Scheduling in Cooperative UWB Localization Networks Using Round Trip Measurements

Liyuan Song, Tingting Zhang, *Member, IEEE*, Xiaofei Yu, Chuan Qin, and Qinyu Zhang, *Senior Member, IEEE*

***Abstract*— In this letter, we consider the scheduling and resource allocation problems in asynchronous ultra wideband cooperative localization networks, where the round trip measurements are applied for range estimation. A general non-data-aided cooperative scheduling strategy is first presented, where the reply signals can be identified by different frequency bands. Therefore, extra information, such as node IDs and processing times, is not required in the reply signals. We then perform resource optimization based on the scheduling strategy using a high accuracy approximate algorithm. Numeric results validate the analysis. We also find that the importance of cooperative localization increases if the anchors are badly deployed or suffer from significant blockages with agents.**

***Index Terms*— Cooperative localization, scheduling, resource allocation, UWB, optimization.**

I. Introduction

With the development of wireless techniques and applications, location based services attract lots of interests from both academic and industrial researchers. In general location aware wireless networks, there are limited anchors with known positions and a number of agents to be located. Due to the fact that some agents may not be covered by enough anchors,[1] the cooperation that enables range estimation among agents is thus a valuable tool to such problems [1], [2].

High accuracy clock synchronization is challenging in practical wireless networks, so the round trip measurement (RTM) is preferred for range estimation. Searching for the optimal scheduling policy of the asynchronous localization networks is important to the system performance, but also difficult (essentially NP-hard) [3]. In [4], the authors assume that the entire measurement is divided into different time slots. Then the tradeoff between the cooperation delay and the performance advantage is discussed. Furthermore, ref [5] gives link selection and scheduling strategies for UWB localization networks based on the spatial TDMA approach.

In typical location-aware networks (e.g., wireless sensor networks), nodes usually share resources that are subject to constraints, such as power, energy and bandwidth. Appropriate resource allocations can significantly enhance the system performance compared to the simple uniform allocations [6]. Existing works mainly focus on the pure power allocation frameworks, both in the centralized and distributed manners [7].

Furthermore, most existing scheduling strategies are *data aided*, which require separate blocks for ranging and communications in each node [8], [9]. Extra data transmissions increase the system complexity and energy consumption. Thus, it is attractive to present non-data aided scheduling strategies, where the communications overheads can be mitigated. Aiming at the mentioned problems, the main contributions of this letter include

- A *centralized*[2] strategy can be determined and optimized accordingly. non-data aided scheduling framework for asynchronous UWB cooperative localization networks using RTMs is presented. The communications overheads are to be mitigated by proper bandwidth allocations.
- Resource optimization including power and bandwidth is carried out correspondingly using a high accuracy approximate algorithm.
- Numeric results are provided to validate the analysis. Optimal (or sub-optimal) cooperation rules can be obtained based on the presented scheduling framework.

II. System Model

A. Network Settings and Signal Models

Consider a 2-D location-aware asynchronous network consisting of N_a agents and N_b anchors with known positions. The sets of agents and anchors are represented by $\mathcal{N}_\mathrm{a} = \{1, 2, \ldots, N_\mathrm{a}\}$ and $\mathcal{N}_\mathrm{b} = \{N_\mathrm{a}+1, N_\mathrm{a}+2, \ldots, N_\mathrm{a}+N_\mathrm{b}\}$ respectively. The position of node k is denoted by $\mathbf{p}_k$. The agents' positions are to be determined by range measurements (using RTMs) with anchors and other cooperative agents. The entire measurement is divided into short time slots. The slot duration is lower bounded by the measurement time T_RTM, required by all agents to obtain the ranging results. The RTM is performed N_t times. Note that there are two time slots in each RTM, there are totally $2N_\mathrm{t}$ time slots.

