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Architecture for Disaster Relief Networks in Underground Coal Mines: A Survey

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Abstract. It is increasingly being recognized that dedicated emergency networks are vital interfaces between rescue teams and trapped-miners in underground mines. This article proposes a network architecture for rescue applications in post-disaster mines, termed as Post-Disaster Emergency Network (PDEN). First, the special requirements for configuring a PDEN are outlined. Then, the emergency data flows transported in a PDEN are classified into uplink flows and downlink flows. The problem of transmission priority differentiation for uplink flows, and the energy efficiency for downlink transmissions are both examined. Finally, some primary numerical results are presented to reveal the effectiveness of the proposed PDEN architecture.

Keywords: Emergency communications; underground communications; device-to-device communications; wireless multicast communications

1. Introduction

Underground mines are typically extensive labyrinths of long and narrow tunnels. The length is up to several kilometers and the width is only a few meters [1]. Many of the mines contain corrosive water and dust, and very toxic and explosive gases, such as carbon monoxide and methane [1]. In such a very hazardous environment, hundreds of mining personnel are distributed throughout the laneway where mining operations are carried out. These facts make underground mining become one of the most dangerous occupations in the world. Some underground disaster accidents, e.g., roof falls, fires, explosions, toxic gases, and floods might end up with fatalities and disabilities. More seriously, when an accident occurs, emergency response for underground mines is much more difficult than those for ground rescue actions [2].

To prevent accident occurrence, most of present underground mines are deployed with special disaster forecasting and warning systems [3]. A typical disaster warning system is mainly composed of the underground-part and the ground-part. The underground-part is actually a type of sensor network, which can gather information such as humidity, methane and gas concentration in mines timely. Due to the geological structure of underground mines, the underground-part typically consists of a mixed wired-and-wireless network. In the long and stable main roadway, a large quantity of sensing data are transported through wired ring-type Ethernet backbones [1], while in the dynamic mining surfaces, it is more flexible and scalable to deploy wireless sensor networks (WSNs) [3]. The uploaded sensing data from the underground-part is then used as the inputs at the ground-part. The ground-part can thus perform data integration (with the accumulated historical data) and knowledge discovery operations. Functioning as an expert system [2], the ground-part can also judge the occurrence risk of disasters. Finally, advance warnings for impending accidents can be given by the disaster warning system. Recently, with the rapid deployment of

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the 3GPP LTE-A cellular networks, WSNs via cellular networks are expected to form so called Internet of Things (IoT). In contrast to traditional human to human (H2H) applications, such as web streaming and file downloading, IoT applications have their own unique features, such as small and infrequent data transmission, time controlled transmission and reception, and group-based policing.

However, a disaster warning system (especially the underground-part) does not function well for the post-disaster rescue effort. First, because most of underground accidents will lead to electricity failure, wired/wireless network facilities thus cannot operate after disasters. Second, although wireless infrastructures can operate on pre-installed battery, they might be physically damaged in accidents, which results in that the residual infrastructures cannot cover the whole disaster area. Moreover, the public safety networks (PSNs) [4] designated for ground rescue actions are not applicable to underground actions either. Similarly, the great challenges to PSNs include no available infrastructures since they were physically damaged, and lack of energy necessary for the user terminals to operate. To cope with this drastic situation, many research works propose emergency systems [5] involving a helium-filled balloon floating around 100 meters off the ground. The balloon can be fitted with an infrastructure capable of transmitting a signal in a radius of more than 3km and getting the radio waves from the satellite. PSNs can thus be made available to the people in disaster-areas. As for the shortage of a terminal’s battery, it can be solved by the usage of mobile solar-cells. However, in underground mines, it is not easy to receive auxiliary facilities and power supply from the outside world. The measures taken for PSNs are described as useless in underground mines.

Based on the above considerations, it is necessary that a PDEN for underground mines should have the following technical characteristics:

- Network deployment cost and confined space of underground mines are two main challenges when designing PDENs. It is desirable that a PDEN could share the same infrastructures and terminals with an available disaster warning system. It thus requires that the PDEN protocol should be backward compatible with the disaster warning system, especially the underground-part.
- After a disaster occurs, the residual sparse infrastructures might not be able to cover the whole disaster-area. It is essential that all the available terminals (including the sensor nodes fixed on the laneway and the mobile terminals carried by trapped-miners) in disaster-areas could work collaboratively with the residual infrastructures to accomplish network reconfiguration.
- As PDENs are built upon partly damaged underground-parts of disaster warning systems, the network stability and connectivity might be volatile during operation. It is demanded that the infrastructures and the terminals of PDEN could cache data and communicate the data reliably when the network is in good condition. Fortunately, in recent years, we have seen an enormous proliferation of smartphones which have been equipped with large storage space between 10 to 64 GB [6].

