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A Localization and In-flight Alignment Protocol for Airborne SINS Based on Flight-vehicle Wireless Sensor Networks

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Abstract: The necessity recurrently comes to align a strapdown inertial navigation system (SINS) in a moving vehicle to guarantee the accuracy and efficiency in the long run-off of the inertial system after a take-off or launch command is issued. This in-flight alignment is therefore achieved by integrating SINS data with some external aiding source inlcluding airborne navigation equipments and networking sensors. In this paper, a localization architecture and alignment scheme is presented for aircraft in a three-demensional fleet network, which is based on wireless sensor network. Firstly, a 3D node localization scheme is designed based on weighed-multidimensional scaling, which adopt spherical locating in the initial stage, and adaptively choose source nodes with high relative reliability to achieve position update. Then a robust filter algorithm is applied to compensate time-varying delay error and large azimuth uncertainty in alignment. Extensive simulation shows that the DMDG-3D localization scheme can provide highly accurate and relatively reliable navigation information in real time, and $l_2 - l_\infty$ filter algorithm can accelerate convergence and give better estimation of the navigation parameters.

Keywords: Wireless sensor network; 3D localization; Network-assistant; In-flight alignment; Robust filter

1. Introduction

The alignment of a strapdown inertial navagation system (SDINS) is the process whereby the orientation of body frame is determined with respect to the navigation frame[1]. In a broad sense, alignment of SDINS can be classified as initial alignment and in-flight alignment (IFA). The IFA is performed with IMU and external sensors during the vehicle flight[2,3], in which the primary assistant sources are satellite system, radar, or other airborne equipment, offering reference signals like position, velocity, or attitude to assist the alignment process[4,5]. However, these sources have disadvantages in redundancy, independence, stability in signal, which will be incipient faults in emergent take-off or warfare. So it is necessary to design a IFA scheme which can obtain navigation information from a integrative self-organizing system rather than a sort of information source.

With the progress of very-large-scale integration, micro-electro-mechanism system (MEMS) and wireless networking technology, the transition from flatform assistant to network assistant has attracted more attention lately. The envisioned applications of wireless sensor networks in military affairs range widely, such as "smart dust", target tracking, C4ISR et al. There are already some successful fleet networks, including joint tactical information distribution system (JTIDS), MIDS and so on. With the assistance of tactical data link (Link-16 or TTNT), the network can provide precise navigation information including position (or relative position), velocity, heading angle, and system clock. A fleet wireless sensor network is designed in the preliminary job with a integrated protocol architectures (DMDG) whose performance is certified by extensive simulation in literature [6,7]. The finial purpose of this paper is to put forward a localization and in-flight alignment algorithm for application layer which can propose high quality of precision and robustness with time-relay delay error and in-motion vehicles.

In the remainder of this paper, some previous work and evaluation indicator will first be derived in its system model. Then, a new 3D localization scheme will be presented. Following this, in-flight alignment utilizing a Fv-WSN interfusion will be realized based on $l_2 - l_\infty$ robust filter. Finally, conclusions will be presented with the future work.

2. Related work and system model

Before presenting the localization scheme and alignment algorithm, we first give a brief account of important techniques about the Fv-WSN foundation.

Firstly, we specify the Fv-WSN adopting in this paper, which is detailed designed in the previous work [7], and summarized into the following points.

- **Physical layer:** high performance network terminal with send-receiver and preprocessor.
- **Link layer:** TTNT data link, anti-interference, available transfer radius for 50*km*.
- **MAC/Routing:** DMDG protocol (Ref.7), with TDMA/CSMA channel sharing mechanism, multi-hops, GLB-DMECR geographic routing.

Formally, the Fv-WSN is represented as a graph $G=(C,E,R_c)$, which consists of a set of mobile nodes, $C=\{C_1,C_2,\cdots,C_m\}$, a set of wireless links, E, and an adjustable transmission radius R_c. Especially, consider a vector device parameters $\gamma=[\gamma_1,\cdots,\gamma_{k+l}]$. Each device has one parameter. The unknown parameter vector is $\theta=[\theta_1,\cdots,\theta_k]$, where $\theta_i=\gamma_i$ ($i=1,\cdots,k$). Note that $\{\gamma_i, i=k+1,\cdots,k+l\}$ are known.

