The Research of Ranging with Timing over Packet Network for the Mine Safety Application

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Abstract—Due to the recent saturation of the traditional telecom markets, the vendors are shifting their focus on to the vertical markets, including but not limited to oil and mine industries. This paper is offering a solution for one of the key issues the mine industry is facing. When the accident happen under the mine, the first thing to do is to locate the workers, there are many methods been proposed; however, each has pros and cons. For example, we can use RFID to locate the people, the problem is when there are too many miners at the same spot, the method doesn’t work well; we can use CDMA indoor GPS system to locate the person, however, the base station is not cheap; we can use IEEE802.15 Zigbee system to locate people, but we need huge amount of nodes to cover reasonable size of mine; for these reasons, we propose to use low cost WiFi system to fulfill the task. We introduce IEEE1588 Precision Timing Protocol into the existing WiFi or similar mesh networks, to increase the Time of Arrival ranging accuracy. This way, with limited increasing of the system cost, we satisfy the customer requirements. To prove the concept, Matlab is used to work out the theoretical bit-flow vacation model and the simple linear-ranging algorithms.

Index Terms — wireless packet network, precise time synchronization, emergency miner locating

I. INTRODUCTION

In wake of recent mining tragedies across the world due to the energy crisis, a number of technology companies have suggested the extension of wireless real-time location technology using low cost WiFi networks to pinpoint miners trapped underground, a solution that could save lives today.

One such company is Northern Virginia-based Ekahau Inc. who announced its Real-Time Locating Systems, which use any standard WiFi network to track the location and the movement of miner trapped underground mines or tunnels in real time [1]. The company claims that the system can leverage any brand of existing WiFi networks inside a mine without the need for proprietary system installation.

It’s basically an indoor GPS system. Such systems have many uses underground, keeping track of explosives, trucks, compressors, drills and above all, the health and safety of workers. A high-tech company in city of Changzhou called Tiandi Ltd has also made the similar product.

With the increase of WiFi networks in mines for Voice over IP phone lines, the proliferation in WiFi networks has created a standard wireless infrastructure in which products like above-mentioned wireless tracker device can operate seamlessly.

The small battery powered WiFi tag, about few tens dollars, has a call button which a miner pushes letting the tag alarm by sending the location to a remote server outside of the mine, through the relay stations underground. Then using wireless connected computers, outside staffs are able to access location information on internal Web pages by pointing their Web browsers to an Intranet page. Movement and location of each tagged miner is tracked in a database and shown on a visual map.

However the main problem is that accuracy provided by the WiFi network is very limited, due to its relatively coarse clock rate, line speed, and the accuracy of Time of Arrival estimation, typical accuracy can be range from 15 meters to 30 meters (1 microsecond at the speed of light), depends on the fluctuation of temperature and the system load under the harsh environment. Ideally, we wish to improve the accuracy to 3 meters, which is equivalent to 0.1 microseconds, without using expensive atomic clocks. Due to the collapse in a mine tunnel can easily spread over 10 meters area; we need to know which side is the worker been trapped in.

Yi Zhu has proposed to combine the WiFi with CDMA network to improve the locating estimation accuracy, when the CDMA network is also available [2]. This paper proposes a method that when there is no CDMA network, simply by improving the clock accuracy, with implementation of the low cost IEEE1588 algorithm in open source software. And using our new residual error estimation algorithm to correct the residual errors, developed during past a few years to keep the hardware cost at the minimum.

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Sub-microsecond timing and synchronization are critical to many real-time embedded applications such as IP-based locating, audio/video synchronization, wireless, electric power generation and control, industrial automation and control, test and measurement, telecommunications, medical, and military. Tight synchronization of multiple distributed devices is a critical issue facing developers of today’s embedded systems. For our case we need to synchronize the clock on the WiFi Access Point (AP), the Relay Station of the Access Point, or any other kind of communication systems, such as Femto Cell or WiMax repeaters etc. interconnected mainly through fiber distribution line.

