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Cooperative localization in 5G networks: A survey[☆,☆☆]

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Abstract

In upcoming 5G networks, key prospects such as increased bandwidth, smaller cells, higher mobile terminal (MT) densities, multiple radio access technologies, and the capability of device-to-device communication are beneficial for localization. Meanwhile, technologies suggested in 5G, such as massive multiple-in multiple-out, would also benefit from the accurate locations of MTs. Therefore, an opportunity to develop and integrate mobile localization technology in 5G networks has presented itself at this early stage. This paper reviews recent literature relating to localization in 5G networks, and emphasizes the prospect for implementing cooperative localization, which exploits the location information from additional measurements between MTs. To evaluate the accuracy of cooperative localization, a performance evaluation approach is also suggested.

Keywords: Cellular networks; Distributed localization; Line-of-sight (LOS); Relative configuration; Global transformation

Contents

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1. Introduction

Location information in a mobile communication system not only enables various location-based applications, but also helps to improve communication system performance [1–3]. Since 1996, the location of any emergency caller has been required by the FCC's E911 mandate in the US and the E112 directive in the European Union [4]. In 2003, the global system for mobile communication (GSM) association presented three examples of location-based service (LBS), *i.e.*, filtering information (for example, selecting nearby points of interest), showing target location on a map, or automatically activating the service when a target enters or leaves a predefined location [1]. Now, location information has been used in scenarios of business initiatives, inquiry and information services, community services, traffic telematics, fleet management and logistics, mobile marketing, mobile gaming, value-added services, as well as location-aware communications [5].

However, the performance of various location-based applications depends on the location accuracy [6]. By using a commercial global navigation satellite system (GNSS), approximately 5-m accuracy can be achieved in the outdoors, where a good view of the sky is available. For localization indoors or in dense urban settings, wireless local area network (WLAN) fingerprinting techniques result in a 3–4 m accuracy, while a huge database of signal fingerprints should be maintained. For 5G networks, an accuracy on the order of 1 m or below has been suggested in a 5G forum white paper [7].

For cellular networks, location service, also known as mobile phone tracking, is supported in 2G and 3G networks through radio resource control (RRC), radio resource location services protocol (RRLP), and IS-801 to meet the requirements of emergency services and commercial applications [8]. In the current 4G long-term evolution (LTE) standards, three independent handset-based positioning techniques, *i.e.*, assisted GNSS, observed time-difference-of-arrival (TDOA), and enhanced cell ID (ECID), are supported [9], where LTE Positioning Protocol (LPP) is implemented to enable positioning over LTE.

Five disruptive technologies would be adopted in 5G, *i.e.*, device-centric architectures, millimeter wave, massive multiple-in multiple-out (MIMO), smarter devices, and native support for machine-to-machine (M2M) communications. Most of them would be beneficial for localization [10]. For example, device-centric architectures improve the densities of base stations (BSs) or access points (APs), which serve as anchors/beacons to provide sufficient line-of-sight (LOS) links to mobile terminals (MTs). Millimeter wave increases the frequency and bandwidth, which increases not only the accuracy of TDOA measurements, but also the resolution of the multipath. Massive MIMO enhances the directional measurement between BSs and MTs and even enables constructing multiple antennas on MTs. Smarter devices admit device-to-device (D2D) communications, which provide a large number of extra LOS links between MTs. Last but not least, native support for M2M communications extends the localization from MTs to a large number of connected devices.

Dense networks and D2D communications enable implementing cooperative localization in 5G networks. Cooperative localization emerges as a self-localization technique in wireless sensor networks (WSNs) and ultrawide bandwidth (UWB) networks [11–13]. This technique is attractive for short- or medium-range localization, especially in indoor or other GNSS-denied scenarios. Based on the internode measurements, each node can obtain its location information relative to each other, and transform the relative location into an absolute one when global reference information is available. In a 5G scenario, D2D communication links can be used to extract direction or range measurements between MTs, and a large number of BSs offer sufficient global reference information. In particular, the distributed manner of cooperative localization reduces the time delay used to get the locations of nearby nodes, which is essential for performing certain intelligent controls, such as self-driving.

