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A Wireless LAN and Voice Information System for Underground Coal Mine

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Abstract: In this paper we constructed a wireless information system, and developed a wireless voice communication subsystem based on Wireless Local Area Networks (WLAN) for underground coal mine, which employs Voice over IP (VoIP) technology and Session Initiation Protocol (SIP) to achieve wireless voice dispatching communications. The master control voice dispatching interface and call terminal software are also developed on the WLAN ground server side to manage and implement the voice dispatching communication. A testing system for voice communication was constructed in tunnels of an underground coal mine, which was used to actually test the wireless voice communication subsystem via a network analysis tool, named Clear Sight Analyzer. In tests, the actual flow charts of registration, call establishment and call removal were analyzed by capturing call signaling of SIP terminals, and the key performance indicators were evaluated in coal mine, including average subjective value of voice quality, packet loss rate, delay jitter, disorder packet transmission and end-to-end delay. Experimental results and analysis demonstrate that the wireless voice communication subsystem developed communicates well in underground coal mine environment, achieving the designed function of voice dispatching communication. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Underground coal mine, Wireless Local Area Networks (WLAN), Wireless-Fidelity (Wi-Fi), IEEE 802.11b, Voice over IP (VoIP), Session Initiation Protocol (SIP).

1. Introduction

1.1. Demand Analysis

Coal mining is mainly carried out underground, and underground tunnel is often tens of kilometers long. The procedure for mine production is numerous, operating location is scattered, and personnel is mobile. Besides, the working condition is harsh, and potential accident is high. These features of underground coal mine production make it urgent to establish a full-function wireless information system covering the entire mine, which integrates wireless voice communication, video surveillance, short message service, equipment control, environmental monitoring and personnel locating into one. Such a system can significantly improve the management level, productivity and safety of the workers for underground coal mine production.

1.2. Existing Technology

The peculiar nature of space and environment restricts the development of the wireless communication system for underground coal mine. So far, there is still not a kind of wireless communication system for coal mine with full-function. The wireless communication systems being used at present mainly include through-the-earth communication system [1], leaky communication system [3] and medium frequency inductive communication system [4, 5]. There are serious limitations in function or in actual use for these systems. For example, the through-the-earth communication system is generally only suitable for one-way communication that the ground send and the underground receive; the leaky communication system is influenced greatly by moist, watering, corrosive gas, dust and others in mines, the fault rate of repeaters, equipment joints and cables in the system is high, hence it is difficult to maintenance; and the medium frequency inductive communication system is influenced greatly by conductors in tunnels, the channel is instable and is susceptible to other electromagnetic waves.

1.3. Technical Development

In order to improve the information level of underground coal mine production, a wireless information system was developed by adopting the current mature WLAN technology. The system integrates traditional decentralized and redundant construction systems for coal mine with different functions into one system, with capacities of wireless voice communication, wireless video surveillance, short message service, equipment control, environmental monitoring and personnel locating [8, 11].

The WLAN technology based on IEEE 802.11b standard [7] is adopted by the wireless information system, which has become the main trend of wireless data communications, with operating frequency of between 2400 and 2483.5 MHz, that is, the total bandwidth is 83.5 MHz. The total bandwidth is divided into 14 sub-channels. The bandwidth of each sub-channel is 22 MHz. To ensure no interference between channels under the condition of many channels working simultaneously, it is required that the center frequency interval between two adjacent channels cannot be less than 25 MHz.

In order to improve the performance of WLAN, technologies such as spread spectrum, power control and diversity reception, are employed by the IEEE 802.11b standard [7]. This standard employs an encoding scheme, named Complementary Code Keying (CCK) based on Direct Sequence Spread Spectrum (DSSS), with characteristics of fixed frequency anti-interference, multipath anti-interference, large transmission range, and high data rate (11 Mbit/s). According to the IEEE 802.11b standard, the spread spectrum processing gain is larger than 10 dB and the CCK processing gain is 11 dB while using DSSS. This makes it suitable for the receiver to work correctly in underground coal mine where multipath interference is intensive. As defined in IEEE 802.11b, when the data rate is 5.5 Mbit/s, each carrier is encoded with 4-bit by using CCK; when 11Mbit/s, encoded with 8-bit. In this way, the system can adopt an appropriate data rate to avoid inter-symbol interference according to the different wireless transmission conditions of underground coal mine.

WLAN employs power control technology to adjust the emissive power and automatic gain control circuit in the receiver channel to compensate the impact of signal fading. The WLAN terminal is in a mobile state, the signal strength changes significantly, therefore, the IEEE 802.11b selects and merges two or more multipath signals with small relevance, that is, the diversity reception technology, reducing the impact of signal fading. These technologies also play an important role in guaranteeing the reliable wireless transmission under the complex condition of underground coal mines.