This article aims to provide a broad overview of open problems encountered, and to propose a unified PDEN framework to support post-disaster rescue actions in underground mines. In what follows, Section II proposes a general network reconfiguration method in post-disaster situations. Section III first classifies the emergency data flows in PDENs into the uplink flows and the downlink flows. Then, for each type of flows, their specific functions are reviewed and feasible methods are presented. In Section IV, some experiment results are provided to verify the effectiveness of the proposed methods. Finally, the article is concluded in Section V.

2. Network Reconfiguration

Without loss of generality, we assume that a disaster warning system adopts Wi-Fi technology to build the underground wireless networks. The Wi-Fi Alliance defines Wi-Fi as any wireless local area network products that are based on IEEE 802.11 standards. Although Wi-Fi may not be the best choice for disaster recovery or emergency network, as the physical layer of Wi-Fi is neither reliable nor highly resistance to bad channel conditions, most of the current warning systems in underground mines are based on Wi-Fi technology. A large share makes it cannot be completely replaced in recent years. Thus, we can take Wi-Fi 802.11 as the network prototype. In this section, we first employ the newly released Wi-Fi Direct technology [7] to implement the post-disaster network reconfiguration as outlined in Section I.

In a typical Wi-Fi network, access points (APs) acting as wireless infrastructures perform the basic network managements, and each Wi-Fi terminal acting as a client must associate to one of the APs. Hence, in *infrastructure* mode, an AP and a terminal are with different set of functionality. However, in Wi-Fi Direct, a terminal can implement both the functions of a normal terminal and of an AP simultaneously. In the following, we refer to a Wi-Fi terminal that implements the functionality of an AP as the software-defined AP (SDAP). Wi-Fi Direct also permits the proximate terminals to negotiate who will take over the AP-like functionality within a cluster. A terminal may be the SDAP in one cluster and be a normal client terminal in another. Note that Wi-Fi Direct can be entirely implemented in software over traditional Wi-Fi radios [8]. It thus appeals to the upward protocol compatibility needed by PDENs.

2.1. Reconfiguration of PDEN Using Wi-Fi Direct

This subsection describes the reconfiguration procedure of a PDEN by using the reduced underground-part of a disaster warning system. Consider a post-disaster area, where the residual APs operating on battery-powered mode work collaboratively with the terminals[1] to realize the network reconfiguration. The detailed network reconfiguration procedure based on Wi-Fi Direct technology can be described as follows.

- *Step 1*: Some of the proximate terminals in a network coverage blind area (e.g., the terminals T_1~T_6 in the green circle region, and the terminals T_7~T_9 and T_2 in the blue circle region) can discover each other[2] and establish a communication cluster by running standard Wi-Fi terminal discovery algorithms [8].
- *Step 2*: After the terminal discovery, the terminals within the same cluster must negotiate to determine which terminal should be considered as the SDAP, i.e., the AP-like functionality for the cluster, by running a pre-defined negotiation protocol. Hence, the other terminals (including the terminals that do not participate in the negotiation) under the coverage of the SDAP can access the PDEN through the SDAP (e.g., terminals T_5 and T_2) as in traditional Wi-Fi *infrastructure* mode.
- *Step 3*: If a chain of such clusters were connected through multi-hop relaying among the SDAPs/APs, the network reconfiguration can be finally realized and the disaster-area can be recovered.

In the network reconfiguration process, the most important step is to select an appropriate terminal to be the SDAP for a cluster. Due to the narrow corridors of underground mines and the same specification of deployed SDAPs, it is assumed that the SDAPs are with equal coverage areas in underground mines, and they can only be connected to an operational AP via a chain of SDAPs. Next we summarize the two important issues, i.e., the SDAP selection criteria and the SDAP selection period when conducting SDAP selection.

