DTN Communication in a Mine

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ABSTRACT

Physical movement of people and equipment in a mine is largely predictable and periodic. Therefore, the data communication system for managing the equipment fleet in a mine could be based on intermediate nodes (trucks, people's phones, and other mobile devices) that physically carry data messages between an operator console and distant mining equipment. We provide a system model for message-based communication in mines using delay-tolerant networking and present its implementation for a specific chromium mine.

1. INTRODUCTION

There are three to four thousand operating mines worldwide. The lifetime of a mine depends on the amount and accessibility of ore and may vary from a few years to tens of years. Within these mines there may be between ten to a thousand pieces of mining equipment – drills, loaders, roof bolters and other special purpose machines – as well as personnel operating in two to three shifts per day.

The mining process is often divided into development and production phases. In the development phase the underground infrastructure and the tunnels to the ore body are created. During the production phase the ore is excavated from the solid rock and transported to the surface.

Both phases have a cycle where different work methods follow each other and each work method uses (a) dedicated type(s) of machine(s). In underground mines, there are typically tens of active work locations in different stages of the development or the production cycles. Managing the equipment fleet and the locations in an efficient way is challenging.

The need to manage a fleet of equipment and personnel operating in an underground mine necessitates robust communications in an environment where radio propagation is limited by the topology of the tunnels and where communication infrastructure is difficult to build and maintain.

Communications are required in two main areas: 1) voice communication (for which various solutions are in operation today) and 2) data exchange for mining operations and monitoring which we address in this paper. The latter requires transmitting measure-ment and operations data collected by mining equipment to a control room and conveying instructions from the control room to the equipment and personnel.

In some development stages (e.g., production drilling) the mining equipment may be out of reach of any communications for days and the operators for entire shifts. The lack of knowledge in the control room about the current state of equipment and personnel, limits the frequency at which the work assigned may be adjusted based on work done. Being able to transmit data between the work site and the control room during the long blackout times would allow increasing efficiency and control of the operation, which in turn may lower operational costs and improve exploitation of the ore.

Technologies currently used for data communications in mines include: *wireless networking (WiFi)*, data over *leaky feeder*, and *manual transfer* with USB memory stick.

WiFi infrastructure can be built within the mine to provide communications between wireless devices and the fixed mine network. However, the topology of many mines severely limits the propagation of radio waves leading to the need to install and maintain a network of hundreds of interconnected access points. Drifts are frequently blasted which makes permanent installations in development areas impossible.

Leaky feeder is a coaxial cable that "leaks", i.e., emits and receives high frequency radio waves. It is used in many mines for voice communication. Data communication over leaky feeder cable is low bandwidth, unstable and expensive and it may not be possible to install the cable within areas that are being actively worked on and a line of sight is required.

Completely *manual transfer* of data can be achieved by physically carrying data on, e.g., USB memory sticks between the mining equipment and the control room. Communications are limited in frequency to once per shift and is subject to human errors (losing or forgetting to deliver the memory stick) and the risk of malfunctions, e.g., due to dirt.

In this paper we propose a communication solution for mines that allows data transfer between mining equipment and the control room without the need for fixed infrastructure by exploiting store-carry-forward networking.

2. SYSTEM MODEL

The system is composed of three types of entities: Any number of *data sources* $S_1, \ldots, S_n$, *data sinks* $D_1, \ldots, D_j$ and *intermediaries* $I_1, \ldots, I_k$. Data sources are assumed to have the capability to generate some volume of information that is required at the data sink entity. Intermediary entities have the capability to transfer data between themselves and between sources and sinks, but they do not generate or consume any data by themselves—except to replicate received messages due to routing algorithms or to delete messages

due to expired lifetime or resource restrictions.

These typically map to real devices such that the data sources are mining equipment (e.g., drills) that regularly generate data, the data sink is a control room within the mine, and the intermediaries are various personal communication devices as well as devices attached to personnel carriers. The reverse communication path can be modeled by a single data source at the control room, and multiple data sinks at the mining equipment. Two examples are given in sections 2.1 and 2.2.