2. Network Structure

2.1. Network Technology

Owing to the advantages of quick and convenient wireless access, easiness of manage and maintain, flexible topology and low-cost construction, WLAN is an effective wireless communication platform of constructing wireless information system for underground coal mine [14]. The wireless information system for underground coal mine based on WLAN mainly consists of ground servers, voice switches (IP PBX), network routers, switching hubs, wireless access points (AP), optical fiber lines, wireless cameras and Wireless-Fidelity (Wi-Fi) phones. The network topology is shown in Fig. 1.

The ground server is installed on the PC, which is used to manage all equipments in networks, including wireless access equipments, and receive packets AP sends. Authorized users can log on the server via LAN or Internet, and know the situations of underground coal mine production and security or operate the underground equipment via the client browser.

The wireless voice communication employs VoIP technology, that is, integrate VoIP technology into the system [9]. The wireless voice communications can be achieved by way of installing SIP soft-switch software [12] on the ground server or configuring separate IP PBX to manage the IP phone in the networks, the IP PBX works as a user agent to complete the registration and exchange of the user information.

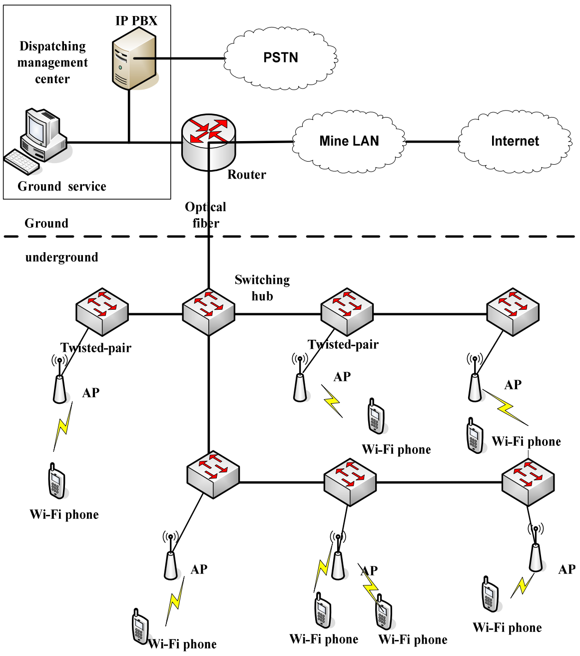


Fig. 1. Network topology of the wireless information system for underground coal mine.

The network router is used to connect multiple networks separated logically, with functions of determining the network address and selecting a route. It can establish flexible connections in many inter-networks environment, and connect various subnets by means of completely different data packets and media access methods. The router only accepts the information of source stations and other routers, which is a network layer device.

The switching hub forwards the re-generated information to the designated port after internal processing, with capabilities of automatically addressing and exchanging. It transfers independently each information package to be delivered from the source port to the destination port according to the destination address, avoiding the collision between it and other ports. Therefore, the switching hub can transfer multiple packets simultaneously without mutual effect, preventing transmission collisions, and improving the actual network throughput.

The wireless AP is a bridge between the wired network and the wireless network in the underground WLAN, and is composed of a wireless output port and a wired network interface, namely 802.3 interfaces [7]. Like a base station in a wireless network, the wireless AP gathers all terminal equipments to the wired network. In addition, with capabilities of network management, the AP manages terminal equipments if necessary. Given that the wireless signals will fade seriously while passing curving tunnels in underground environment, the wireless AP in tunnels should meet the requirements of line-of-sight transmission or relay AP should be placed at curving points in tunnels, to improve the network reliability.

For the backbone transmission network of the underground WLAN, optical cables should be used. Routers should have capabilities of redundant backup and self-recovery function, to ensure normal communications in the event of emergency. Power should be supplied independently for all wireless devices such as APs, wireless network cameras and mobile terminals to improve the network reliability, and to prevent electromagnetic interference between devices.

2.2. Logical Structure of System

The wireless information system for underground coal mine, mainly consisting of wireless voice communication, wireless video surveillance, short message service, equipment control, environmental monitoring and personnel locating, the logical structure of which is shown in Fig. 2.

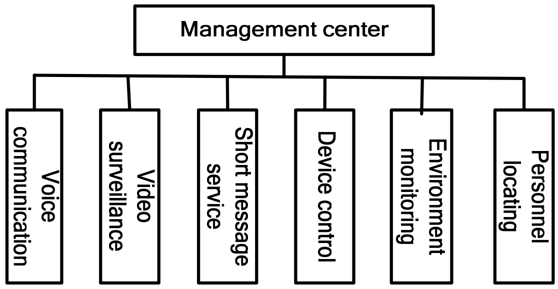


Fig. 2. Logical structure of the system.

