An Ultra-Wide Band Based Ad Hoc Networking Scheme for Personnel Tracking in Emergencies

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Abstract— **This paper describes an ultra wideband (UWB) based ad hoc networking scheme which enables a control center to track all emergency personnel deployed in buildings in an incident area, and also enables communication of other types of data directed from emergency personnel, including status information and alarm in particular. In this network, GPS-enabled vehicles form a coordination reference framework. They also serve as egress points to collect data generated by emergency personnel. Additional dropped terminals are used to expand the network coverage. A Time Division Multiple Access (TDMA) based medium access protocol is used by terminals to access the radio channel. An anycast routing protocol is proposed and designed. This protocol enables each ad hoc device attached to emergency personnel to discover a communication path to one of the egress points. The network management related information is included in packet headers. Thus terminals can select free time slots and construct routes by overhearing neighbor's transmissions. Taking the advantage of the periodically nature of position calculation and reporting, each terminal is maintained with up-to-date network status.**

Keywords- ultra-wide band; ad hoc; tracking; routing; indoor; emergencies

I. Introduction

In emergency situations (e.g., fire and earthquake), rescuers are widely spread out in an incident area, most probably within buildings which may be partly collapsed. It would be advantageous to track the locations of emergency personnel to coordinate rescue operations, aid people in danger, and then to increase the emergency response effectiveness.

A tracking system generally involves positioning (i.e., determination of positions) and reporting (sending positions to a central point). In the past decade, many solutions have been proposed for personnel tracking within buildings. These solutions are based on infrared [1], ultrasound [2], or WLAN technology [3]. However, these systems can not be used in emergency situations because they all require pre-installed infrastructure which may be either inoperable or even not existing at the incident buildings. What's more, most of them can not provide sufficient resolution. Therefore there is a need for a rapidly deployable system which is set up ad hoc without counting on existing infrastructure and can determine and track the location of emergency personnel with high precision and reliability in an unplanned and hostile radio environment.

In this paper, we present an ultra-wideband (UWB)-based ad hoc networking scheme which can provide precise locations and track the movement of all the emergency service personnel deployed in a disaster area, and also enable basic communication between emergency personnel. Due to the intrinsic features of UWB, i.e., it can provide very accurate timing and high resistance of multipath distortion, and hence can provide precise positioning (within 10 cm) as well as reliable communications at the same time in an indoor environment [4]. This can be used to increase the safety and effectiveness of emergency service workers operating inside buildings. In order to achieve a wider coverage area, we intend to focus on the UWB technology which provides relatively long radio range which is around 150 meters indoor and 1 km outdoor [4]. The achievable data rate is hence limited to around 15 kbps, which is more than sufficient to transport the measured position data to a central control center. In our scheme, the locations and additional information (e.g., status-related information) of each individual personnel are collected by a control center which is located outside the building. This information enables the control center to have a graphical view of the whole emergency operations. The system is also capable of receiving and disseminating of critical incident information, like panic alarm from personnel or evacuation indication messages flooded from the control center. Fig. 1 shows a high level application overview of the envisioned tracking system. The system does not need to be part of a building's

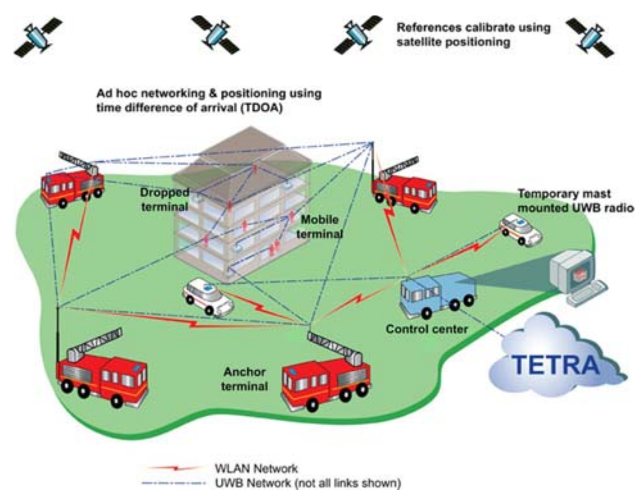

Figure 1. Network overview

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infrastructure and can be set up quickly on the scene of an incident. It is envisioned that the system can be used as a plug-in module with existing emergency networks and may interwork with fixed networks such as TETRA to enhance the performance of existing emergency rescuing operations.

