On locating multiple ultrasound emitter in chorus

Lei Song
NEC Labs China
Beijing, China
Email:Song_lei@nec.cn

Yongcai Wang
IIIS, Tsinghua University
Beijing, China
Email: wangyc@tsinghua.edu.cn

***Abstract*—Although TOA based positioning by narrow-band ultrasound is not fairly new as research problem, there are still some open questions. In this paper, an interesting issue, that how to locate multiple ultrasound transmitters simultaneously, is addressed. This problem is difficult because of two reasons. Firstly, Two segments of ultrasound wave on same frequency, if overlapped in time-domain at receiver end, can not be separated efficiently. Secondly, the emitter of narrow-band ultrasound signal can not be identified on the receiver end. To avoid collision and anonymity, emitters are arranged to non-overlapped timeslot in traditional TOA based positioning system. The disadvantage of timeslot based mechanism is obvious, that the refreshing rate drops when number of timeslot increase. In this paper, we reduce the number of timeslots by allowing multiple emitters to send ultrasound signal simultaneously. Although the collision and anonymity of ultrasound signal are still inevitable at receiver end, the position of each emitter can be estimated by assigning the incomplete TOA measurement to several groups and adjust the assignment according to make distance measurements in each group are consistent with each other. As the feasible assignment is exponential to number of emitter, which are intractable to go through, importance sampling and particle filter is used to reduce the number of feasible assignment by taking historical position of each emitter into account. This method is named *UltraChorus* because emitter can "sing" concurrently. The performance of UltraChorus is evaluated by multi-agent simulation.**

I. INTRODUCTION

Using narrow-band ultrasound pulse (NUP) as ranging media for TOA positioning is popular in wireless sensor network, because only basic I/O ability on transmitter/receiver is required to get TOA measurement of high precision. In corresponding system, an ultrasound pulse is generated by transmitter and caught by receiver. By measuring the propagation time of the wave-front, the distance between transmitter and receiver can be obtained in centimeter level[1]. With measured distances the position of emitter can be located if the location of receivers are known. In last decade, there are a lot of research focusing on this topic. In other word, so far, there are quite few thing we can do to improve the performance of narrow-band ultrasound in positioning system except some open issues. Among these issues, the contradict between number of supported emitters and positioning refreshing rate is a interesting one.

In narrow-band ultrasound signal based positioning system, two or more ultrasound transmitters are not allowed to emit signal at the same time. There are two reasons why this constrains exits. First reason is referred as *anonymity* of ultrasound signal. Because there are no room to encode information into a narrow-band ultrasound pulse, receiver can not identify the source of a segment of ultrasound wave. The second reason is referred as *collision* of ultrasound signal. When two or more segments of ultrasound wave from different transmitter overlaps in time domain on the receiver. Only the wave-front of the first one can be identified, while the wave-front of the other are lost. In this case, the number of TOA measurement is less than the number of transmitters.

Because of this two reasons, in previous NUP based positioning systems, such as bat and cricket, transmitters are designed to work in TDMA protocol. In this case, in time slot occupied by ith transmitter, all the receivers only caught one pulse from ith transmitter, therefore the drawback of anonymity and collision is eliminated. But in the other hand, the refresh-rate of location drops linearly to the number of emitter supported in this system. A trade-off between system capacity and positioning delay has to be made.

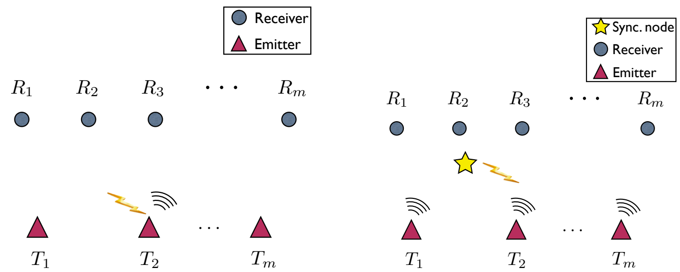
Facing this issue, some research use encoded braodband ultrasound to replace NUP. Both *anonymity* and collision are resolved by employing CDMA technology into both transmitter and receiver[2]. To achieve encoding and decoding, high performance MCU or DSP is required, which increase the cost and reduce the batter-life. Some research try to use the AOA(angle of arrival) as compensate to increase the spatial resolution of receiver to tackle the simultaneously arrived pulse[3]. Both of these method required extra sensor of computing unit.