This paper is organized as follows. In Section 2, we introduce the localization in 5G networks, including some new technologies beneficial for localization, an MIMO channel model for deriving range and direction measurements, and the prospects for location-awareness. Emphasis on cooperative localization is detailed in Section 3, with a performance evaluation tool given in 4. Finally, Section 5 concludes this paper.

2. Localization in 5G networks

2.1. 5G networks

5G is arriving around 2020. Compared to current mobile communication systems, new technologies would be adopted. These technologies may provide 10–100$\times$ higher user data rate, 1000$\times$ higher mobile data volume per area, 10–100$\times$ higher number of connected devices, 10$\times$ longer battery lifetime, and 5$\times$ reduced end-to-end latency [14]. Apart from these achievements related to communications, it has been reported that network-based localization in three-dimensional space would be supported in 5G, with accuracy from 10 m to less than 1 m on 80% of occasions, and better than 1 m for indoors [7]. Using such accurate location information, 5G would be the first generation to benefit from localization in wireless network design and optimization [2].

It should be noted that network-based localization would be supported in 5G. In previous generations, localization performed on MTs did not achieve appropriate accuracy, especially in indoor scenarios. To cope with this problem, network-based localization is preferred, where idle period downlink (IPDL) is implemented in the 3G standard UMTS to increase adjacent BS hearability, and position reference signals (PRSs) are specified in LTE Release 9. Now, 5G development is in the early stages. There is an opportunity to develop and integrate mobile radio-based localization technology in 5G from the beginning. With an initial integration of appropriate technologies corresponding to both communication and localization, location-aware communication could be realized and a large number of LBS services could be natively supported. By missing this opportunity, a huge investment may be required to obtain location information with limited coverage and accuracy, and the contribution to communication and potential economic services will be greatly reduced.

Some innovative technologies related to localization are listed below.

1. Smaller Cells: Cell size has shrunk from hundreds of square kilometers in first generation (1G) cellular networks to fractions of a square kilometer in urban areas to date. In 5G, there would be nested small cells, such as picocells (range under 100 m) and femtocells (WiFi-like range), as well as distributed antenna systems (similar coverage to picocells) [15]. In small cells, radio channels are dominated by the LOS-path. For example, a channel model constructed by extensive measurement campaigns in the 3rd generation partnership project (3GPP) employs a channel model based on extensive experiments, which sets the LOS probability higher than 0.7 for a maximum distance of 35 m.
2. Higher Frequencies and Signal Bandwidths: From CRLB analysis, the variance of the TOA measurements is lower bounded as

$$\mathrm{var(TOA)} \geq \frac{1}{8\pi^2 B T_s F_c^2 \mathrm{SNR}} \tag{1}$$

for a signal with bandwidth B (Hz) which is much lower than the center frequency F_c (Hz) and owns a constant signal-to-noise ratio (SNR) over the signal bandwidth, where T_s is the duration of the signal. This indicates that higher frequencies and signal bandwidth improve the TOA measurement accuracy. Moreover, higher signal bandwidths allow a better resolution of multipath components, which increases the probability to find LOS path and thus reduces the error caused by multipath biases. Higher carrier frequencies, in particular in the mm-wave spectrum, are dominated by the LOS receptions since any NLOS path is prone to be blocked. This reduces the bias caused by misusing NLOS paths. Furthermore, higher frequencies enable massive MIMO schemes, which could provide extra direction measurements by setting multiple antennas on individual terminals.
3. Higher MT Densities and Device-to-Device Communications: The character of dense MTs with D2D communication capability distinguishes 5G from previous cellular networks in facilitating high-accuracy localization. Through synchronization or channel estimation between MTs, internode measurements can be extracted to derive location information relative to each other. As the number of connected MTs increases, the internode measurement number increases with the square of the MT number. Since connected MTs are near, more LOS paths with sufficient SNR could be observed to substitute the faint NLOS measurement from distant BSs. Additionally, D2D communications allow the exchange of necessary data, which can be used to distribute the localization task, share channel information, transfer location information, and set up anchors (terminal with known locations). Simply put, cooperative localization would be a naive choice in 5G networks.

