Precise Location Technology Based on Chirp Spread Spectrum

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Abstract—This article introduces chirp spread spectrum technology (CSS for short) and optimized location algorithm. Symmetric double-sided two way ranging technique (SDS–TWR for short) is applied to improve accuracy and range of measurement. Linear frequency modulation ranging technology utilizes protocols combining CSMA / CA and TDMA, and adjusts dynamically transmission rate and frame length according to noise, interference and multipath to ensure optimal throughput and accurate distance information. System has anti-jamming capability and covers great distance.

Keywords—Chirp Spread Spectrum; precise location; symmetric double-sided two way ranging; Code Modulation technique

I. INTRODUCTION
Precise positioning technology is widely used, such as underground coal mine location, communication and security surveillance. In the work face, it can be applied to monitor and locate production equipment, personnel and rescue system. Overseas, mine personnel tracking and locating system generally sends message to ground in wireless method by infrared ray or others through leaky cable. The ground computer processes data received to determine the underground personnel location. United States, Japan and other countries have realized mine-wide members tracking and locating, but, in this way, the cost is very high. In early 1990s, the first mine high-frequency locating system came in England. The mine vehicle dynamic location is introduced into China in the late 90s. In domestic market, the most of mine management systems adopt high frequency, mixing of high and low frequency or GPRS technology. But properties usually are inadequate or existing some defects and deficiencies.

CSS ranging and communication technology is a two-way wireless communications technology with low complexity, low power, low data rate and low cost. The technology is not entirely unique, new standards. Its physical layer, media access control layer and link layer protocol are in line with IEEE 802.15.4a standard, and improve and expand on this basis. It forms star, sheet or mesh networks through the wireless communication individual nodes.

II. CSS MODULATION TECHNOLOGY

A. CCS signal modulation
Chirp is a frequency modulation pulse. Chirp signal transmission process produces chirp pulse. Figure 1(a) shows the linear change of signal frequency in the interval of $T$, and this change was increasing or decreasing in monotonic manner, in other words, the signal frequency rises from the low to high (Up-Chirp signal for short) at a given time frame, otherwise called Down-Chirp signal. The relationship between frequency and time of chirp signal is showed in Figure 1(b). The signal frequency changes from $\omega_0$ (signal bandwidth) to $\omega_0 + \omega_{BF}$ in time $T$. Chirp-UWB signal is generated by a delay lock loop circuit (DDL for short), shown in Figure 1.

![Figure 1. Chirp-UWB signal generation diagram](image)

Chirp pulse mathematical formula:

$$U(t) = \frac{AM}{\sqrt{BT}} \cos(2\pi f_0 t + \frac{\mu f_0}{2} t + \varphi)$$

(1)

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adjusted at the transmitter in necessary. When information is more important, if A is regulated larger (larger amplitude), signal energy will enhance to lead to smaller relative error rate; On other hand, to less important message, A can be tuned relatively small. The parameter is sensitive to noise.

Frequency Modulation (FM for short) - frequency modulation ensures stability to interference. Signal transmission time always occupies the entire available bandwidth, even if the data rate does not need to use entire bandwidth. So this achieves the spread spectrum effect. The disadvantage is the almost twice bandwidth as much as AM.

Phase Modulation (PM for short) - real signal information can be hidden inside different phase. One of main advantages of multi-dimensional multi-access technology is the amplitude of transmission signal can be maintained constant. Solve large bandwidth problems, but the interference problem of carrier frequency still exists.

There is good autocorrelation between UP-chirp signal and DOWN-chirp signal. The autocorrelation expresses:

\[
\psi_c(t) = BT \sin(\sqrt{BT}(1-|t|/T)/\pi BT) \cos(\pi f t), -T < t < T
\]

(2)

So the interaction of Up- and Down-chirp signal is used to the impulse response to filter coherently. The output waveform posses the sharp time domain characteristics, which is compressed by BT-times (called gain compression ratio) compared with the send chirp signal in the time domain, which is equivalent to symbol width decreasing, multipath superposition effect reducing, and inter-symbol interference lowering. Matched filter is designed by the SAW device. The relevant programmed parameters of SAW adjust the amplitude attenuation caused by the actual signal transmission channel and time delay parameters. The received signal includes surrounding noise and severe multipath interference when system adopts traditional Gaussian pulse chirp to detect and communicate. Therefore, UWB communication adopts chirp signal as pulse form. This time-bandwidth product (BT) is much larger than 1, so chirp pulse has strong anti-interference ability during transmission.

Sinc signal: two basic symbols of complementary characteristics are utilized in multi-dimensional multi-access technology to process and transmit. A special nature of two signals is the same spectrum. Sinc pulse is adopted in baseband part of transmitter and receiver. At time of BT=1, the signal possess excellent Time-Bandwidth Product. Based on this unique, fundamental frequency signal chip is the best and generated easily at transmitter. The signal is detected and measured by simple amplitude discrimination at the receiver.