2.1 Evaluating indicators

The following four components compose the evaluating indicator for localization and in-flight alignment performance, including coverage rate, link consumption indicator, time synchronism, and accuracy, in which the first two indicators have been defined in the previous research [6,7]. In this section, we will discuss the last two indicators[9-14].

- **Time synchronism:** mainly correlated with time-relay delay in transmission[8], which is estimated by send-receiver time, transfer time, and clock deviation et al. To meet the minimum requirements in range error($\le 10m$), relative stability in frequency should less than 10^{-10}, and alignment accuracy in frequency less than 5×10^{-9},then the time-relay delay can meet the minimum base line ($\|\tau\|\le 50ms$).
- **Accuracy:** based on the post-processed relative position error ΔP_{rela}, misalignment angle estimation $(\Delta\theta,\Delta\gamma,\Delta\psi)$, and velocity error estimation $(\Delta V_E,\Delta V_N)$. It is assessed through mean, root mean square (RMS), minimum, or maximum computation.

3. Three-dimensional localization scheme

In this section, we specialize for location estimation using TOA measurement in a Fv-WSN. Specifically, consider l reference and k blindfolded nodes. The node parameters $X=[x_1,x_2,\cdots,x_{k+l}]^T$, where, for 3D system, $x_i=[x_{i1},\cdots,x_{ij}]$, $j=3$. The 3D localization problem corresponds to the estimation of blindfolded node coordinates $\theta=[\theta_x,\theta_y,\theta_z]$.

$$\theta_x=[x_1,\cdots,x_n],\ \theta_y=[y_1,\cdots,y_n],\ \theta_z=[z_1,\cdots,z_n] \quad (1)$$

3.1 Localization scheme discription

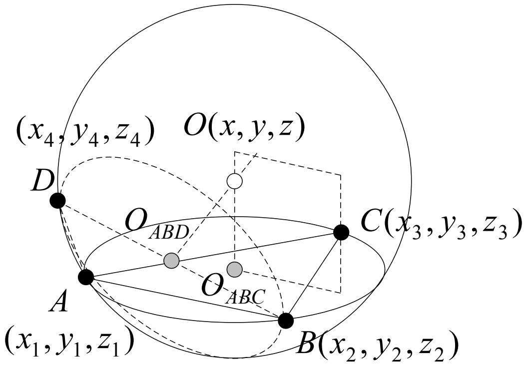
This subsection generally presents the main schedule of the localization scheme, which comprises four steps.

- **Step 1:** Informance gathering. Running in every initiation of its TDMA slot, gathered information involving available neighbor number $(d_{ij}\le 2\cdot r_c)$, 1-hop neighbor's detailed information $(ID, PRI, TS_{CA}, C_{Msg}, V_C\ ,\ \phi_C, t_A, etc)$ (defined in Ref.6), 2-hop relay information (MT, C_{mani}), aggregate a set of neighbor nodes.
- **Step 2:** Geometric localization. Dynamically select four or more neighbors from the set (Step.1) based on *PRI*, *GDOP*, and distance d_{ij}, ranging by TOA, aggregate and update local coordinate $(x_{loc}, y_{loc}, z_{loc})$ by spheric localization algorithm, then establish or renew global relative coordinate.

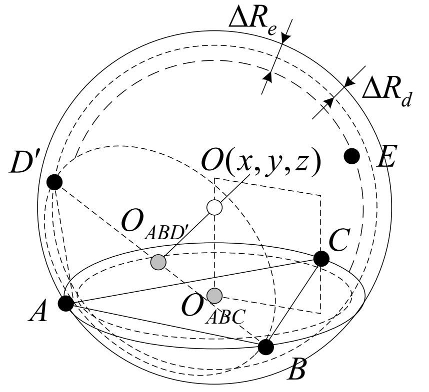
- **Step 3:** Stepwise refinement localization. Perform algorithm in paragraph 3.2, mainly to confirm adaptive weight vector w_{ij}, and obtain partial cost function J_i, which is used to update the global relative coordinate $(x_{rela}, y_{rela}, z_{rela})$, and transform to global geodesic coordinate $(x_{abs}, y_{abs}, z_{abs})$ finally.
- **Step 4:** Upload information. Evaluate the result from Step.3 and decide the cycle index, then broadcast the result by data link (forms in Ref.7).