With the widespread adoption of Ethernet as an embedded networking technology, new standards have emerged to add precision timing and synchronization to Ethernet itself - notably the IEEE 1588 Precision Time Protocol (PTP) [3]. PTP leverages Commercial Off-the-Shelf (COTS) networking standards, equipment, and cabling to provide precision timing to distributed embedded devices. But unlike older approaches, PTP offers significant advantages in cost, performance, reliability, and flexibility. PTP can even operate across heterogeneous networks incorporating not only Ethernet, but also other standards including CAN, fiber, ZigBee and IEEE802.11 WiFi that are popularly seen in the mine communication deployments.

Using PTP, embedded systems developers can synchronize distributed devices to accuracies in the nanosecond range. And PTP offers “no new wires” simplicity and low cost software or limited hardware add-on by reusing the existing COTS network infrastructure to distribute timing information and achieve synchronization across the network itself. PTP eliminates the need for extra equipment at each embedded device, such as massive GPS receivers for outdoor usage or GPS repeaters for indoor usage, and extra connections, such as additional coaxial or fiber cables needed by the traditional IRIG standard.

However, PTP has its own weak point, which is the accuracy of the clock heavily relies on the network conditions, when the network is congested, the Protocol Data Unit (PDU) will not be arrive at the distributed clocks on time, one solution is to use the Jitter buffer, or Virtual clock to absorb or count for the variations through the network, unfortunately the network congestion is a random phenomenon that could be Fractal by mother of nature, which means no matter how big the jitter buffer or how accurate intermediate clock is, one can never smooth out the random jitter. As such, we need an algorithm to predict the residual jitter that cannot be removed completely. The second weak point of PTP protocol is the calculation of time based on the assumption of the symmetrical path for the forward and backward links, in reality again, this may not be true; the only way to tell if the path is symmetrical or not is through statistical modeling, this is what we are offering in this paper.

A complete mathematical model for estimating the residual bit flow jitter is proposed in next section, and the initial Matlab calculations are also demonstrated, the future direction of the research is given as well, at the last section.

II. WIRELESS MINE COMMUNICATION SYSTEMS

A. WiFi Mesh Networks

The application of wireless network in the tracking of mine operation is shown in Fig. 1. This system consists of three parts, which are location information acquisition part, date communication part and location computer system; with the underground personnel location system, miners with RFID will be tracked down by the WiFi APs which are distributed in the laneways of the coal mine, and the information will be sent to the location computer to analyze the precise position of the miners [4]. In this system, the GPS plays a simple role of realization of the function for the regulation of all clocks, namely calibrating the time to insure the ranging precision [5].

B. Femto Cell Networks

Typical Femto cell is a household station, which acts like a wireless AP integrating the simple function of Node B and RNC. It can be installed in the indoor, such as the office and home. Fig. 2 shows us a Femto cell system, which is deployed in the coal-mine.

The CDMA wireless communication system for mine based on the Femto base station adopts the unified IP Softswitch Technology and the open pattern structure. This system is composed of the main system and Femto base stations on the ground, and the Femto repeater (RP) and terminal units underground; for example, the units can be cellphone for mine, PDA, date terminal and image terminal and so on. Just like Fig. 1 shows us, the main system on the ground formed the nucleus of the entire system, which consists of SIP Softswitch platform and the application servers. The SIP CDMA softswitch platform has the advantages of open interfaces and good...
generality, it substitutes for nucleus network of the traditional CDMA communication system, and decrease the cost of the CDMA communication system for mine. This system based on the Industry Ethernet can be deployed in the most coal mines, and it can access the Femto base station conveniently as long as there is a network covered, in addition, it has low cost of network construction and ideal maintenance capabilities [6].

The main problem with above Femto deployment is that the base station may be installed above ground for easier maintenance, only the booster antenna is send down to the underground through fiber connections, in such a low cost setting, the TOA measured by the base station does not reflect the distance between mobile handheld to the antenna at all. The only way to make use of such network to measure the distance is to install additional timing hardware at the antenna site, to time stamp the ranging packet.