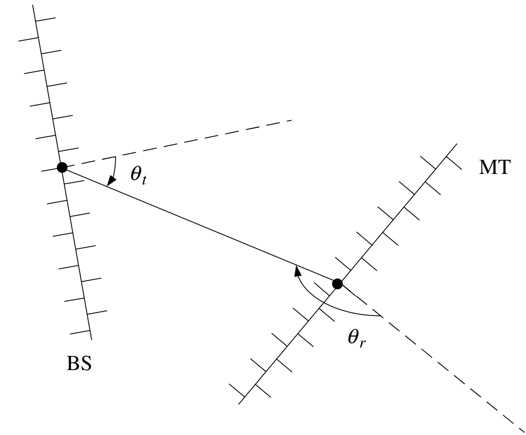

Fig. 1. Two-dimensional MIMO channel: The distance between the antennas of the transmitter and the receiver, the AOD θ_t, and the AOA θ_r are estimated by receiving the transmitted signals.

2.2. Measurement model

With the development of MIMO technologies, multiple antennas appear on the BSs as well as MTs. Here, we consider a general case where a transmitter and a receiver are equipped with N_t and N_r antennas respectively, seen in Fig. 1 [16]. This constitutes an MIMO system when neither N_t nor N_r is degenerated to 1.

Suppose the signal to be transmitted is composed of M_t beams at time t, denoted by $\mathbf{x}(t) = [x_1(t), \ldots, x_{M_t}(t)]^T \in \mathbb{C}^{M_t}$. It is transmitted over N_t antennas through a beamforming matrix $\mathbf{F} = [\mathbf{f}_1, \mathbf{f}_2, \ldots, \mathbf{f}_{M_t}] \in \mathbb{C}^{N_t \times M_t}$ as $\mathbf{Fx}(t)$. Under the assumption of narrowband communication, the channel can be expressed as an $N_r \times N_t$ matrix

$$\mathbf{H} = \sqrt{\frac{N_t N_r}{\rho}} h \mathbf{a}_r(\theta_r) \mathbf{a}_t^H(\theta_t), \tag{2}$$

where ρ is the path loss between the transmitter and the receiver, h is a complex gain of the LOS path, and $\mathbf{a}_t(\theta_t) \in \mathbb{C}^{N_t}$ and $\mathbf{a}_r(\theta_r) \in \mathbb{C}^{N_r}$ are the antenna steering and response vectors with angle-of-departure (AOD) θ_t and angle-of-arrival (AOA) θ_r respectively.

In practice, $\mathbf{a}_t(\theta_t) \in \mathbb{C}^{N_t}$ and $\mathbf{a}_r(\theta_r) \in \mathbb{C}^{N_r}$ depend on the arrangement of the antennas. For example, when a uniform linear array (ULA) is considered, the vector $\mathbf{a}_t(\theta_t)$ can be written as

$$\mathbf{a}_t(\theta_t) = \frac{1}{\sqrt{N_t}} \left[1, e^{j\frac{2\pi}{\lambda} d \sin(\theta_t)}, \ldots, e^{j(N_t-1)\frac{2\pi}{\lambda} d \sin(\theta_t)}\right]^T \tag{3}$$

and vector $\mathbf{a}_r(\theta_r)$ can be expressed similarly, substituting the subscript t with r in (3).

Through the channel $\mathbf{H}$, the signal observed by N_r antennas on the receiver is given by

$$\mathbf{y}(t) = \mathbf{HFx}(t-\tau) + \mathbf{n}(t), \tag{4}$$

where $\mathbf{y}(t) \in \mathbb{C}^{N_r}$, τ is the propagation delay between the transmitter and the receiver, and $n(t) \in \mathbb{C}^{N_r}$ is a Gaussian noise vector with zero mean and two-side power spectral density $N_0/2$.

Based on (4), one can estimate the delay τ, AOD θ_t, and AOA θ_r from the observed $\mathbf{y}(t)$ and the known pilot signal $\mathbf{x}(t)$, and even obtain the location of the transmitter under the known receiver location (or vice versa). Here, it should be pointed out that there exists a time offset between the transmitter and the receiver, which needs to be eliminated through TDOAs of multiple synchronized receivers, just like the method used in GNSS localization. The channel coefficient h can also be estimated, while it may be used in communication.

2.3. Prospects of location-awareness

With sufficiently precise location information, 5G networks would be the first generation to benefit from location information [2]. Despite the improved location-based service or even cyber-physical systems such as robotics and intelligent transportation systems, location information can aid in solving certain technical challenges in 5G, complementarily to existing and planned technological developments. Some of these aspects are listed below.

