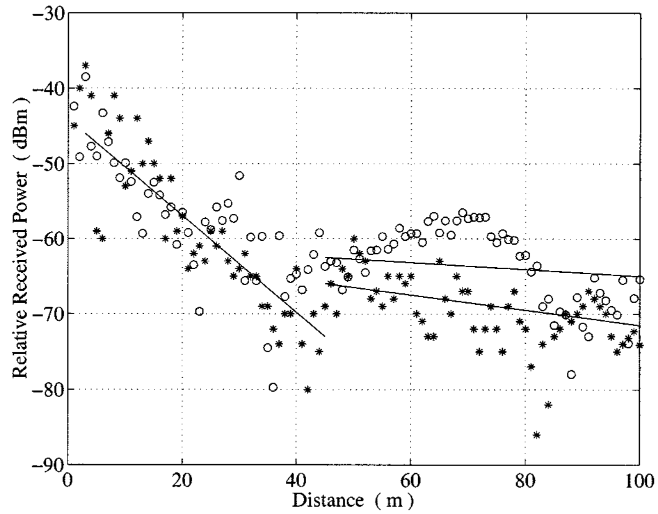

Fig. 2. Plots of relative received power as a function of distance for the trolley passageway in Guan Di coal mine; (o) for horizontal polarization, (∗) for vertical polarization.

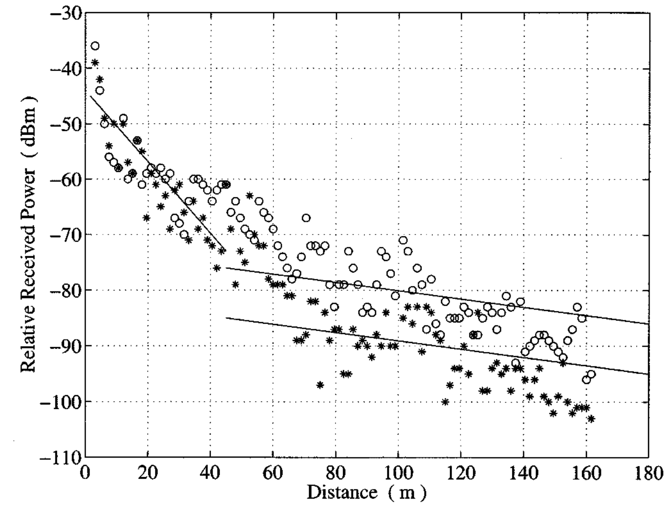

Fig. 3. Plots of relative received power as a function of distance for the trolley passageway in Wang Tai Po coal mine; (o) without trolleys, (∗) with trolleys.

veyor leader in the longwall face, respectively. The measurement procedures follow the steps described in [7]. As the measurement system was not intrinsically safe, a gas inspector kept monitoring the methane level in the measurement sites to ensure the safety when the measurements were being made.

III. Results and Discussion

Linear regression analysis is employed to study the variation of received power over the distance from the transmitter to the receiver. It is observed that the propagation characteristics are quite different in the passageways as compared with those in the mining area. Two distinct propagation regions separated by a breakpoint exist in the passageways but not in the mining area. Thus, in order to have a more accurate fit, a two-slope regression fit is called for to the data collected in the passageways, and a single straight line estimation is sufficient for the data obtained in the mining area.

A. Passageway Results

The passageways are tunnels. They can be regarded as oversized imperfect waveguides. The propagation will exhibit the guided wave characteristics. The propagation loss in the passageways thus can be even smaller than that in free space.

