

WHOLE-MINE DEMONSTRATION OF TROLLEY PHONE COMMUNICATION IMPROVEMENTS
THROUGH USE OF THE DEDICATED-WIRE TECHNIQUE

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ABSTRACT

A whole-mine demonstration experiment was performed to assess the practical feasibility and utility of the dedicated-wire technique for overcoming poor trolley carrier phone system performance at a large underground coal mine. The technique involves the use of a single, low-loss, properly terminated and branched auxiliary wire placed in the rail haulageway. This auxiliary dedicated-wire allows signals to electromagnetically couple to the trolley wire/rail transmission line, and thereby significantly decrease the overall signal attenuation rate of the trolley wire/rail line. The in-mine dedicated-wire demonstration program and its findings and conclusions are described. The dedicated-wire technique is shown to be a valid and practical one for significantly improving carrier phone system performance in coal mines.

PROBLEMS WITH CARRIER PHONE SYSTEMS

The trolley carrier phone system is one of the basic and important mine communication systems widely used in U.S. coal mines. The trolley carrier phone system is used in electric rail haulage mines for dispatching coal haulage traffic throughout a mine's rail network. Therefore, it is a vital communication system that directly affects a mine's ability to transport the coal to the surface safely and efficiently.

Carrier phone systems have been of great utility in operating mines throughout the years. However, problems related to poor signal propagation are quite common. These problems occur because the trolley wire powered electric rail haulage system over which the carrier phone signals travel was designed to carry DC traction power to mine vehicles. The network of trolley wires and rails is, therefore, a notoriously poor transmission medium for 100-kHz radio frequency (RF) signals. This poor radio frequency behavior has three specific causes:

Bridging loads - The trolley wire/rail system has to contend with numerous bridging loads which create undesirable RF transmission characteristics. From an RF transmission viewpoint, the main bridging load offenders include the many rectifiers that supply traction power, as well as the many motors, pumps, heaters, and lights placed across the trolley wire/rail.

Table 1 lists the expected values of bridging impedance for a number of bridging loads commonly found in coal mines. The table includes the value of insertion loss. Insertion loss is the loss in signal level that would occur on an otherwise unencumbered transmission line of 200 ohms characteristic impedance when a single load is bridged across the trolley wire/rail. The table shows that a rectifier with a minimum setback from the trolley wire/rail exhibits an impedance of about 2 ohms and produces a 34.1-dB insertion loss at 100-kHz. The reduction in voltage is 51 to 1, hence, very few of these loads will quickly attenuate the carrier phone's transmitted signal to unusable levels. Furthermore, even a carrier phone with a 20-ohm standby impedance in its receiving mode produces a 15.6-dB insertion loss and a voltage reduction of 6 to 1. Similar offenders are the personnel heaters frequently used in coal mines. Thus, it doesn't take many of these to completely use up the transmitted carrier signal.

Branches - The trolley wire/rail has numerous branches to serve the main haulage requirements of extensive coal mines. Since the branch junctions do not control how the RF energy is split to the branches, the distribution of the RF energy from a transmitter is unknown.

Terminations - The trolley wire/rail is not terminated at its ends to produce a matched load condition for the RF carrier phone signals. Therefore, standing waves are created by the open-circuit mismatches, and contribute to the standing wave problems also introduced by the bridging loads and branches.

In the face of these transmission problems, it is rather amazing that the trolley carrier phones are as effective as they are in U.S. coal mines. This effectiveness is a tribute to the ingenuity and dedication of mine maintenance personnel who find ways to make the system work. However, most mines continue to have either intermittent or chronic problems with their carrier phone systems.

SOME COMMONLY USED SOLUTIONS

There have been many attempts at curing the problems mentioned above. One has been the tuning of rectifiers. Sometimes this is done by placing a capacitor at the junction of the rectifier leads and the trolley wire/rail line. If the rectifier is set back far enough, about

TABLE 1
CHARACTERISTICS OF BRIDGING LOADS

<u>Bridging Load</u>		<u>Estimated Impedance at 100 kHz (ohms)</u>	<u>Insertion Loss* (dB)</u>	<u>Loss in Voltage</u>
Rectifier with minimum setback		2	34.1	51 to 1
Rectifier with 50-foot setback†		9†	21.6	12 to 1
Rectifier with 100-foot setback†		19†	15.9	6 to 1
Carrier phone with 20-Ω receiver		20Ω	15.6	6 to 1
Carrier phone with 100-Ω receiver		100Ω	6.0	2 to 1
Jeep or portal bus motor		500Ω	1.6	1.2 to 1
44-ton locomotive motor		60Ω	8.5	2.7 to 1
Vehicle with two 150-W, 32-V headlights isolated resistively**	300-V	60	8.5	2.6 to 1
	600-V	120	5.3	1.8 to 1
Illumination lights (assumed to be 200-W load)	300-V	450	1.7	1.22 to 1
	600-V	1800	0.5	1.06 to 1
Single insulator		200,000	0.0043	1.0005 to 1
1 mile of insulators with 12-foot spacings (440 insulators)		-	1.90	1.2 to 1
1000-W personnel heater	300-V	90Ω	6.5	2.1 to 1
	600-V	360Ω	2.1	1.3 to 1
5000-W personnel heater	300-V	18Ω	16.3	6.6 to 1
	600-V	72Ω	7.6	2.4 to 1

Notes:

*This insertion loss is that calculated for an otherwise unencumbered trolley wire/rail having a 200-Ω characteristic impedance, using the formula

$$L = 20 \log_{10} \frac{2R + Z_0}{2R}$$

where R is bridging load resistance.

For a trolley wire/rail having a large number of loads, load interaction will cause the total net transmission loss, in most practical cases, to be less than the sum of these tabulated losses due to load interaction.