Different types of intermediaries I can be identified based on their movement pattern. *Fixed periodic* intermediaries will come into contact with the data sources and the data sinks at fixed, deterministic times. These can be, for example, pickups that transport workers at the beginning and end of shifts. *Periodic* intermediaries are also intermediaries that come into regular contact with the data sources and the data sinks, but do not necessarily follow a strictly fixed schedule. Such movement can result from a shift supervisor periodically checking the drilling locations. *Random* intermediaries move nondeterministically within the environment coming into contact with other intermediaries, and possibly data sources and data sinks. This type of movement may result from human mobility, for example, during breaks.

2.1 Cut and Fill Mining Scenario

In cut and fill mining, "drifts", or horizontal passageways, are dug around the ore deposit with stopes perpendicular to the strike of the ore. Figure 1 shows a typical layout of one level of such a mine. The whole mine contains a large number of such levels spaced between, e.g., 25 meters.
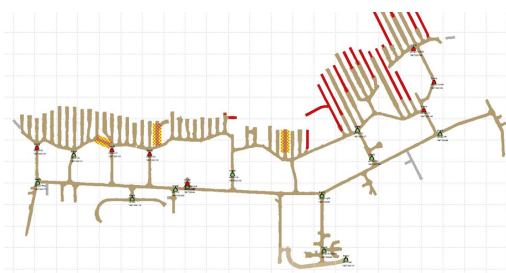

Figure 1: One production level with WiFi access points (light brown current, red development plans).

Such mines can be fitted with WiFi access point networks at drift intersections. WiFi infrastructure can be used to cover a significant portion of the drifts by installing large numbers of access points, or to only cover some critical areas by installing a smaller number of access points. In either case the stopes cannot be covered by WiFi access due to their large number and mining operations (e.g., blasting) taking place in them. Figure 2 shows the coverage reached by a single access point.

In the cut and fill mining scenario the data sources are typically the mining equipment working in the stopes outside of the WiFi coverage and the data sink is the control room. These roles are reversed when considering communications from the control room to the work sites, e.g., for carrying work orders. Personnel move to and from the work sites between shifts on pickup trucks which can be fitted with nodes to behave as intermediaries. Furthermore, the personnel may be carrying personal communication devices such as VoIP phones that can also be used as intermediaries.

In mines with good WiFi coverage the system only needs to carry data one hop from the equipment in the stopes to the nearest access
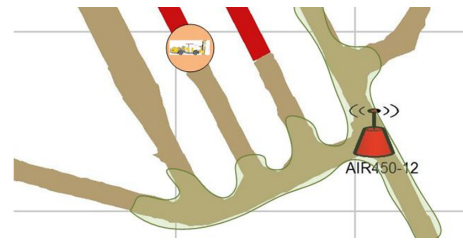

Figure 2: A working drill rig outside WiFi coverage.

point. In mines without WiFi infrastructure the data may need to be carried all the way between the control room and the work sites by intermediaries, resulting in networks with large number of hops.

2.2 Room and Pillar Mining Scenario

In room and pillar mining, a horizontal plane is excavated resulting in "rooms", or open areas, with "pillars" left behind to support the roof. This results in a mine layout and mobility that are markedly different from cut and fill mining (compare Figures 1 and 3). In particular, the movement of equipment and personnel is not restricted to paths laid out by the drifts.
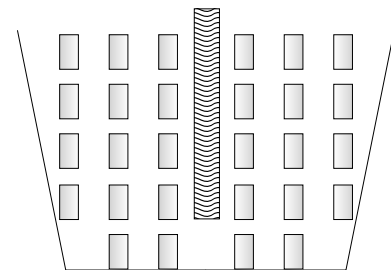

Figure 3: Floor plan of a room and pillar mine with a conveyor belt in the middle.

Similarly to cut and fill mining, room and pillar mines can also be covered by WiFi infrastructure by installing a network of access points. But this approach suffers from the same signal propagation problems as in cut and fill mines due to the pillars shadowing and blocking radio signals. Furthermore, while drift intersections serve as natural points to install access points, a large number of access points may be needed to provide good coverage. In addition, in room and pillar mining the mining operations take place along the walls and are not confined to stokes, meaning that there are large areas where access points cannot be installed.