The received signal at node j from node k through multipath propagation could be written as.[3]

$$r_{kj}(t) = \sum_{l=1}^{L_{kj}} \sqrt{\frac{P_k}{d_{kj}^{\varrho}}}\alpha_{kj}^{(l)} s(t - \tau_{kj}^{(l)}) + z_{kj}(t), \quad t \in [0, T_\mathrm{ob}) \quad (1)$$

Manuscript received February 6, 2016; revised March 10, 2016 and April 4, 2016; accepted April 11, 2016. Date of publication April 27, 2016; date of current version July 8, 2016. This work was supported in part by the National Natural Science Foundation of China under Grant No. 91338112, No. 61101124, and in part by Shenzhen fundamental research project under Grant No. JCY20150930150341‌85. The associate editor coordinating the review of this letter and approving it for publication was N. Alsindi. *(Corresponding author: Tingting Zhang.)*

The authors are with the Communication Engineering Research Center, Shenzhen Graduate School, Harbin Institute of Technology, Shenzhen 518055, China (e-mail: sly_hit@163.com; zhangtt@hitsz.edu.cn; whyxf2014@163.com; 610776770@qq.com; zqy@hit.edu.cn).

Digital Object Identifier 10.1109/LCOMM.2016.2558499

[1]In 2-D scenario, a minimum of three anchors are required.

[2]A server is assumed to be able to collect all parameters of the network, by which the scheduling.

[3]In this letter, we adopt the IEEE 802.15.4a CM1 channel model as the propagation environment, since it is a typical scenario for UWB ranging.

where P_k is the transmit power of node k, d_{kj} is the distance between node k and j. $s(t)$ is a known transmit waveform. ϱ indicates the pathloss exponent during the transmission. $\alpha_{kj}^{(l)}$ and $\tau_{kj}^{(l)}$ are the normalized amplitude and delay of the l^{th} path respectively. L_{kj} is the number of multipath components in the link. $z_{kj}(t)$ represents the additive white Gaussian noise (AWGN). The observation interval is described by $[0, T_{\text{ob}})$.

B. Error Models in Round Trip Measurements

In the RTMs, we do not consider the clock drift between nodes. The error of RTMs in multipath environments can be modeled as Gaussian distribution. The ranging performance can be described as the ranging information intensity (RII), which is defined as the inverse of the CRLB of ranging errors [10]. RII between node k and j is

$$\lambda_{kj} = \frac{1}{\text{CRLB}_{\text{RTM}}} = \xi_{kj} \frac{4P_k\beta_k^2 P_j \beta_j^2}{d_{kj}^{\varrho}(P_k\beta_k^2 + P_j\beta_j^2)} \tag{2}$$

where P_k and β_k are used to represent the power and effective bandwidth of node k. Note that if the signal waveform is suitably chosen (e.g. sinc-shaped pulses), and the carrier frequency is fixed, effective bandwidth could be equivalent (or proportional) to the real signal bandwidth [11]. The channel gain ξ_{kj} is determined by the channel properties, such as the path overlap coefficient, the normalized amplitude of the direct path (DP) component, signal energy and so on [6], [10]. In order to simplify the presentation, we describe ξ_{kj} as a positive constant without loss of generality, by which the obtained RII can be scaled.

C. Position Error Bound

As defined in [12], the squared position error bound (SPEB) is derived from the equivalent Fisher information matrix (EFIM). The definition of SPEB of agent k is

$$\mathbb{E}\{||\hat{\mathbf{p}}_k - \mathbf{p}_k||^2\} \geq \mathcal{P}(\mathbf{p}_k) \triangleq \text{tr}\{\mathbf{J}_{\text{e}}^{-1}(\mathbf{p}_k)\} \tag{3}$$

where $\mathbf{J}_{\text{e}}(\mathbf{p}_k)$ is the EFIM of agent k's position obtained by measurements, $\hat{\mathbf{p}}_k$ is an estimate of position $\mathbf{p}_k$.