**At the trolley wire carrier frequency the bridging impedance of a locomotive or vehicle appears to be dominated by the headlights. Motors have impedances at carrier frequencies that are somewhat larger than these values and therefore the load imposed by the lights only is considered. Newer vehicles with DC-to-DC converters that supply the light circuits have appreciably less effect.

†The bridging impedance of a setback rectifier is higher in value than one with minimum setback due to the feed wire inductance. These figures assume a feed wire inductance of 0.3 μH/ft and a frequency of 100 kHz. The values of Z will be somewhat less, but not significantly for 88-kHz operation.

50 feet to 100 feet from the trolley wire/rail, the inductance of the power leads can be tuned to raise the effective rectifier impedance at the carrier frequency. Similar tuning has been used on fixed motors, and in some instances on jeeps and locomotives.

The most effective prior practice was the use of the pager telephone wire pair driven in common mode as an auxiliary carrier signal wire. This practice requires the use of signal couplers interconnecting the trolley wire/rail and the pager telephone line at several locations. Some large mines may use as many as 50 to 100 of such couplers.

The problem with this practice is twofold. First, each coupler takes an unspecified amount of carrier signal power off the telephone line and transfers it to the trolley wire/rail line. This uncontrolled and unmatched transfer takes place at a somewhat arbitrary number of locations in the hope of carrying carrier phone signals throughout the mine rail network. Second, the telephone lines operating in common mode suffer from many of the same problems as the trolley wire/rail line, namely, uncontrolled branching and lack of terminations. Therefore, the carrier phone signal distribution still remains largely uncontrolled and arbitrary. Furthermore, as a mine expands, this uncontrolled signal distribution results in nulls, or deadspots, in the trolley wire signal appearing throughout the mine. This, in turn, leads to changing the position of these couplers or adding couplers according to some inadequate empirical or "time honored" rules of thumb that produce only temporary relief because of the absence of real control on the RF signal transmission characteristics.

THE DEDICATED-WIRE TECHNIQUE

The dedicated-wire technique is based on having a controllable RF signal path throughout the entire mine, unencumbered by bridging loads and uncontrolled signal splits at branch points. This approach uses an auxiliary transmission line, consisting of a single wire supported on the wide side of the haulageway and the rail return, which is terminated in a matched load at each of its ends. When carrier phone coverage is wanted to places on branch lines, matched signal splits are used to distribute the RF power in a totally controlled manner to all the desired branches.

Under Bureau of Mines Contract H0346045, we investigated several means for improving carrier phone communications in mines. Part of this work involved measurements for characterizing the trolley wire/rail as an RF transmission line. The Renton mine outside of Pittsburgh was visited to perform measurements on a disconnected section of the trolley wire/rail and obtain information pertinent to predicting the transmission

of carrier signals on the trolley wire/rail line. These measurements revealed the need to develop a better theoretical understanding of carrier signal propagation along trolley wire/rail lines, particularly with regard to the influence of the conductive rock/coal medium surrounding the trolley wire/rail. James Wait and David Hill, of NOAA and ITS respectively, under an independent Bureau contract, developed a theoretical model to predict the influence of the surrounding conductive medium on the signal attenuation rate along the trolley wire/rail transmission line. It was shown that the added loss imposed by the conducting medium is extremely small compared to the losses produced by the many bridging loads and branches on the trolley wire/rail line, but is a major component of the low signal loss along the unencumbered dedicated-wire/rail line.

Another part of our work involved the development of a theoretical model to describe how a dedicated-wire could improve the transmission of carrier phone signals in coal mines. The dedicated-wire technique is based on providing a parallel low-loss transmission line comprised of the rails and a single conductor strung in the haulageway. The natural electromagnetic coupling between the dedicated-wire/rail line and the trolley wire/rail line provides the necessary amount of signal coupling to maintain a useful signal level on the trolley wire/rail throughout the mine's rail haulage network. The theory shows that the signal levels on an extremely lossy trolley wire/rail can be markedly improved by the use of such a dedicated-wire. This is particularly true for dispatcher to vehicle and vehicle to dispatcher communications, because the dispatcher's carrier phone can be connected directly to the low-loss dedicated-wire. The theory predicts that trolley wire/rail lines with attenuation rates as high as 20-dB per kilometer can be converted to lines which exhibit only 1-dB or 2-dB per kilometer by installing a single parallel dedicated-wire in the haulageway.

The theoretical model represents the trolley wire/rail as a continuous, lossy transmission line. An actual trolley wire/rail is a poor transmission line because of the many discrete bridging loads noted above. The theory treats the trolley wire/rail as a line characterized by continuously distributed, uniform shunt and series loss, while the dedicated-wire/rail is treated as a low-loss line having only continuously distributed, uniform series loss. For most examples examined by this theory, a representative loss of 1-dB per kilometer was used for the dedicated-wire/rail line in the absence of the trolley wire/rail line.

An example of the theoretical results are shown for the geometrical configuration and conditions illustrated in Figure 1, where we assume the following dimensions in meters:

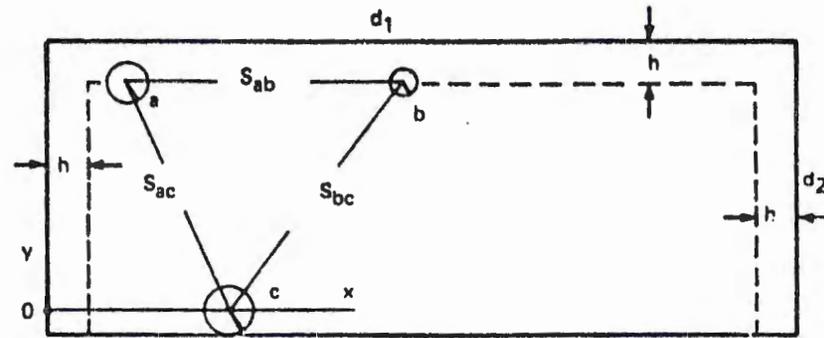


FIGURE 1 MODEL GEOMETRY – CROSS SECTION OF TUNNEL, OF DIMENSIONS $d_1 \times d_2$, SHOWING THE TROLLEY WIRE, DEDICATED WIRE, AND RAIL, OF RESPECTIVE RADII a, b, c , SEPARATED BY DISTANCES S_{ab}, S_{bc}, S_{ac} .