This article is organized as follows. Section II presents the proposed network architecture. Section III presents the positioning and MAC schemes. Section IV provides the networking solutions. Section V gives some initial validation results. The last section gives conclusion remarks.

II. NETWORK ARCHITECTURE

The proposed system consists of four types of network elements – control center, anchor terminal, mobile terminal and dropped terminal – as illustrated in Fig. 1.

The control center, probably only one in the system, provides the main display to the emergency services coordinators, showing the position and status information for all emergency service personnel.

Anchor terminals are generally installed in emergency service vehicles and are located outside the buildings. Anchor terminals perform two roles in the network. First, they are self-locating with differential GPS and form a reference coordinate framework for the whole tracking system. The GPS capabilities of anchor terminals avoid labor-intensive task of calibration. Each anchor terminal also contains a UWB transceiver used for ranging and communications with other terminals. Second, anchor terminals serve as data sinks for position reporting so that other types of terminals only need to send their data to one of the anchor terminals. Anchor terminals then forward data packets to the control center. This creates diversity of egress points and distributes traffic in the network. To avoid those links which are near the control center becoming overloaded, anchor terminals are connected via existing higher speed radio links, e.g., WLAN, to the control center. We assume that the higher speed radio network is highly reliable and will be left out for discussion.

Mobile terminals are UWB transceivers worn by emergency personnel as they enter the incident zone during a mission. They have the capabilities to run positioning and communication applications through the UWB interface. They also have telemetry sensors and an alarm button, to measure status related information and send user alarms. Mobile terminals also have capabilities to indicate to user that additional terminals should be dropped when the connectivity is low.

Dropped terminals are deployed by emergency personnel at some strategic locations to expand network coverage or increase network connectivity when personnel are deep in a building. Dropped terminals are physically similar to mobile terminals, i.e., they are also UWB transceivers and are capable of running positioning and communication applications. Dropped terminals are deposited when the mobile terminal attached to a rescuer detects the connectivity is low and gives notifications to the user. In practical, the placement shall also consider the real physical environment [4]. For example, open area where is unlikely to be damaged is preferred than area where is full of obstacles and likely to be damaged.

Each terminal in the network is configured beforehand with a short unique address (ID) which is only valid in the incident network, instead of using a universally unique address (e.g., an IEEE MAC address, IPv4 or IPv6 address), to save the limited available data rate.

III. LOCALIZATION AND CHANNEL ACCESS

To determine the unknown position of a radio device in 3-dimension, ranges of this device to minimum of four reference nodes (i.e., whose positions are known in advance) are needed [5]. In our work, the localization is based on an iterative multilateration technique. More specifically, at the network startup phase, a mobile terminal measures its position with respect to at least four anchor terminals which have obtained their positions via built-in GPS. After the mobile terminal estimates its position, it becomes a new reference itself. This also applies to dropped terminals. The algorithm proceeds until all mobile and dropped terminals are located. In order to cope with the pedestrian like mobility (in the order of 5 m/s), terminals should regularly update their positions and report to the control center at least once a second.

To determine its precise position, a terminal sends ranging requests sequentially to a minimum of four selected reference terminals and then waits replies from those references after a predefined time delay. Thus the round trip time and hence the distances to the reference terminals can be calculated. Having measured ranges to at least four reference nodes, positioning algorithm based on triangulation technique is used to estimate the position of a target terminal from reference terminals. After that, the target terminal will broadcast its own position and can then be used as references to others. Details of the triangulation technique could be found in, e.g., [5]. We assume there is a dedicated functional module in mobile and dropped terminals which is responsible for scheduling the positioning, selecting the reference neighbors and calculating positions.

In order for all terminals are synchronized for the range request/reply conversation, a dedicated control channel which continuous sends pilot symbols is used to synchronize all terminals in the system. Taking advantage of the high synchronization, an extension to the slotted ALOHA scheme is used for medium access. As shown in Fig. 2, access to the physical channel is organized into slot and superframe.