3. System Control Software

The management and control of the wireless information system for underground coal mine is implemented by the system control software on the ground server, which is developed in C# programming language under the development environment of Visual Studio 2005, as shown in Fig. 3.

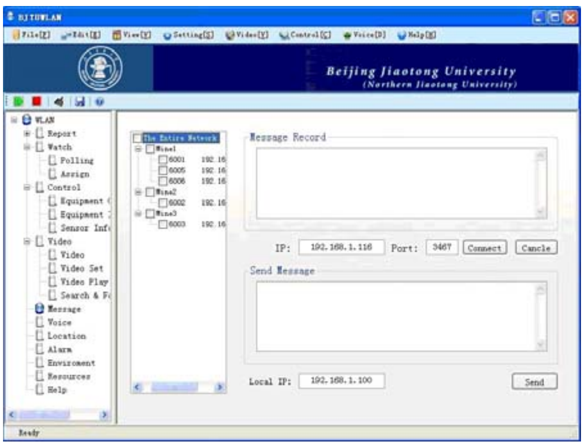


Fig. 3. System control software.

As can be known from the left side of Fig. 3, the system control software mainly consists of modules, including wireless voice communication, wireless video surveillance, short message service, equipment control, environmental monitoring and personnel locating. The software realizes each function by calling the corresponding function module which is developed in C++ programming language. Dynamic link library (DLL) technology is employed to combine the function modules with the system control software, that is to say, each function module is encapsulated as a DLL file in advance. The system control software calls the DLL files to implement the call of each of function modules.

4. Wireless Voice Communication Subsystem

4.1. Wireless Voice Communication

The wireless voice communication subsystem for underground coal mine achieves wireless voice communication via Session Initiation Protocol [12]. Session Initiation Protocol is a signaling protocol of IP phones, which is proposed by Internet Engineering Task Force (IETF), and is based on plain text. It can manage the sessions in different access networks and support any type of communications between terminal devices, such as instant information processing, video session and collaboration session.

The Wi-Fi phones, called SIP terminals, are distributed for the underground miners according to the actual needs, and number them (e.g. 6001). The IP PBX adds identification (ID) number and IP address for SIP terminals according to the number. Then the wireless voice communication can be achieved in the wireless information system as shown in Fig. 1.

The development of the wireless voice communication subsystem for underground coal mine mainly includes the development of a voice dispatching interface and the development of a call terminal based on SIP on the ground server, namely SIP terminal software, as shown in Fig. 7 and Fig. 8 respectively. On the one hand, the dispatching interface displays the distribution of each of SIP terminals underground; on the other hand, it can start the SIP terminal software and smartly schedule the call object. The SIP terminal software numbers SIP terminals and registers IP address information via IP PBX, and can call other SIP terminals by selecting free lines.

4.2. Voice Dispatching Interface

The voice dispatching interface is mainly used to display the distribution of underground SIP terminals and start the SIP terminal software. SIP terminals are displayed by means of storing their distribution information. There are two ways to start the SIP terminal software, one of which is to initiate SIP calls via the menu item in the menu bar, the other is to choose a SIP terminal displayed on the voice dispatching interface and then click the "buttonVoice" control on the interface. The interface defined a total of three controls: buttonRegister, buttonVoice and buttonHangup, corresponding respectively to registering SIP, initiating SIP call and hanging up call. The starting flow chart of the SIP terminal software in the voice communication subsystem is shown in Fig. 4.

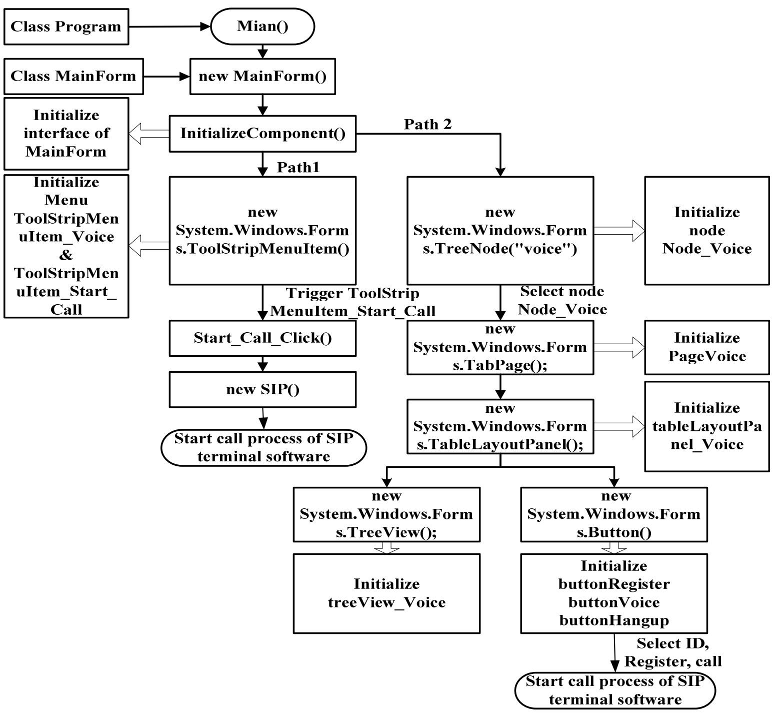


Fig. 4. Starting flow chart of the SIP terminal software.