$d_1 = 5$	$a = .015$	$X_a = .5$
$d_2 = 2.5$	$b = .0015$	$Y_a = 2.2$
$h = .3$	$c = .1$	$X_c = 1.25$
		$Y_c = 0$

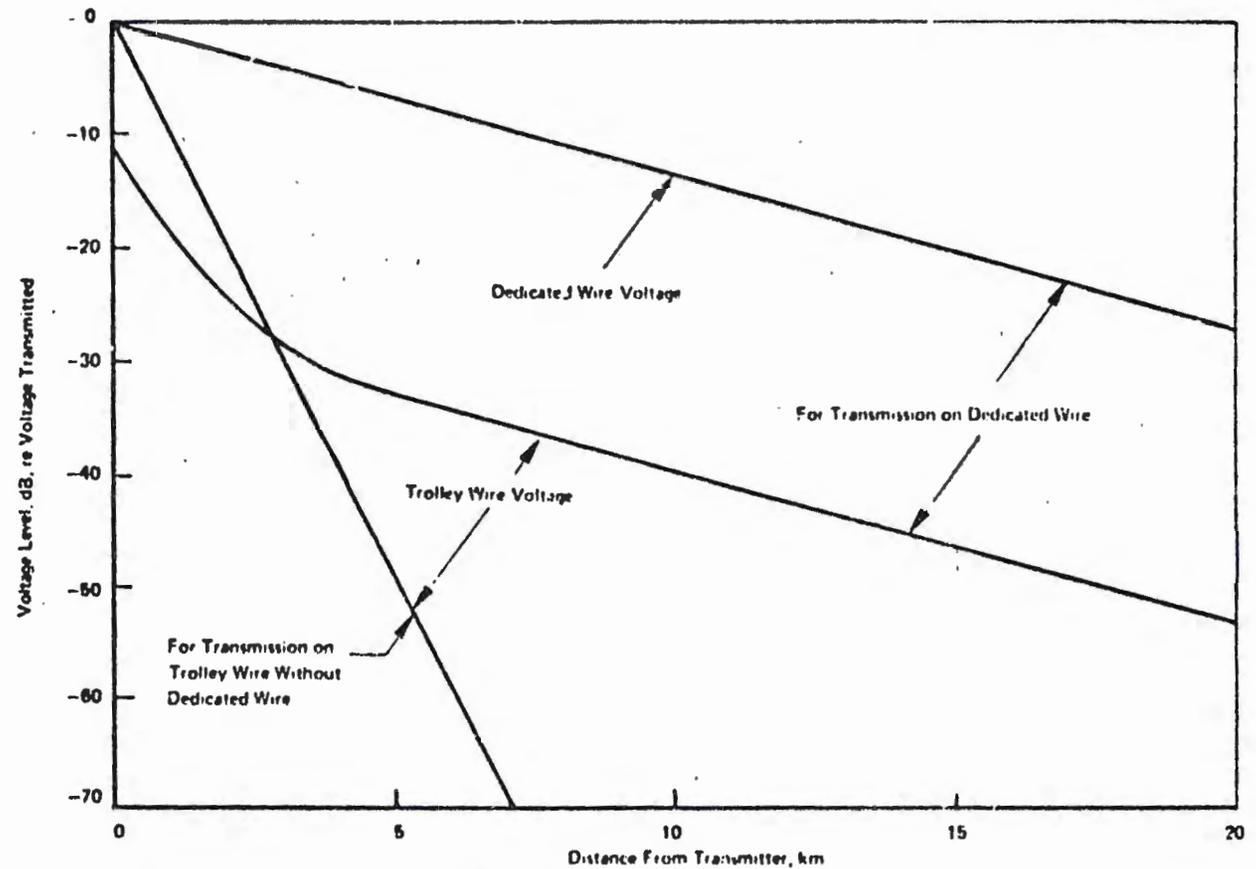
In the example, the dedicated wire is placed at $X = 2.2$ meters, $Y = 2.2$ meters, for calculations of signal strength versus longitudinal distance, Z , from the transmitter. In the example of Figure 2, the dedicated-wire voltage and trolley wire voltage are plotted for the transmitter connected to the dedicated-wire. All voltages are measured with respect to the rail which serves as a common conductor. For comparison, the unfavorable trolley wire voltage for the transmitter connected to the trolley wire in the absence of the dedicated-wire is also shown.

The theoretical results for the dedicated wire were so promising that the Bureau of Mines sponsored a small-scale demonstration at an operating coal mine, under Contract JO377098. This demonstration was made at Consolidation Coal's Montour No. 4 coal mine south of Pittsburgh. About 20,000 feet of No. 12 insulated wire was installed in the mine. The installation included one matched signal split to a loading area and two end-of-line terminations. The improvement in communications was significant. In fact, the branch signal split to the loading area provided direct communications between the dispatcher and locomotive operators at this distant load point for the first time at this time.

