UNDERGROUND TUNNEL COMMUNICATION INNOVATIONS

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ABSTRACT

Tunnels are rugged environments with large moving equipment, explosives and hazards including water, dust and gas. To date, there are few underground communication and tracking systems available for tunnel projects that support OSHA (Occupational Safety and Health Administration) compliance.

After the 2006 Sago Mine disaster, research and development was performed to improve communication systems for the underground environment. Today, more than 250 US mines utilize these new technologies to improve productivity, reduce costs and enhance safety.

This paper explores these new technologies and provides guidance for planners through the process of selecting a tunnel communication solution. It reviews the key requirements and constraints for consideration and provides an overview of various communication and networking technologies and discusses their strengths and weaknesses.[1]

Tunnel Network Considerations

This section reviews tunnel environment characteristics which are key considerations when selecting a tunnel communications network.

Tunnel Environment

Irrespective of the type of tunnel project (new construction, repair or remediation), the tunnel geometry, geology and work flow processes are key considerations. Tunnel dimensions and geology affect radio propagation and installation. A common practice is to use concrete for tunnel lining which is conducive to mounting equipment like radio nodes, antennas and power lines. In addition, depending on the composition of the concrete, the lining provides a circular waveguide path for Radio Frequency (RF) signals of certain wavelengths with the ideal wavelength being dependent on the tunnel dimensions [2, 3]. Alternatively, tunnels with porous geology are conducive to water and gas ingress, driving requirements for equipment with high Ingress Protection (IP) ratings and possibly Intrinsically Safe (IS) requirements.

Installation Considerations

New and existing tunnel projects include permanent and semi-permanent installations as well as quick, modular installations. If the project timeline is long enough and power is available, the best systems use line power and back-up batteries for uninterrupted communication. Rugged equipment is needed in addition to proper mounting to prevent obstruction or damage for a long life. Figure 1 shows two examples of equipment mounting schemes in tunnels using existing infrastructure.

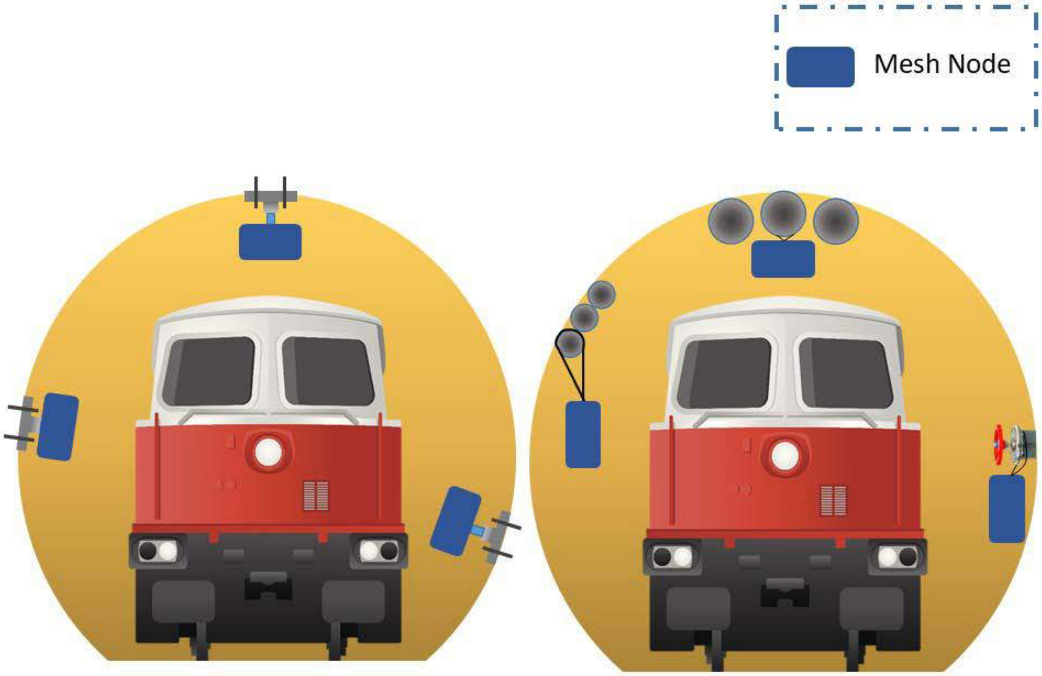

Figure 1: Left, permanent node installation using brackets. Right, temporary node installation using existing infrastructure

Using existing line power and built-in battery backup for normal operation minimizes maintenance. Short-term projects have similar mounting and monitoring requirements but require smaller size and less weight for mobility. If power availability is a problem or the project requires voice, data and tracking for a few weeks or months, the best solution is a fully battery powered solution. Ideally the system would offer the ability to hang equipment in various locations of the entry using minimal manpower and no heavy machinery as shown in Figure 1. Smaller and lighter equipment allows mounting with basic hooks or rope hangers or possibly placing on existing structures or the ground as shown in Figure 2.