As shown in Fig. 4, it is needed to define some controls and components for the development of the dispatching interface. Thus, the SIP terminal software can be started via the event processing functions that these controls and components correspond to.

4.3. SIP Terminal Software

The SIP terminal software based on SIP protocol is developed in C# programming language. The whole SIP terminal software is designed as a SIP class which contains the interface with SIP terminals and the event processing functions associated with the interface controls. There are mainly five core controls designed: registration button, call button, hang-up button, answer button and refuse-to-answer button, which started the event processing functions to achieve the corresponding functions. The running flow chart of the SIP terminal software is shown in Fig. 5.

After the design and development of the voice dispatching interface and the SIP terminal software of the voice communication subsystem, the system control software may implement voice dispatching communications under the coordination of the IP PBX. In addition, increased functions such as group call, urgent call, three-way call and telephone conference could be easily achieved according to the actual need, to meet the higher demands of the wireless voice dispatching communication for underground coal mine.

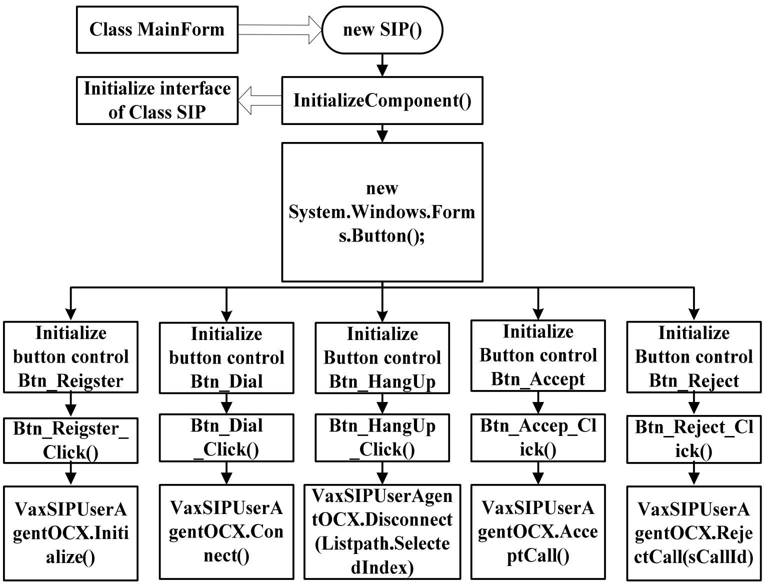


Fig. 5. Running flow chart of the SIP terminal software.

5. Underground Coal Mine Testing

The major functions of the wireless voice communication subsystem for underground coal mine were tested in 411-meter-deep level tunnels in Shangwang coal mine, in Erdos, Inner Mongolia, China. Test scenario in tunnels, equipment connection of the testing network and the layout of testing system along tunnels are shown in Fig. 6a, Fig. 6b and Fig. 6c respectively. The main tunnel is about 4.2-meter wide, 4-meter high, and the transmit power of APs is 20 dBm.

5.1. Communication Process Testing

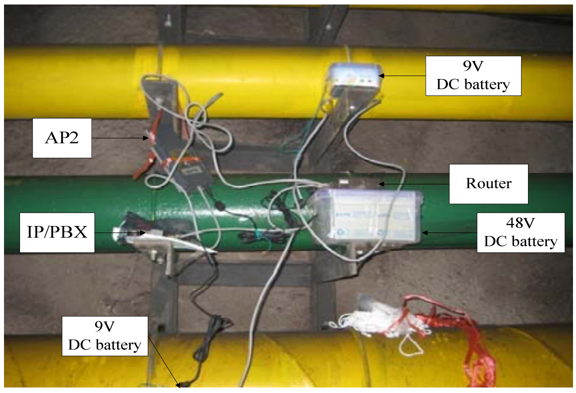
Add two Wi-Fi phones named 6001 and 6004 respectively to the IP PBX, the IP address of 6001 is 192.168.1.107, and 6004 is SIP terminal software on the voice dispatching server side. Fig. 7 shows the voice dispatching interface in testing. Then, register the two SIP terminals on the IP PBX, and click the phone icon on the interface, 6004 calling 6001. The call interface is shown in Fig. 8.