SELECTION OF MINE FOR LARGE SCALE DEMONSTRATION OF DEDICATED-WIRE

The results of the Montour No. 4 experiments were sufficiently promising that the Bureau of Mines decided to conduct a large scale mine experiment. Under Bureau of Mines Contract JO308036, we were asked to locate a candidate mine, install a dedicated-wire, and measure the performance improvement achieved. The following criteria were used to identify and screen potential candidate mines.

- Severe problems with the trolley carrier phones
- 300 or 600 volt DC trolley powered rail haulage
- Main line track haulage extending 5-10 miles with branching
- Carrier phones of solid-state vintage
- Production of about 0.5 to 1 million tons per year
- More than ten sections



Note: For Attenuation Rates of $\alpha_T = 10$ dB/km For The Trolley Wire Rail Line in the Absence of the Dedicated Wire Rail Line, and $\alpha_D = 1$ dB/km For The Dedicated Wire/Rail Line in The Absence of The Trolley Wire Rail Line.

FIGURE 2 DEDICATED WIRE MODEL – THEORETICAL VOLTAGE LEVELS VERSUS DISTANCE

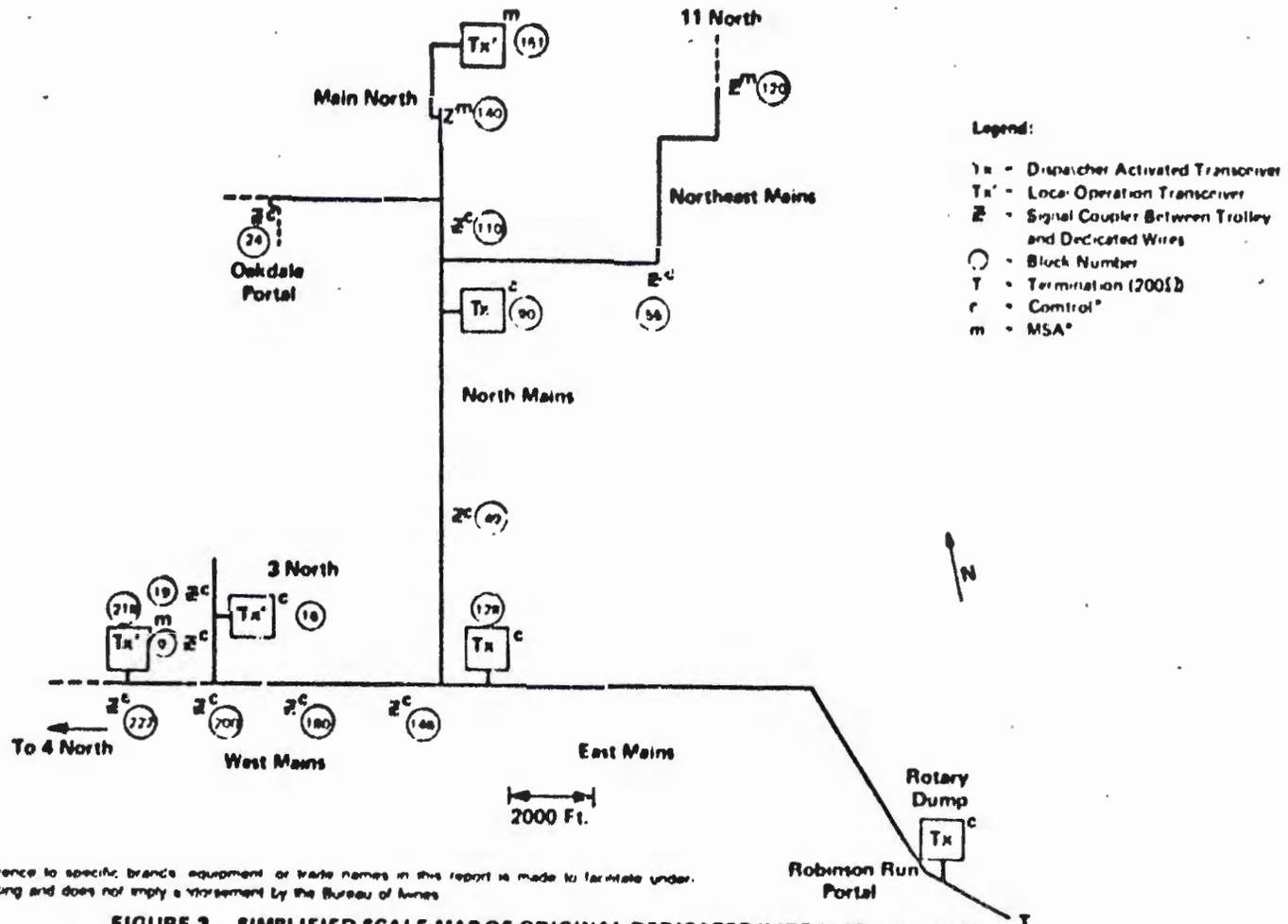
- High coal
- Economically viable in the long term
- Relatively low hazard regarding roof and gas emission
- Preferred location in the vicinity of Pittsburgh, Morgantown, Wheeling, Charleston, Birmingham, or St. Louis

Four candidate mines were visited and evaluated before the final selection of Consolidation Coal's Robinson Run No. 95 coal mine in Shinnston, West Virginia. This mine is a large, high-production, longwall-type, drift-entry coal mine with about 11 miles of 300 volt DC main line track haulage. The mine exhibited severe trolley carrier phone communication problems during the relatively wet springtime. This poor performance occurred annually, and caused considerable consternation and operational difficulties. The mine, therefore, welcomed our attempts to improve its trolley carrier phone communications.