- Path Loss: Owing to the path loss, the received power reduces when distance increases. Location knowledge, and thus distance knowledge, serves as an indication of the SNR level, which helps to select a nearby BS or an optimal multi-hop path between a source–destination pair.
- Shadowing: The shadowing effect occurs when the received signal power fluctuates owing to objects obstructing the propagation path. It depends on the locations of the transmitter and the receiver, where local channel information can be explored through nearby terminals.
- MIMO: Beamforming in an MIMO system combines a multiple-antenna phased array such that signals at particular angles experience constructive interference while others experience destructive interference. These angles can be derived by the location knowledge, which is used to achieve spatial selectivity.
- Propagation Delay: The signal propagation delay can be obtained by dividing the distance by the known signal propagation speed.
- Doppler: Velocity, the first derivative of the location with respect to time, determines the Doppler shift of the received signal.
- Spatial Interference: To minimize the interference to other users, the transmit power, frequency band, and even the direction of beamforming can be efficiently adapted to the known locations of nearby users.
- Routing: Geographic routing moves data packets to their intended destination, relying on geographic location information. With this information, a message can get to the destination without knowledge of the network topology or a prior route discovery.
- Proactive Allocation: Location-aware resource allocation techniques can reduce overheads and delays by predicting channel quality.

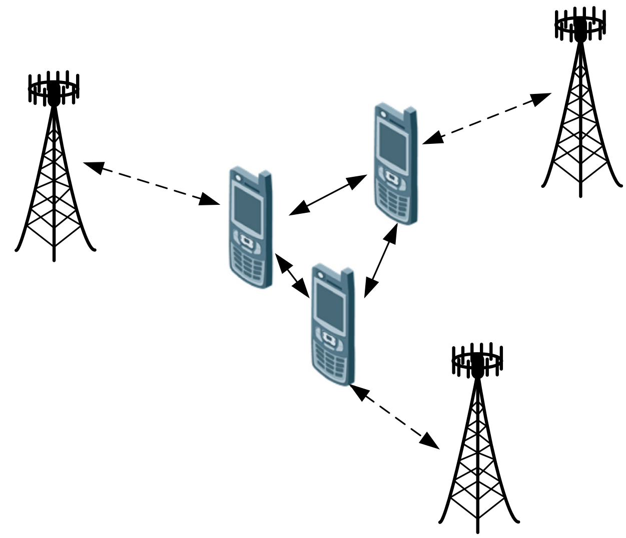

Fig. 2. Cooperative localization: Communication links between the BSs and MTs, as well as the links between the MTs, can all be collected to exploit the locations of the MTs, where BS locations are assumed to be known.

3. Cooperative localization

D2D communications allow performing cooperative localization in 5G networks [17]. As seen in Fig. 2, the inter-MT links provide relative location information between the MTs, which serve as a supplement to the BS–MT links.

3.1. Problem formulation

Suppose a 5G network composed of N nodes, which consist of MTs, BSs, APs, or any object capable of emitting/receiving radio signals. From the radio signals, the receiver can extract the relation between the locations of the receiver and the transmitter by measuring or estimating one or more signal metrics, *e.g.*, connectivity, range measurements, and angle measurements. Using these measurements, one can estimate the locations of the nodes, perhaps needing some reference information, such as anchors (nodes with known locations).

Internode measurements provide only partial location information [18,19]. For example, connectivity involves no information on the network scale, orientation, and global location, range measurements specify the network scale but still cannot point out network orientation and global location, and bearing measurements determine the orientation of the network. To get absolute locations, global reference information provided by the known locations of BSs should be involved [20–22].

3.2. Localization update

In the location update process, measurements are aggregated to provide inputs to a localization algorithm. Then, the location information can be derived in following manners [11].

- Centralized Versus Distributed: In centralized localization, all measurements are transferred to BSs, and a central processor determines the locations of the nodes. Owing to the cellular architecture of a 5G network, the centralized localization is feasible to localize cheaply with limited computation and/or memory resources, and can provide high accuracy by fusing GPS locations or local signal fingerprints. In distributed localization, nodes infer their own locations based only on locally collected information. The information includes the internode measurements among the nodes nearby, together with the nearby node locations. Distributed algorithms are scalable and thus attractive for large networks with a limited number of BSs. Moreover, distributed localization avoids the time delay in uploading measurements and downloading locations, which is crucial for some applications, such as self-driving.