By capturing SIP call signaling between 6001 and 6004 via the Clear Sight Analyzer, the communication processes between 6001 (192.168.1.107) and IP PBX, as well as between IP PBX and 6004 are found, which are shown in Fig. 9 and Fig. 10 respectively. In Fig. 9 and Fig. 10, TD means Time Difference, RTA means Real-Time Analysis.

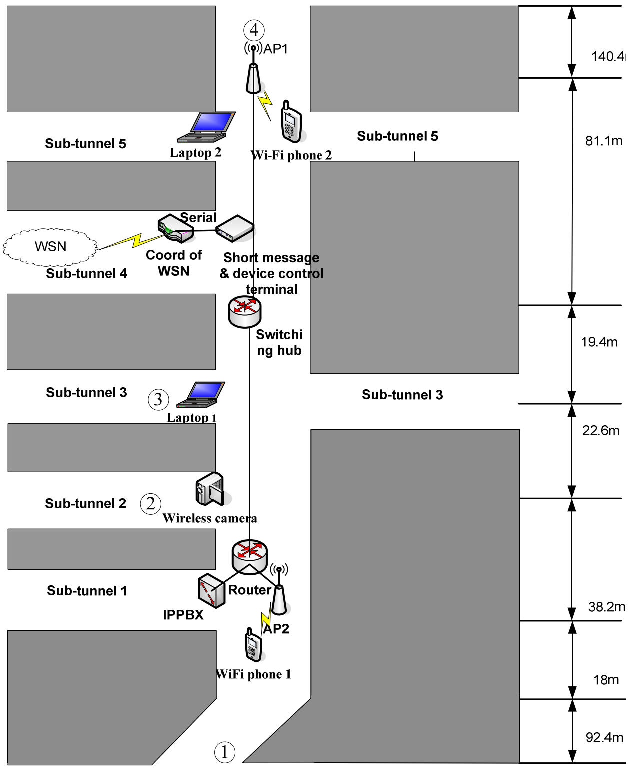
The analysis of the SIP signaling above results in the registration process of SIP voice call, which is shown in Fig. 11.

After registration of the Wi-Fi phone, the processes of establishing and removing SIP call on SIP terminal software are going on, and the analysis results are shown in Fig. 12.

(a) Test scenario in tunnels



(b) Equipment connection of testing network



(c) Layout of testing system along tunnels

Fig. 6. Introduction of testing system.

Fig. 7. Voice dispatching interface.

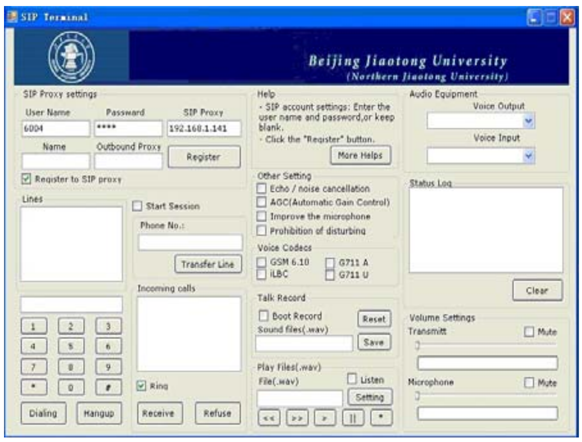


Fig. 8. Call interface.

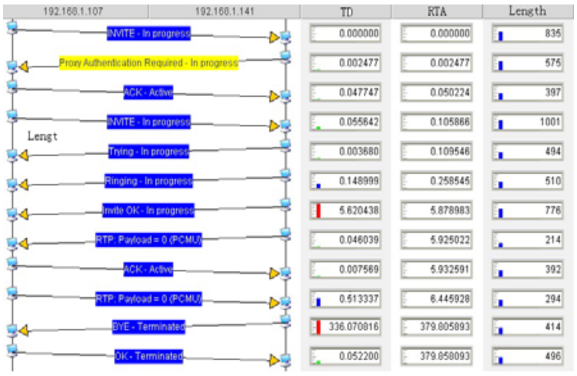


Fig. 9. The communication process chart between 6001 and IP PBX.

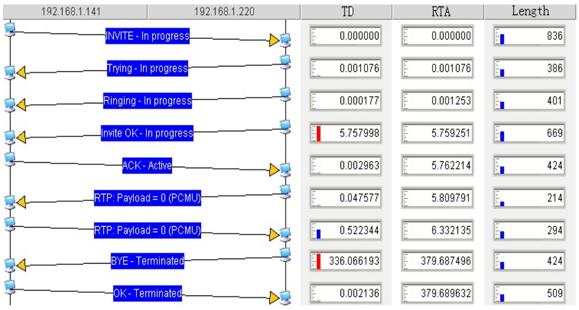


Fig. 10. The communication process chart between IP PBX and 6004.