Fig. 2 shows the plots of the relative received power together with the two-slope regression fits against the transmitter and the receiver separation for the trolley passageway in the Guan Di coal mine. Measured when there was no trolley between the transmitter and the receiver, the circles are for horizontal polarization and the asterisks for vertical polarization. Note that two propagation regions separated by the breakpoint (BP) located at the distance of 45 m from the transmitter exist. In the region before the breakpoint (BBP), the received signal levels drop quickly: they decrease from about −46 dBm at 3 m to −73 dBm at 45 m for both horizontal and vertical polarization, and the propagation loss over the distance of 42 m is 27 dB. While in the region after the breakpoint (ABP), the received signal level starts to decrease slowly, the propagation losses are 4.3 dB/100 m and 7.1 dB/100 m for horizontal and vertical polarization, respectively. The difference of signal loss with distance is an interesting propagation phenomenon. It is found that this phenomenon can be explained and predicted by a hybrid tunnel propagation model. The hybrid tunnel propagation model consists of the free-space propagation model, the modified waveguide propagation model, and the method to locate the BP. In the region BBP, the guided propagation by the tunnel waveguide structure has not been well established, the propagation path has the first Fresnel zone clearance, the propagation behaves as in free space, the free-space propagation model is applicable, and the propagation loss exponent is 2 [1]. In the region ABP, the guided propagation by the tunnel waveguide structure has been stabilized, the propagation occurs as in an oversized imperfect waveguide, the modified waveguide propagation model becomes applicable, and the propagation loss exponent is one [10]. The location of the breakpoint is the distance at which the first Fresnel zone becomes obstructed. It can be estimated by the ratio of the square of the maximum dimension of the tunnel cross section to the wavelength [11]. The larger loss exponent causes the signal level to drop quickly in the region before the breakpoint, while the smaller loss exponent results in the signal level to decrease slowly in the region after the breakpoint. The predicted propagation losses are 24 dB over the distance of 42 m in the region before the breakpoint, 3.52 dB/100 m for horizontal polarization, and 6.31 dB/100 m for vertical polarization in the region after the breakpoint. In the calculation, the relative permittivity of the passageway walls equal to 10 is used [10]. The measured and calculated propagation losses agree quite well.

The effects of trolleys on the propagation were measured in the trolley passageway of the Wang Tai Po coal mine. The circles in Fig. 3 show the result for vertical polarization measured when there was no trolley between the transmitter and the receiver, while the asterisks in Fig. 3 display the result for vertical polarization measured when there were 20 cascaded trolleys stationed at 60 to 102 m. The comparison of the best fit line of the circles with that of the asterisks indicates that the received signal

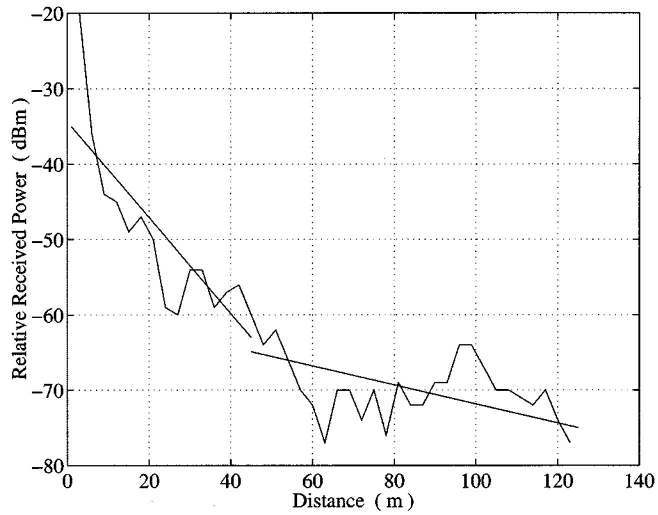

Fig. 4. Plot of relative received power as a function of distance for the belt passageway in the Wang Tai Po coal mine.

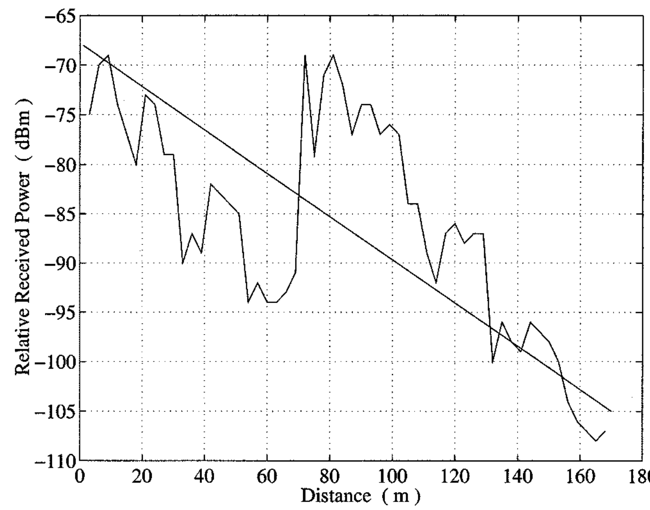

Fig. 5. Plot of relative received power as a function of distance for the headgate entry in the Wang Tai Po coal mine.