The mine had already taken steps to improve its trolley carrier phone communications by installing an auxiliary signal wire throughout the main haulageways of the mine. However, this signal wire was not equipped with signal splitters at the branching junctions, nor with matched terminations at the ends of the lines. In addition, frequent use was made of signal couplers interconnected between the signal wire and the trolley wire. A simplified scale map representation of the trolley carrier phone network along the mine haulageways is shown in Figure 3. This figure shows the main remote carrier phone transceiver at East Mains 128 block used by the dispatcher, and the numerous signal couplers. This transceiver is located well inside the mine at a more central location in an attempt to adequately reach all vehicles in the mine.

OPTIMIZED DEDICATED-WIRE CONFIGURATION

Figure 4 illustrates the configuration of the optimized dedicated-wire installation at Robinson Run mine after conversion from the configuration shown in Figure 3. We converted the existing auxiliary signal wire into a fully controlled, dedicated-wire installation with the assistance of mine personnel during a single shift under non-operational strike conditions. This was accomplished by installing four signal splitters indicated by the star configuration of resistors, installing a total of six terminations indicated by the grounded resistors at the ends of dedicated-wire, and by removing all 12 signal couplers connected between the dedicated-wire and trolley wire.



*Reference to specific brand's equipment or trade names in this report is made to facilitate understanding and does not imply a recommendation by the Bureau of Mines.

FIGURE 3 SIMPLIFIED SCALE MAP OF ORIGINAL DEDICATED WIRE INSTALLATION ALONG ROBINSON RUN MINE RAIL HAULAGE NETWORK

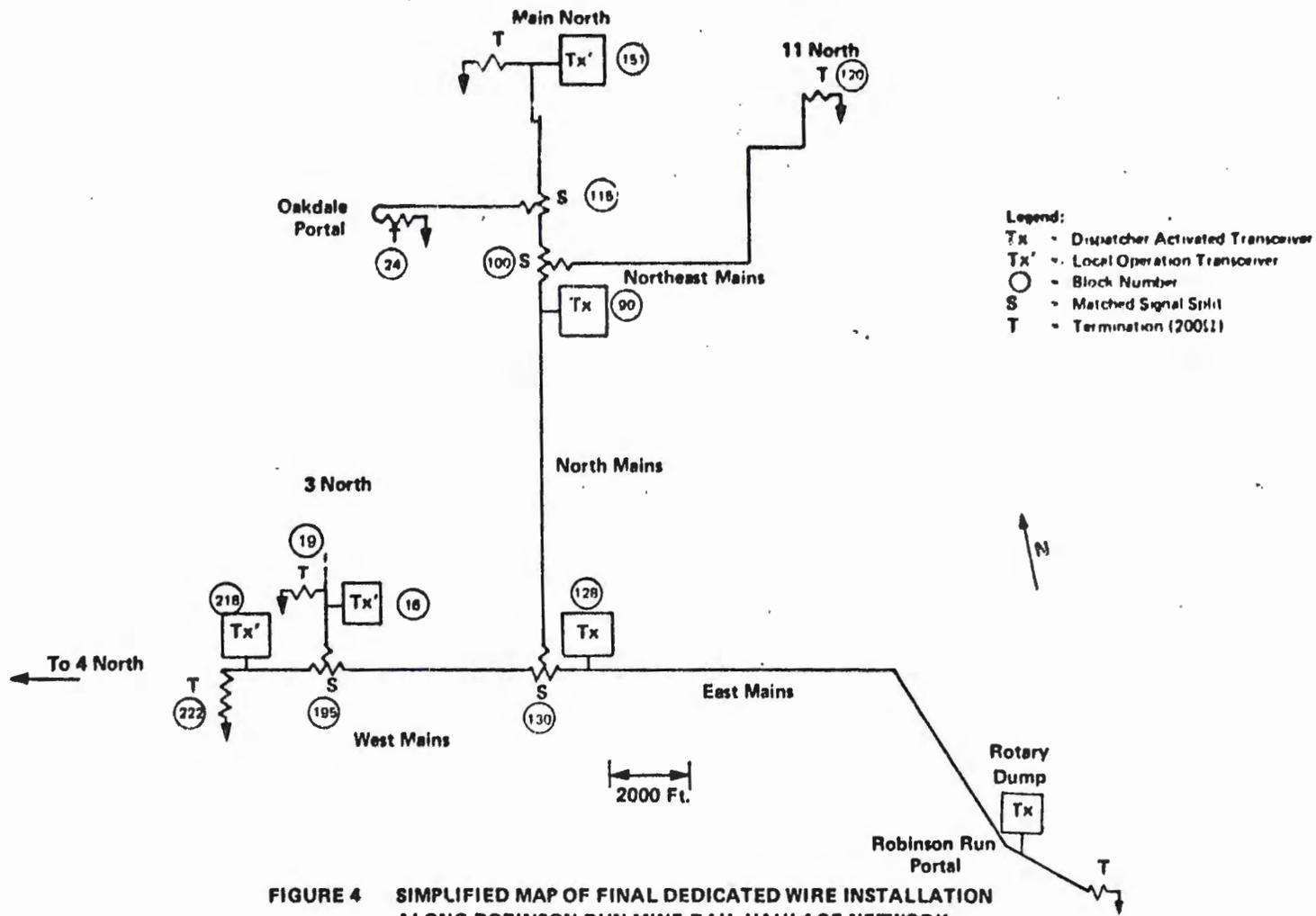


FIGURE 4 SIMPLIFIED MAP OF FINAL DEDICATED WIRE INSTALLATION ALONG ROBINSON RUN MINE RAIL HAULAGE NETWORK

In dealing with the transmission of RF signals along a dedicated-wire/rail transmission line, it is important to know its characteristic impedance. Our measurements and calculations of characteristic impedance in mines have shown that the dedicated-wire/rail characteristic impedance will range somewhere between 150 ohms and perhaps 300 ohms for most practical conditions. We have chosen 200 ohms as the representative characteristic impedance for the dedicated-wire/rail transmission line. Therefore, the component values for all signal splitters and line termination resistors are based on this selection; namely, the terminations are 200-ohm resistors, and the signal splitters consist of three 67-ohm resistors.