Figure 2: Temporary node installation for short term projects using the ground, outcrops or existing holes

If a project requires inspection in a branch or adit shown in Figure 3, the ability to set up temporary infrastructure extensions is useful.

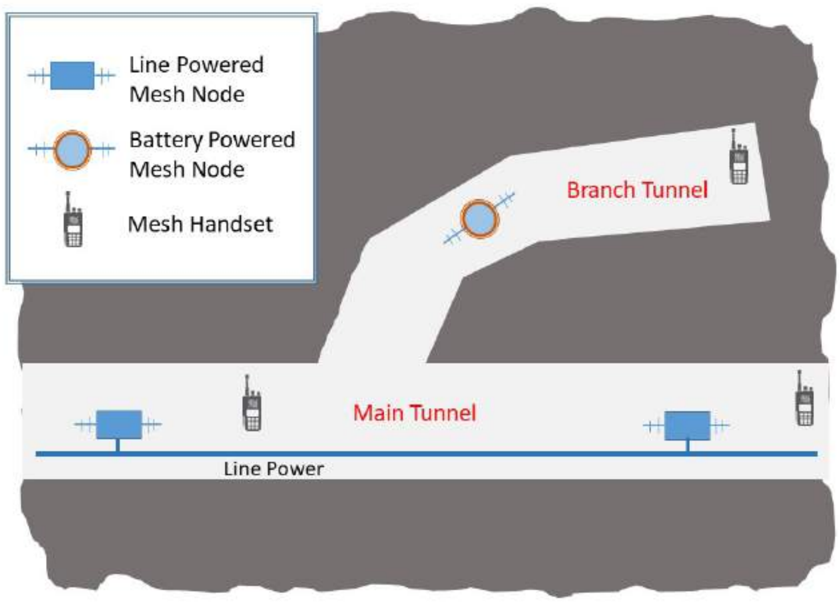

Figure 3: Mixed system solution with line and battery powered nodes

Obstructions & Tunnel Impairments

A Tunnel Boring Machine (TBM) is commonly used for tunnel construction. Proactive communication solutions account for the TBM structure and provide effective data transmission along the TBM and to the surface [4]. In addition, other equipment in tunnels create time-varying obstructions in the middle of the network. Effective system solutions must account for environmental interference and fading effects created by mobile and stationary equipment regardless of the tunnel size [1].

Tunnel Network Applications

Personnel Communications, Tracking & Compliance

Per OSHA, "the employer must maintain a check-in/check-out procedure to ensure that above ground personnel maintain an accurate accounting of the number of persons underground" [5]. Legacy tracking systems are manual with a check-In/check-out brass board or sign in list. This solution is inexpensive but prone to intentional or unintentional human error and may require a dedicated person. Some newer systems provide a situational awareness display (digital blueprint) of the tunnel and track people and equipment automatically using RFID-based technology, thus eliminating the manual check in/check out process. Tracking equipment includes battery operated tracking devices worn or carried by personnel and mounted on equipment. Solutions that are more sophisticated provide multiple tiers of devices including simple personnel and asset trackers as well as higher-tier integrated devices, supporting voice and text communications as well as tracking in a single portable radio. The ability to address different user needs through tiered devices and to provide specific services in specific locations is important since it enables flexibility when trading off equipment cost against operational needs.

OSHA requires tunnel projects to support a minimum of two forms of voice communication and have an on-site personnel tracking system. In addition, other federal, state and local regulations may increase the regulatory requirements for underground projects. For example, MSHA requires two-way communication and tracking (C&T) of all mine personnel, 24 hour battery backup of all C&T systems, 14 days of data for personnel tracking and gas monitoring along with specific ventilation plans for each mine. The Department of Energy (DOE) requires 50' tracking accuracy in some of their underground facilities that store hazardous waste.