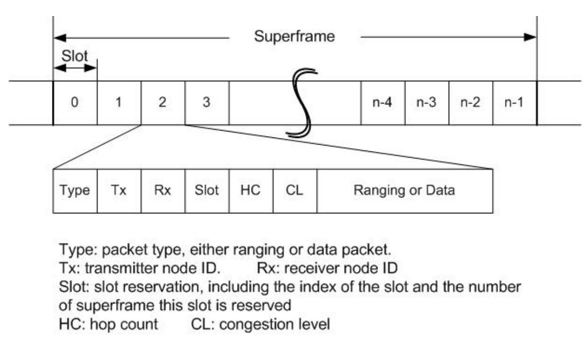

Figure 2. Data channel structure

In order not to cause any interference between data transmission and positioning, each slot can be used for transmitting either a data packet or a ranging packet. A data packet contains the position reporting or status related information from mobile or dropped terminals. A ranging packet contains the four sequential ranging requests, ranging replies from selected reference terminals and position broadcasting. Consequently, a slot may last for several tens of milliseconds to finish a ranging packet, providing the low data rate. This further leads a superframe to be in the order of second to support a sufficient node density if a terminal needs to transmit at least twice in a superframe, once for positioning and once for reporting.

Each terminal includes its slot reservation for the next or the next several superframes in the header of each packet (see Fig. 2), thus neighboring terminals can choose free slots to avoid transmission collisions. Embedding the slot reservation in the header of a packet is to avoid using a dedicated packet for the announcement and then to save the rare radio resources.

IV. ROUTING

To report positions to the control point, all mobile terminals shall form a multi-hop wireless network and hence a routing protocol shall be used for this purpose. Traditional routing protocols proposed for multi-hop mobile ad hoc network, e.g., AODV [6], DSR [7], and DSDV [8], are not suitable for our scheme because they use dedicated packets for route construction and route maintenance and introduce a lot of overhead into the network. This is not affordable in our system, since the data bandwidth is quite limited, and much should be used for positioning aspects and actual data transmission. What's more, the routing protocol used for an emergency network should be simple for terminals to join the network, such that it can easily extend its coverage by adding new units.

The design of a routing protocol should be optimized for the underlying traffic in the network. The majority traffic in our network is position and status updating from mobile and dropped terminals. Other type of traffic that would come up in the network are alarm messages, either sent from mobile terminals to the control center (e.g., indication of aid required) or sent on the reverse direction (e.g., evacuation alarm). However, sending alarm messages are rare cases. Therefore, the fundamental objective of routing in the network is that mobile terminals and dropped terminals have a best route to one of the anchor terminals which are used as information collectors in the UWB network. End-to-end acknowledgement and retransmission in case of transmission failure are not necessary, as transmitting a fresher updating packet is more important than retransmit an outdated packet.

The construction of routes from mobile and dropped terminals to anchor terminals is achieved by constructing trees which are rooted at anchor terminals and grows with mobile terminals or dropped terminals as branches, as depicted in Fig. 3. More specifically, anchor terminals initiate route construction by broadcast routing information <*hop count*, *congestion level*>. To save power and bandwidth, routing information is also embedded in each packet header (see Fig. 2) to save bandwidth. Anchor terminals set *hop count* as 0 as they

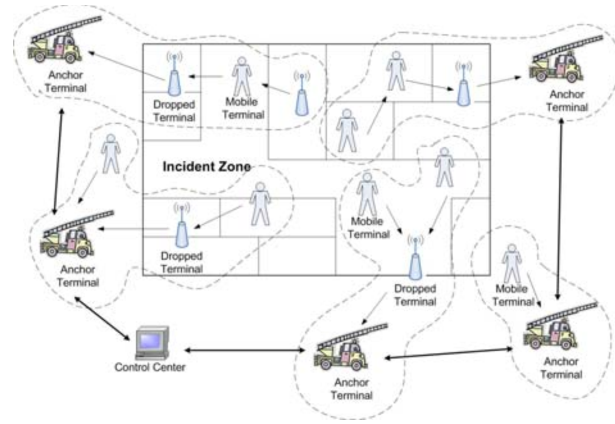

Figure 3. Routing tree construction in the UWB network

are the origins. The hop count indicates the number of hops a terminal with reference to an anchor terminal. The *congestion level* is set as the occupation rate of their outgoing queues. When a mobile terminal or a dropped terminal receives the broadcast from a neighboring anchor terminal, it creates an entry in its routing table for that neighbor based on the information carried in the packet header. Each entry contains three fields: *terminal ID*, *hop count*, and *congestion level*. If the entry exists, that means the terminal has received data from the same neighbor before, the hop count and congestion level will be then updated. If the terminal does not receive any packet from that neighbor for a certain period of time, then the corresponding entry will be deleted.