Sinc pulse(baseband): 

\[
U(t) = U_s \frac{\sin(\pi Bt)}{\pi Bt}
\]

(3)

Sinc pulse(radiofrequency):

\[
U(t) = U_s \frac{\sin(\pi Bt)}{\pi Bt} \cos(2\pi f t + \phi)
\]

(4)

CCS signal is usually 2-band. 1us linear frequency sweep at chirp window.
Figure 6 shows 2-ary orthogonal correlation, non-correlation and corresponding simulation error rate of chirp signal. Performance loss is due to very small non-orthogonal between Up- and Down-chirp signal.

CSS physical layer can work in multi-path interference, narrowband or broadband environment. Chirp has anti-interference ability to intrinsically narrow-band interference for its relatively high bandwidth in transverse. Multi-path effects can be reduced by the natural frequency diversity of waveform. Receivers’ correlator can reduce the impact of broadband interference. Forward Error Correction (FEC for short) can further decrease interference and multipath effects.

B CSS signal modulation techniques:

On-Off-Keying (OOK), for example:
Up-chirp = "1"; Null ="0".

Allow two independent coexisting networks.

Superposed chirps (possible states): Null/Up-chirp/Down-chirp/
Superposition of Up- and Down-chirp
Allow one network with double the data rate.

Chirp signals have the following advantages:
(1) Chirp signal generating circuit is simple, and the development meets establishment of interior chirp equipment radiation mask of FCC;
(2) The multi sub-band system is easy realized because which meets sine function characteristics;
(3) In very wide frequency range, without regard to the signal group delay characteristics;
(4) Very strong performance against multipath interference.

III. CSS RANGING AND COMMUNICATION TECHNOLOGY

CSS ranging and communication technologies are mainly applied in the two-way wireless communications of automatic control with close distance, low complexity, low power, low data rate, low-cost. Each CSS ranging data transmission and communication network module is similar to a base station of mobile network. In the context of entire network, they can communicate with each other; in addition, the whole network can also be connected with various kinds of other network. In difference, CSS ranging and communications networks is primarily established for data automatic transmission, and mobile communications network is primarily applied to voice communications. Each CSS network node not only collects and monitors objects directly, such as sensors, but also transfers over data of other network nodes automatically. In addition, each CSS network node connects wirelessly isolated node that does not assume the task of transit network information in their coverage. Each CSS node can support multiple to 31 sensors and controlled devices, which have 8 different interfaces to capture and transmit digital and analog.

CSS wireless networks work in (2.4-2.48Ghz) ISM radio of frequency bands for free (Industrial, Scientific, Medical industry, scientific research, medical), with 16 spread spectrum communication channel, 250K transmission rate, data transfer capabilities, strong anti-interference and highly integrated spread spectrum. It can cover from tens of meters, a few hundred meters to several kilometers. Power consumption is also very small. The sleep state power consumption is only 1uW, and a short distance working state radio draws 30mW. Generally, life of two batteries is up to one year in case of not high frequency to use. The new wireless network Technology, by software designing, may form a wireless dynamics data transmission internet of multi to 65,000 nodes with several interconnected transfer stations. Each station is a network node with its address which can assume the task of sending and receiving, but also undertake the task of data transfer. The whole network connects with the outside
communication system through any network node and supports a variety of existing communication protocols and standards.

System security performance is very good. Hardware itself supports CRC and AES-128. In different from the general mobile communication network, each node is a simple little base station, which can communicate with each other. With automatic addressing and routing functions, doesn’t worry about the problem of localized radio waves block leading to cut off the communication. Through the design of network management software, the entire network realizes monitoring each fixed (or mobile) node in real time. When large amounts data is transmitted, network reduce overall flow by increasing the number of high-speed data export nodes and forming a complex network structure. At the same time, we can increase each node’s own information processing capabilities to reduce the network load, such as increasing node memory, establishing appropriate network unloading point to reduce network.

IV. LOCATION PRINCIPLE ANALYSIS

IEEE802.15.4a positioning process is generally divided into two steps: first, select the appropriate method to measure a distance between known target and base station, and then choose a certain geometric or statistical algorithms to integrate these distance information to determine location of target. IEEE802.15 subcommittee lists the final five positioning methods in accordance with 4a agreement, namely:

- Time Of Arrival (TOA);
- Time Difference Of Arrival (TDOA);
- Signal Strength Ranging (SSR);
- Angle Of Arrival (AOA);
- Near-Field EM Ranging (NFER);

The paper introduces TOA in detail.

A. Location technology (range-based)

1) Multilateral Location

The number of measurement equation is equal to the number of variables on multilateral location (exception: Trilateration). Find the optimal approximate solution, and need to consider the case of no solution. Normal method: least-squares procedure, maximum likelihood method, minimum mean square deviation.