Determining the application requirements (voice, text, tracking, sensors) up front is key, since the system design varies based on these applications. In addition, for personnel and equipment tracking, one must consider the required tracking resolution; this varies from zonal indication to real-time GPS-like positioning. Invariably, underground tracking systems rely on anchor nodes. The most advanced systems provide nodes which operate as both communications nodes and anchor points as well as anchor point only nodes allowing the tracking resolution to be refined independent of wireless network coverage requirements. In a zonal system, the anchor points are readers that detect when a tracker is nearby and relays that information back to a server. The server will then state that the location of that tracker is "around" the reader. These systems are typically cheaper with tracking resolution in the range of 2000'. Alternately, real-time tracking systems compute location between anchor points with accuracy within a few hundred feet or less. For systems which include sensors, data sampling rates impact network requirements.

Asset Visibility and Equipment Monitoring

As tunneling project precision and schedules drive the profit picture for new construction, the need to effectively and efficiently deploy, maintain and utilize capital equipment (Overall Equipment Effectiveness (OEE) is an important consideration. In most tunneling programs, the Tunnel Boring Machine (TBM) is the most critical piece of equipment with data monitoring requirements for voltage, current, frequency, active and reactive power to voice and tracking coverage of equipment and personnel the entire length of the TBM. The TBM is typically the farthest distance from the entrance/exit point, supports a majority of underground miners and requires low-bandwidth (voice and tracking data) to high-bandwidth (machine statistics and video surveillance) support. Other tunnel equipment including shuttles, man trips and trains also have tracking and data requirements. The need for high-bandwidth in industrial applications has increased exponentially in recent years since equipment has become increasingly sensitive to even minute changes in the power supply voltage, current and frequency [6]. The TBM communications solution should support a wide range of bandwidth requirements while ensuring safety and minimizing maintenance. Greater tracking accuracy that leads to streaming data and large volume data is useful in key areas like the TBM, switches and the shaft for safety and operational efficiency [7]. Remote monitoring is useful to ensure proper operation throughout the life of the project [8].

Remote Monitoring and Control – point control, sensors, IoT (Internet of Things) devices, etc.

For voice, data and sensor communication, current systems range from manual tracking with pen and paper to fully automated data collection and analysis with alerts. Underground sensors monitor water, ventilation, gas, dust, frequency and power among other things [8]. Sensor data sampling varies from a few times a day to many times a second and is critical for efficient project planning [4]. Sensors are available in wired and wireless options where considerations are needed for cable, antennas, batteries and portability. Sensors and alarms sometimes require high data rates for streaming, spatial distribution, and near-real-time analysis for anomaly detection and emergency control [8]. Cameras are one type of sensor that allows remote monitoring at the expense of high power and bandwidth requirements. Similar to handset radios, it is convenient for sensors to combine multiple functions to save on labor, maintenance and cost.

Data Analysis and Response

Once the data arrives at a dispatch station, tablet or handset, the ability to analyze and determine inefficiencies, failure points and safety concerns is powerful. The top priority for data analysis is personnel and equipment safety but a properly designed solution addresses operational metrics as well. Basic monitoring includes power levels, air flow, gas levels, up/down time, water levels, etc. The faster that anomalies are detected, the quicker the situation is resolved [4, 6]. In addition, higher resolution is required to detect slight fluctuations [4, 6]. The ability to monitor any system from underground concurrently with a remote location for support is extremely important. The amount of data being passed between users, sensors, machines and the various computers dictates the type of network capabilities required for Data Mining and Big Data [4, 6].

Safety

Tunnel projects pose many hazards which requires a disaster resilient system that monitors personnel location and hazardous levels of air, gas and water [3, 8]. Personnel location is critical in case of a health emergency while it is also highly useful for operational and technical issues. Precise location in the event of an emergency could save someone’s life since supervisors are able to determine personnel and equipment location to accurately determine time of arrival for rescue crews. Additionally, the ability to detect trends such as gas or dust build-up is useful so technical experts are alerted for appropriate adjustments [4]. Most underground environments are noisy and prevent standard level verbal communication. Public announcement devices along with audible and visual alarms at key locations ensure safety information is conveyed in the presence of high ambient noise. Wireless versions of these devices make installation and recovery simpler. Every underground project also needs to meet the law as dictated by MSHA or OSHA. These laws include communication, tracking and hazard monitoring regulations. From a safety perspective, the best system is one that meets the regulations which also providing operational efficiency gains.