III. THE NODES’ TIMING CONTROL

A. The mobile nodes’ timing problem and solution

The energy and computation power that the wireless mobile nodes or RF tag carried around is limited, it is unrealistic to require the mobile node to keep an accurate network synchronized clock; however, it is possible to have APs to offer the accurate synchronized clock itself, and use that clock as a base, to keep track of a clock drift for each mobile node in its vicinity, and correct the errors if any for them. Every time a mobile node entered the region, the AP will ask the node send a timing packet, and ask its upstream and downstream AP to check if they have heard the node, since the mine network is always in a line set up, each AP knew how far there are from each other. As shown in Fig. 4, in this way, the AP node is able to calculate the clock difference and keep a correction table for the mobile node, using (2). AP nodes will exchange the information about the RSSI (Radio Signal Strength Indicator), whoever has the stronger signal will be the master node responsible to keep the table and do the calculation for the mobile node, and send it to the center station above the ground. In the situation where the mobile station can only be heard by one AP, then RSSI values at different location are used to reversibly build up the correction table, by using the standard TOA formula (1) and RF link budget formula (3).

For example, as Fig.3 shows, if AP measured TOA$_1$=23us at the RSSI=-10dBm, AP measured TOA$_2$=15us at the RSSI=-4dBm, and then we knew that the distance to the mobile unit is halved, mobile clock has an offset say LAG can be computed by using (1), where X is the current distance, X=TOA$_1$-TOA$_2$=23-15=8us, and LAG=7us. Note that if RSSI is not accurate, then the calculation will not be accurate, whenever possible 2 AP method should be used, which will be explain in below.

\[
\begin{align*}
    TOA_1 &= LAG + Y \\
    TOA_2 &= LAG + X
\end{align*}
\]

B. The fixed nodes timing issue and solution

In our design, the mobile node is not required to do any clock synchronization, since we wanted to have simplest mobile unit, to lower the mass manufacture cost. However, all the Access Points or the Packet Repeaters must have the function of clock synchronization, such that when the mobile unit sending the ranging packet with time stamps, the nearest AP is able to calculate the distance, by using Time of Arrival method, as well as the correction based on the neighborhood information. Correction is done in following way, for example, if we set up an AP besides every safety cave, the distance between each cave and AP is 500 meters, the propagation time will be STT=16.67 microseconds. If AP$_1$ measured TOA$_1$= 10.33us, AP$_2$ measured TOA$_2$=20.34us, and then we knew that the mobile clock has a LAG=7us by using (2). STT is Single Trip Time.

\[
LAG = \frac{TOA_1 + TOA_2 - STT}{2}
\]
The received signal strength is a function of the transmitted power and the distance between the sender and the receiver. The received signal strength will decrease with increased distance as the equation below:

\[
\text{RSSI} = -(10n \log_{10} d + A)
\]  

(3)

n: signal propagation constant, also named propagation exponent.

d: distance from sender.

A: received signal strength at a distance of one meter.

The distribution of A and n can be found in Fig. 5.

C. RSSI—Practical considerations

Section C described the theoretical RSSI value as a function of the distance. This section discusses how the RSSI value can be measured in the real world. When using the ideal formula for signal strength it’s pretty straightforward to do the calculation, but when using real values, uncertainty must be taken into account. Most of this uncertainty is handled by the hardware, but some software handling should be added to increase the accuracy. The methods presented in this section have one main goal: obtain an RSSI value that correlates to the distance in the best possible way.

D. Simple ways to filter the RSSI values

Various filters can be used to smooth the RSSI value. Two common filters are simple averaging and feedback filters. Averaging is the most basic filter type, but it requires more data packets to be sent. Feedback filters use only a small part of the most recent RSSI value for each calculation. This requires less data, but increases the latency when calculating a new moving position.

The average RSSI value is simply calculated by requiring a few packets from each mobile node each time the RSSI value are measured and calculated according to (4):

\[
\text{RSSI} = \frac{1}{n} \sum_{i=0}^{n} \text{RSSI}_i
\]  

(4)

If a filter approximation shall be used, this can be done as shown in (5). In this equation the variable is a typically 0.75 or above. This approach ensures that a large difference in RSSI values will be smoothed. Therefore it is not advisable if the node that should be tracked can move long distance between each calculation.

\[
\text{RSSI}_n = a \cdot \text{RSSI}_n + (1-a) \cdot \text{RSSI}_{n-1}
\]  

(5)

E. Calculated RSSI vs. measured RSSI

The Fig. 6 shows, from left to right, the theoretical RSSI value, next when a slowly varying components, and finally when adding fast varying components, for example under influence of multipath components. The rightmost figure shows the signal that is closest to reality.