2.3 Node Connectivity

Figure 4 shows a connectivity example in a cut and fill mine with WiFi infrastructure: a drill connects to 23 different access points during its movement in the mine. The short disconnection periods show the drill moving between its production operations and make up 80%; more important, however, 20% of the disconnections last longer than several hours (up to more than a day in this data set), showing a clear need for augmenting the WiFi infrastructure. The contact periods indicate that about 50% of them are below the access points sampling interval of some 40 s, indicating very limited communication opportunities; contact periods of more than 3 min only occur when the drill is up for maintenance. This behavior is typical and calls for a delay-tolerant communication with mobile mining equipment.
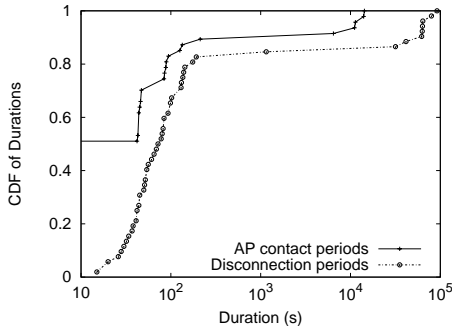
Figure 4: Intermittent connectivity of a single drill over the period of one week.

2.4 Exploiting Node Mobility

The mobility of intermediaries within a mine may be modeled by a cyclic timetable, similarly to the bus, or railway schedules.[1] In that timetable, each row describes the movements of a single intermediary node I_j within, say, 24 hours. A link ending in the equipment node E_i at time t means that I_j arrives to the vicinity of E_i at time t. One intermediary may pass another on its way between equipment E_i and E_j.
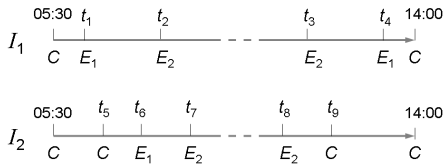

Figure 5: Part of a mine timetable; very small sojourn intervals are not shown. E_i and C are an equipment node and the control room, respectively.

For example, the first row, labeled I_1 in Figure 5 represents the path of a pickup that delivers the operators from the vicinity of control room C in the beginning of the shift (at 05:30) to their respective production sites containing equipment E_1 and E_2. The pickup remains near E_2 until the end of the shift (at 14:00), when it delivers the operators back to the vicinity of C.

As another example, the second row, labeled I_2 in Figure 5 represents the path of a shift supervisor's vehicle that moves between the vicinities of C, E_1 and E_2 during the shift.
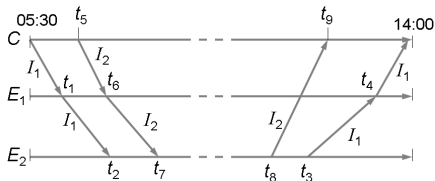

Figure 6: Timetable with rows showing C and E_i.

The information in the timetable can be represented also as a directed graph in which each row represents E_i and the edges rep-

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[1]Optimization of timetables given various constrains have been studied extensively. (See [6] and the references therein). Please note that in our case, the timetable of a mine can be assumed to be given.

resent the movement of intermediate nodes. (See Figure 6). All edges are directed according to the flow of time from left to right. A slanted edge I_k starting in E_i at time t_1 and ending in E_j at time t_2, represents an intermediary node I_k that leaves the vicinity of E_1 at time t_1 and arrives at the vicinity of E_j at time t_2. A horizontal edge starting at time t_i and ending at time t_j corresponds to I_k simply staying in the vicinity of E_i for $t_j - t_i$.

The above example is completely deterministic, and thus ideal. In reality, the time it takes an intermediary to traverse parts of its route, as well as the route taken may vary. For example, the pickup I_1 may sometimes remain at E_1 longer on some shifts than on others. As another example, the shift supervisor I_2 may take the (cyclic) route $C \rightarrow E_2 \rightarrow E_1 \rightarrow C$, instead of $C \rightarrow E_1 \rightarrow E_2 \rightarrow E_1 \rightarrow C$ on some shifts.