Project / System Requirements

This section builds on the challenges presented in the overview and discusses project requirements for data collection, transmission, analysis and safety. A designed solution accounts for all aspects of the project instead of providing a simple system to meet a subset of the requirements.

Service type – "What network service, why & where?"

Important considerations for choosing a networking or communication system are what type of service, for what purpose and where the service is needed. Systems deployed in other underground environments focus on regulatory requirements, service types, how the network supports workflows and cost implications. Network service types are divided into several categories including Internet Protocol (IP)-based data services (i.e. laptops, smart phones), voice services (Push-To-Talk (PTT) radios, Voice Over Internet Protocol (VOIP) phones, page phones), Supervisory Control And Data Acquisition (SCADA) data services (sensors, text, control) and personnel tracking/fleet management services. Underground projects monitor hazardous gasses, dust and water along with location and communication status of all underground personnel [9]. An overview of different technologies to provide these services is highlighted herein.

The page phone is a simple yet reliable technology that requires the phones along with twisted pair cable. This system meets the singular goal of voice communication but has limited accessibility (phone locations only), less re-use (throw-away cable) and is less reliable (i.e. single cable failure disrupts tunnel communications). Wireless handset radios using a variety of technologies give operators more freedom and mobility over a page phone system. Handheld radios support voice and texting capabilities while accommodating accessories like throat and speaker microphones.

Types of Underground Networking – Wired or Wireless?

The infrastructure network in the tunnel can consist of all wired equipment (infrastructure & phones), a hybrid system - wired infrastructure with wireless portables or all wireless infrastructure and portables. Some tradeoffs to consider when selecting your network include:

- Service(s) required
- Power availability
- Installation time
- Project duration

- Mobility
- Propagation environment – i.e. tunnel size
- Reliability and safety
- Data rate
- Total cost of ownership – initial price (cost per foot), maintenance, re-usability

Less expensive “all wired” systems utilize phones running over twisted pair wires or Ethernet. These are easy to use but restrict communications to a hard-wired phone limiting mobility and impacting productivity. For low amounts of data, simpler systems like Mine Phones or Leaky Feeder are sufficient.

For wired data transmission, RS-485, Ethernet, twisted pair and fiber are popular choices and support page phones, sensors, ventilation and other point control devices. As with many other cabled solutions, twisted pair may have a single point of failure where all devices on one side of the break are down until repaired. Fiber solutions range from cheap to expensive based on number of modes and durability. This is the best wired option for high-bandwidth requirements at the cost of being difficult to maintain and repair. Fiber repair requires a clean environment and great precision which is unfortunate since it also has a single point of failure.

Hybrid systems are prevalent including walkie-talkies which can communicate on leaky feeder (wired) networks. Leaky feeder systems are wired systems using RF “leaky” coax connecting amplifiers spaced approximately 1000 feet apart throughout a tunnel. A headend unit is installed above ground which transmits RF signals down the coax cable. The benefit of these is that they are easy to use, but as shown in Figure 4, they suffer from poor reliability, limited range and high installation and maintenance cost. Another consideration is the high recurring scrap component and cable cost. Leaky feeder systems are a popular way to provide voice but require laborious effort for installation and maintenance while generating high recurring cable costs [1, 9]. Leaky feeder systems are subject to noise with performance degradation each time the cable is damaged and repaired.