The signal splitters were fabricated by installing three power resistors connected to a common junction inside Hoffman boxes with three access ports. The ports allow each of three signal wires at a branch point to be attached to a corresponding resistor via a terminal strip. Signal terminations were fabricated in equally simple fashion by placing a single resistor in a Hoffman box, with one terminal connected to a rail bond and the other resistor terminal connected to the end of the signal wire. To facilitate checking the condition of the dedicated-wire, the resistors were isolated from ground by a series capacitor. Figure 5 shows the configuration of these boxes.

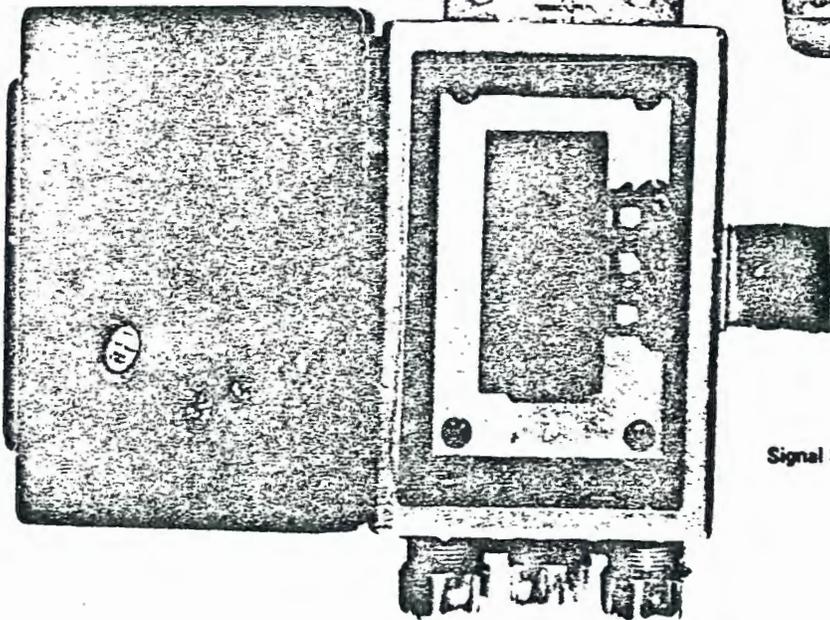
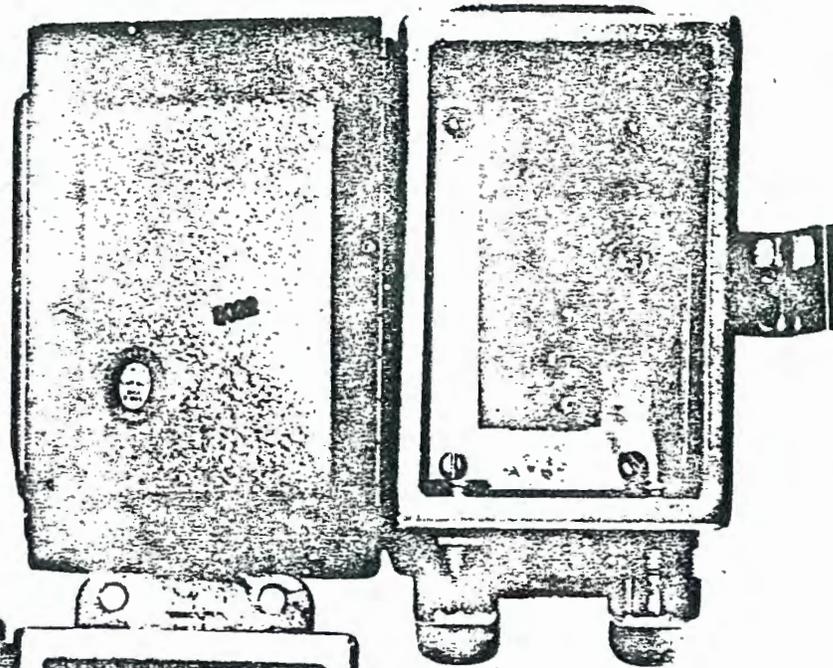
COMPARISON OF "BEFORE" AND "AFTER" PERFORMANCE

Comprehensive carrier phone signal measurements were made throughout the mine rail haulage network before and after the conversion to a true dedicated-wire configuration. The values of trolley wire voltage produced by the dispatcher's transmitter at a large number of points were measured and plotted versus distance from the transmitter, to produce a "signal map." The current in the signal wire was also measured at each trolley wire voltage measurement location, to relate trolley wire voltage behavior with signal wire current behavior.

The following observations were made of the general behavior shown by the "before" measurements.

- There was a common occurrence of standing waves in the signal wire current. This is not surprising because of the unmatched branches and the unterminated ends of the signal wire.
- There were several locations where sudden, large and unpredictable changes occurred in the signal wire current level. This condition was produced by the branches and also by the signal couplers connecting the signal wire to the trolley wire/rail. The signal couplers were found to cause significant current drains from the signal wire at some locations.
- There was a non-optimum transfer of current from the dispatcher's transmitter to the signal wire due to the nonmatched condition of the signal wire/rail line.

Termination Box



Arthur D Little Inc

0 1 2 3 4 5
| | | | |
Centimeter Scale

Signal Split Box

FIGURE 5 PHOTOGRAPHS OF TERMINATION AND SIGNAL SPLIT BOXES

• There were locations where fixed transceivers located throughout the mine drew excessive current from the signal wire due to low standby impedance of the transceivers.