Those variations can be modeled by representing the segment lengths and the choice of alternative paths as random variables whose distributions are determined empirically.

We note, however, that due to production cycles and safety requirements, the movement inside a mine is mostly deterministic. Therefore, variations in mobility patterns can be modeled as random fluctuations of a deterministic timetable. This is in contrast to, e.g., urban environment, where variations in mobility patterns may be quite large.

3. APPLYING DTN IN A MINE

As shown in Section 2 the physical movement of people and equipment in a mine produces space-time paths (paths that do not exist in full at any one instance of time, but which can be constructed from multiple hops over a longer period of time). These paths cannot be used for communications by the networking solutions that require end-to-eend connectivity, but can be exploited through store-carry-forward networking.

In other words, the data communication system for managing the equipment fleet in a mine could be based on intermediate nodes (trucks, people's phones) that physically carry data messages from the sender to the receiver. Techniques for implementing such systems are provided by Delay Tolerant Networking (DTN) technologies [1]. In addition, we can borrow concepts from routing using humans, data mules, and message ferries as message carriers as has been extensively researched for DTNs (e.g., [7, 8, 12]). However, the mobility in mines differs from previous work in several aspects: 1) human workers in mines move more predictably than people on the street, 2) their devices are known, 3) the motion of nodes is largely more scheduled than data mules, and 4) in contrast to message ferries, the mining nodes are not controlled to deliver data but follow other purposes.

The use of wireless sensor networks for monitoring of mines has been suggested in [5, 11]. These are special-purpose networks typically based on static sensor nodes, while we propose a generic communication system through the exploitation of mobile wireless nodes.

For data communication in mines during normal operation we have identified the following main requirements: *i.) Dependability*, i.e. reliable transmission of data between mining equipment and control rooms. Loss of data should be avoided, and if it occurs, recognized and reported. However, a large communication delay of, e.g., the work time of one personnel shift is acceptable. *ii.) Management-less operation:* once installed, the communication system should transmit data and recover from failures automatically. *iii.) Security:* The access to a mine is typically tightly controlled by the owner. Still, there is the threat of disrupting in-mine communication by an infected device that is smuggled into the mine. Also, equipment from competing manufacturers is often

used in the same mine.

Thus, security requirements include integrity of data against modifications by intermediary nodes, mitigation of potential DoS attacks, and secrecy of data from different manufacturers and competing companies.

3.1 Communication Model

Communicating entities: Control room C, n mining equipment nodes: $E_1, \ldots, E_n$, and k Intermediary nodes: $I_1, \ldots, I_k$. The mining equipment E creates a message from, e.g., a four hours of collected sensor data. The messages are sent opportunistically to control room C through intermediaries I_1, I_2, etc. When a control room C receives a message m it sends an acknowledgment, $ACK(m)$, to E, also through intermediaries. From the received data, the control room is able to derive the state of $E_1, \ldots, E_n$.

Communication in the other direction, from the control room C to mining equipment E, is done in a similar way. It will occur for instance, if C needs to load work assignment to E, or if it has not heard from E for long time.

Contacts between mining equipment are also possible.

Given the largely predictable schedules of equipment and human mobility, this knowledge can be exploited to calculate optimal routes deterministically in the control room, e.g., as suggested in [4]; the respective time-space-graph information can be distributed via simple flooding. However, for mines with well-developed infrastructure networks, one or two hop communication may be sufficient for message delivery. In such cases, a variant of epidemic routing [10] may be sufficient, especially if messages are small (as in our specific case). This provides robustness against schedule changes and allowing the use of unplanned opportunities.

3.2 Protocol Considerations

DTN layer and routing protocols do not necessarily provide guaranteed delivery; messages may be deleted from the system before they reach their destination. Thus another protocol is required to meet the dependability requirement.

There are two common cases for deletion of messages. The entity holding a message will delete it if: *i.)* The message is obsolete: The message holding time expires, or the message was successfully delivered and an ACK for that message has been received. Reliability requirement implies that ACK message should be authenticated and integrity protected. *ii.)* Memory limit: the device is out of memory. A sender will always wait for ACK, but an intermediary may delete the message immediately after forwarding.