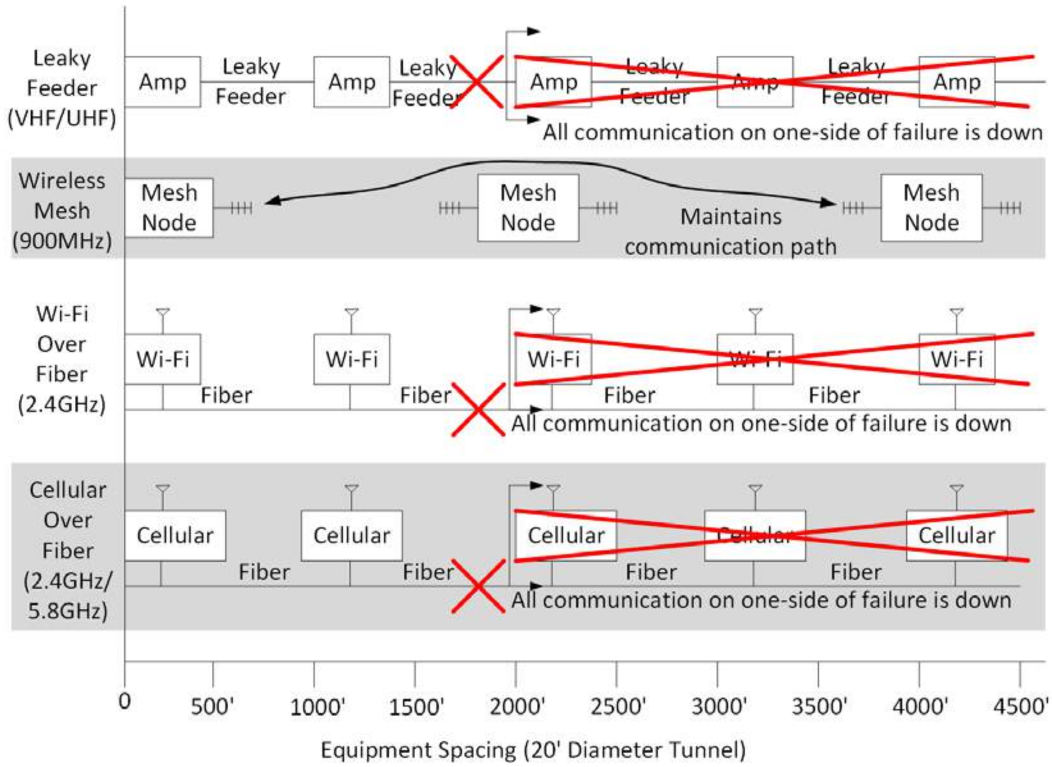

Figure 4: Technology comparison within a tunnel, including network response to failure

Hybrid systems sometimes utilize traditional Wi-Fi access points which rely on wired Ethernet or fiber infrastructure. Studies have shown that Wi-Fi propagation in tunnels and underground environments may have limited range which drives up solution cost [10]. Another emerging trend in the hybrid space to watch is Long-Term Evolution (LTE) or 4G pico-cells, with wired infrastructure and wireless smartphone/tablet clients. However, regulatory, spectrum and service model uncertainties still exist for private LTE solutions.

For high-bandwidth wireless solutions, it is a misnomer to consider Wi-Fi and LTE completely wireless as they only communicate between nodes using the cabled backbone – it is a hub and spoke architecture which relies on a wired backbone. Thus, it is categorized as a hybrid system. Features include the ability to use common cell phones and other Wi-Fi/LTE supported devices. Node and antenna configuration are typically required for these systems and they have a single point of failure unless redundant paths are provided. A true wireless mesh system allows handset to be wireless without any wired backbone whereas Wi-Fi or Radio over Fiber (RoF) solutions still require fiber or wired Ethernet. [1]

“All wireless” systems have increased flexibility, mobility and may have better re-use factors to consider. However, as they are wireless by nature, careful consideration must be given to understanding impacts of tunnel aperture and equipment blockage, while care must be taken to ensure reliable connectivity. The data transmission distance dictates the size and type of network along with metrics like redundancy, power and data volume. One wireless system gaining popularity is wireless mesh networks. Mesh radios are like tiny micro-routers in a fire brigade which pass or “hop” network information along the tunnel. When properly designed, they are easy to install, maintain and deploy for underground applications.

Redundancy is typically inherent to mesh systems by means of scalability, flexibility along with ease of setup and maintenance whereas wired systems need parallel runs of cable to avoid a single point failures [3]. Mesh networks typically have a wireless backbone which is convenient for installation, recovery, redundancy and safety [3] but over large distances may not support the high data rate or bandwidth of fiber. Newer technology systems extend communication between handsets by means of mesh and fiber [9]. Mesh networks use radios installed at periodic locations whereas Wi-Fi and LTE systems use fiber and Ethernet for the communication backbone. Current voice and data monitoring solutions range from these cabled systems to wireless mesh, Wi-Fi or cellular systems [9, 11].