- Absolute Versus Relative: Absolute localization refers to providing location information in a predefined coordinate system. The coordinate system is usually given by a geographic coordinate system, such as latitude, longitude, and elevation in GPS localization or implied in anchor locations. Relative localization provides location information in the context of ones neighbors or local environment. Without a given coordinate system, relative location is also known as relative map [19] or relative configuration [18,23]. Some details can be found in Section 4.
- Noncooperative Versus Cooperative: Noncooperative localization determines the locations of MTs based on only the measurements between MTs and BSs, without the internode measurements between MTs. To get the locations, multiple BSs are required. As a result, specific settings, such as IPDL in the 3G standard UMTS, should be involved to increase adjacent BS hearability. In cooperative localization, D2D communications remove the need for all MTs to be connected to multiple BSs, thus long-range BS transmissions are replaced with multi-hop communications among the densely located MTs. Since D2D links have higher SNR and lower probability of NLOS path, cooperative localization can offer increased accuracy and coverage compared with noncooperative localization.

4. Performance evaluation

The internode measurements specify only the relative locations of the nodes. To investigate their contributions, the concept of relative configuration is introduced [18] to represent the relative locations, while the global transformation represents certain global attributes of absolute locations. However, the definitions of the relative configuration and the global transformation depend on the measurement types [23]. To be clear, the definitions corresponding to the range measurements are provided here, which would be the most common used in 5G localization.

4.1. Definitions

The global transformation is defined by the congruence/rigid transformation of a network composed of N nodes with location vector $\mathbf{s} = [s_{1,x}, s_{1,y}, \ldots, s_{N,x}, s_{N,y}]^T$, which is given as [24]

$$\mathcal{T}(\mathbf{s}) = \mathbf{\Gamma s} + x\mathbf{1}_x + y\mathbf{1}_y, \tag{5}$$

where the total rotation/reflection matrix $\mathbf{\Gamma} = \mathrm{diag}(\mathbf{\Gamma}_0, \mathbf{\Gamma}_0, \ldots, \mathbf{\Gamma}_0)$ is a $2N$-by-$2N$ block diagonal matrix whose 2-by-2 diagonal blocks are $\mathbf{\Gamma}_0$, which is a 2-by-2 orthogonal matrix indicating a global rotation/reflection operation, $\mathbf{1}_x = [1, 0, \ldots, 1, 0]^T \in \mathbb{R}^{2N}$, $\mathbf{1}_y = [0, 1, \ldots, 0, 1]^T \in \mathbb{R}^{2N}$, and x and y indicate the translation parameter in the x and y directions, respectively.

The relative configuration captures the relative location information of the N nodes. It is defined as invariant object to the congruence/rigid transformation (5). Mathematically, it forms an equivalence class with respect to the global transformation.

4.2. Coordinate representation

The relative configuration and global transformation are non-Euclidean objects. They cannot be represented in a global coordinate system. To investigate some of their properties, a reference vector $\mathbf{r} = [r_{1,x}, r_{2,y}, \ldots, r_{N,x}, r_{N,y}]^T \in \mathbb{R}^{2N}$ is induced to specify a local coordinate system of the relative configuration and the global transformation.

The coordinate representation of the global transformation of $\mathbf{s}$ is defined by partial Procrustes fitting [25] $\mathbf{r}$ onto $\mathbf{s}$ as

$$\mathbf{r_s} = \arg\min_{\mathcal{T}(\mathbf{r})} \|\mathbf{s} - \mathcal{T}(\mathbf{r})\| = \mathbf{\Gamma}^\star \mathbf{r} + x^\star \mathbf{1}_x + y^\star \mathbf{1}_y. \tag{6}$$

Geometrically, this partial Procrustes fit can be viewed as superimposing a known relative configuration given by $\mathbf{r}$ onto $\mathbf{s}$. In (6), $\mathbf{\Gamma}^\star$, $x^\star$ and $y^\star$ can be derived in closed form [24].