3.2 3D localization algorithm

As shown in step 2-3, vehicles first get four or more 2-hop neighbors and perform localization procedure based on Theorem.1, then adaptively choose source nodes with high reliability to achieve position update.



(*a*) **Ideal distribution**



(*b*) **Uncosphere distribution**

● Anchor node ● Unknown node ○ Point of intersection

Figure 1. DMDG-3D localization scheme

Theorem 1. Given a sphere O, $O = \{(x, y, z) | x^2 + y^2 + z^2 = r_c^2\}$, $\exists$ $A(x_1, y_1, z_1)$, $B(x_2, y_2, z_2)$, $C(x_3, y_3, z_3)$, $D(x_4, y_4, z_4) \in O$, if reference node A, B, C, D is uncoplaner, as shown in Fig.1, the coordinate of sphere center $O(x, y, z)$ can be calculated uniquely [6, 15-19].

Theorem.1 is proven in Ref.6. Especially, if A,B,C, D is uncosphere or collinear, as shown in Fig.1(b), the coordinate of $O(x, y, z)$ can't be confirmed directly. In this case, we adjust radius r_c to select four or more optimal nodes within the same concentric sphere, e.g, in Fig.1(b), node D is prior to E because $\Delta R_d < \Delta R_c$,and the nodes A,B,C,D' are more approximate to a concentric sphere, then (x, y, z) can be calculated by theorem.1, in which the positional errors in approximation are estimated by least-squares procedure.

Note that we realize the stepwise refinement localization by weighting least squares, as in SMA-COF algorithm[2], in which $\theta = [\theta_x, \theta_y, \theta_z]$ is the minimum optimum solution to partial cost function J_i.

$$J_i = \sum_{j=1, j \neq i}^{k} w_{ij} (\hat{d}_{ij} - d_{ij}(X))^2 + \sum_{j=k+1}^{k+l} w_{ij} (\hat{d}_{ij} - d_{ij}(X))^2 + f(x_i) \tag{2}$$

where w_{ij} is weight vector, $w_{ij} \geq 0$. If there is no available measured value between node i and j, $w_{ij} = 0$. In (2), we substitude the distance value $\left|\hat{d}_{ij}^2 - d_{ij}^2\right|$ into $\left|\hat{d}_{ij} - d_{ij}\right|$ to reduce the magnifying effect in weighting process.

Iterative routine is adopt to get the minimum solution for (2), in which the $(n+1)$'s iterative result can be shown as in (3).

$$x_i^{(n+1)} = [x^{(n)} g_i^{(n)}] / [\sum_{j=1, j \neq i}^{k} w_{ij} + 2 \sum_{j=k+1}^{k+l} w_{ij}] \tag{3}$$

where $g_i^{(n)} = [g_1, \cdots, g_{k+l}]^T$ is weight vector, which is defined as in (4) sectionally.

$$g_j = \begin{cases} w_{ij}[1 - \hat{d}_{ij} / d_{ij}(X^{(n)})], & j \leq k, j \neq i \\ 2 \cdot w_{ij}[1 - \hat{d}_{ij} / d_{ij}(X^{(n)})], & j > k \end{cases} \tag{4}$$

The weighting mechanism is according with relative reliability λ, in which the relative reliability between node i and j can be calculated in (5).

$$\lambda_i(j) = [\Delta RX_i(j)]^{-1} = [\Delta \overline{X}_i(j) + NX_i(i) \cdot \hat{d}_{ij}]^{-1} \tag{5}$$

where $\Delta \overline{X}_i(j)$ is the self-localization error between node i and 1-hop neighbor node j. $NX_i(i)\cdot\hat{d}_{ij}$ is the range error of node i inducted by $\hat{d}_{ij}$. $\Delta RX_i(j)$ is the relative error considering $\Delta\overline{X}_i(j)$ and $NX_i(i)$, which can be calculated in (6-8) particularly.

$$\Delta\overline{X}_i(j)=\frac{1}{m}\sum_{j=1}^{m}\left|\hat{d}_{ij}-d_{ij}\right| \quad j=1,\cdots,m \tag{6}$$

$$NX_i(i)=[\sum_{j=1}^{m}\left|\hat{d}_{ij}-d_{ij}\right|]/\sum_{i=1}^{m}\hat{d}_{ij} \tag{7}$$

$$\Delta RX_i(j)=\Delta\overline{X}_i(j)+NX_i(i)\cdot\hat{d}_{ij} \tag{8}$$

Then w_{ij} can be confirmed in the follow equations.

$$w_{ij}=\lambda_i(j)/\sum_{j=1}^{m}\lambda_i(j) \tag{9}$$

As is shown in (9), the weight vector w_{ij} is direct ratio to relative reliability $\lambda_i(j)$, which can evidently increase effect of the neighbor node with higher relative reliability, and enhance the performance of localization and rate of convergence.