It has been shown in [12] that the EFIM of N_{a} agents in a cooperative localization network can be written as a $2N_{\text{a}} \times 2N_{\text{a}}$ matrix. The $(i, j)^{\text{th}}$ element of the EFIM is

$$\mathbf{J}_{ij} = \begin{cases} \mathbf{J}_{\text{e}}^{\text{A}}(\mathbf{p}_i) + \sum_{k \neq i} \mathbf{C}_{i,k} & i = j \\ -\mathbf{C}_{i,j} & i \neq j \end{cases} \tag{4}$$

In (4), $\mathbf{J}_{\text{e}}^{\text{A}}(\mathbf{p}_k)$ and $\mathbf{C}_{kj}$ are the ranging information (RI) of agent k obtained from all anchors and agent j, respectively, expressed as

$$\mathbf{J}_{\text{e}}^{\text{A}}(\mathbf{p}_k) = \sum_{j \in \mathcal{N}_{\text{b}}} \lambda_{kj} \mathbf{q}_{kj} \mathbf{q}_{kj}^{\text{T}} \tag{5}$$

$$\mathbf{C}_{kj} = \mathbf{C}_{jk} = (\lambda_{kj} + \lambda_{jk}) \mathbf{q}_{kj} \mathbf{q}_{kj}^{\text{T}} \tag{6}$$

where $\mathbf{q}_{kj} = [\cos(\phi_{kj}), \sin(\phi_{kj})]^{\text{T}}$ indicates the angle information between node k and j. SPEB characterizes the fundamental limit of localization accuracy, and is used as the performance metric in this letter.

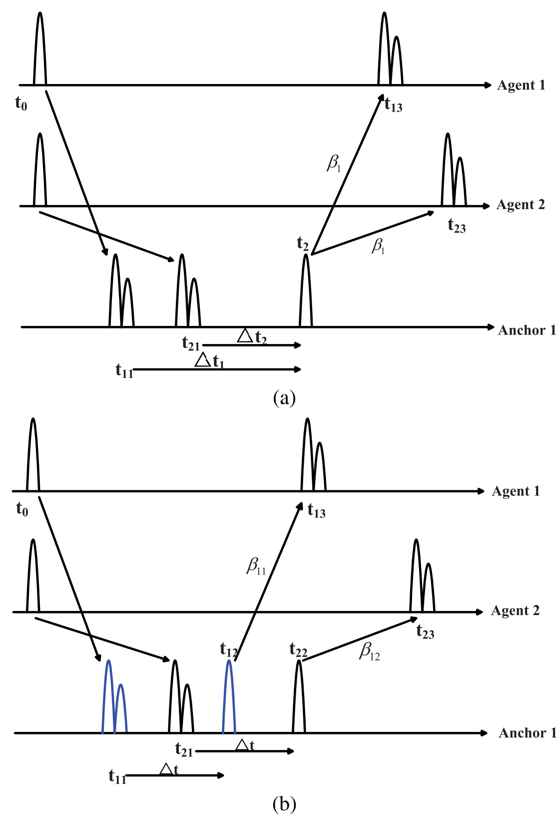

Fig. 1. Scheduling model in the single-RTM scenario. (a) Scheduling using broadcast. (b) The presented strategy.

III. Scheduling in Asynchronous Cooperative Localization Networks

In this part, we first present an improved non-data aided scheduling framework using RTMs, by which the extra auxiliary information such as node IDs and processing times are not required. After that, corresponding resource optimization based on the strategy is performed. A high accuracy approximate algorithm is provided to solve the nonconvex optimization problem.

A. Improved Scheduling Policy Using FDM

In [8], a general scheduling policy using RTMs in asynchronous cooperative localization networks is given as follows.

- In the first time slot, all agents try to initialize the RTMs by broadcasting signals simultaneously with specified power and bandwidth.
- In the second time slot, anchors and *cooperative* agents also reply in a *broadcast* manner.

In Fig. 1(a), anchor 1 replies the signals to agent 1 and 2 in a broadcast manner at t_2. Thus the reply signals are generated simultaneously with the *same* frequency bands (β_1 in Fig. 1(a)). Note that the distances between any two nodes are most likely *different*, it leads to different processing times (Δt_1 and Δt_2 in Fig. 1(a)), which are essentially unknown to the agents. So auxiliary information such as node IDs and processing times are required along with the reply ranging signals.

In order to mitigate the communication overheads, we modify the second step in the scheduling policy using a frequency division multiplexing (FDM) way, i.e., different frequency bands are allocated to the reply signals with respect to different "targets". As shown in Fig. 1(b), the reply signals on β_{11} and β_{12} are to be collected by agent 1 and 2, respectively. So the processing time Δt can be predetermined and known to all nodes beforehand. The information such as node IDs and processing times are thus not required, that reduces the communication overheads.