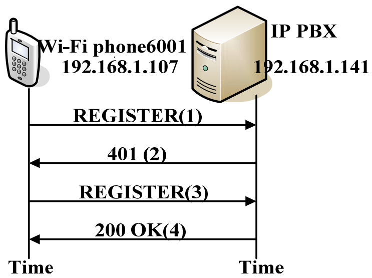


Fig. 11. Registration process of user.

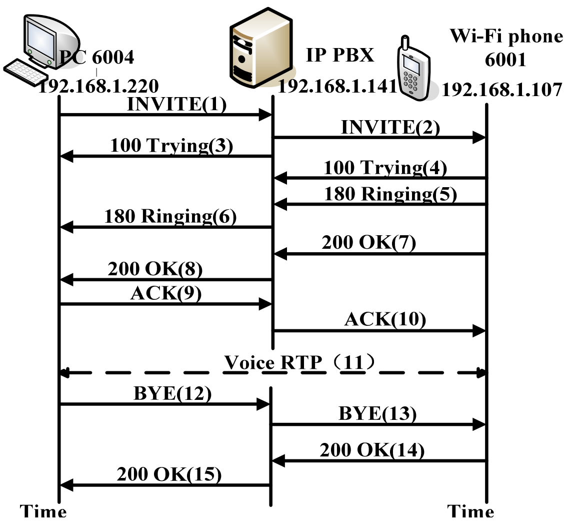


Fig. 12. Calling process of user through IP PBX.

According to the above testing and analysis of registration of the Wi-Fi phone, and the processes of establishing and removing SIP call between the Wi-Fi phone and the SIP terminal software, it is proved that the function of SIP voice dispatching communications designed for the voice communication subsystem for underground coal mine achieves the design requirements.

5.2. Voice Communication Coverage Testing

As shown in Fig. 6 (c), while Wi-Fi phone 2 moving from AP2 to AP1, the distance of wireless communication and the corresponding field intensity were logged at a total of four test points, which were test point 1: around AP2; test point 2: sub-tunnel 2; test point 3: sub-tunnel 3; test point 4: around AP1. The results are recorded in Table 1.

Table 1. The results of the distance and the corresponding field intensity.

Wi-Fi Phone 2	Distance to AP2 (m)	Distance to AP1 (m)	Field intensity within AP2 (dBm)	Field intensity within AP1 (dBm)	AP subor-dinated
Test point 1	110.4	271.7	-85	-90	AP2
Test point 2	38.2	123.1	-70	-89	AP2
Test point 3	60.8	100.5	-85	-88	AP2
Test point 4	301.7	140.4	-90	-85	AP1

As can be known from Table 1, the wireless voice communication range is about 140.4 m in the case of line-of-sight transmission (e.g. test point 4). The range was about 110.4 m in the case of curving tunnels (e.g. test point 1). Under the condition of same transmit power, the average communication range measured underground coal mine is about 50 m longer than that tested on our campus, which is out of our expectation. We believe that the premier reasons are as follows: the operating frequency of WLAN is 2.4 GHz, which is IMS opening band, there are other WLAN on our campus, therefore, there are co-channel interference and adjacent channel interference between these WLAN, affecting the voice communication range, while there are no such interference in underground coal mine; on the other hand, the testing cross section of the tunnels is wide, and no obvious obstacles exist in the tunnels. These factors make that the voice communication effect examined underground coal mine is even better than that on our campus.

6. Analysis of Voice Quality

Voice quality of VoIP is an assessment criteria of service level provided to users [4]. Quality of Service (QoS) is considered as a degree of network reliability to meet the needs of a particular application service. According to the report of VoIP analysis generated during the underground testing, a total of four performance parameters affecting VoIP quality of the voice subsystem are analyzed via Clear Sight Analyzer, which are end-to-end delay, delay jitter, packet loss rate and transmission of disorder packets.

6.1. Overall Performance Indicator

Means Opinion Score (MOS) is generally considered as a measure of the VoIP QoS index [10]. When MOS is 4 or larger, the voice quality is considered to achieve the telecommunication level which may collect fees; when smaller than 3.0, it is considered not to satisfy most listeners. R-value is a number of between 1 and 100 that is used to quantify the voice subjective quality of the voice communication system, in particular the digital network with transmission of VoIP via μ law [13]. R-value is used in the sound testing process, which is obtained according to the degree of users' satisfaction with the sound signal, that is, when R-value is larger than 80, the user will satisfy with the sound signal; while R-value is smaller than 60, almost all users won't satisfy with it. The overall performance indicators of the testing network were generated automatically by Clear Sight Analyzers, including MOS, which are shown in Fig. 13.