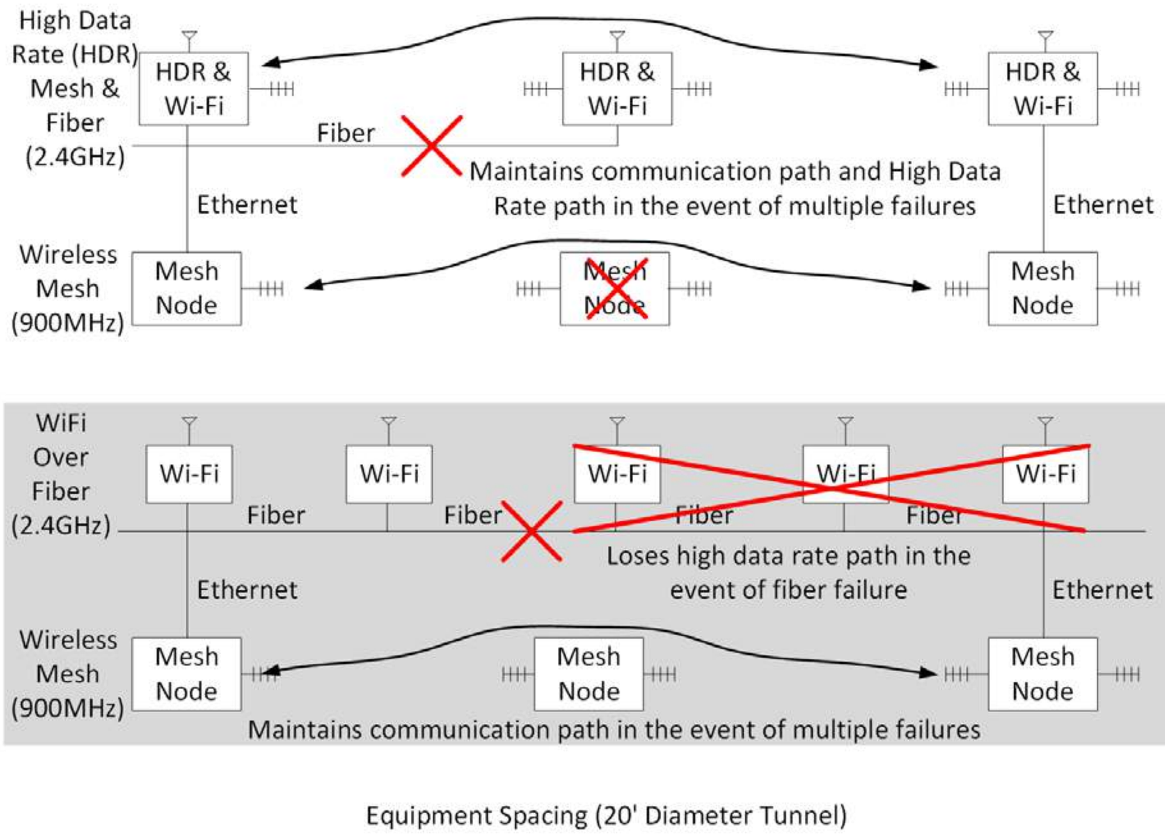

Figure 5: Hybrid technology comparison within a tunnel, including network response to failure

Wireless mesh is typically more mobile which is convenient for installation and recovery with options for line and/or battery power. Some mesh networks have limited data throughput while others provide voice and high-bandwidth options. Research as far back as the 70s shows that high frequency propagation in tunnels is highly effective since the tunnel works like a waveguide and works well even with tunnel variations [2, 12]. High data rate mesh networks are much easier to install and maintain but don't have the maximum bandwidth afforded to fiber. Most mesh nodes run on battery and/or power where the computing power and bandwidth dictate battery life. Permanently installed systems prefer to use line power when available with battery backup. Mesh systems are digital which provide the benefits of combining voice clarity with texting, tracking and other data solutions. With large amounts of data, fiber or high-bandwidth wireless like mesh or Wi-Fi are required. Research is ongoing to show how mixing wired (fiber) and wireless (mesh) systems, overcomes shortcomings for both and an example is given in Figure 5 [9].

System Solutions

This section describes how to design a modular system to meet a project's requirements while minimizing the disadvantages of non-recoverable equipment, unnecessary labor or a minimally compliant system. Most systems on the market have strengths and weaknesses and understanding your particular case helps navigate the choices for an underground project. For example, a simple RFID tracking solution is an inexpensive way to track assets and personnel underground but is not capable of passing voice or interfacing with high-bandwidth equipment. A properly designed solution incorporates all the potential uses the tunnel system may be required to support (i.e. voice, data, tracking, etc.) while being fiscally responsible and safe.