Remark 1: Compared to the existing broadcast based scheduling, a point to point strategy is applied to improve the network. Although more reply signals are required in the new strategy, the processing time of whole network is fixed for RTMs, which is attractive for system designs.

Remark 2: According to the definition of SPEB, the EFIM can be accumulated from multiple measurements [12]. So this non-data aided scheduling strategy can be extended to the $N_{\rm t}$-RTM scenario, i.e., the agents are active in odd time slots, while anchors and *cooperative* agents reply signals in the even time slots.

B. Resource Allocation

Since the bandwidth is applied in the scheduling policy, we need to perform bandwidth allocation in addition to power allocation. The resource allocation problem can be formulated as follows.

$$\mathscr{P}_1: \ \min. \sum_{k\in\mathcal{N}_{\rm a}} \mathcal{P}(\mathbf{p}_k) \tag{7}$$

$$\text{s.t. } 0 \le P_k^{(2t-1)}, P_{l,k}^{(2t)}, \quad P_{j,k}^{(2t)} \le P_0 \tag{8}$$

$$\sum_{t=1}^{N_{\rm t}} \Big(\sum_{k=1}^{N_{\rm a}} P_k^{(2t-1)} + \sum_{k=1}^{N_{\rm a}} \sum_{l=1}^{N_{\rm a}} P_{k,l}^{(2t)} \Big) \le P_{\rm agent} \tag{9}$$

$$\sum_{t=1}^{N_{\rm t}} \Big(\sum_{j=1}^{N_{\rm b}} \sum_{k=1}^{N_{\rm a}} P_{j,k}^{(2t)} \Big) \le P_{\rm anchor} \tag{10}$$

$$\sum_{k=1}^{N_{\rm a}} \beta_k^{(2t-1)} \le B_0 \tag{11}$$

$$\sum_{l=1}^{N_{\rm a}} \sum_{k=1}^{N_{\rm a}} \beta_{l,k}^{(2t)} + \sum_{j=1}^{N_{\rm b}} \sum_{k=1}^{N_{\rm a}} \beta_{j,k}^{(2t)} \le B_0 \tag{12}$$

where $k, l \in \mathcal{N}_{\rm a}$, $j \in \mathcal{N}_{\rm b}$, $t \in \{1, 2, \ldots N_{\rm t}\}$. $P_k^{(2t-1)}$ and $\beta_k^{(2t-1)}$ are the transmit power and bandwidth of agent k at the odd time slots (in a broadcast way), $P_{l,k}^{(2t)}$ and $\beta_{l,k}^{(2t)}$ are the transmit power and bandwidth from node l to node k at even time slots, respectively.

In the objective function (7) of $\mathscr{P}_1$, we try to minimize the total SPEB of all agents by appropriate resource allocation strategies. Constraints (8) indicates the peak transmit power limit of any individual node. Constraints (9) and (10) show the total power limits for agents and anchors, respectively, in all $N_{\rm t}$ measurements. As indicated in RTMs, in each time slot, the frequency bands occupied by different nodes are not allowed to overlap. Constraints (11) and (12) are thus added to avoid interferences in the odd and even time slot, respectively.

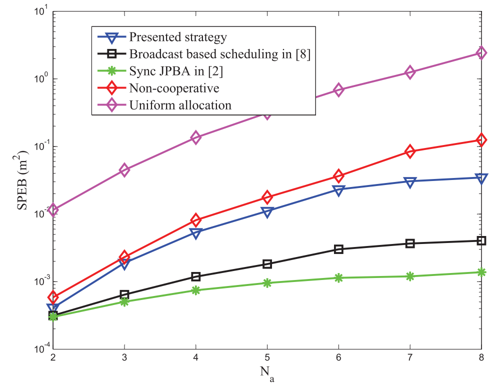

Fig. 2. Accuracy results of the single-RTM scheduling.