Route selection is based on hop count and congestion level. The neighbor which has the lowest hop count is selected as the parent terminal, through which a mobile or dropped terminal can reach the closest anchor terminal. If two or more parent candidates have the same hop count, then the candidate who has the smallest congestion level will be selected. Hop count is used as the main selection criteria because the delays imposed by the MAC protocol (the length of a superframe is in the order of second) cannot be tolerated by the tracking application for longer routes and the routing protocol has to first cope with short paths. What's more, shortest path will introduce fewer transmissions and hence less traffic load into the network compared with longer path [9]. Congestion level is used to circumvent congested terminals.

After parent selection, the terminal shall update its own routing information, i.e., the hop count will be incremented by one with respect to the hop count of its parent, and the congestion level will be replaced with the occupation rate of its outgoing queue, if it's greater than the one of its parent. The updated routing information is then included in the header of every outgoing packet. This procedure proceeds until all the terminals obtain the topology of the network.

Since every terminal transmits regularly either for ranging or position updating, the routing information is always being updated in the network, and mobile or dropped terminals can be maintained with up-to-date network topology information. This provides them the ability to adapt to network changes caused by the mobility, joining or leaving of terminals.

As mentioned, alarm messages are also accommodated in the network. Although they are rare, they are very important and should be delivered with high reliability. For the alarm messages sent out from mobile terminals, the control center shouldn't miss any of them. Thus this type of alarm message requires to be acknowledged at the control center and be retransmitted in case of failure. The routing described so far has only provided forward routes, i.e., from mobile or dropped terminals to anchor terminals. The reverse route can be established if each intermediate terminal notes from which children terminal it has received an alarm. However, the established reverse route may not be valid when the acknowledgement arrives, since the reverse route could take several superframe time, hence several seconds, to be used and in the meantime the network topology changes. This is especially true when some danger occurs, people's mobility patterns will change and cause the network topology to change faster. Therefore, when a user alarm is generated from a mobile terminal, the alarm message should be transmitted periodically (every superframe) until the acknowledgement arrives. This allows the reverse route to be refreshed closer to the time it is actually used. For the alarm messages flooded from the control center, each terminal who receives them is requested to broadcast those flooding messages twice to increase the probability that all mobile terminals can receive the alarms.

To optimize the network performance, some techniques are adopted. First, when the updated congestion level at an intermediate terminal is higher than a threshold, the terminal will notify its application layer to reduce the traffic rate to prevent even worse congestions. Second, alarm messages and related acknowledgement are transmitted with higher priority than other types of packets (i.e., position and status packets). Third, data aggregation at each intermediate terminal is adopted to assemble several alarm, position, and status packets into a bigger one to fill the MAC frame and to optimize the use of time slots.

V. FUNCTIONAL VALIDATION OF THE NETWORKING SCHEME

Some initial validation experiments have been done through simulations in OMNeT ++ [10] to verify the basic operation of the networking approach. We used a static random distribution of 50 mobile terminals and 50 dropped terminals in a 300×300m area, with 10 anchor terminals distributed around the perimeter. Table I shows the results over five iterations of the scenario. The only one terminal which cannot report its position is due to physically isolation rather than protocol breakdown, and the position update losses are due mainly to queue overflows. The initial set of results show the basic soundness of the networking scheme and show achievable update intervals within the required bounds (1s).

TABLE I. NETWORKING VALIDATION RESULTS

Number of reporting terminals	*Average position update success rate*	*Average position update interval*	*Average report delay*	*Average path length*
99	93.5%	1.06s	1.18s	1.7

VI. CONCLUSIONS AND FUTURE WORK

This paper has proposed an UWB-based ad hoc networking scheme for personnel tracking in emergencies. The scheme allows a control center monitoring the whole rescue situation including the location and status of each personnel. The network also enables reliable transmission of critical alarm messages either from personnel to the control center or vise versa. The proposed networking scheme does not rely on pre-installed infrastructure and radio terminals can be self-organized for operation. Terminals reserve time slots during a superframe for periodical positioning or data transferring. An anycast routing protocol is used for terminals to report their positions. Taking the advantage of the periodical nature of position updating, routing information is included in each packet header hence no dedicated routing packets are introduced to the network.

Future work will be carried out to set protocol related parameters and assess the protocol by performing more simulations. The proposed scheme will further be validated in a 40 node testbed based on UWB hardware developed in the EUROPCOM project.

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