IV. THE PRECISION TIMING PROTOCOL AND VACATION QUEUE BIT MODEL

A. Network solutions

Precise time information is important for distributed systems within automation applications, whether coordinate underground digging robots or simply measure the distance between mobile users. With the Precision Time Protocol (PTP) described in IEEE 1588, it is possible to synchronize distributed clocks with an accuracy of less than 0.2 microseconds via a packet network. The demands on the local clocks and the network computing are relatively low.

As explained in previous section, mobile clock will not be accurate; however, the access points especially those neighborhoods with each other must be as accurate as possible. For many reasons, not every clock is exact. Now and later it has to be checked whether the deviation is tolerable and whether the clock needs to be corrected. Communication between the neighborhood clocks is
necessary, and can be done through the high-speed packet network.

Two effects are in evidence when setting clocks: independent clocks initially run at an offset. To synchronize them, the more inaccurate clock is set to the more accurate one (offset correction). The second thing is that real clocks do not run at the same speed. Therefore, the speed of the more inaccurate clock has to be regulated (drift correction).

There have previously been different ways to synchronize distributed clocks through a network. The most common ones are the Network Time Protocol (NTP) and the simpler Simple Network Time Protocol (SNTP). These methods are widely distributed in LANs (Local Area Networks) or in the Internet and allow accuracies into the millisecond range.

Another possibility is the use of radio signals from GPS satellites. However, for underground application, satellite is not visible, and relaying massive satellite signal through the fiber optical into ground is more expensive than simply coordinate neighborhood clocks. Further more, GPS is used to obtain the absolute time accuracy with regards to Greenwich time; here we only look for the relative accuracy, for measuring distance.

Another solution is to send a high-precision time pulse, e.g. Pulse Per Second (PPS) signal to every user on separate lines. However, this requires an enormous additional wiring effort. Which is not practical for underground mine applications.

This is where the Precision Time Protocol (PTP) described in IEEE 1588 comes in play. It has been developed with the following objectives: Synchronization accuracy in the sub-microsecond range, Minimum requirements of the processor performance and network bandwidth which enables it to be implemented on low-cost devices, with low administration effort, via popular Ethernet network.

PTP knows three types of clocks and acts as a master to slave protocol. A clock in an end device is known as an Ordinary Clock (OC), a clock in a transmission component like an Ethernet Switch is a Boundary Clock (BC) or Transparent Clock (TC). As Fig.7 shows, a master is typically controlled by a GPS clock, synchronizes the respective slaves connected to it.

The synchronization process is divided into two phases. First, the time difference between the master and the slave is corrected, this is the offset correction. Two modes (with IEEE1588-2008) are known for the synchronization process.

Two-step-mode:
In two-step-mode the master sends a synchronization message – SYNC message – with an estimated value of the time cyclically to the connected slaves. Parallel to this, the time at which the message leaves the sender is measured as precisely as possible, if possible by hardware support directly on the medium. The master then sends this actual exact transmission time of the corresponding sync message to the slaves in a second message - follow-up message. The reception time of these messages are measured as exactly as possible and can correct the correction value (offset) to the master from it. The slave clock is then corrected by this offset. If the transmission line were to have no delay, both clocks would be synchronized.

One-step-mode:
The master sends a synchronization message – SYNC – message with the precise value of the time cyclically to the connected slave. Other than in two-step-mode, the precise time is inserted into the SYNC message “on-the-fly” by the hardware. No FOLLOWUP – messages are needed in this mode. The calculation of the offset is the same as in two-step-mode.

The second phase of the synchronization, the delay measurement, determines the run time between slave and master. So-called Delay Request and Delay Response messages determine this in a similar way and the clocks adjusted accordingly. This can also be achieved in one-step or in two-step mode.

Boundary clocks are required wherever there is a network congestion that inserts significant delay fluctuation or blocks the propagation of the PTP messages completely. Boundary clocks have typically more than 2 ports, with one port serving as a PTP slave port to an upstream master clock, and the other ports serving as PTP clock masters to downstream PTP clocks. BC acts like a “proxy” for the “grandmaster”.