C. Optimization Algorithms

Note that $\mathscr{P}_1$ is nonconvex due to the SPEB formulations in the objective functions. So appropriate approximate algorithms are thus required. A Taylor linearization (TL) method based on the trust region approach is presented in [8]. Here we give the main steps of TL. More details could be found in [8] and references therein.

Since the nonconvexity of SPEB is mainly caused by RII in (2), we can perform first order Taylor expansion of λ_{kj} around a certain expansion point. RII can thus be written as

$$\lambda_{kj}(\boldsymbol{\theta}) \approx \lambda_{kj}^{\rm TL}(\boldsymbol{\theta}) = \lambda_{kj}(\boldsymbol{\theta}^{(m-1)}) + \nabla_{\boldsymbol{\theta}} \lambda_{kj}(\boldsymbol{\theta}^{(m-1)}) \Delta\boldsymbol{\theta} \tag{13}$$

combined with the trust region constraint,

$$||\boldsymbol{\theta} - \boldsymbol{\theta}^{(m-1)}|| = ||\Delta\boldsymbol{\theta}|| \le R_{\boldsymbol{\theta}}^{(m)} \tag{14}$$

where $\boldsymbol{\theta}$ represents all parameters to be optimized. m is the index of iteration. $R_{\boldsymbol{\theta}}^{(m)}$ is radius of the trust regions at $m^{\rm th}$ iteration.

By inserting $\lambda^{\rm TL}(\boldsymbol{\theta})$ into RII, an approximated SPEB under Taylor linearization is attained. Then we could solve the approximate TL problem iteratively, until the solution converges.

IV. Numeric Results and Discussions

In this part, we show the numeric results of the presented scheduling problems. The total power for all agents and anchors are both normalized, i.e., $P_{\rm anchor} = P_{\rm agent} = 1$. The bandwidth constraint within one slot is $B_0 = 1$. A network with $N_{\rm a}$ agents and $N_{\rm b}$ anchors are deployed inside a square area with typical wireless personal area network coverage, i.e., $U([0, 20] \times [0, 20])$. The channel gain is derived from IEEE 802.15.4a CM1 channel model. The pathloss exponent is set as 2. Shadowing between agents and anchors are also considered (with an occurrence probability of 0.5). All scheduling problems are solved by the standard solver package CVX [13].

Different scheduling strategies, including the broadcast based scheduling in [8], synchronous joint power and bandwidth allocation (JPBA) in [2], non-cooperative scheduling, and a simple uniform allocation are introduced for performance analysis. Four conclusions can be drawn from Fig. 2, i.e., (i) in asynchronous networks, both cooperative strategies outperform the non-cooperative one.

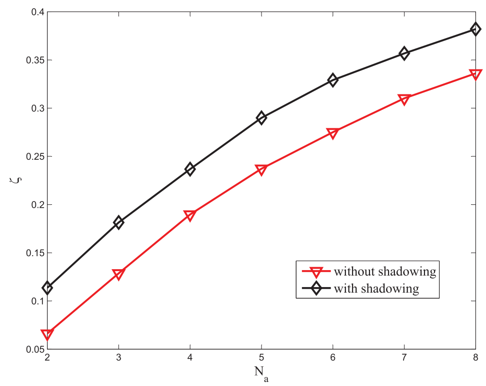

Fig. 3. Resource allocation parameter with respect to the agent number.

It is intuitive, since appropriate cooperation among agents benefits the system performance, which is also the goal for cooperative localization. (ii) The results achieved by broadcast-reply scheduling are better than the presented strategy. The reason is also straightforward according to *remark 1*. The extra communication requirements are not reflected in Fig. 2. (iii) Synchronous networks achieve the best results among all strategies, due to the fact that no reply signals are required in one way ranging. However, high accuracy synchronization is challenging in wireless networks, so the results in synchronous networks are mainly used as benchmarks here. (iv) All optimized strategies are better than the simple uniform allocation approach. It shows that, when the network is subject to resource constraints, proper scheduling and allocation methods are of great importance to localization systems.