2) Signal strength

The distance is solved through channel model according to estimated distance of signal spread attenuation. On time-varying characteristics of the channel, channel is affected by Multi-path Fading and Non-of-Sight Blockage.

\[
PL(d) = PL(d_o) - 10n \log \left( \frac{d}{d_o} \right) - \sigma
\]

(3) Signal propagation time / time difference

\[
d = (T_1 - T_0) \times V
\]

(a)

\[
d = \left( (T_3 - T_1) - (T_2 - T_0) \right) \times \frac{(V_{RF} - T_{us})}{V_{RF} \times T_{us}}
\]

(b)

\[
d = \left[ (T_3 - T_1) - (T_2 - T_0) \right] \times \frac{V}{2}
\]

(c)

Figure 8. Position calculation

(4) Receive signal phase (PDOA)

By measuring the phase difference, obtain round-trip time, and calculate from round-trip distance.

\[
d = c \cdot \frac{\phi}{2\pi f_c} = c \cdot \frac{\phi}{2\pi} = \lambda \cdot \frac{\phi}{2\pi}
\]

(6)

\[f_c\] - signal frequency, \(\lambda\) - wavelength of transmitted signal, \(\phi\) - phase difference of transmitted signal and reflected signal. Range of \(d\) is \([0, \lambda]\). The phases of
different position distinct $\lambda$, and then receive the same phase.

(5) Near-field electromagnetic ranging
Utilize phase difference of near-electromagnetic fields to measure the distance. RF signal includes electric and magnetic fields.

The scope of distance is between $0.05\lambda \sim 0.5\lambda$ by mean of near-field electromagnetic method, and the best measurement range is between $0.08\lambda \sim 0.3\lambda$.

(6) Received signal angle positioning

B. TOA ranging technology

The basic idea of TOA positioning method is to measure the time from target of transmitting signal to known base station locations, calculate the distance between the two and then get the target position by account synthetically different distances away from the goal to at least three known base station locations.

The time of arrival ranging is rather simple in synchronization propagation system between target and base station. Base station receives the time information locating target sent, and subtracts the time data in database and then multiplies by the propagation speed of electromagnetic wave to get the distance value. System need take into account the offset of two clocks when clocks are not synchronized, which need to the locating base station responds to packet. Show in figure 13.

Node A - target, node B - base station, $tp$ - the signal transmitted time from node A to node B, $t0$- the clock time offset of node B relative to node A clock, $T_{1AT}$ - the first data packet time node A sends, $T_{1BR}$ - the first data packet time node B receives, $T_{2BT}$ - the second data packet time node B sends, $T_{2AR}$ - the second data packet time node A receives($T_{1AT}$, $T_{1BR}$, $T_{2BT}$, $T_{2AR}$ are included in the data transmission). $tp$ is solved by the following equations to measure indirectly distance of A and B.

Equation:

$$ T_{1BR} = T_{1AT} + tp + t0 $$

$$ T_{2AR} = T_{2BT} + tp - t0 $$

$$ tp = \frac{1}{2} \left[ (T_{2AR} - T_{1AT}) - (T_{2BT} - T_{1BR}) \right] $$

$$ t0 = \frac{1}{2} \left[ (T_{2BT} + T_{1BR}) - (T_{2AR} + T_{1AT}) \right] $$

The ranging function completes through the information transmitter retained. Multiple measuring can improve $tp$ and $t0$ value accuracy, allowed to correct frequency offset.
V. RANGING LOCATION TECHNOLOGY

A. TOA location algorithm

When the distance is ranged, moving target locates in the base station as the center of the circle. Ideally, in the two-dimensional space, the location of this moving target can be only intersection of three circles, shown in Figure 14.

\[ d_1 = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} \]  
\[ d_2 = \sqrt{(x_2 - x)^2 + (y_2 - y)^2} \]  
\[ d_3 = \sqrt{(x_3 - x)^2 + (y_3 - y)^2} \]

Statistical algorithm is geometry based on more base stations. After repeated measurement, higher accuracy is acquired with the corresponding statistics algorithm.

B. TOA ranging technology

TOA consists of two technologies: Two Way Ranging (TWR) and One Way Ranging (OWR).

OWR: if nodes have been synchronized to a common clock, measuring distance can be taken One Way Ranging.

\[ \tilde{T}_{OFA} = \frac{1}{2}(T_1 - T_0 - T_{Repl}) \]  
\[ \tilde{d}_{AB} = \tilde{T}_{OFA} \cdot c \]

TWR: two transceivers of non-synchronized clock measure the round-trip transmission time.