Technical

All solutions on the market advertise voice communications, some have tracking and some also support data applications. The optimum solution takes into consideration the project environment, uses and total cost of ownership. For example, if a particular tunneling project requires high-bandwidth data transmission but has areas that are subject to heavy traffic (adding breakage opportunities for the fiber) and is dirty and/or dangerous to cable, fiber alone may not result in the optimum network solution. Similarly, if you are running a short-term maintenance or inspection project a wired solution may not be cost effective to install for such a short duration. A hybrid system may be the best solution for a particular tunnel program. For example, running fiber in the TBM chassis may make sense but if you are worried about install cost/maintenance/breakage of fiber, a high data rate wireless mesh makes more sense. This solution is especially useful if machinery only operates in a particular area for a short period of time but needs to pass high-bandwidth data. This combined solution capitalizes on the bandwidth of both solutions while minimizing repair and labor costs [9]. As shown in Figure 6, wireless propagation provides an excellent solution in tunnels when properly designed to maximize node and antenna location along with antenna polarization and tunnel conditions [7].

Figure 6: Wireless propagation comparison over frequency

The ideal solution is a hybrid that uses wireless nodes spaced at great distances to eliminate cable and labor costs while using small repeaters for adits and leaky feeder in areas of obstruction or interference. From a safety standpoint, a Wireless Mesh Network (WMN) is one of the best choices and is widely used for establishing communication networks during disaster recovery due to its scalability, flexibility and ease of setup and maintenance [3]. This proposed hybrid system utilizes redundancy and performance while keeping the cost and maintenance low. A system that is able to wield the power of a “leaky feeder antenna” along with omni-directional and directional antennas like Yagis afford the best flexibility. Care is needed when using leaky feeder since the radiated signal is too weak for proper operation in tunnels where the distance between the cable and handsets is too great.

Project timeline and power availability vary from one project to the next so a system that uses line power and/or batteries is ideal. A tunnel might run power to installed nodes but for locations where work is planned for only a few weeks, batteries may be used. This hybrid “power system” is arguably the best way to minimize labor and unnecessary maintenance [7] while meeting any technical requirements. The ability to provide consistent, redundant communications throughout the tunnel at all times prevents unsafe outages [3]. If any type of data transmission is limited at the face due to the need to run cable, personnel and asset safety is compromised [3, 4]. With the hybrid solution, any tunnel project can maintain several layers of communication throughout the tunnel wirelessly while running cable as needed for operational or safety considerations.

Economics

Deployment of an underground network system is a critical criterion for the tunneling industry, particularly when teams are only using the system for the duration of the project. Thus, re-usability is an important consideration in the total cost of ownership picture. If 30-40% of the total cost is in cabling or installation, how much of that cost is recoverable and what can be re-used? If re-use is limited it should be included as a recurring cost for every new project. Integrity of cables, connectors and amplifiers becomes a consideration of maintenance cost of wired systems.

Throughput, propagation impairments and redundancy are important considerations for wired networking solutions. Be wary of networking providers which do not execute site surveys to understand your particular environmental challenges. After considering your tunnel environment and your service needs, the next step is to compare pricing on various options. We highly recommend an analysis based on total cost of ownership (TCO) over the networking equipment life cycle. IWT has worked with customers to develop TCO models of various networking solutions to optimize their budget and performance needs. Often the best solution is not the lowest initial equipment cost but results in higher operational efficiency, component recovery, lower install cost, reduced maintenance and has a better net present value than the "initial" lowest cost solution. Often the recurring cost analysis is left out which yields a long-term, lucrative return on investment (ROI).

Initial Expenses

Using the life cycle approach a hybrid technology solution might be optimum where a tunneling project purchases equipment modularly instead of using equipment from one system in the "One Size Fits All" model. This mix and match methodology allows the project team to use multiple technologies for use case optimization. If a project requires high-bandwidth, install high data rate wireless nodes to interface between a fiber port and the face of the operation then backfill the mesh network with fiber to limit downtime and unnecessary cable damage. For voice communication, use wireless antenna based propagation in open tunnel then leaky feeder in the presence of interference, blockage (e.g. rail system) or in small aperture spaces. Additionally, if an area is hazardous to cable or requires communication for a short period of time, use wireless propagation.