The peer delay mechanism measures the port-to-port propagation delay time between two directly connected ports. The peer delay mechanism is independent of the state of a port (master or slave). It operates separately in both directions of the link. The Boundary clocks (BC) defined in version 1 of the IEEE1588 Standard has two problems when used in (highly) cascaded networks: there is nonlinear decreasing synchronization accuracy and rising resynchronization time after network reconfiguration. To eliminate these effects the concept of transparent clocks has been introduced in the IEEE 1588 standard version 2. Transparent clocks were added in IEEE1588 - 2008 to correct the “residence time” of the network device like an Ethernet Switch. The residence time is accumulated in a field (correction field) of the SYNC (one-step) or FollowUP (two-step) message. Since transparent clocks are stateless they have no impact on the reconfiguration time of networks. No “proxy” stands in the middle.
Peer-to-Peer TCs use the peer delay mechanism for the delay measurement. In addition to providing PTP event transit time information the P2P TC also provides corrections for the propagation delay of the link connected to the port receiving the PTP event message (correction field).

B. Jitter estimation

When Precision Time Protocol is to be used in our miner locating system, the PTP protocol stack need to be implemented. This can be done easily on the processor and has minimum pressure on the network bandwidth. PTP can even be implemented in embedded systems with simple 32 or even 16 bit micro-controllers. The only requirement for achieving a high precision is as exact a measurement of the PTP message transmission and reception times as possible. This must take place very close to the hardware or directly in the firmware driver and with as a best predictive accuracy as possible.

When using additional hardware support for time stamping, the precision can be increased. A little logic is necessary for this integration, for example, a CPLD, DSP, FPGA or ASIC directly at the network input and output. There is a list of early vendors who offer solutions on IEEE1588 standard web. In such a system where several ordinary clocks connected by an Ethernet switch with boundary clock function, a typical accuracy of +/-60ns was achieved, practically independently of the network load or workload of the CPU.

If PTP is used through Ethernet networks, special attention must be paid to the network infrastructure. Since hubs have almost no influence on the accuracy of the protocol due to their practically constant throughput time, the run times must be taken into account when using switches. PTP measures the run times in the network and measures the clocks accordingly. However, run time variations, as they always occur in switches, depends on the traffic load and the CPU load, lead to inaccuracy. In our mine applications, the switch can not be avoided, and the load can be high due to large amount of sensor data going on including locating information, temperature, CO, CO2, CH4, SO2, image, video logs etc [7].

Since switches store the received data packets completely and queuing effects can considerably delay the transmission under certain circumstances, significant fluctuations may occur here. At low network load, this effect hardly has an influence, but at greater network load this can considerably worsen the synchronization accuracy. The introduction of transparent clocks in IEEE1588-2008 solves this drawback by measuring the residence time of each network transmission device.

However, introduce additional hardware both underground and above ground will increase the cost significantly, our customers wish to keep the cost minimum, and thus we were tasked to calculate the run time, and compensate it. After careful examine of the current process architecture, we decided use following gated queuing model, as you can see in the Fig. 8, to model the run time [8].

The first queue is used to model the Real Time Operating System (RTOS) used in switch or access point, the second queue is used to represent the CPU, when the PDU comes in, RTOS will response first; however, due to multi-thread operation, there is a delay for RTOS switching back from previous task to the current one, we model such situation as a vacation queue [9], once the RTOS comes back from “vacation”, it will pass the work to CPU, however CPU might be busy on some thing else, its load will also dictate how fast it can complete the task, as such we need at least two cascade queue to model the run time [10]. The analytic solution is given by Ref. [11]; here we focus on numerical calculations, to offer some engineering guidelines in flowing sections.

As a common clock reference is essential for time sensing applications such as an accurate ranging of the distance. Time stamping of protocol data is one of the most difficult problems that researcher and engineer of a distributed system will encounter. Prior effort in time synchronization over multi-hop wireless sensor networks has mainly focused on Centralized solutions using beacon signals as timing references. However, centralized solutions do not scale well, for example, every 500 meters, we will do a hop, a mine with 50km will requires 100 hops, and for such a distributed networks the use of central timing references becomes impractical.