The resource allocation results are studied in this part. According to the presented strategy, a resource indicator for cooperation (ζ) is defined as

$$\zeta = \frac{P_{\text{agent-reply}}}{P_{\text{anchor}} + P_{\text{agent}}} \tag{15}$$

From Fig. 3, we could see that, (i) when the agent number increases, the cooperation among agents becomes more and more important. The reason is that, since the anchor number is fixed, when there are too many agents, some of them may be located in "bad" positions, which could not be covered by anchors well. Under this condition, cooperation from other agents becomes an important alternative method. (ii) When shadowing exists between the agents and anchors, cooperation also becomes obvious. It agrees to the observations in [2], that when anchors are severely blocked, in order to achieve the best localization accuracy, more resources will be allocated to agents for cooperation.

V. Conclusion

In this letter, we present a non-data aided scheduling strategy for asynchronous UWB cooperative localization networks. A high accuracy algorithm is proposed to solve the resource allocation problem. According to the results, we can see that (i) the presented scheduling strategy is able to mitigate the communications overheads, which reduces the system complexity. (ii) Appropriate resource allocation is of importance to the system performance when the total resources are limited. (iii) Cooperation among agents becomes more important when the anchors are badly deployed, or blocked by obstacles. These conclusions, and presented strategies provide insights to the practical cooperative localization system development.

References

[1] M. Z. Win *et al.*, "Network localization and navigation via cooperation," *IEEE Commun. Mag.*, vol. 49, no. 5, pp. 56–62, May 2011.

[2] T. Zhang, A. F. Molisch, Y. Shen, Q. Zhang, and M. Z. Win, "Joint power and bandwidth allocation in cooperative wireless localization networks," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2014, pp. 2611–2616.

[3] S. Dwivedi, A. De Angelis, and P. Händel, "Scheduled UWB pulse transmissions for cooperative localization," in *Proc. IEEE Int. Conf. Ultra-Wideband*, Sep. 2012, pp. 6–10.

[4] G. E. Garcia, L. S. Muppirisetty, E. M. Schiller, and H. Wymeersch, "On the trade-off between accuracy and delay in cooperative UWB localization: Performance bounds and scaling laws," *IEEE Trans. Wireless Commun.*, vol. 13, no. 8, pp. 4574–4585, Aug. 2014.

[5] G. E. Garcia, W. Hu, W. P. Tay, and H. Wymeersch, "Joint scheduling and localization in UWB networks," in *Proc. IEEE Int. Conf. Commun. Workshop (ICCW)*, Jun. 2015, pp. 724–729.

[6] W. Dai, Y. Shen, and M. Z. Win, "Distributed power allocation for cooperative wireless network localization," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 1, pp. 28–40, Jan. 2015.

[7] W. Dai, Y. Shen, and M. Z. Win, "Energy-efficient network navigation algorithms," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 7, pp. 1418–1430, Jul. 2015.

[8] T. Zhang, A. F. Molisch, Y. Shen, Q. Zhang, H. Feng, and M. Z. Win, "Joint power and bandwidth allocation in wireless cooperative localization networks," *IEEE Trans. Wireless Commun.*, submitted for publication.

[9] S. Monica and G. Ferrari, "An experimental model for UWB distance measurements and its application to localization problems," in *Proc. IEEE Int. Conf. Ultra-WideBand (ICUWB)*, Paris, France, 2014, pp. 297–302.

[10] Y. Shen and M. Z. Win, "Fundamental limits of wideband localization—Part I: A general framework," *IEEE Trans. Inf. Theory*, vol. 56, no. 10, pp. 4956–4980, Oct. 2010.

[11] C. Qin, L. Song, T. Zhang, Y. Shen, A. F. Molisch, and Q. Zhang, "Joint power and spectrum optimization in wireless localization networks," in *Proc. Int. Conf. Commun. Workshops (ICCW)*, Jun. 2015, pp. 859–864.

[12] Y. Shen, H. Wymeersch, and M. Z. Win, "Fundamental limits of wideband localization—Part II: Cooperative networks," *IEEE Trans. Inf. Theory*, vol. 56, no. 10, pp. 4981–5000, Oct. 2010.

[13] M. Grant and S. Boyd, *CVX Users Guide for CVX Version 1.21*. 2010. [Online]. Available: http://web.cvxr.com/cvx/doc/CVX.pdf