Terminal A requests to Terminal B, and then terminal B send information after accepting the signal through prescribing protocol delay and/or processing time.

\[ \tilde{T}_{OFA} = \frac{1}{2}(T_1 - T_0 - T_{Repl}) \]  
\[ \tilde{d}_{AB} = \tilde{T}_{OFA} \cdot c \]

Requestor transmits information with time tag to responder, and then responder back to send a signal to requestor to indicate synchronization completed after receiving and synchronizing this information. At last requestor determines transmission time by receiving end of such signals.

Symmetric double-sided two way (SDS–TWR) ranging is shown in figure 17. Double-sided: both nodes implement the sending and receiving signals process. Symmetrical: the time delay of both nodes is the same (\(T_{replyA} = T_{replyB} \)).
Distance calculation:
\[
d = c \cdot \left( \frac{(T_{\text{roundA}} - T_{\text{replyA}}) + (T_{\text{roundB}} - T_{\text{replyB}})}{4} \right) \tag{18}
\]

Distance Error \((E_{AB})\):
\[
d(1 + E_{AB}) = c \cdot \left( \frac{(T_{\text{roundA}} + 1 + E_{\Delta t}) - T_{\text{replyA}}(1 + E_{\Delta t}) + (T_{\text{roundB}} + 1 + E_{\Delta t}) - T_{\text{replyB}}(1 + E_{\Delta t}))}{4} \right) \tag{19}
\]

The different rates or migration of clock A and clock B causes some problems. Assume +10 ppm for clock A and -10 ppm for clock B. Two clock signal transmission time for large values. Calculated according to (6) formula:
\[
I_p = 0.5 \times (1 \times 1.000060e-3(1+10e^{-6})-1e^{-3}(1-10e^{-6})) = 40e^{-9}
\]

Problem: Difference between large numbers (e.g. 1ms) with different accuracies (+10ns, -10 ns) has high inaccuracy. Result is error. Effect of high inaccuracy after subtracting two large numbers measured with different clocks can be avoided by using SDS–TWR ranging Let’s analyze the calculation of the propagation delay for SDS–TWR.

Using the same example numbers as before, yields result according to (13) formula:
\[
t_p = 0.25 \times (1 \times 1.000060e-3(1+10e^{-6})-1e^{-3}(1+10e^{-6})) + 1 \times 1.000060e-3(1+10e^{-6})-1e^{-3}(1+10e^{-6})) = 30e^{-9}
\]

Correct result is gained.

**TABLE I. RANGING ERROR**

<table>
<thead>
<tr>
<th>d</th>
<th>( \Delta d )</th>
<th>( \Delta T_{\text{reply}} )</th>
<th>( \Delta d )</th>
<th>( \Delta T_{\text{reply}} )</th>
<th>( \Delta d )</th>
<th>( \Delta T_{\text{reply}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10cm</td>
<td>±0.012cm</td>
<td>±0.012cm</td>
<td>±1.2cm</td>
<td>±1.2cm</td>
<td>±120cm</td>
<td>±120cm</td>
</tr>
<tr>
<td>1 m</td>
<td>±0.012cm</td>
<td>±0.012cm</td>
<td>±1.2cm</td>
<td>±1.2cm</td>
<td>±120cm</td>
<td>±120cm</td>
</tr>
<tr>
<td>10 m</td>
<td>±0.05cm</td>
<td>±0.012cm</td>
<td>±1.2cm</td>
<td>±1.2cm</td>
<td>±120cm</td>
<td>±120cm</td>
</tr>
<tr>
<td>100 m</td>
<td>±0.4cm</td>
<td>±0.4cm</td>
<td>±1.2cm</td>
<td>±1.2cm</td>
<td>±120cm</td>
<td>±120cm</td>
</tr>
<tr>
<td>1 km</td>
<td>±4 cm</td>
<td>±4 cm</td>
<td>±4 cm</td>
<td>±4 cm</td>
<td>±120cm</td>
<td>±120cm</td>
</tr>
</tbody>
</table>

Conclusion: Even 20 µs Symmetry Error allows excellent accuracy of distance! Symmetry Error below 2 µs can be guaranteed in real implementations!

VI. CONCLUSION

The precise location technology integrates to apply computer technology, wireless network communication technology, digital signal processing and radio frequency identification technology to achieve precise positioning of personnel and equipment in real time. The wireless network platform based CSS technology adopts protocols combining CSMA / CA and TDMA, and adjusts dynamically transmission rate and frame length according to noise, interference and multipath to ensure optimal throughput and accurate distance information. The platform resolve beyond-the-horizon problems because of the horizontal and vertical bending fluctuations in the coal mine tunnel and work face and realize to identify direction ultimately.

**REFERENCES**


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Yan Zhang was born in Inner Mongolia Autonomous Region China on October 24, 1980. She majored in electrical technology at Liaoning Technical University in Fuxin city, China, and got bachelor’s degree in July 2002. In March 2005, she gained master’s degree on control theory and control engineering at same university.

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