The coordinate representation of the relative configuration of $\mathbf{s}$ is defined by partial Procrustes fitting [25] $\mathbf{s}$ onto the reference $\mathbf{r}$ as

$$\mathbf{s_r} = \arg\min_{\mathcal{T}(\mathbf{s})} \|\mathbf{r} - \mathcal{T}(\mathbf{s})\|. \tag{7}$$

This operation can be viewed as superimposing the configuration onto a reference $\mathbf{r}$. A closed-form solution is given in [23].

4.3. Error metric

For any estimate of $\mathbf{s}$, denoted by $\hat{\mathbf{s}}$, one can derive $\hat{\mathbf{s}}_\mathbf{r}$ and $\mathbf{r}_{\hat{\mathbf{s}}}$ as the coordinates of the relative configuration and the global transformation. Under these two coordinate systems, the squared distances between the coordinate representations, *i.e.*, $\|\hat{\mathbf{s}}_\mathbf{r} - \mathbf{s}_\mathbf{r}\|^2$ and $\|\mathbf{r}_{\hat{\mathbf{s}}} - \mathbf{r}_\mathbf{s}\|^2$ evaluate the estimation error of the relative configuration and global transformation.

The coordinate representation depends on the reference $\mathbf{r}$. Which $\mathbf{r}$ is the best? In practice, it is suggested to set the reference $\mathbf{r}$ at the true location $\mathbf{s}$. In this case, $\|\hat{\mathbf{s}}_\mathbf{r} - \mathbf{s}_\mathbf{r}\|^2$ and $\|\mathbf{r}_{\hat{\mathbf{s}}} - \mathbf{r}_\mathbf{s}\|^2$ can be simplified as $\epsilon_r = \|\hat{\mathbf{s}}_\mathbf{s} - \mathbf{s}\|^2$ and $\epsilon_t = \|\mathbf{s}_{\hat{\mathbf{s}}} - \mathbf{s}\|^2$, named relative error and transformation error [24]. Here, it should be noticed that $\|\hat{\mathbf{s}}_\mathbf{s} - \mathbf{s}\|^2$ plus $\|\mathbf{s}_{\hat{\mathbf{s}}} - \mathbf{s}\|^2$ does not equal the squared error $\epsilon = \|\hat{\mathbf{s}} - \mathbf{s}\|^2$, where a different definition of relative and transformation errors [18] holds. Some geometric properties of the relative and the transformation errors can be found in Fig. 3.

As an important benefit of introducing the relative configuration and the global transformation, CRLB analysis for

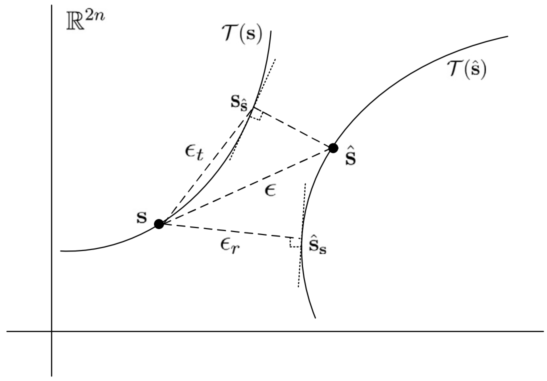

Fig. 3. Relative and transformation error: The relative error ϵ_r quantifies the distance from $\mathbf{s}$ to the relative configuration trajectory of $\hat{\mathbf{s}}$. The transformation error ϵ_t refers the squared distance between $\mathbf{s}$ and its global transformation closest to $\hat{\mathbf{s}}$.

the corresponding coordinate representations and relative-transformation errors defined both in [18,24] can be performed to derive a benchmark localization algorithm [24,26].

5. Conclusion

Seamless localization can be realized in the era of 5G. Through D2D communications, MTs can determine their locations in a cooperative manner, which would not only increase the localization accuracy, but also decrease the time delay. Moreover, other technologies envisaged in 5G are also beneficial for implementing accurate localization. MIMO technologies offer direction measurements, dense networks lead to a large number of LOS links, higher signal bandwidths improve the accuracy of range measurements, and higher carrier frequencies increase the resolution of multipaths. In addition to communication, it could be expected that localization, especially cooperative localization, would be an important feature in 5G networks.

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Conflict of interest

The authors declare that there is no conflict of interest in this paper.

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