TABLE I
PROPAGATION LOSSES AFTER THE BREAK POINT IN dB/100 m IN THE PASSAGEWAYS

Passageways	Measurements	Predictions	Remarks
Guan Di	4.3	3.52	H-H Polarization
Guan Di	7.1	6.31	V-V Polarization
Wang Tai Po	7.5	6.31	Without Trolley
Wang Tai Po	7.5 (10)	6.31 (10)	With Trolley
Wang Tai Po	7.5+5.8	6.31+5.8	Belt

level is approximately 10 dB lower over and after the range occupied by trolleys. This can be explained as follows. The existence of these trolleys blocks some of the propagation paths and causes an additional propagation loss. Therefore, the received signal level becomes lower. No obvious change of the received signal level in front of the cascaded trolleys is observed.

The propagation in the belt passageway was only measured in the Wang Tai Po coal mine. The relative received power of vertical polarization together with the two-slope regression fits against the distance between the transmitter and the receiver is shown in Fig. 4. Like the propagation in the trolley passageway, the propagation in the belt passageway also exhibits two distinct regions. The propagation loss before the breakpoint is 28 dB over the distance of 42 m, which is very close to that in the empty trolley passageway. The propagation loss after the breakpoint is found to increase by 5.8 dB/100 m as compared with that in the empty trolley passageway. Since both trolley and belt passageways have almost the same tunnel structure, the propagation loss due to the tunnel itself should be very close. Thus, it is believed that the increased 5.8 dB/100 m loss is caused by the belt conveyor itself.

The measured and calculated propagation losses after the breakpoint for the passageways are summarized in Table I. It is interesting to note that the hybrid tunnel propagation model plus the measured losses due to the trolleys and the belt conveyor could be used to predict the radio coverage in the actual passageways of longwall coal mines.

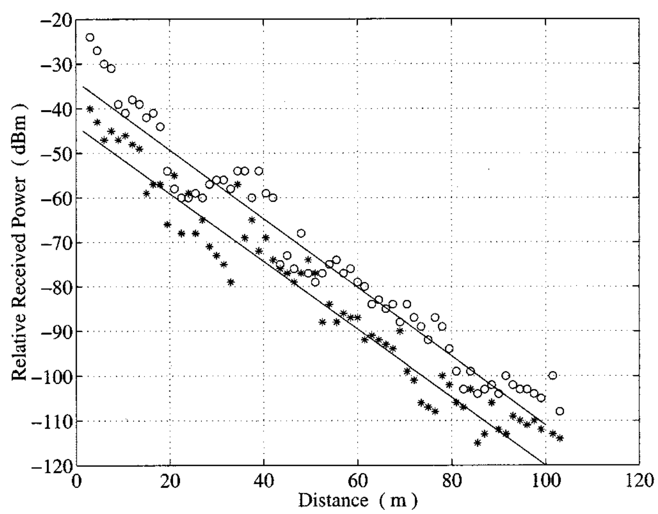

Fig. 6. Plots of relative received power as a function of distance for no. 3 longwall face in the Wang Tai Po coal mine; ($*$) for horizontal polarization, (o) for vertical polarization.

B. Mining Area Results

Most of the mining area is occupied by mining equipment. The propagation paths are often obstructed. In addition, the mining area is rather irregular. The incoherent scattering plays an important role in the propagation. The propagation is expected to undergo high attenuation.

Fig. 5 shows the plot of the relative received power together with the single straight-line regression fit against the transmitter and the receiver separation for vertical polarization in the headgate entry of Wang Tai Po. It is seen that the received power starts at a much lower level because there were many metallic objects in the vicinity of the transmit antenna and the line of sight propagation path was obstructed easily and frequently. The measured propagation loss is 22 dB/100 m with the standard deviation of 1.75 dB.

The asterisks and circles in Fig. 6 show the relative received power measured along the shearer operatorway in longwall face no. 3 of Wang Tai Po for horizontal and vertical polarization, respectively. Note that the received power level for vertical polar-