We propose a simple accumulative message composition mechanism in conjunction with acknowledgments for providing guaranteed delivery. When composing a new message either in response to new data being generated or a timer expiring, the data source will bundle all previously sent data that has not yet been acknowledged into a single message.

This mechanism allows data in lost messages to be resent in subsequent ones. If the messages are created faster than they are acknowledged, overhead will be generated. This overhead is significant only if the messages are large in comparison to buffer and link capacities and if the round trip time is much longer than the message generation period.

Furthermore, the routers can replace older messages with newer ones in order to avoid congestion due to duplication. If the offered load starts to approach the system's capacity, more advanced congestion control mechanisms will be required. Such mechanisms are out of scope for this paper.

4. SOLUTION ARCHITECTURE

The generic model for the solution for data communication in mines based on DTN technology is described in Section 3. This section defines a more detailed solution specifically for the Outokumpu Kemi mine. The goal is to define a system architecture capable of transmitting data from mining equipment outside of wireless LAN coverage to a control room by using pickups as carriers.

4.1 Target mine

Our target mine, where we intend to test these ideas in practice during the second half of the year, is Outokumpu's chromium mine in Kemi, Finland. The mine, which is located in Northern Finland, is Europe's largest chromium mine. It conforms to the *cut and fill mining* scenario (see Section 2.1) and we show an example plan of a production level in that mine in Figure 1. Each production level has approximately 20 WiFi access points connected to the mine backbone. New drifts are continuously developed.

The data collection tablets attached to the drills (the data sources) are robust notebook PCs designed for an industrial environment and running Windows XP. They are equipped with WiFi radio technology, and currently the data collected by a drill is manually uploaded to the control center by the operator when that drill is moved into coverage of the mine's infrastructure WiFi network.

The control room server is connected to an Oracle SQL database server, and the data is passed on to the database server through a Web Services interface. The data generated by the drills is in XML format. Typical message sizes are 10-100 Kb.[2] All devices have static IP addresses.

The miners in Kemi are carrying Cisco VoIP phones that communicate over the mine's WiFi network, however, they do not have APIs to implement the proposed system.

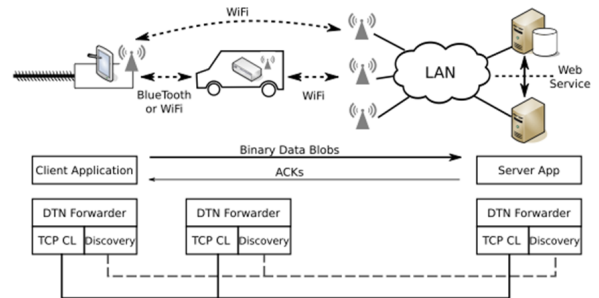## 4.2 Data Communication System Architecture

Figure 7: Data communication system architecture.

The overall architecture of the data communication system is shown in Figure 7. The main physical components are: 1) drill with an attached tablet PC for data collection, 2) pickup used to ferry workers to/from the drill, 3) wireless access points located in various points in the mine that provide connectivity to a local area network, and 4) database and other servers located in a server room connected to the local area network.

We add an embedded device with wireless interfaces and Linux OS to the pickup. The embedded device is built from off-the-shelf components and fitted in a dust and weatherproof enclosure. When the drill is located outside the coverage area of the wireless access

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[2]Larger message sizes of 1-10 MB are possible in the future if maps need to be transferred from the control room to the mining equipment.

points, the pickup acts as a data ferry to carry the data from the drill to the wireless LAN coverage area. The data collection tablet PC and the pickup use either ad-hoc mode WiFi or Bluetooth for connectivity. The mine personnel can carry additional mobile devices in case the pickup does not come sufficiently close to the drill for a direct connection.

4.3 Software Architecture

The software architecture is composed of three elements: 1) DTN Forwarder that implements store-carry-forward style router based on the Bundle Protocol [9] and the TCP Convergence Layer [2], 2) Client application that reads measurement data from the file system of the data collection tablet attached to the drill and bundles it for delivery, and 3) Server application that receives the data sent by the client and forwards it to the database server by using a Web Service interface.