"Before" and "after" performance is compared in two sample plots. Figure 6 shows the trolley wire voltage and the dedicated-wire current in the Northeast Mains region of the mine. This is the region furthest from the dispatcher's transceiver. The current level in the dedicated-wire after the conversion is significantly higher, and is accompanied by a significant increase in the trolley wire voltage level over much of the Northeast Mains. These plots also illustrate that the performance is significantly improved, in spite of the fact that the matching is imperfect along the dedicated-wire in this region (as indicated by the residual standing wave in the dedicated-wire current). The standing waves are due to the fact that the characteristic impedance varied as a function of distance along this haulageway because of the heavily sagging dedicated-wire installation in this region. The favorable behavior found even under highly variable installation practices underscores the robustness of the dedicated-wire technique in the face of adverse mine environments.

Figure 7 shows the "before" and "after" behavior in the West Mains region of the mine. The "after" curve illustrates the expected stepwise drop in dedicated-wire current when a split is passed; while the "before" curve shows the uncontrolled nature of the signal wire current, and the severe current drains caused by two of the signal couplers (indicated by Z's in the figure). In addition, the voltage curves indicate the significant improvement in trolley wire voltage even to substantial distances of 0.5 miles beyond the termination of the dedicated-wire.

Computation of the signal attenuation rate on the dedicated-wire showed an average value of 0.33 dB per thousand feet or 1.74 dB per mile. This value is small enough that strong signals can be expected on the dedicated-wire even for an extensive network of such a wire.

FINDINGS AND CONCLUSIONS

The effectiveness of the dedicated-wire technique as a means for significantly improving and extending the performance of trolley carrier phone communications has been demonstrated in two operating mines. The installation of a dedicated-wire can be made with the simplest possible equipment and parts. It can be accomplished by suspending a single No. 12 or larger insulated wire from the roof or rib on the wide side of the mine haulageway like a pager phone line installation (see U.S. Code of Federal Regulations, Title 30, Chapter 1, Paragraph 75.516-2), and then applying terminations and signal splitters where the haulageway layout requires them. The signal splitters and terminations are simple--consisting of three resistors contained in a protective electrical enclosure for splitters, and a single resistor and series capacitor in a similar enclosure for terminations. Furthermore, all terminations and splitters are located at well known places in the mine; i.e., terminations at the ends of the dedicated-wire and splitters at the main junctions of the rail haulage network. This makes maintenance of

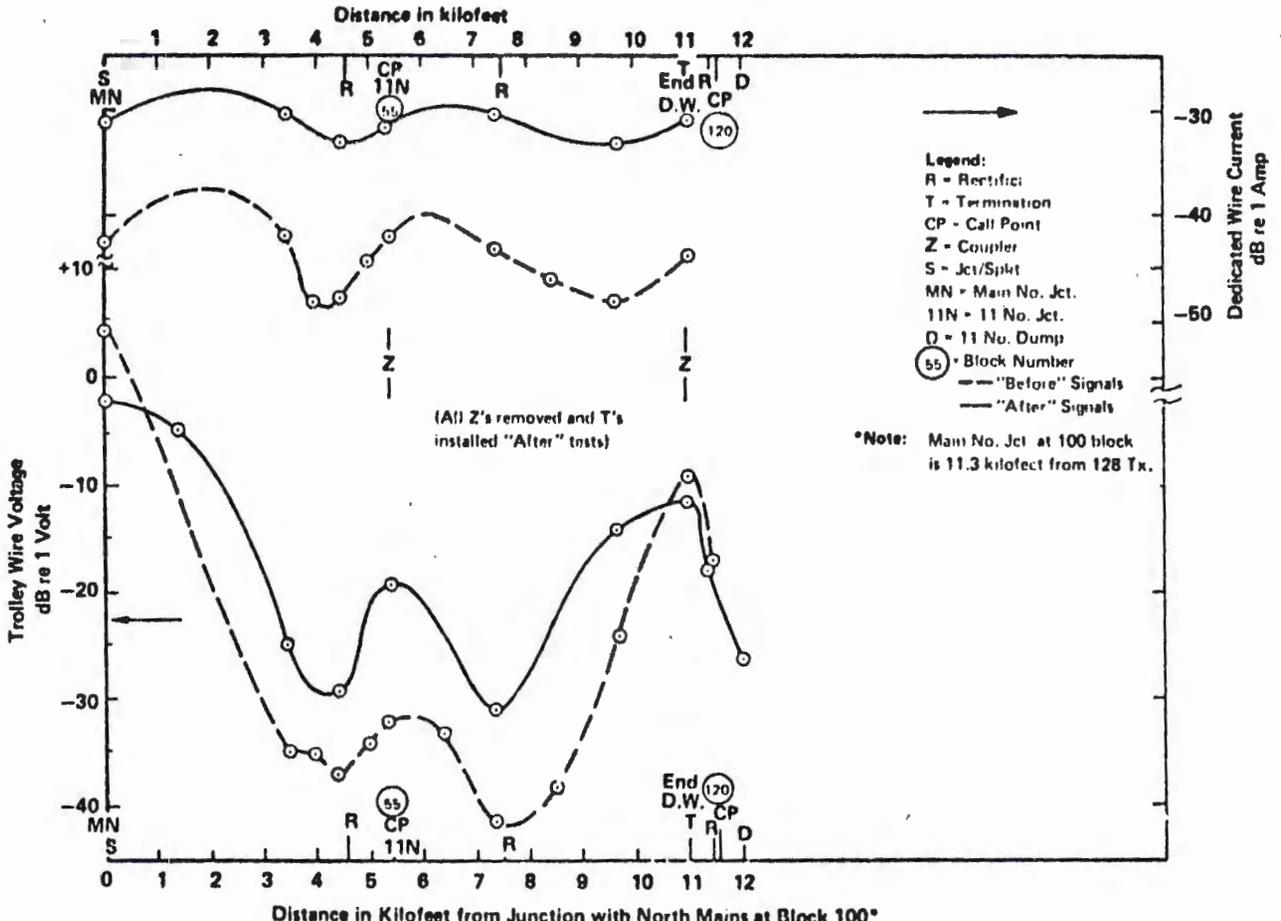


FIGURE 6 COMPARISON OF "BEFORE" AND "AFTER" CARRIER PHONE SIGNALS FOR NORTHEAST MAINS, NORTH MAINS JUNCTION TO 11 NORTH DUMP