4. In-flight alignment algorithm

With the Fv-WSN operated on DMDG scheme and the real-time position and velocity supplied by DMDG-3D scheme, the alignment for MINS is turning into a traditional integrated alignment problem, which can apply the technique generated from GPS/INS system.

4.1 System description and definitions

In this subsection, we investigate the problem of alignment model for MINS with nonlinear disturbance and uncertain time-relay delay in the output. Consider the following system:

$$\overline{\Sigma}:\quad \begin{aligned} x(k+1)&=A_\lambda x(k)+B_\lambda w(k)\\ z(k)&=H_\lambda x(k)\\ y(k)&=C_\lambda x(k)+D_\lambda w(k)\\ \hat{y}(k)&=r(k)y(k)+(1-r(k))y(k-1)\end{aligned} \tag{10}$$

Here $x(k)\in R^n$ is the state vector; $y(k)\in R^m$ is the measured output, in Fv-WSN/MINS model, $m=9$,ie., three positon errors ($\delta L,\delta\lambda,\delta h$), two horizontal velocity errors ($\delta V_E,\delta V_N$), and four attitude errors ($\delta q_0,\delta q_1,\delta q_2,\delta q_3$); $z(k)\in R^p$ is the signal to be estimated; $w(k)\in R^l$ is a zero-mean white noise with identity power spectrum density matrix; $r(k)\in R$ is a sequence meeting the statistical regularity of *Bernoulli*; $A_\lambda,B_\lambda,C_\lambda$, D_λ and H_λ are appropriately dimensioned matrices.

4.2 Robust l_2-l_∞ filter algorithm

We consider a full-order filter for (10) as follows:

$$\begin{aligned}\hat{x}(k+1)&=A_f\hat{x}(k)+B_f\hat{y}(k)\\ \hat{z}(k)&=C_f\hat{x}(k)+D_f\hat{y}(k)\end{aligned} \tag{11}$$

where $\hat{x}(k+1)$ is the filter state, A_f,B_f, C_f, D_f are filter parameters with compatible dimensions to be determined.

Then we can obtain the following filtering error system:

$$\begin{aligned}x_f(k+1)&=A_{cl}x_f(k)+A_{dcl}x_f(k-1)+B_{cl}\overline{w}(k)\\ e(k)&=C_{cl}x_f(k)+C_{dcl}x_f(k-1)+D_{cl}\overline{w}(k)\end{aligned} \tag{12}$$

where $x(k)=[\delta L\ \ \delta\lambda\ \ \delta h\ \delta v_E\ \ \delta v_N\ \ \delta v_U\ \ \delta q_0\ \ \delta q_1\ \ \delta q_2\ \ \delta q_3]^T$, and $\overline{w}(k)=[\varepsilon_x\ \ \varepsilon_y\ \ \varepsilon_z\ \ \nabla_x\ \ \nabla_y\ \ \nabla_z]^T$, the vector A_{cl}, A_{dcl}, $B_{dc}, C_{cl}, C_{dcl}, D_{cl}$ as defined in [4,5].

Theorem 2. Given scalars $\gamma>0$, and filter parameters A_f , B_f , C_f , D_f .The filtering error system (12) is asymptotically mean-square stable with a prescribed l_2-l_∞ attenuation leval $\gamma>0$, if there exist $\lambda_{11},\lambda_{12},\lambda_{21}$, $\lambda_{22}\in R^1$; positive definite symmetric matrices P_{1i},P_{3i},R_{1i}, R_{3i}, and matrices $P_{2i},R_{2i},V_1,V_2,V_3,\hat{A}_f,\hat{B}_f,\hat{C}_f,D_f$ satisfying