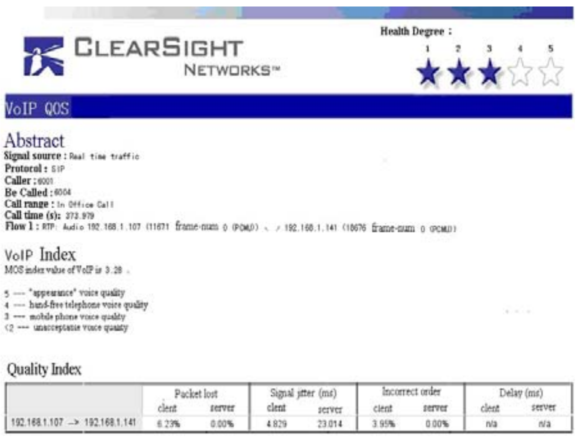


Fig. 13. The whole VoIP QoS index of the testing network.

Fig. 13 shows four performance indicators in terms of packet loss rate, signal jitter, disorder and delay that can reflect the voice quality of systems. As can be known from Fig. 13, during the call time of 373.979 seconds, MOS was 3.28. According to the voice communication between the underground staff via Wi-Fi phones, it was indicated that QoS of the developed wireless voice communication subsystem for underground coal mine met the listening quality requirements for the voice communication.

6.2. Packet Loss Rate

Packet loss refers to that packets carrying voice frames do not reach the receiver in time [6]. The main causes of it include data packets are damaged during the network transmission, and data packets are discarded for network congestion, network fault, or reaching the receiver too lately. As can be known from Fig. 14, which shows the packet loss report of testing network, in the uplink transmission from the client Wi-Fi phone (IP address is 192.168.1.107) to the voice server (IP address is 192.168.1.141), 11671 packets were sent, 776 packets were lost, so packet loss rate was approximate to 6.6 %; in the downlink transmission from the voice server to the client Wi-Fi phone, 18676 packets were sent, no packets were lost, so packet loss rate was 0. In general, the voice transmission can be ensured real-time if packet loss rate is lower than 8 %.

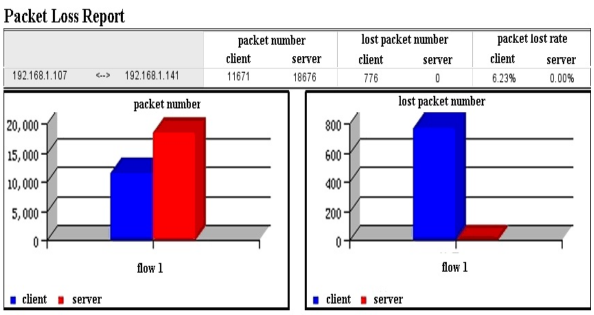


Fig. 14. The report of packet loss.

6.3. Delay Jitter

Delay jitter refers to the differential value between end-to-end delays of two continuous packets in data stream [2], which is the result of delay variation between packets of Real-time Transmission Protocol (RTP). Delay jitter has a significant impact on the transmission performance of VoIP services, and is disadvantageous for reconstructing voice packets by original sequence and cycle model. Queue delay in routers is a common cause of it, if the RTP packet in routers must wait other packages before sent, jitter occurs. Most VoIP phones can handle jitter of up to 40 ms before voice quality is degraded. As can be known from Fig. 15, which shows the jitter report of testing network, the client jitter delay of testing network was 4.829 ms, the server jitter delay was 23.014 ms, far shorter than the dithering limit of 40 ms. Thus, both the Wi-Fi phone and the SIP terminal software on the voice dispatching server side had sufficient capacity of dealing with these jitters, to ensure that the voice information was transmitted in a relatively stable state.

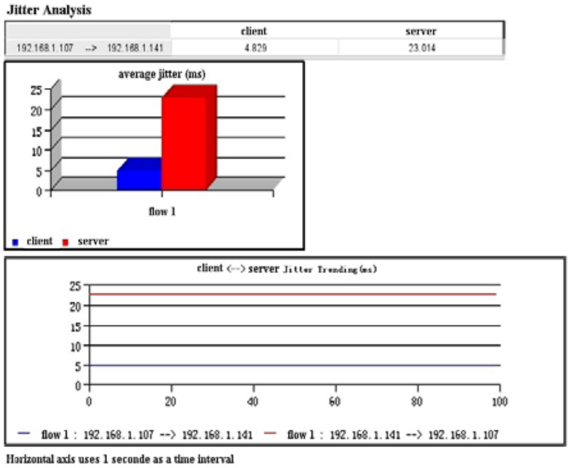


Fig. 15. The analysis report of jitter.