4.3.1 DTN Forwarder

The DTN Forwarder is a store-carry-forward router that can discover peers within the same local area network or over Bluetooth, open links to the discovered peers, exchange bundles over the links, store received bundles for extended periods of time while waiting for new contacts and delete bundles in response to delivery notifications. It will be deployed on every device that is part of the forwarding network, including the data collection tablet, server machine, pickup machine, and any personal mobile devices.

Peer discovery is done using a LAN broadcast based mechanism, such as Bonjour, or by using the Bluetooth discovery. Forwarding nodes will advertise their open TCP listening sockets to which other nodes can open connections.

Bundles received by the forwarding node are written to a hard drive to survive possible reboots. Data stored by the forwarding node is only deleted if the node receives a delivery notification (ACK) or if it runs out of storage space. Forwarding nodes will try to synchronize all the messages that they carry during a contact. This will result in a simple epidemic routing within the forwarding nodes network. More advanced routing strategies are a subject to further study.

Since we propose an accumulation mechanism to ensure reliable delivery, the forwarder can drop all older versions of the message once it receives a newer copy. This ensures that the forwarder will be holding at most one copy of each application lever message.

4.3.2 Client Application

The Client application will be deployed on the data collection tablet attached to the drill. It will monitor a specified location of the local file system for new data. Once new data is detected, the client bundles it for delivery and passes it to the local DTN Forwarder node for delivery.

The Client application may periodically retransmit the data, or transmit aggregate messages until it receives a delivery notification. After receiving the notification, the client can delete data from the data collection tablet. Since ACKs are used to delete data from the system, they should be signed and integrity protected in order to stop possible attackers from deleting data by sending malicious ACKs.

4.3.3 Server Application

The Server application is deployed on a machine in the control room and is well connected to the database server. The server application will receive data from the client and pass it to the database server through a Web Services interface (or similar). Once it has successfully delivered the data, it creates a delivery notification

message that is passed to the DTN Forwarder.

In addition to the drill data, the server may also receive and handle logging and diagnostics data generated by the Client application and DTN Forwarder applications in the network. This data will be stored locally on the server machine and/or delivered to a remote site for analysis.

5. IMPLEMENTATION AND VALIDATION

With the target mine in mind, we have done an implementation of a DTN Forwarder in Java using a Bundle Protocol and TCP Convergence Layer stack developed at Aalto University. Additionally, a simple client and server application has been implemented for testing and validation purposes.

The DTN Forwarder is designed to run on all network elements taking part in the bundle exchange, including the edge nodes i.e. the clients and the server. On the client and server nodes an additional application layer is attached to the DTN Forwarder to provide the desired functionality, whereas the intermediate nodes run DTN Forwarder as a plain forwarder.

DTN Forwarder acts as a store-carry-forward router and forwards bundles using simple epidemic routing. Any time the forwarder receives a bundle that it is not already carrying, it stores the bundle for forwarding. Each stored bundle is then forwarded to any peer that is discovered, providing that A) the bundle was not received from the discovered node, B) the discovered node is not the original sender of the bundle and C) the bundle has not already been sent to the discovered node. In the server and client nodes, the forwarder accepts messages from the application layer, and turns those messages into bundles that are stored for sending. The forwarder delivers any received bundle payloads to the application layer in case the endpoint identifier (EID) matches a registration.

The bundles queued for forwarding are stored in memory, but a backup copy is written to disk and read at startup to enable recovery from reboots and to protect from data loss.

Peer discovery is implemented using UDP multicast, with beacon packets sent at regular intervals (in the order of a few seconds). The discovery mechanism is based on DTN IP Neighbor Discovery (IPND) [3]. While IPND is still a work in progress, it provided a basis for a simple but robust discovery mechanism. The DTN Forwarder is designed to work with a number of different peer discovery mechanisms as generic discovery agents and to be easily extensible. Different discovery mechanisms can be run at once and discovery agents can be attached to network interfaces.