$$\begin{bmatrix}\psi_{11}&\psi_{12}&\psi_{13}&\psi_{14}&\psi_{15}&\psi_{16}\\ *&\psi_{22}&\psi_{23}&\psi_{24}&\psi_{25}&\psi_{26}\\ *&*&-\gamma^2 I&\psi_{34}&\psi_{35}&\psi_{36}\\ *&*&*&\psi_{44}&0&0\\ *&*&*&*&\psi_{55}&0\\ *&*&*&*&*&-a\psi_{55}\end{bmatrix}<0$$

$$(i=1,\cdots,S) \tag{13}$$

where $E=[I_{k*k}\ \ 0_{(n-k)*k}]^T,\psi_{ij}(i,j\le 6)$ is defined as in [20-25].

Then the filtering error system (12) is mean square exponentially stabilized and has the preset H_∞ performance. The filter parameters

A_f, B_f, C_f, D_f in (12) is $A_f = V_2^{-1}\hat{A}_f$, $B_f = V_2^{-1}\hat{B}_f$, $C_f = \hat{C}_f$, $D_f = D_f$.

When the parameters λ_{11}, λ_{12}, λ_{21}, λ_{22} is preset, the formula (13) is simplified as a linear matrix inequality. Then the optimal value of γ can be resolved using LMI Toolbox of MATLAB in real time.

5. Simulation and discussion

5.1 Network operation and experiment setup

The localization procedure begins at the moment of take-off, when the network terminal is starting up and receiving network-assistant information. Then the vehicle climbs up to 1015 meters, and reverts to level flight, $V_{level} = 200$ m/s, till to end of the localization process. Then the vehicle turns into the alignment procedure, which enhances the performance by “S” maneuver, $T_{alignment} \le 40$ s. In this section, we use MATLAB 7.1 to test the proposed 3-D localization scheme and in-flight alignment’s performance, which are based on the Fv-WSN system and DMDG scheme designed before. The main simulation parameters are listed in Table.1.

Table 1. Main Simulation Parameters

Parameters	Values
Network size(r,h)(km)	20,5
The number of sensor nodes	30 or 50
Distribution of sensor nodes	random
MAC/Routing protocol	DMDG
Initial geographic position(E,N,U) (°)	120,30,5
Initial speed of the vehicle(E,N,U) (m/s)	0, 0, 0
Initial attitude angle of the vehicle (φ,θ,γ) (°)	0,0,45
Vibration of the vehicle (m/s)	0.01
Initial misalignment angle of MINS ($\delta\varphi,\delta\theta,\delta\gamma$)	10,1,1
Constant zero-deviation of accelerometer (g)	1×10^{-4}
Constant deviation of gyroscope (°/h)	0.02
Random zero-deviation of accelerometer(g)	5×10^{-6}
Random deviation of gyroscope(°/h)	0.01
Network time-relay delay (τ) (ms)	≤50

5.2 Simulation result and analysis

(1) *Localization performance of DMDG-3D algorithm*

Fig.2 shows the positional error ΔP_r and coverage rate P_{cover} in different range measure error ΔP_r.

When the distribution of the sensor node is random and the message radius $r_c = 5000\ m$, the localization algorithm can guarantee a full coverage in DMDG protocol, while in LEACH protocol the coverage rate had a slight reduction(P_{cover}=80.32% when $\Delta P_r = 40\%$). Positional error in DMDG protocol is probably 1/4 as in LEACH ($\Delta P_a = 1.3\%$ when $\Delta P_r = 5\%$).

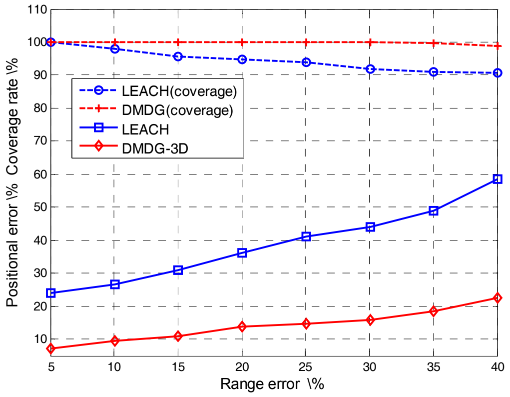


Figure 2. Fv-WSN performance with ranging error

Fig.3 shows the positional error and RMSE with DMDG-3D algorithm when $r_c = 5000$, $\Delta P_r = 50m$, mean square deviation of environment noise $\sigma = 10^{-4}$, and simulated for 500s.