6.4. Transmission of Disorder Packets

Each voice frame has a serial number, which is placed at the RTP header to mark the correct order of packets in the stream. In general, if the serial number is monotone increasing, then no datum in the connection and transmission of the stream lose, and there are no logical path faults in the network. Whereas, if there are disorder packets in the transmission along network paths, then the order of voice frames reach the receiver is changed. In extreme cases, the transmission of disorder packets would affect seriously the quality of VoIP services [2].

As can be known from Fig. 16, which shows the report of disorder packets, in the uplink transmission from the client Wi-Fi phone (IP address is 192.168.1.107) to the server IP PBX (IP address is 192.168.1.141), 11671 packets were sent, 461 packets' order was incorrect, so the rate of incorrect was smaller than 4 %; while there was no packets in incorrect order at the server side, indicating that RTP packets reached the receiver basically in order.

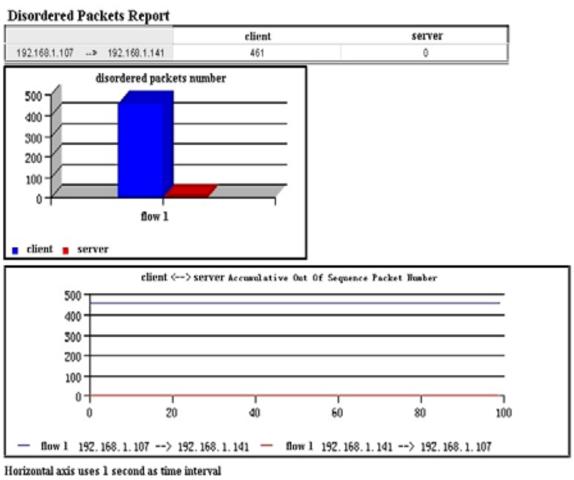


Fig. 16. The report of disorder packets.

6.5. End to End Delay

End-to-end delay is one of the most important factors that affect the quality of interactive voice communications, which must be controlled within a certain range [2]. For users, the strict end-to-end delay refers to the delay of the voice information from the sender' s mouth to the receiver's ear, but in general, only considering the delay of packets carrying voice information from the sending system to the receiving system. The end-to-end delay varies with the different network loads, the shorter the end-to-end delay is, the better the voice quality users feel is. As to the testing wireless voice subsystem, since the router and the voice server were connected by optical cable, and the distant between them was small, then the end-to-end delay between them was close to 0. Therefore, the network end-to-end delay mainly referred to the delay between the Wi-Fi phone and the voice server. As can be known from Fig. 17, which shows the report of delay analysis, the delay between the client and the server was 0.5 ms. R-value and MOS on the client side were 66.36 and 3.28 respectively, while R-value and MOS on the server side were 91.63 and 4.37 respectively. Therefore, the delay of the whole voice communication subsystem was very short, and the quality of the overall voice communication was excellent.

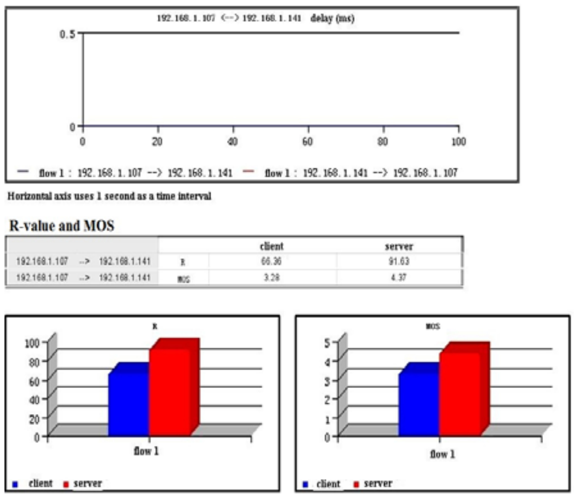


Fig. 17. The analysis report of delay.

7. Conclusions

According to the actual requirements of underground coal mines, adopting the IEEE 802.11b WLAN technology, the wireless information system for underground coal mine was constructed, and the wireless voice communication subsystem was developed. The underground actual testing results show that the server management system developed has capacities of registering Wi-Fi phones, establishing and removing calls via the voice dispatching interface, achieving the voice dispatching function. The performance indicators of the service quality of the developed wireless voice communication subsystem for underground coal mine in terms of MOS, packet loss, delay jitter, transmission of disorder packets and end-to-end delay, have met the technology requirements of the voice transmission based on VoIP technology. In addition, it is also demonstrated that the voice coverage of the system along tunnels is well for little interference from other system in underground coal mine environment. At this point, it is feasible to construct the wireless information system for underground coal mine based on WLAN technology. These efforts will lay important foundations for the further development and concrete implementation of such a system.

Acknowledgements

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