Many systems on the market provide voice, tracking and generic data transmission from sensors or machinery. Our experience shows that a hybrid model provides a lower sustained cost and better TCO. To get a full TCO picture, planners must consider the cost of scrap cables left behind, maintenance, installation, including the costs of running cables as well as the overall quality of the equipment as possible hidden costs that are left out of initial pricing. We have seen these costs approach 25-35% of the initial system price on an annual basis. Some questions to consider include:

- Are you using equipment designed for these environments – are your handsets designed to military or heavy industry standards (i.e. MIL-810)?
- Do I have the equipment to install and repair if it breaks on site (e.g. fiber splicer)?
- Will these products support multiple projects or do I have a heavy replacement cost?

Recurring Expenses

Cheap equipment minimizes re-use, yielding a significant recurring cost disadvantage. This analysis assumes that infrastructure for most systems is durable enough to use for multiple projects and the recurring cost is minimal. The ability to re-use cable after completion of a project is another factor. Cable that requires replacement, rework and/or preparation between jobs directly affect recurring costs [9]. Twisted pair, leaky feeder and Modbus cable all have relatively low initial purchase prices but continual repair and replacement cost accumulates quickly.

Table 1: Cost Comparison of Typical Tunneling Cable

Technology	Price/Foot (20' Diameter Tunnel)	Total Cost of 5 Miles Non- Recoverable
Fiber Cable (Cheap)	$0.20	$5,280.00
Fiber Cable (Rugged)	$1.50	$39,600.00
Leaky Feeder Cable (50 Ohm)	$2.50	$66,000.00
Leaky Feeder Cable (75 Ohm)	$1.50	$39,600.00
Modbus	$2.00	$52,800.00
Tracking System Cable	$1.00	$26,400.00

Table 1 shows how recurring costs from various cable types accumulate, minimizing or completely eliminating any advantages of a low purchase price. The types of cable that are typically non-recoverable range from twisted-pair and Modbus to Leaky Feeder and Fiber.

Labor Expenses

System equipment cost is typically the driving factor when purchasing a system but the previous section shows how recurring costs have a significant impact on ROI. Some inexpensive wired systems (Mine Phones) have minimal initial labor but often only meet one project requirement requiring substantial additional investment to support additional requirements. While many types of cable are easily installed with the proper equipment, the installation of a modular system with minimal cable is significantly faster. Installation labor is a considerable expense but many systems like Wi-Fi (which are also cabled) also require configuration performed by a trained, technical expert. If the Wi-Fi nodes or the IP addresses aren't configured correctly, part of the system or the entire system won't work. While maintenance labor to service some cable types like twisted-pair or AC/DC power cable is relatively low, other cable types such as leaky feeder cable and fiber are quite high. Repairing these types of cable often costs more than replacement due to the expertise and equipment required. When using fiber, a hybrid architecture limits fiber damage and the associated labor costs while meeting bandwidth requirements. In addition, the labor costs for technical experts to identify problems are quite high. A system that incorporates analytical analysis with the necessary alerts significantly minimizes these types of labor costs. Time spent identifying and repairing damage affects the bottom line and diverts attention from normal operational duties.

Technical Recommendations and Summary

Designed Solution

As shown in this article, the best solution for most projects is designed to meet the requirements while minimizing inherent system disadvantages. By purchasing a standard system to meet one or two specific needs like voice or tracking, the inherent disadvantages lead to other technical deficiencies and unnecessary initial or recurring costs. Most tunnel operations want to determine the best system and this is accomplished by finding a company that is not an equipment provider but a solution provider.

Build As You Go

In addition to designing a solution for a particular tunnel or project, it is very important that ongoing tunnel growth is considered. If the tunnel splits, has interference, or other anomalies, system flexibility is a must. Simply providing a system to meet the initial requirements will fail to meet ongoing challenges and changes throughout the project life. The correct solution accounts for the initial requirements while providing flexibility, scalability and system modularity to meet ongoing challenges.

Budgetary Friendly

Typically, the major disadvantage of a custom solution with modular capabilities exceeds the allocated project budget. We postulate that a properly designed solution combines the strengths of typical systems and allows the modular mindset. The properly designed solution is designed around Total Cost of Ownership, maximizing workforce safety and regulation compliance.

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