Reference [12] mentioned a distributed synchronization by using nearest neighbor communication. The mechanism was inspired by natural synchronization in colonies of fireflies and was implemented in an embedded wireless network. The authors pointed out that synchronization is not always obtained in a network on time, because normal nodes are “dead” while transmitting and hence cannot always receive synchronization messages from reference nodes. This algorithm may fit well with our application, since we wanted synchronize the neighbor nodes to the maximum accuracy, and do not care about the rest nodes, logically the location of the mine worker is ranged in between the neighbor nodes. In addition, fiber and wireless will mutually backing up each other during accident period.

The locating function is needed during the emergency situations, at which point, the part of network, may going down due to the explosion, the timing algorithm has to be pure distributed. The so-called Reachback Firefly algorithm was implemented in a sensor testbed and results were compared with simulations in [13]. In their work, the authors were able to apply and evaluate realistic effects of radio wave communication to the
bioinspired synchronization mechanism and to provide a robust time-synchronized networked system [14].

The foreseeable scale of future networked sensor systems is encouraging scientists and engineers to use asynchronous methods, mimicking the biological systems, such as flocks of birds, using their way of coordinate flying speed, to adjust the clock speed, for the establishment of precise clock synchronizations. Instead of assuming that the network system is in a well-defined state at any point in time one must instead rely on a distributed system design that relies on probability propagation distance between wireless and fiber interchangeably. With such statistical approach in mind, we can distinguish the fixed propagation delay from the variable queuing delay bit jitter.

VI. MATLAB RESULTS

A. The assumptions

The Discrete Quasi Deterministic Queues are assumed, Quasi Deterministic Queues are analogous to a continuous flow of entities passing over a point over time. This type of analysis is usually carried out when the number of entities to be simulated is large, as this will ensure a better match between the resulting cumulative stepped line representing the state of the system and the continuous approximation line. We use this model so that we can accurately model the timing up to bit level, not just at byte or packet level. Only at bit level can we capture all the software, firmware and hardware influencing on the wireless and wired timing accuracy.

The Fig.9 below depicts graphically a deterministic queue characterized by a region where demand ($\lambda$) increases progressively while supply ($\mu$) keeps steady. On the contrary, Fig. 11 demonstrates that a deterministic queue is under the circumstance where demand keeps steady and supply declines gradually. The load is equivalent to demand divided by supply ($\lambda/\mu$). Fig. 10 describes the variety of delay jitter when there is a relative time error in mobile clock.

The queue length (i.e., state of the system) corresponds to the maximum bits between the cumulative and serviced curves, b) The waiting time, denoted by the horizontal distance between the two cumulative curves in the diagram is the individual bit waiting time of an arriving to the queue at time c) The total delay is the area under bounded by these two curves d) The average delay time is the quotient of the total delay and the number of entities processed e) The average queue length is the quotient of the total delay and the time span of the delay.

The residual jitter is defined as the jitter after the jitter buffer that partially absorbed the major part of the jitter; the jitter is the instant delay.

The Demand and Supply curves are derived from known flow rate functions ($\lambda$ and $\mu$), which of course are functions of time. The diagrams shown represent a simplified scenario arising in our practical situation. The time variations in the system come from the daily work pattern on the mine. Most of the queuing processes at the access point and switch are non-steady thus analytic models seldom apply perfectly. Simulation is a bit closer to the real life. Data recorded on mine over time can be used to feed these quasi-deterministic, non-steady bit models. The capacity function is perhaps the most difficult to quantify because both RTOS and CPU performance is affected by the state of the system (i.e., multi-thread vacation, queue length among others).

The following three figures are parts of our original results from Matlab simulations, Fig.12 is Demand bit curve, and Fig. 13 is CPU Capacity curve, namely Vacation curve, the last one, Fig. 14 depicts the Total Delay Jitter result which is also called Residual Jitter in this paper.
VI. CONCLUSIONS

In this paper, we have proposed an inexpensive firmware upgrade solution and related to the vacation bit queue model to solve the problem for miner locating encountered in the current mine safety operations. The Matlab simulations and calculation methods are used to carry out the initial proof of the concept. Much detail design work is still ahead of us, the further research into particle swarm intelligence and its application for simplification of the mobile clock virtual synchronization worth’s additional efforts. Virtual synchronization is done by AP during the lost of GPS Grandmaster clock. The actual field test will be scheduled later 2012.

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