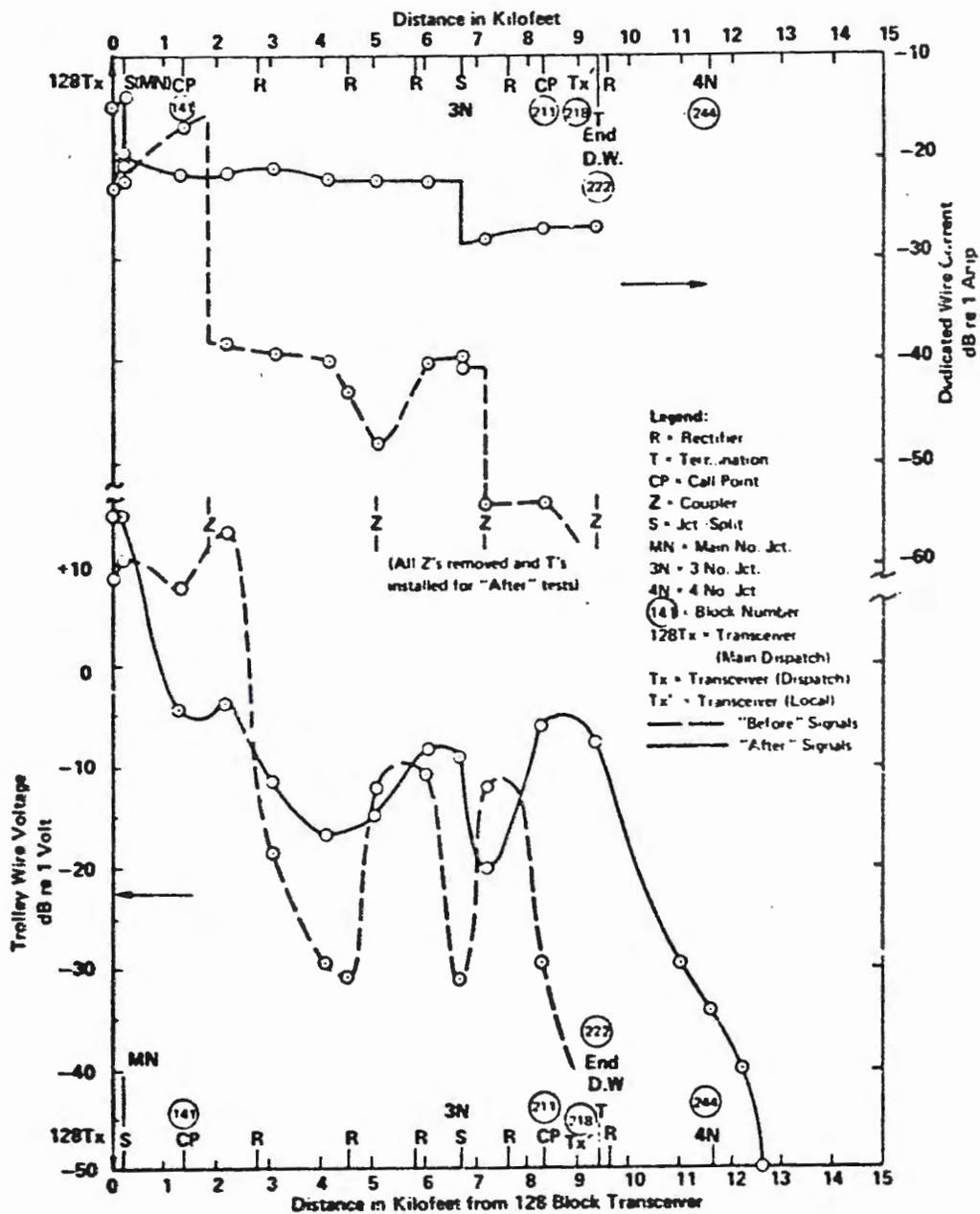


FIGURE 7 COMPARISON OF "BEFORE" AND "AFTER" CARRIER PHONE SIGNALS FOR WEST MAINS, 128 BLOCK TRANSCEIVER TO 4 NORTH

the system easy, allowing problems to be quickly diagnosed and performance easily maintained, usually with simple ohmmeter measurements. This ease of maintenance has been verified by the maintenance personnel at both mines where we have installed and demonstrated the dedicated-wire technique.

We note that these improvements in carrier phone system performance and maintenance are gained without any connections whatever between the dedicated wire and the trolley wire/rail. In this way, the potential hazard of inadvertently transferring the high voltage DC on the trolley wire to other signal wires in the mine is completely avoided. Furthermore, the dedicated wire can readily be extended as the mine expands without resorting to the "black magic" procedures associated with locating signal couplers in "appropriate" places to provide adequate signal levels along the trolley wire/rail.

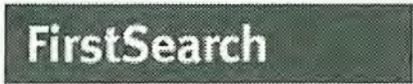
In summary, we feel that this dedicated-wire technique has great promise for solving trolley carrier phone problems in mines in an efficient, economical, safe, and easily maintained fashion.

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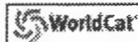
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