2.2. SDAP Selection Criteria

For instance, there are three terminals, namely T_4, T_5 and T_6, which may serve as the SDAP for cluster C_1. But which terminal is the optimal one to be the SDAP is mainly determined by the following factors:

- *Energy consumption*: when an SDAP is selected considerations shall be given to energy consumption at both intra-cluster communications and inter-cluster communications (e.g., the inter-cluster data relaying between SDAP T_5 of cluster C_1 and SDAP T_2 of cluster C_2). In situations where these two goals are conflicting with each other, a proper trade-off needs to be investigated.
- *Residual energy*: An SDAP operating on the battery mode must assume multiple network functionalities, such as intra-cluster terminal discovery and time synchronizing and inter-cluster information relaying. It will undoubtedly consume a large amount of energy of the SDAP. Therefore, the residual energy of the terminals in a cluster is another important factor to be considered for selecting an appropriate SDAP.

[1] To upgrade the network connectivity, a certain amount of terminals can be reserved in refuge chambers. These terminals could be placed randomly throughout the disaster-area by the trapped-miners after a disaster occurs.
[2] The discovery service provided in Layer two of Wi-Fi standard, allows wireless terminals to discover their neighbors and to establish connections. For a detailed description of the features, the interested reader is referred to [8] and the references therein.

2.3. SDAP Selection Period

Most of the terminals in a PDEN are mobile terminals carried by trapped-miners, and the residual energy of a terminal continually reduces over time. To maintain the network connectivity, while trying to consume as little battery as possible at terminals (thus to prolong the lifetime of the PDEN), it is necessary to change the cluster head (i.e., SDAP) of a cluster on a periodic basis. A generic procedure for periodic SDAP selection is described as follows.

- *Step 1*: Once an SDAP selection is activated in a cluster by a pre-set timer, the current SDAP should broadcast a message to all the terminals in the cluster for requiring their current energy information.
- *Step 2*: After receiving the broadcast message, each client terminal in the cluster should update the related two pieces of information and feed them back to the current SDAP.
- *Step 3*: After gathering the feedback messages, the current SDAP could determine the next optimal SDAP for the cluster (of course it may be itself again) based on some selection rules. Then it broadcasts a message in the cluster to inform all the client terminals the newly selected SDAP.
- *Step 4*: The cluster management task is transferred to the newly selected SDAP, and a new timer for the next SDAP update also starts at the SDAP.

It should be noted that a shorter update interval can reflect the network topology changes more accurately, which in turn potentially reduces energy consumption. However, signaling overhead for such updates may increase.

3. Data Transmission in PDENs

After disasters occur in underground mines, water-inrush and earthquake usually lead to roof-collapse. The rescuers carrying equipment cannot access the accident area immediately. In such a situation, an earth auger is usually used to drill a hole through the blockage. A gateway AP which connects the underground PDEN to the ground-part of the disaster warning system can be delivered through the hole, and the information used for rescue action can thus be communicated between the two previously isolated parts. The data flows transported over PDENs can be classified into the following two categories.

- *Uplink flows*: the uplink transmissions in PDENs are to upload the sensing data to the ground-part of the disaster warning system. The information is important for making rescue plan, and it can also be accumulated as historical data to study the forming mechanism of underground disasters.
- *Downlink flows*: After obtaining the uploaded information from the PDEN, the ground-part of the disaster warning system can make the optimal rescue plans, e.g., the best refuge chamber position and the best escape routes for individual trapped-miners. The information can be distributed to each of the relevant trapped-miners through the downlink transmissions in PDENs.

Next, we can further characterize the specific requirements of the uplink and the downlink transmissions.

3.1. Priority Differentiation for Uplink Transmissions

As part of APs and terminals in underground mines might be crashed in accidents, it results in that the ground decision-making might be paralyzed with incomplete information. It will further lead to inherently impractical relief solutions. To alleviate the incomplete information problem, the authors in [9] propose a data evacuation method inspired by the "blackbox" solution in flight industry. The idea of the data evacuation method is to utilize the surviving time interval of damaged wireless devices, namely, the duration in which these devices still function after a disaster, to sense and transmit vital data to the caches in safe devices. As wireless devices may not be damaged immediately as the occurrence of an accident, uplink transmissions can keep working for a while before they become completely paralyzed.

From an engineering perspective, the more comprehensive information is gathered, and the more precise "the last shot" of accident areas can be reproduced. It is preferably that the transmission priority should be allocated to the APs/terminals in more dangerous situations. Thus they can upload their sensing information before they are ultimately destroyed. For that purpose, we need to differentiate the uplink transmission priorities based on the current devastating degree of the sensing terminals. In detail, the following design metrics should be taken into consideration.

