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In-Cave Wireless Communication System

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***Abstract*— Usually wireless communication is preferred to wired communication within caves considering the known difficulties of laying wires and related equipment in such rugged environments. Nevertheless both the inner structures of the caves and RF challenging conditions within the caves make the use of wireless solutions, like walkie-talkies or CB radios, deficient. In this paper, we propose a Wireless Multimedia Sensor Network (WMSN) based communication architecture which can guarantee a desired level of uninterrupted connectivity and communication quality. Our proposed system, which is called In-Cave Wireless Communication System (ICWCS), consists of backbone nodes and mobile nodes which design is based on our previous general purpose wireless sensor node VF1A[4]. Backbone nodes are basically responsible for the connectivity within the ICWCS network, whereas mobile nodes have similar functionality like cellular phones. ICWCS provides reliable and efficient communication within caves.**

Keywords- In cave communication, wireless multimedia sensor networks, wireless multimedia sensors, voice streaming, voice over sensor network

I. INTRODUCTION

In this paper, we propose robust voice communication architecture for caves based on wireless multimedia sensor networks. Although the outdoor use of radio frequencies (RF) for communication has been a very ingrained and convenient technique for a quite long time, indoor environments make the use of RF signals for communication difficult because of attenuation, reflection, refraction, diffraction and scattering that have negative effect on RF signals [1]. In caves, obstacles such as walls, rocks and curvatures with rough surfaces amplify the negative effects of the aforementioned distortions on the RF signals, making wireless voice communication especially difficult [6][7]. Our proposed architecture aims to overcome these difficulties by use of a Wireless Multimedia Sensor Network (WMSN) with densely deployed backbone nodes and scattered mobile nodes, so RF communication between mobile nodes over the backbone can guarantee a desired level of uninterrupted connectivity and communication quality.

There are some different types of cable-based systems used for in-cave communication. One of them is known as "single-wire telephone (SWT)". The SWT, also known as earth-return telephone, uses the conductivity of the ground to provide a return path for the current. So, only one core cable is used in SWT, which reduces the weight of the cable by fifty percent [2].

In caves, both coaxial and single core copper cables become bulky to handle especially with increased cable lengths. Therefore more weight efficient solutions for in-cave communication are preferred. One such solution is the use of optical fibers. Optical fibers weigh less, have greater bandwidth and noise immunity compared to copper cables which tend to pick up random noise from the environment with longer cable lengths [3].

Although noise and cable weight problems can be compensated with the use of optical fibers, there are still problems associated with the installation of these cable based communication network within caves. Caves with multiple paths require the cables to be split into multiple branches and each branch requires a connection to the main cable. These connections can be made relatively easily with copper cables but each new connection has negative effect on the communication quality. On the other hand, connecting optical fibers together is a highly skilled task and requires the use of special hardware.

Therefore, in this paper we propose a WMSN based architecture for in-cave communication which is basically composed of densely deployed backbone nodes and scattered mobile nodes. We call our proposed solution In-Cave Wireless Communication System (ICWCS).

II. RELATED WORK

The first theoretical results about the real-time streaming capability in a generic multi-hop WSN is presented in [13]. The authors define capacity bounds in order to estimate the amount of data can be delivered in real-time by sensor nodes before packet deadlines. They proposes different media access schemes for real-time communication over sensor networks with the goal of bounding the end-to-end delay.

Voice transfer over low-power multi-hop wireless networks has been investigated in several recent studies. Systems for voice streaming over WSN are presented in [10]. They developed *FireFly,* a sensor node which adopts a TDMA-based network scheduling to meet audio timing requirements. It is equipped with a dual radio system used for low-power wake-up radio triggering. The sensor platform is built on a stable framework for real-time streaming and provides several features, such as a TDMA link layer capable of collision-free communication, multiple-task scheduling on each node and an implementation of low-rate low-complexity network scheduling.

Li, Xing, Sun and Liu [9] reported the design and implementation of Quality-aware Voice Streaming (QVS) for WSNs. QVS has been built upon SenEar, a new sensor hardware platform they developed for high-bandwidth wireless audio communication. The primary design objective of QVS is to provide *robust* voice quality for concurrent voice streaming in dynamic environments. QVS employs an empirical voice model to automatically evaluate the current voice quality of streams and provide feedback for audio compression/duplication adaptation. This mechanism can achieve robust voice streaming in the face of dynamic variations in link quality and network topology. To support multiple concurrent voice stream transfers, QVS adopts a distributed admission control algorithm that assigns stream data rates based on available network capacity measured by each node locally.

In [11], Brunelli and Teodorani analyze the feasibility of voice transmission over commercial off the shelf ZigBee hardware. They implemented a low cost and low-power system capable of real-time streaming across multiple hops adopting an architecture based on the system on chip CC2430 [14].

The design goal of the systems mentioned above is to support the transfer of voice streams from nodes to the sink. In contrast, our system is designed to transfer of voice streams also between nodes.