In this paper a new method to process simultaneously arrived ultrasound pulse is presented. The basic idea is that we doesn't increase the sensing ability of existing system such as cricket and bat, although they produce incomplete measurement when emitters start to work simultaneously. All we want to do is infer the location of target by post-processing on incomplete measurement. More specially, we infers feasible location of each target and find the set of location with maximum likelihood as estimation result. In this process, we reduce the complexity of finding feasible location by involving estimated location of emitters in previous instant as prior-knowledge.

The rest part of this paper is organized as follows, in section 2 the formal statement of problem addressed in this paper is presented. In section 3, the method named *UltraChorus* is proposed as solution to NUP based multi-emitter locating problem. In section 4, the method is evaluated by simulation.

II. PROBLEM MODELING

The system component of TOA based positioning system working in timeslot is illustrated in figure 1(a). m receivers are deployed in fixed spot, whose position is denoted by



(a) Working in timeslot (b) Working in chorus

Fig. 1. The system architecture of TOA Based positioning system working on different mode

$X(R_i), i \in [1, m]$. n mobile emitter can move freely, whose position is denoted by $X_t(T_i), i \in [1, n]$ at instant t. In timeslot occupied by ith emitter, emitter i transmit the NUP and a radio signal at exactly the same time. Each receiver can catch the NUP and radio signal. By measuring the arrival time difference between NUP and radio signal. The distance between T_i and $R_j, j \in [1, m]$, which is denoted by $D_t(T_i, R_j), j \in [1, m]$, can be obtained in one time slot. Briefly, in time slot mode, m distance can be obtained in one time slot. The origin of all distance is T_i. Based on $D_t(T_i, R_j), j \in [1, m]$ and $X(R_j), j \in [1, m]$, $X(T_i)$ can be calculated. As a result, for m emitter, m time slot is required to locate all emitter with certainty.

When system working in chorus mode, the system architecture is shown in figure 1(b). A new component, sync node, is added to the system. Once the sync node broadcast a radio signal at instance t, all receivers, $\{T_1, T_2, \ldots, T_m\}$, emit the NUP simultaneously. In ideal case, on any receiver R_i, m UDP from $T_i, i \in [1, m]$ are pairwise isolated in time domain, therefore we can obtain n distance from receiver R_i. Because the total number of receivers is m, $m \cdot n$ distance, $D(R_i, T_j), i \in [1, m], j \in [1, n]$, can be obtained at instance t.

Although the working in chorus mode can greatly improve the number of distance obtained in one time slot, the *anonymity* and *collision* is inevitable. Even in the ideal mode, because the origin of each distance is unknown, we had to assign the mn distance measurement into m subgroup before positioning. We can find all possible assignment within n round. At round j, we choose one out of m distance reported by each receiver and put them into subgroup j. After n round, the mn distance is separated into m subgroup. We can apply positioning algorithm on each subgroup to get feasible position for each emitter. The number of different assignment is

$$N_a = m!^{n-1} \tag{1}$$

Because the distance in one subgroup are not always consist with each other and can not produce valid position estimation. Most of the assignment are not feasible. But is intractable to go through N_a assignment to find the most feasible one. Briefly, the *anonymity* can introduce complexity that can not be tolerated.

In unideal state, the UDP on each receiver can not be separated in time domain. Because only the first wave-front can be detected, some distance measurement are lost. As a result the distance we can get in one timeslot is less than mn but greater than m. Briefly, the distance set is incomplete due to the *collision* happened in receiver end.

Taking both *collision* issue and *anonymity* issue into account, the formal statement of problem addressed in this paper comes as follow.

Give: location of receivers, $X(R_i), i \in [1, n]$, and incomplete distance measurement $\tilde{D}_t \subset \{D(R_i, T_j), i \in [1, m]\}$ at instant t.

Ensure: let $\mathbf{X}_t(T_{1:m})$ denote the location of m emitters at instant t. Then we want to find the maximum likelihood estimation to $\mathbf{X}_t(T_{1:m})$ condition on $\tilde{D}_t$,

$$\hat{\mathbf{X}}_t(T_{1:m}) = \underset{\mathbf{X}_t(T_{1:m})}{\arg\max}\, p(\mathbf{X}_t(T_{1:m}) | \tilde{D}_t) \tag{2}$$

The brutal force algorithm to solve equation 2 is to go through N_a possible assignment. With each assignment, we can get a candidate for $\mathbf{X}_t(T_{1:m})$

III. Analysis and Algorithm

Determined by the character of NUP, only incomplete and anonymous distance measurement can be obtained on receiver. In this section the character of distance obtained on receiver is analyzed. Although information is not sufficient to locate each emitter directly, we found that solution space of equation 2 can be reduced greatly and solution with maximum likelihood can be found with high probability.