- To estimate the physical damage of an AP or a terminal accurately, a common standard for evaluating the severity of different underground accidents should be defined. As in [9], each devastating event in mines could be described by the following elements: (1) the center point of the zone where the devastating event occurs; (2) the intensity of the devastating event; (3) the attenuation coefficient of disaster propagation; (4) the region that the devastating event affects. In practice, there might be multiple different types of devastating events happen over a same region. However, the definition of a complex mining disaster model is beyond the scope of the communication research area, which can only be accomplished collaboratively with mining engineering. The accumulation of rich historical disaster information will facilitate this work.
- APs and terminals in PDENs should have additional functionalities. For instance, besides gathering normal environmental information, they are required to be able to sense the post-disaster environment, e.g., the intensity of earthquake and the smoke and gas density before gas explosion. Based on these sensing information, the APs and the terminals are able to rank the current safety level of itself, e.g., safe, critical, or dangerous, according to pre-defined evaluation criterion.

3.2. Wireless multicast based downlink transmissions

Since PDENs are battery-powered and are deployed in isolated underground mines, it is infeasible to replace or recharge batteries for the underground APs and terminals. Thus, PDENs are extremely energy constrained, and it is necessary to extend the network lifetime for supporting rescue actions. In literature, network lifetime extension can be implemented through reducing energy consumption for individual wireless devices. Consider the proximate trapped-miners are always in need of the same rescue messages. So, inspired by the ideas proposed in ref. [4], we utilize wireless multicast technology [10] to implement the energy efficiency downlink transmissions.

In recent days, the 3rd Generation Partnership Project (3GPP) has introduced Multimedia Broadcast/Multicast Service (MBMS) in its Release 6 [11] and enhanced it in Release 8 [12] which is called Enhanced MBMS (EMBMS). Although multicast has huge potential to push the limits of NGNs, e.g., acquiring significant improvement in energy and spectrum efficiency and reliable multicast transmission, it is one of the most challenging issues currently being addressed in the context of 3GPP Long Term Evolution (LTE) systems [13]. Among the challenges, an important issue is to reliably disseminate large, rich multimedia content to multiple concurrent recipient UEs over wireless channels with low network overhead [14]. Although wireless point-to-point transmissions (i.e., unicast) successfully uses fixed-rate coding and ARQ mechanism (recipient-initiated requests for retransmission of lost data) to provide reliability, the analogue of this solution is not applicable to wireless point-to-multipoint transmission schemes. Consider a BS distributing a mobile TV entertainment to dozens of UEs. As the UEs lose data packets, their requests for retransmissions can quickly overwhelm the BS in a process known as feedback implosion [15]. Moreover, in order to adapt the multicast rate according to the different channel conditions of the recipient UEs, global channel state information (CSI) is required at the BS. This inevitably brings a huge burden for networks with a large number of recipient UEs. It was outlined in [16] that rateless codes, e.g., raptor codes and fountain codes enable a reliable multicast transmission without CSI feedback and ARQ. Using rateless codes, the BS generates a continuous stream of information bits, e.g., H bits, from the source message, and a different portion of the bit stream is transmitted in each time slot. Then each recipient UE can recover the original message whenever it accumulates a total of H bits over a series of time slots, regardless of which portions of the bit stream were received. This is in sharp contrast with conventional fixed-rate codes where the BS must keep track of global CSI as well as all data packets that each UE has received throughout the content delivery process. Recently, rateless codes have been introduced into the standards of MBMS [11] and DVB [17].

In contrast to unicast, where a transmitter can only send the same file separately to each intended receiver by using different power levels and the applied power depends on the receiver's channel quality, multicast is more efficient to disseminate the same content simultaneously to multiple receivers. It can thus save energy, time and bandwidth resources. However, as the receivers in underground mines may experience very different channel conditions, it is difficult for a multicast transmitter, e.g., an SDAP or an AP, to transmit at a power level and satisfy the rate requirement for each of the receivers. In most cases, the multicast power is selected according to the worst channel to ensure the successful reception at each receiver. When most receivers are in good channels but very few are with poor channels, the receivers with poor channels may become the bottleneck for the multicast. As a result, the required multicast power is absolutely high at the SDAP/AP. To alleviate this bottleneck, we propose to utilize device-to-device (D2D) retransmission [18] to enhance the performance of the wireless multicast services in PDENs. D2D communications [18] are proposed for cellular networks which allow proximate user terminals to communicate with each other directly. The high channel quality of short-range D2D links can facilitate high data rates, reducing transmit powers, prolonging terminals' battery lives, and offloading the heavy traffic of APs.