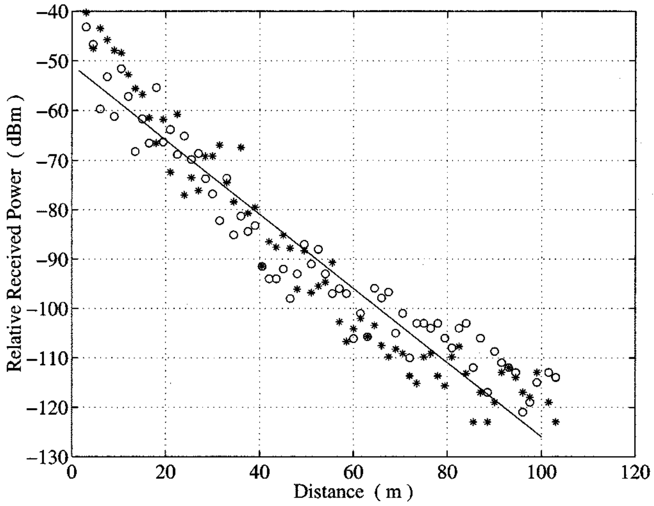

Fig. 7. Plots of relative received power as a function of distance for no. 9 longwall face in the Wang Tai Po coal mine; (∗) along the prop minerway, (o) along the shearer operatorway.

TABLE II
ADDITIONAL LOSSES DUE TO CURVATURES AND LONGWALL COAL MINING EQUIPMENT

Description	Additional Loss (dB)
Trolleys	10-13
Parallel Trolleys	20-25
Shearer	5-10
Just Behind Prop	5-8
Equipment near face	5-10
78°	20
90°	25
150°	10
175°	5

ization is stronger compared to that for horizontal polarization, however, they have the same 75 dB/100 m propagation loss. The standard deviations are within 2.0 dB. The asterisks and circles in Fig. 7 illustrate the relative received power for longwall face no. 9 of Wang Tai Po. Both are vertical polarization and were measured along the shearer operatorway and the prop minerway, respectively. It is evident that there are no significant differences in the received power levels for both cases. Again, the propagation losses are 75 dB/100 m, and the standard deviations do not exceed 2.2 dB. The patterns of the relative received power levels in the longwall face of Guan Di are not shown here as they are very similar to those in longwall face no. 9 of Wang Tai Po.

C. Additional Losses

The additional losses due to the obstruction of radio paths by coal mine bents and common coal mining equipment are also measured. The measurements of different polarized signals indicate that the additional losses are independent of polarization. Table II provides typical additional losses caused by bents and common longwall coal mining equipment. As shown, the additional loss is related to the sharpness of bents and the cross-sectional area ratio of longwall coal mining equipment to their operational spaces. The additional loss is 5 dB due to a 175° bent and increases to 25 dB for a 90° bent. The maximum additional loss due to obstruction by common longwall coal mining equipment is 25 dB, which occurs when two trains of trolleys are in parallel.

IV. CONCLUSION

In this paper, the results of radio propagation losses at 900 MHz in two underground longwall coal mines were summarized. We identified two operational zones, that is, the passageways and the mining area, common to all longwall coal mines, and measured the propagation losses within these zones. The propagation loss was found to be highly correlated to the distance between the transmitter and the receiver in the passageways. Two propagation regions separated by a breakpoint were observed. The breakpoints in the passageways were found to be 45 m from the transmitter. In the passageways, the measured propagation losses before the breakpoint are all around 27 dB over the distance of 42 m. The propagation losses in the passageways after the breakpoint are much lower. They are about 13.3 dB/100 m in the belt passageway and 6.75 dB/100 m plus 10 dB additional loss in the trolley passageway. In the headgate entry of the mining area, the propagation loss is 22 dB/100 m with the standard deviation of 1.75 dB. In the longwall faces of the mining area, the measured propagation losses are 75 dB/100 m, and the standard deviations do not exceed 2.2 dB. The additional loss due to obstructions by bents and common longwall coal mining equipment was also measured. It was shown that the additional loss is independent of polarization, related to the sharpness of bents and the cross-sectional area ratio of coal mining equipment to their operational spaces. The additional loss due to bents or common longwall coal mining equipment can be up to 25 dB. Based on these results and from the propagation perspective, we believe that microcellular radio communications systems like CT2 Plus are feasible in coal mines.

A hybrid tunnel propagation model consisting of the free-space propagation model and the modified waveguide propagation model was used to explain the propagation characteristics in the passageways. Together with the measured additional loss, the hybrid tunnel propagation model could be used to predict the radio coverage in the actual passageways of longwall coal mines. No theoretical model is available for the mining areas of longwall coal mines. Fortunately, the measurements showed that the propagation losses do not vary largely in the mining areas of the longwall coal mines, say, the propagation losses in three longwall faces are all around 75 dB/100 m.

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