A. *limitation of distance measurement*

As discussed in last section, the incomplete is caused by the overlapping of NUP on receiver end. As shown in figure 2, let t_w denote the width of a NUP and $t_\triangle$ denote the arrival time difference of two successive NUP. When $t_\triangle \leq t_w$, they overlap. To reduce the probability of overlap, the width of NUP should be as small as possible.

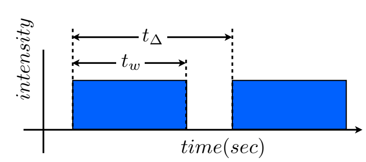


Fig. 2. Two successive NUP are overlapped if the interval is less than width

In practice, the t_w is determined by the length of NUP from emitter and the length of aftershock on receiver end. We measured these two length on Cricket node[1] with oscilloscope. The result is shown in figure 3, in which the upper channel is the wave captured at emitter and the lower channel is the wave captured at receiver end. At emitter end, the length of NUP is about $100\mu s$, while in receiver end this length is about $5ms$. This experiment show that the t_w in Cricket is about $5ms$, any two successive NUP with interval shorter than $5ms$ overlaps with each other. As the NUP is only $100\mu s$ at emitter side, the $5ms$ NUP at receiver is mainly aftershock. As the aftershock is decided by the sensing character of device, t_w can be considered as a constant. Obviously ranging error caused by overlapping is upper bounded by $t_w \times V_u$, if overlapping of 3 or more NUP never happens. Here V_u is the velocity

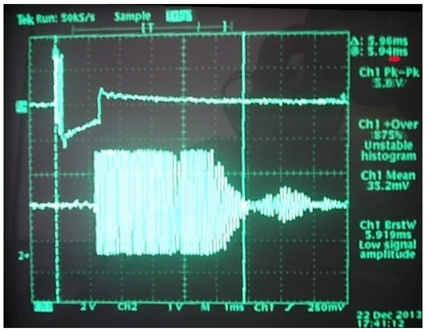


Fig. 3. The NUP on emitter and receiver

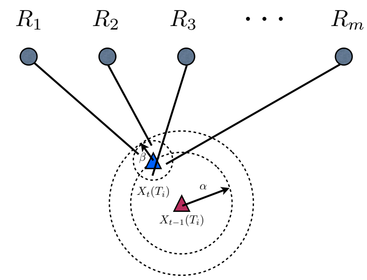


Fig. 4. The feasible arrangement can be inferred from last location and ranging error

of ultrasound. Here we constrains the number of overlapping NUP to guarantee maximum width of overlapped NUP. How to achieve this "at most 2" constrains will be explained later. Taking t_w in Cricket node and V_u in normal condition as example, $t_w V_u = 1.65m$.

B. Limit of emitters' movement

Although the motion of emitter is unpredictable, their trajectory still satisfy basic criteria, says the trajectory of emitter is continuous in spatial. Therefore the location of emitter at t is more close to its location at $t-1$ than the location of other emitter at time $t-1$. I.e., following equation holds,

$$\begin{aligned}&\forall j \in [1,m], j \neq i\\ &p(||X_t(T_i) - X_{t-1}(T_i)|| < ||X_t(T_i) - X_{t-1}(T_j)||) = 1 - \delta\end{aligned} \tag{3}$$

where δ is a small positive number. With equation 3, we can draw the conclusion that positions of T_i at t and $t-1$ are close with high probability. Especially, if a emitter is attached to an object whose maximum velocity known, then $||X_t(T_i) - X_{t-1}(T_i)||$ is upper bounded by positioning interval times maximum velocity with high probability. i.e. $X_t(T_i)$ is in a circle with high probability, whose center is $X_{t-1}(T_i)$ and radius is r_i. Here r_i is determined by sampling interval and velocity of T_i.

C. Location algorithm

By combining limit of distance measurement and of emitters' movement, we can limit the feasible arrangement. As shown in figure 4. The feasible $X_t(T_i)$ is limited to circle $(X_{t-1}(T_i), \alpha), \alpha = V_e \cdot \Omega$, while V_e is the upper bounder of emitter's velocity. For each receiver R_j,there are must be a distance $D_t(R_j, T_i)$ from receiver R_j can reach a point in cycle $(X_t(T_i), \beta), \beta = V_u \cdot T_w$. As a result, following theorem holds.