III. WMSN FOR CAVE COMMUNICATION

The basic purpose of ICWCS is to provide a reliable voice communication channel over a WMSN between the members of a team in a cave as shown in Fig. 1. ICWCS consists of two different types of nodes. The skeleton of this network is formed by "backbone nodes" which are mounted on the walls of the cave. "Mobile nodes", which have similar functionality like cellular phones, are carried by the team members.

A. *Backbone Nodes*

Backbone nodes are stationary nodes and their design is based on our previous general purpose wireless sensor node "VF1A" [4]. They have a processor module, an RF transceiver module, a memory module and a power management module. These nodes are responsible for maintaining the backbone connectivity within the cave, the registration and roaming activities of mobile nodes, routing call information between mobile nodes, and carrying the control and voice data over the wireless network.

B. *Mobile Nodes*

Mobile nodes are carried by cavers and include features beyond the standard ones of a wireless sensor node for the interaction with the cavers. These features include a graphical display, a microphone, an earphone and a control keypad.

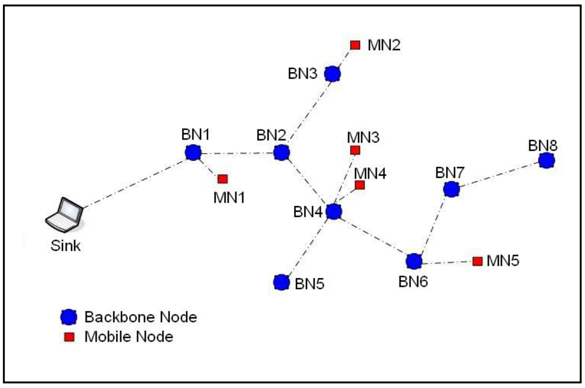

Figure 1. ICWCS Network

The graphical display is used to inform the user about the current status of the mobile node which includes RF signal strength, remaining battery capacity, connected backbone node, etc. The control keypad is used to manage both incoming and outgoing voice calls. The design of the mobile nodes is also based on VF1A, but as stated above has some extra features. Also for digitizing and playing back of voice a low power codec was added to the design of VF1A.

C. *Directory Service*

In wireless sensor networks, nodes lack a global id like an IP address in legacy networks, therefore a simple yet efficient method for addressing nodes is required. VF1A sensor nodes have a unique 64-bit id which was used for the identification and addressing of the nodes in ICWCS.

Each mobile node and thus its user are registered to the ICWCS directory server, which stores the ids of the backbone and mobile nodes, usernames, status and location information of the mobile nodes. The information stored in the directory server is used for establishing real-time communication between online users, monitoring and detecting battery related connection failures, and to narrow the reconnaissance area in the case of a rescue operation within the cave.

Each backbone node also registers itself to the ICWCS directory server for backbone network monitoring. Status information including remaining battery capacity of backbone nodes will be sent to the directory service periodically.

The directory service is usually run on a computer outside the cave, but to accelerate directory operations, backbone nodes employ a caching mechanism. The information within the cache of the backbone nodes is updated periodically.

IV. ICWCS OPERATION

Several steps including deployment, initial setup, etc. must be performed before an ICWCS becomes operational. The details of these steps are given in the following subtopics.

A. *Deployment*

Wireless sensor networks can be deployed either manually or randomly. In ICWCS, the backbone nodes are required to be deployed manually as the cavers move along the cave farther. Each backbone node has a simple RSSI indicator, which shows the connection quality to the last deployed backbone node, so the user has the opportunity to place the backbone node at an optimum distance to the last backbone node. This way a dynamic backbone network is deployed within the cave as the cavers move forward.

B. *Initial Setup and Routing*

Whenever a new backbone node is permanently laid out, the updated topology information is exchanged between the backbone nodes and then sent to the directory service. When updating topology information, the backbone nodes exchange their routing tables to recalculate the next hop to every other backbone node. For the routing protocol we preferred to employ a simplified link state routing algorithm which is suitable for wireless sensor networks because of its low message overhead [5]. This way all backbone nodes know how to reach a particular backbone node and thus its registered mobile nodes. A sample routing table exchange operation is given below in Fig. 2.

The “age” column in the routing table is used to detect the dead backbone nodes in the network. When a backbone node does not receive data from a neighboring backbone node within a predefined timeout, the value of the corresponding age column is decremented by one. An age column with a value of zero indicates a dead neighbor backbone node. Table I shows the final routing table of backbone node BN4 for the network given in Fig. 1.

C. *Mobile Node Registration*

Each mobile node must register itself to the ICWCS network to become operational. When a mobile node is powered on, it broadcasts a registration request message in order to register itself to the ICWCS directory service. The backbone nodes that receive registration message initiate a directory service lookup for the verification of the identity of the mobile node. Upon receiving a positive reply regarding the identity of the mobile node, the backbone nodes acknowledge this registration request back to the mobile node. In cases where more than one positive acknowledgement is received by the mobile node, the mobile node decides which backbone node to register with using the RSSI functionality.