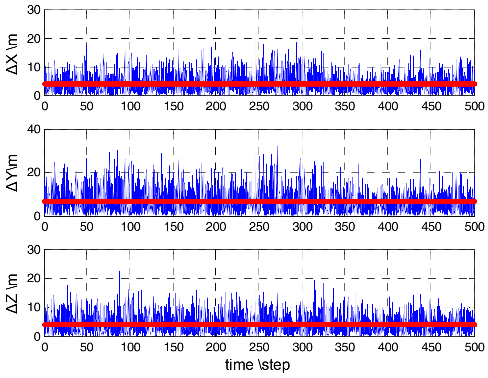


Figure 3. Positional error and RMS error in DMDG-3D

The result is listed in Table.2.

Table 2. Analysis of simulation result

Parameter	$\Delta P_{rela}/\%$	$\Delta P_{abs}/m$	RMSE/m
Δx	0.124	4.041	9.761
Δy	0.263	6.682	13.254
Δz	0.147	4.199	10.675

(2) *In-flight alignment algorithm with* $l_2 - l_\infty$ *filter*

Fig.4 is the comparation of in-flight alignment performance based on robust $l_2 - l_\infty$ filter and EKF when the time-relay delay $\|\tau\| \le 50ms$, and other related initial parameters defined as in Table.1. We first seek the optimum value for the variances in

Theorem.1 with LMI toolbox, obtain $\gamma_{\min}=0.46$, then design the robust l_2-l_∞ filter (11). Simulation results are shown in Fig.4 and detailed performances are listed in Table.3.

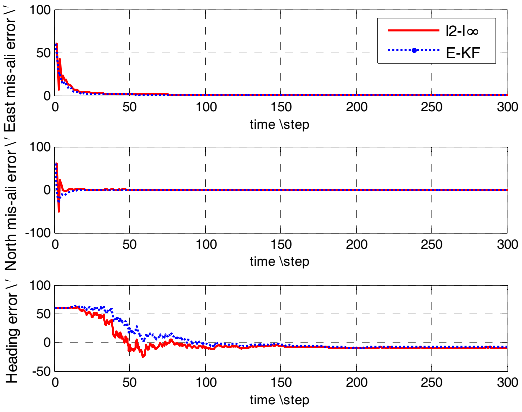


Figure 4 (a). Comparation of misalignment errors between robust l_2-l_∞ filter and EKF

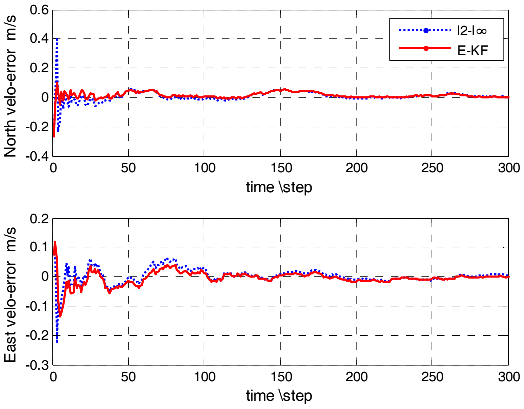


Figure 4 (b). Comparation of velocity errors between robust l_2-l_∞ filter and EKF

Table 3. Analysis of in-flight alignment simulation result based on Fv-WSN

Parameter	$\Delta\theta/''$	$\Delta\gamma/''$	$\Delta\psi/'$	ΔV_E	ΔV_N
EKF	33.76	30.15	5.12	0.023	0.035
12-l∞	21.14	21.01	3.54	0.012	0.022

6. Conclusion and future directions

In this paper we propose a new 3D localization scheme and an in-flight alignment algorithm for aircrafts in fleet network, which is established based on WSN technique and with a DMDG networking scheme. Simulation results show that the weighting localization algorithm can guarantee an accurate position estimation and high coverage in a sparse dynamic network, and the l_2-l_∞ filter can acquire a more rapid and precise calculating results with random time-relay delay. To further improve the accuracy of the localization and alignment, more work should be taken to analyze more complex error including NLOS, and modified topology control arithmetic for load-balance, which will be discussed in our future paper.

Acknowledgments

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