Theorem 1: For any emitter T_i, given $X_t(T_i)$ and $\tilde{D}_t$. There must be a set of distance $\{\tilde{d}_t^j\} \subset \tilde{D}_t, j \in [1,n]$. Such that $\forall j \in [1,n]$, $\tilde{d}_t^j$ has one end in XR_i and the other ender can reach circle $(X_{t-1}(T_i), \alpha + \beta)$

Proof: Apply limit of distance measurement and limit of emitters' movement together. For each receiver, there must exists one distance measurement with one end fixed on R_i and the other end can reach big circle $(X_{t-1}(T_i), \alpha + \beta)$ ■

Theorem 1 shows that given $X_{t-1}(T_i)$, all distance with T_i as origin at time t should be able to touch the disk $(X_{t-1}(T_i), \alpha + \beta)$. This result can be used to reduce the feasible sub-group. For each disk $(X_{t-1}(T_i), \alpha + \beta)$, the distance which can touch this disk is denoted by $\tilde{D}_t^i$. Obviously $\tilde{D}_t^i \subset \tilde{D}_t$. Suppose in $\tilde{D}_t^i$, there are $m^j, j \in [1,n]$ distances which are obtained by receiver R_j. Then the number of assignment containing in $\tilde{D}_t^i$ is N_a^i, which equals to:

$$\tilde{N}_a^i = \prod_{j=1}^{n} m_j \tag{4}$$

Therefore $\tilde{D}_t^i$ can contribute $\tilde{N}_a^i$ candidate for $X_t(T_i)$. Because m_j is the number of distance obtained by receiver j whose length is constrained in small interval, $m_j < m$ with high probability. We can set $\hat{X}_t(T_i)$ to be the one with maximum likelihood out of $\tilde{N}_a^i$ candidates. Here the likelihood is considered evaluated by taking the validate of trajectory. We give trajectory with more stable velocity more likelihood, which is consist with how target move in practice. Technically, this consideration is achieved by involving particle filter. A Particle $\mathcal{P}_t^k(T_i)$ is a sequence of emitter T_i's position candidate. For each T_i, there are L particle is reserved. Once $\tilde{N}_a^i$ position candidate is obtained at t, each of L particles is concatenated with a new position candidate. Totally, $\tilde{N}_a^i \cdot L$ particles are obtained. These particle are sorted in ascending order of cost function, and only first L is reserved. Suppose the location reserved in particle k for target i is denoted by $X_t'^k(T_i)$,The cost function is as follows:

$$C(\mathcal{P}_t^k(T_i)) = ||(X_t'^k(T_i) - X_{t-1}'^k(T_i)) - (X_{t-1}'^k(T_i) - X_{t-2}'^k(T_i))|| \tag{5}$$

In this estimation process, $X_{t-1}(T_i)$, the latest historical position of T_i, plays an important role. But $X_{t_1}(T_i)$ is affected by cumulated error. To guarantee the accuracy of $X_{t-1}(t_i)$, a accuracy evaluation and reset method is plugged into the location process. As denoted in figure 5, when we got $X_t(T_i)$, the validation of $X_t(T_i)$ is judged. If the judging result is *Yes*, $X_{t-1}(T_i)$ is updated by $X_t(T_i)$. Otherwise, we think $X_t(T_i)$ is not correct estimation. A *reset* process is started. In reset process, each emitter is given a individual timeslot to guarantee the correctness of $X_{t-1}(T_i)$.

As a synthesis, the full algorithm for solving equation 2 is presented. As this algorithm could support multiple emitter sending their NUP simultaneously, it is called *UltraChorus*

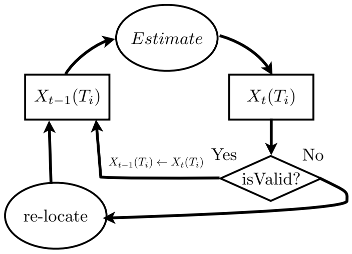


Fig. 5. Plug validation module into locating process

Algorithm 1 UltraChorus

Require: $\tilde{D}_t$ is the set of distance measurement obtained at t. $X(R_i), i \in [1, n]$ is the location of n receivers.

Ensure: $\{\hat{X}_t(R_i)\}, i \in [1, m]$ as the MLE to the location of $R_i, i \in [1, m]$.

if isFirstRound **then**
  Reset();
  isFirstRound $\leftarrow$ FALSE;
  $\mathcal{P}^k(T_i) \leftarrow \emptyset, \forall i = [1, m], k = [1, L]$
end if
for $i = 1, i \leq m; i++$ **do**
  $\tilde{D}'_t(T_i) =\leftarrow \{d | d \in \tilde{D}_t, ||d - ||\}$
end for

IV. Evaluation

V. Conclusion

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