D. *Call Management*

A mobile node can retrieve a list of the online users within the ICWCS network and show this information to the user on its graphical display. The retrieved list of the online users can be a partial list when the ICWCS network is in the beaconing state and the backbone node does not have access to the connection table (Table II) on the directory service or a full list when the directory service is accessible. Users can then select any of the online users, and initiate a voice communication with that user.

The id of the selected destination user’s mobile node is sent to the registered backbone node to forward the call request to the destination mobile node. If the user of the destination node accepts the incoming call request, a voice communication channel between the source and the destination mobile node is established. Otherwise a negative acknowledgement is returned to the source mobile node.

The current Mobile Node connection table of the network on the directory service is shown in Table II.

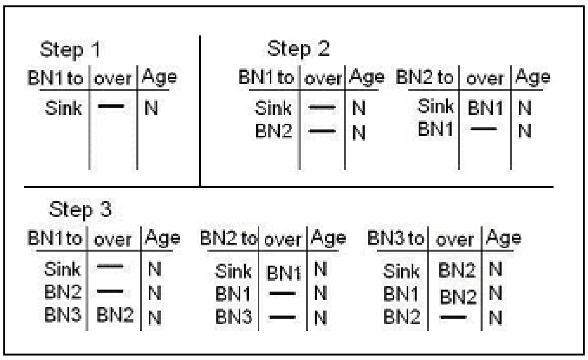

Figure 2. Initial Routing Setup

TABLE I. FINAL ROUTING TABLE OF BN4

To	Reach Over	Age
SINK	BN2	N
BN1	BN2	N
BN2	--	N
BN3	BN2	N
BN5	--	N
BN6	--	N
BN7	BN6	N
BN8	BN6	N

TABLE II. MN CONNECTION TABLE

Mobile Node	Backbone Node	Age
MN1	BN1	N
MN2	BN3	N
MN3	BN4	N
MN4	BN4	N
MN5	BN6	N

E. *Broken Link Detection and Recovery*

When a backbone node becomes dead, the backbone network will be broken unless the two immediate upstream and downstream neighbors of the dead backbone node can establish a direct connection. In this case, the ICWCS enters the beaconing state. In this state, the operation of the dead backbone node should be resumed by either replacing the batteries or the node itself. Each backbone node uses the age column in its routing table to detect whether the beaconing state should be entered. After each successful communication with the neighboring backbone nodes, each backbone node updates the corresponding age values with the predefined timeout value. Whenever the value in an age column becomes zero this indicates that no successful communication has occurred within the timeout period, so the backbone node concludes that the corresponding backbone node is dead. In the beaconing state, the detecting upstream and downstream backbone nodes broadcast a warning message to all online mobile nodes and the directory server. This way, still reachable users get notified about this network failure. The backbone nodes which forward the broadcast message delete the entry for the failed backbone node from their routing table.

After the dead backbone node is replaced, the new backbone node advertises its presence to the neighboring backbone nodes, which triggers the regeneration of the routing tables over the ICWCS backbone network.

When a connection is established between mobile nodes, the participating backbone nodes save an entry in their caches to accelerate future call establishment to these mobile nodes. With this caching mechanism, future calls to the cached mobile nodes will not require an interaction with the directory server, unless the mobile node has roamed to another backbone node.

Additionally when no connection to the directory server is available, the mobile nodes may still be able to communicate with the other reachable mobile nodes, unless they have changed their registered backbone node. For example, assuming that the mobile nodes MN2 and MN3 in Fig. 1 have established a connection over the time and the backbone node BN4 has cached the ids of MN2 and MN3, MN2 can still establish a new connection to MN3 even if BN1 becomes dead, which would have normally prevented querying the directory service for the location of MN3.

V. ENERGY ISSUES

For the two different types of wireless sensor nodes employed in ICWCS, two different types of batteries were used according to the power requirements of the nodes. Backbone nodes are stationary and they must be operational for long periods of time, so they are equipped with high capacity batteries. On the other hand mobile nodes are equipped with batteries of lesser capacity for making them more portable. Also spare batteries can be carried by the users to extend the standard standby and operational time.

In our current design, ICWCS backbone nodes were powered with 12V, 1.3Ah batteries which provide a little more than 7 days of continuous operation. The mobile nodes were equipped with three rechargeable 1.2V, 700mAh AAA size batteries which provide nodes thirty hours of continuous operation.

VI. CONCLUSION

In this research, we have focused on building a reliable voice communication network with the use of wireless multimedia sensor nodes in RF challenged indoor environments. We have designed wireless multimedia sensor nodes based on our previous researches.

Two different types of wireless sensor nodes were designed based on the design of our previous sensor node VF1A. One sensor node design was used as the backbone nodes of the ICWCS and the other one with multimedia features was used as the mobile nodes.

Our current implementation of ICWCS handles only one active point to point voice communication. We are currently working on the concurrent voice communications with multicast and broadcast capabilities to improve the performance of ICWCS.

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