Currently, the DTN Forwarder is implemented to use WiFi and wired Ethernet. The ability to use Bluetooth radio for bundle transfer may be added later on, especially if mobile phones are to be used as intermediate nodes.

5.1 Engineering Issues

A number of issues arise from the implementation which need to be considered when building a complete system.

Communication between Drill and Pickup: The drill and the pickup will typically communicate over WiFi. A reliable mechanism needs to be in place to let the tablet PC connect to either the infrastructure network or the ad-hoc network of the pickup, whichever is available, and to prefer the infrastructure network. Such functionality is provided by many operating systems, but its speed and robustness may vary.

The pickup should be equipped with external WiFi antenna to improve connectivity.

Using Mobile Phones as Relays: In addition to devices attached to the mining equipment and pickup trucks, mobile phones carried by the mine personnel may be used as intermediary nodes. Such

devices often have limited storage, processing and battery power. A DTN Forwarder must be able to limit the resource use by, for example, opting to use Bluetooth instead of WiFi and only forwarding a small number of messages.

Communication between pickups (ad-hoc): There do not seem to be significant gains from such communication in the target mine scenario; the additional complexity for switching the radio interface (or providing a third one) would be significant. Therefore, communication between pickups will not be pursued for the specific target mine but could be pursued in more generic scenarios.

Communication between pickups (via infrastructure): In the target mine any number of pickups can communicate with one another while they are in the mine infrastructure network. There does not seem to be a need for direct pickup-to-pickup communication: message delivery will be done to a node inside the mine infrastructure network and delivery ACKs will be sent by this very node.

Monitoring: To determine the correctness, effectiveness, and efficiency of the solution, a monitoring system can be developed to obtain information about delays and operational errors. The collected data should be sufficient to estimate the performance gain (in terms of earlier data delivery and savings in manual data collection) provided by the system.

Clock synchronization: The devices may use simple NTP-based clock synchronization whenever they are connected to the mine infrastructure WLAN. This is required if lifetime-field in the bundles is used to identify expired bundles for deletion. However, only rough clock synchronization is needed.

5.2 Validation

The implementation has been tested on a setup with three nodes, consisting of two edge nodes running DTN Forwarder together with a client/server application and one node running a plain DTN Forwarder. The forwarder was connected to one of the edge nodes using WiFi and to the other one using wired Ethernet. Bundles are successfully forwarded between the nodes, and the DTN Forwarder correctly deals with network outages on any link, so that bundles are stored and forwarded when a peer becomes available again.

The delay before a node discovers and connects to a peer that becomes available largely depends on the frequency of the discovery beacons. When a new beacon is discovered, the connection is established in the time scale of the TCP handshake between the nodes. Additional delay is introduced by the time required for the WLAN interface to notice and associate with a network that has become available and for the device to acquire an IP address from a DHCP server. In our tests we found that the total delay was 8 ± 2 seconds, which means that the system is capable of working with all the contacts shown in Figure 4.

A typical tested beacon interval was three seconds, and the beacon Ethernet frames size was 70-100 bytes depending on the length of the Endpoint Identifier (EID) advertised.

We consider the base technology to be ready for real test deployment in the target mine (see 4.1) this fall after some additional monitoring capabilities have been implemented.

6. CONCLUSION AND FUTURE WORK

In this paper we have described how to implement data communications in a mine using the technique of store-carry-forward of messages by intermediary nodes. This method of communication is facilitated by the fact that the movement of people and equipment in a mine is mostly deterministic. We expect that communication solution to increase the level of optimization and control of the mining operation.

We have shown that store-carry-forward networking can be used to provide a generic communication service for otherwise unconnected nodes in a mine, and we have done an implementation of such a system. We expect deployment in the target mine to uncover any remaining gaps in the technology.

Topics for future work include larger scale experiments and deployment in the target mine and the design of routing that is optimized for the timetable of a specific mine, including applicability of existing routing algorithms for mobility models encountered in mines.

We hope that the technique of store-carry-forward of messages by intermediary nodes can be used also in other industrial environments (e.g., shipyards and factories), where it is difficult to achieve sufficient coverage with conventional networks.

Acknowledgments

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