By allowing the terminals in good channel conditions to retransmit their correctly received data to those experiencing relatively poor channel conditions, such that the AP/SAP can multicast at a low power level. The following concern is how to perform the D2D retransmissions in the most efficient way, i.e., with the least energy, time and frequency resources to achieve the target data throughput. There might be more than one terminals that can decode the multicast data correctly. Retransmission with more terminals can effectively reduce the possibility of single-point failure, but on the other hand, it also consumes more resources. So we face the problem of selecting the proper number of the retransmitter terminals. As different channels always lead to different capacities for the D2D links, we should carefully select the D2D retransmission route to detour those D2D links with poor channels.

In addition, different from traditional cellular multicast service, it may be SDAPs rather than APs that perform multicast in PDENs. Since SDAPs are built upon normal terminals, this introduces additional challenges due to the limited capability of SDAPs. To reduce the multicast burden of SDAPs, the fountain coding method could be used in the physical layer of a PDEN. Fountain codes allow the distributed multicast receiver terminals to recover the full original content of a message once a minimum set of encoded symbols is received, regardless of the specific received sequence of encoded symbols. If the multicast is initiated by an SDAP, it does not need to keep track of the data that each terminal has received throughout the content delivery process. This obviously reduces the huge network burden for SDAPs. To achieve this task, a cross-layer design based algorithm development and optimization should be employed.

3.3. Simulation Results

In [9], the authors have introduced the DE method to differentiate the uplink transmission priorities based on the current devastating degree of sensing terminals. To verify the efficacy of the DE method, extensive simulation has been provided in [9] which can illustrate the fundamental tradeoff between the two design metrics, i.e., evacuation time and evacuation ratio. Interest readers are referred to [9], and, in this section, we only focus on the downlink transmissions. The following simulations are to show that the proposed D2D retransmission based multicast scheme not only can save the transmission energy for the SDAPs/APs, but also can shorten the multicasting time, which is clearly much needed in time-critical rescue actions.

The simulated D2D cluster is shown in figure 4, where the SDAP is located at the coordinate (0 m, 0 m), the number of the client terminals is fixed at 80 and their coordinates are generated randomly in a circle area with radius r = 100 m. We assume that the SDAP needs to disseminate a file with the size of H = 0.1 Mb to all the terminals in the cluster, and the system bandwidth is W = 1 MHz. We consider the channels are with large-scale path-loss attenuation, small-scale Rayleigh fading and additive white Gaussian noise (AWGN). The path gain is set to $0.097/d^4$, where d is the distance between the transmitter and the receiver (in meters). The channel gains between any two terminals are independent and exponentially distributed, which corresponds to Rayleigh fading of their amplitudes. The channel gain γ between any two terminals has the probability density function (pdf) $f_\gamma(\gamma) = \frac{1}{\gamma}\exp\left(-\frac{\gamma}{\bar{\gamma}}\right)$, where $\bar{\gamma}$ is the mean channel gain of the channel. We set $\bar{\gamma} = 1$.

When traditional multicast scheme (TMS) being used, the transmit power of the SDAP is set to P_{SDAP} = 1 W. To reduce the network overhead for acquiring the channel state information of the SDAP, we employ fountain codes [10] in the system. Therefore, the SDAP can generate a continuous flow of source bits from the intended message so that any collection of 0.1 Mb from the data flow can guarantee reliable recovery of the original message regardless of which portions of the bit flow were received. In the D2D retransmission based multicast scheme (DRMS), selected terminals (that have correctly received the multicast message) are allowed to retransmit their message via the D2D links.

First, we show the impact of the D2D retransmitter number on the energy consumption of the multicast. We designate the first N terminals which have successfully decoded the 0.1 Mb message as the D2D retransmitters, and their retransmission power is set to $P_{\mathrm{UT}} = 0.1$ W. In the simulation, we vary the AGWN at the receiver terminals from −110 dB to −70 dB, and we increase the number of the D2D retransmitters N from 1 to 19 at a step of 3. After averaging over 1000 channel realizations, the simulation result is shown in Fig. 1, where the energy consumption ratio is computed as the ratio of the total energy consumption in the DRMS to the energy consumption in the TMS.

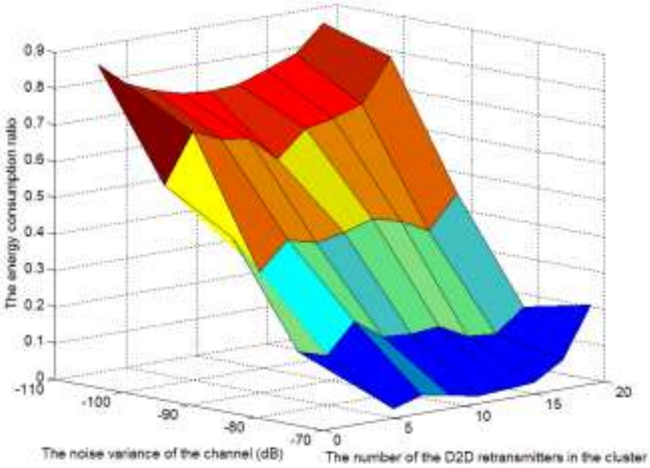

Fig. 1: The energy consumption for downlink transmission

From Fig. 1, we observe that the energy consumed in the DRMS is always lower than that consumed in the TMS. The DRMS can save more energy in the low signal to noise ratio (SNR) region. For example, when the noise variance is higher than −90 dB, nearly 70% energy can be saved by the DRMS. In addition, we can also observe that the energy consumption in the DRMS has little relationship to the number of the D2D retransmitters. Nevertheless, a best performance can be achieved when the number of the D2D retransmitters is just half of the total number of the terminals in the cluster.

Next, we show the impact of the number of the D2D retransmitters on the time consumption of the multicast. Using the same simulation settings as above, after averaging over 1000 channel realizations, the simulation result is shown in Fig. 2, where the time consumption ratio is computed as the ratio of the total transmission time consumed in the DRMS to the time consumed in the TMS.

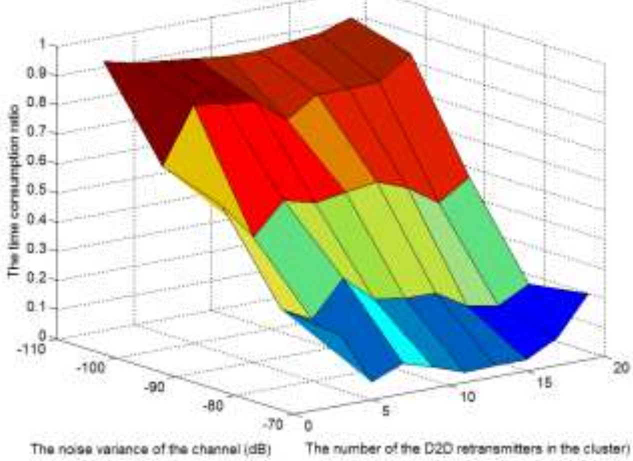

Fig. 2: Transmission time of the DRMS

From Fig. 2, we observe that the transmission time consumed in the DRMS is always lower than that consumed in the TMS. The transmission time of the DRMS is only 10%~30% when the noise variance is higher than −90 dB. Again, we see that time consumption of the DRMS has little relationship to the number of the D2D retransmitters in the cluster. Nevertheless, a minimum transmission time can be always achieved when the number of the D2D retransmitters is half of the total number of the terminals in the cluster[3]. The reason can be explained as follows. As the number of the D2D retranmitters increases (from 0 to the half of the total client terminals in the system), the transmission rates of the other client terminals increase due to the cooperative relaying of the D2D retransmitters. However, as the number of the D2D retransmitters increases further (from the half to the whole of the client terminals in the system), the system degrades gradually to the traditional multicast system due to the decrease of the cooperation gain. Hence, we can draw a conclusion that the proposed DRMS can effectively improve the energy efficiency and real-time performance of the downlink transmission in PDENs.

4. Conclusions

This article proposes to utilize the survived APs and terminals to rebuild the communication network in post-disaster underground mines. To ensure the damaged terminals can timely upload their sensing information to the safety terminals before losing their sensing ability, a priority differentiation scheme is proposed for the uplink transmissions. To extend network life to support rescue actions, a D2D retransmission based multicast scheme is proposed for downlink transmissions. The simulation results show that the proposed methods can effectively improve the energy efficiency and real-time performance of the emergency network.

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